



DPC: 24/30443602 DC

**BSI Group Headquarters**

389 Chiswick High Road London W4 4AL

Tel: +44 (0)20 8996 9000

Fax: +44 (0)20 8996 7400

www.bsigroup.com

Date: 14 March 2024

Origin: European

**Latest date for receipt of comments: 13 May 2024**

Project No. 2021/02450

Responsible committee: CB/203 Design &amp; execution of steel structures

Interested committees:

Title: Draft BS EN 1993-4-2 Eurocode 3. Design of steel structures. Part 4-2: Tanks.

Please notify the secretary if you are aware of any keywords that might assist in classifying or identifying the standard or if the content of this standard

- i) has any issues related to 3rd party IPR, patent or copyright
- ii) affects other national standard(s)
- iii) requires additional national guidance or information

**WARNING: THIS IS A DRAFT AND MUST NOT BE REGARDED OR USED AS A BRITISH STANDARD. THIS DRAFT IS NOT CURRENT BEYOND 04 June 2024**

This draft is issued to allow comments from interested parties; all comments will be given consideration prior to publication. No acknowledgement will normally be sent. **See overleaf for information on the submission of comments.**

No copying is allowed, in any form, without prior written permission from BSI except as permitted under the Copyright, Designs and Patent Act 1988 or for circulation within a nominating organization for briefing purposes. Electronic circulation is limited to dissemination by e-mail within such an organization by committee members.

Further copies of this draft may be purchased from BSI Shop <http://shop.bsigroup.com> or from BSI Customer Services, Tel: +44(0) 20 8996 9001 or email [cservices@bsigroup.com](mailto:cservices@bsigroup.com). British, International and foreign standards are also available from BSI Customer Services.

Information on the co-operating organizations represented on the committees referenced above may be obtained from <https://standardsdevelopment.bsigroup.com/>.

Responsible Committee Secretary: Ms Aský Desta (BSI)

Direct tel: 0208 996 7171

E-mail: [asky.desta@bsigroup.com](mailto:asky.desta@bsigroup.com)

Full document details: 24/30443602 DC

## Introduction

This draft standard is based on national and international discussions. Your comments on this draft are invited and will assist in the preparation of the consequent standard.

For international standards, comments will be reviewed by the relevant UK national committee before sending the consensus UK vote and comments to the international committee, which will then decide appropriate action. If the international standard is approved, it is usual for the text to be published as a British Standard.

For national standards, comments will be reviewed by the relevant UK national committee and the resulting standards published as a British Standard.

## UK Vote

Please indicate whether you consider the UK should submit a negative (with supporting technical reasons) or positive vote on this draft. Please indicate if you are aware of any reason why this draft standard should not be published as a British Standard.

## Submission of Comments

- **Annotated drafts are not acceptable and will be rejected.**
- All comments should be submitted online at <https://standardsdevelopment.bsigroup.com/>. You will need to register in order to comment.

## Template for comments and secretariat observations

|                  |                        |
|------------------|------------------------|
| Date: xx/xx/20xx | Document: ISO/DIS xxxx |
|------------------|------------------------|

| 1  | 2                                          | (3)                          | 4               | 5                                                                                                                                  | (6)                                                                      | 7                                                  |
|----|--------------------------------------------|------------------------------|-----------------|------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|----------------------------------------------------|
| MB | Clause No./ Subclause No./Annex (e.g. 3.1) | Paragraph/ Figure/Table/Note | Type of comment | Comment (justification for change) by the MB                                                                                       | Proposed change by the MB                                                | Secretariat observations on each comment submitted |
|    | 3.1                                        | Definition 1                 | ed              | Definition is ambiguous and needs clarifying.                                                                                      | Amend to read '...so that the mains connector to which no connection...' |                                                    |
|    | 6.4                                        | Paragraph 2                  | te              | The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK. | Delete reference to UV photometer.                                       |                                                    |

English Version

Eurocode 3 - Design of steel structures - Part 4-2: Tanks

Eurocode 3 - Calcul des structures en acier - Partie 4-2 :  
Réservoirs

Eurocode 3 - Bemessung und Konstruktion von  
Stahlbauten - Teil 4-2: Tankbauwerke

This draft European Standard is submitted to CEN members for enquiry. It has been drawn up by the Technical Committee CEN/TC 250.

If this draft becomes a European Standard, CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

This draft European Standard was established by CEN in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

CEN members are the national standards bodies of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye and United Kingdom.

Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

**Warning** : This document is not a European Standard. It is distributed for review and comments. It is subject to change without notice and shall not be referred to as a European Standard.



EUROPEAN COMMITTEE FOR STANDARDIZATION  
COMITÉ EUROPÉEN DE NORMALISATION  
EUROPÄISCHES KOMITEE FÜR NORMUNG

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

# Contents

Page

|                                                                       |    |
|-----------------------------------------------------------------------|----|
| European foreword .....                                               | 5  |
| 0 Introduction.....                                                   | 6  |
| 1 Scope.....                                                          | 9  |
| 1.1 Scope of EN 1993-4-2 .....                                        | 9  |
| 1.2 Assumptions .....                                                 | 10 |
| 2 Normative references.....                                           | 10 |
| 3 Terms, definitions, symbols, sign conventions and units .....       | 11 |
| 3.1 Terms and definitions .....                                       | 11 |
| 3.2 Symbols .....                                                     | 16 |
| 3.2.1 Roman upper-case letters.....                                   | 16 |
| 3.2.2 Roman lower-case letters .....                                  | 17 |
| 3.2.3 Greek letters .....                                             | 19 |
| 3.2.4 Subscripts .....                                                | 19 |
| 3.3 Sign conventions .....                                            | 20 |
| 3.3.1 Conventions for global tank structure axis system .....         | 20 |
| 3.3.2 Conventions for structural element axes in circular tanks ..... | 22 |
| 3.3.3 Conventions for stress resultants for circular tanks .....      | 22 |
| 4 Basis of design.....                                                | 24 |
| 4.1 Basic requirements .....                                          | 24 |
| 4.2 Units.....                                                        | 25 |
| 4.3 Tank classification.....                                          | 25 |
| 4.3.1 Reliability differentiation .....                               | 25 |
| 4.3.2 Structural complexity classification for tanks .....            | 25 |
| 4.3.3 Tank group classification.....                                  | 27 |
| 4.4 Verification by the partial factor method .....                   | 27 |
| 4.4.1 Partial factors for actions on tanks .....                      | 27 |
| 4.4.2 Partial factors for resistances .....                           | 28 |
| 4.4.3 Serviceability limit states .....                               | 28 |
| 4.5 Limit states.....                                                 | 29 |
| 4.6 Actions and environmental effects.....                            | 29 |
| 4.7 Material properties .....                                         | 29 |
| 4.8 Geometrical data .....                                            | 29 |
| 4.9 Modelling of the tank for determining action effects .....        | 29 |
| 4.10 Design assisted by testing.....                                  | 29 |
| 4.11 Durability.....                                                  | 29 |
| 5 Properties of materials.....                                        | 30 |
| 5.1 General.....                                                      | 30 |
| 5.2 Structural carbon and carbon manganese steels.....                | 31 |
| 5.3 Structural stainless steels.....                                  | 31 |
| 5.4 Toughness requirements.....                                       | 32 |
| 5.4.1 General.....                                                    | 32 |
| 5.4.2 Minimum design metal temperature.....                           | 32 |
| 6 Basis for structural analysis .....                                 | 33 |
| 6.1 Ultimate limit states.....                                        | 33 |

|       |                                                                                              |    |
|-------|----------------------------------------------------------------------------------------------|----|
| 6.1.1 | Basis.....                                                                                   | 33 |
| 6.1.2 | Plate thickness to be used in resistance calculations.....                                   | 33 |
| 6.1.3 | Fatigue .....                                                                                | 33 |
| 6.1.4 | Allowance for temperature effects .....                                                      | 33 |
| 6.2   | Analysis of the circular cylindrical shell structure of a tank .....                         | 33 |
| 6.2.1 | Modelling of the structural shell .....                                                      | 33 |
| 6.2.2 | Methods of analysis.....                                                                     | 33 |
| 6.2.3 | Geometric imperfections and tolerances.....                                                  | 36 |
| 6.3   | Tanks constructed using corrugated sheeting.....                                             | 36 |
| 7     | Design of cylindrical shell walls .....                                                      | 37 |
| 7.1   | Basis.....                                                                                   | 37 |
| 7.1.1 | General.....                                                                                 | 37 |
| 7.1.2 | Cylindrical shell wall design .....                                                          | 37 |
| 7.1.3 | Catch basins .....                                                                           | 38 |
| 7.2   | Resistance of the cylindrical shell.....                                                     | 38 |
| 7.2.1 | General.....                                                                                 | 38 |
| 7.3   | Cylindrical shell plate thickness in a stepped-wall to resist liquid pressures .....         | 39 |
| 7.4   | Design for resistance to external pressure and wind .....                                    | 42 |
| 7.4.1 | General.....                                                                                 | 42 |
| 7.4.2 | The primary ring to provide top boundary for buckling under external pressure and wind ..... | 43 |
| 7.4.3 | Stepped shell wall design for buckling under external pressure and wind .....                | 43 |
| 7.4.4 | Secondary rings to increase the buckling resistance under external pressure and wind .....   | 48 |
| 7.5   | Differential settlement.....                                                                 | 50 |
| 7.5.1 | General.....                                                                                 | 50 |
| 7.5.2 | Local differential settlement in tanks with floating roofs.....                              | 51 |
| 7.6   | Support arrangements for a cylindrical shell.....                                            | 51 |
| 8     | Design of circular roof structures .....                                                     | 51 |
| 8.1   | General.....                                                                                 | 51 |
| 8.2   | Alternative roof structural forms .....                                                      | 52 |
| 8.3   | Considerations for individual structural forms.....                                          | 53 |
| 8.3.1 | Unsupported shell roof structure .....                                                       | 53 |
| 8.4   | Conical, spherical dome or flat roof with rafter or truss supporting structure .....         | 53 |
| 8.4.1 | Plate design general.....                                                                    | 53 |
| 8.4.2 | Conical roof plate design using nonlinear theory .....                                       | 54 |
| 8.4.3 | Design of the roof supporting structure .....                                                | 55 |
| 8.4.4 | Flat or inverted cone roof design .....                                                      | 55 |
| 8.4.5 | Dome roof design .....                                                                       | 56 |
| 8.4.6 | Roof centre ring.....                                                                        | 58 |
| 8.4.7 | Column supported roof structure .....                                                        | 59 |
| 8.4.8 | Bracing and rings where roof plates are not connected to the rafters.....                    | 59 |
| 8.5   | Spherical or conical shell roof without roof supporting structure.....                       | 60 |
| 9     | Roof to shell junction and primary ring (eaves junction) .....                               | 61 |
| 9.1   | General: conventional arrangement.....                                                       | 61 |
| 9.2   | Primary ring or girder at the shell to roof junction (eaves ring) .....                      | 61 |
| 9.3   | Inverted cone roof primary ring or girder at the shell to roof junction .....                | 64 |
| 10    | Tank bottoms and annular plates.....                                                         | 65 |
| 10.1  | General.....                                                                                 | 65 |
| 10.2  | Annular plates.....                                                                          | 66 |
| 10.3  | Bottom central plates (sketch plates) .....                                                  | 67 |

|               |                                                                                               |           |
|---------------|-----------------------------------------------------------------------------------------------|-----------|
| <b>11</b>     | <b>Openings in the cylindrical shell or roof .....</b>                                        | <b>68</b> |
| <b>11.1</b>   | <b>General.....</b>                                                                           | <b>68</b> |
| <b>11.2</b>   | <b>Shell nozzles of small size .....</b>                                                      | <b>68</b> |
| <b>11.3</b>   | <b>Design of cylindrical shell manholes, access doors and nozzles of large size for LS169</b> |           |
| <b>11.4</b>   | <b>Cylindrical shell wall design for LS3 in the presence of shell openings.....</b>           | <b>70</b> |
| <b>11.5</b>   | <b>Design of openings in the roof.....</b>                                                    | <b>71</b> |
| <b>12</b>     | <b>Design for static stability of anchored and unanchored tanks.....</b>                      | <b>71</b> |
| <b>12.1</b>   | <b>Unanchored ground supported tanks .....</b>                                                | <b>71</b> |
| <b>12.1.1</b> | <b>Uplift .....</b>                                                                           | <b>71</b> |
| <b>12.1.2</b> | <b>Overturning.....</b>                                                                       | <b>72</b> |
| <b>12.2</b>   | <b>Anchorage design for anchored ground supported tanks .....</b>                             | <b>72</b> |
| <b>12.2.1</b> | <b>General.....</b>                                                                           | <b>72</b> |
| <b>12.2.2</b> | <b>Anchorage design.....</b>                                                                  | <b>73</b> |
| <b>13</b>     | <b>Ultimate limit states in pedestal tanks .....</b>                                          | <b>74</b> |
| <b>13.1</b>   | <b>Structural forms .....</b>                                                                 | <b>74</b> |
| <b>13.2</b>   | <b>Actions on pedestal tanks .....</b>                                                        | <b>75</b> |
| <b>13.3</b>   | <b>Design of conical segments.....</b>                                                        | <b>75</b> |
| <b>13.4</b>   | <b>Design of spherical and toroidal segments .....</b>                                        | <b>75</b> |
| <b>13.5</b>   | <b>Tower design .....</b>                                                                     | <b>75</b> |
| <b>14</b>     | <b>Serviceability limit states .....</b>                                                      | <b>75</b> |
| <b>14.1</b>   | <b>Cylindrical shell wall .....</b>                                                           | <b>75</b> |
| <b>14.2</b>   | <b>Tank roofs.....</b>                                                                        | <b>76</b> |
|               | <b>Bibliography .....</b>                                                                     | <b>77</b> |

## European foreword

This document (prEN 1993-4-2:2024), has been prepared by Technical Committee CEN/TC 250 “Structural Eurocodes”, the Secretariat of which is held by BSI. CEN/TC 250 is responsible for all Structural Eurocodes and has been assigned responsibility for structural and geotechnical design matters by CEN.

This document is currently submitted to the CEN Enquiry.

This document will supersede EN 1993-4-2:2007 and its amendments and corrigenda.

The first generation of EN Eurocodes was published between 2002 and 2007. This document forms part of the second generation of the Eurocodes, which have been prepared under Mandate M/515 issued to CEN by the European Commission and the European Free Trade Association.

The Eurocodes have been drafted to be used in conjunction with relevant execution, material, product and test standards, and to identify requirements for execution, materials, products and testing that are relied upon by the Eurocodes.

The Eurocodes recognize the responsibility of each Member State and have safeguarded their right to determine values related to regulatory safety matters at national level through the use of National Annexes.

## 0 Introduction

### 0.1 Introduction to the Eurocodes

The Structural Eurocodes comprise the following standards generally consisting of a number of Parts:

- EN 1990, Eurocode — Basis of structural and geotechnical design
- EN 1991, Eurocode 1 — Actions on structures
- EN 1992, Eurocode 2 — Design of concrete structures
- EN 1993, Eurocode 3 — Design of steel structures
- EN 1994, Eurocode 4 — Design of composite steel and concrete structures
- EN 1995, Eurocode 5 — Design of timber structures
- EN 1996, Eurocode 6 — Design of masonry structures
- EN 1997, Eurocode 7 — Geotechnical design
- EN 1998, Eurocode 8 — Design of structures for earthquake resistance
- EN 1999, Eurocode 9 — Design of aluminium structures
- New parts are under development, e.g. Eurocode for design of structural glass

### 0.2 Introduction to the EN 1993 series

EN 1993 applies to the design of buildings and civil engineering works in steel. It complies with the principles and requirements for the safety and serviceability of structures, the basis of their design and verification that are given in EN 1990 – Basis of structural and geotechnical design.

EN 1993 is concerned only with requirements for resistance, serviceability, durability and fire resistance of steel structures. Other requirements, e.g. concerning thermal or sound insulation, are not covered.

EN 1993 is subdivided in various parts:

EN 1993-1, *Design of Steel Structures — Part 1: General rules and rules for buildings;*

EN 1993-2, *Design of Steel Structures — Part 2: Bridges;*

EN 1993-3, *Design of Steel Structures — Part 3: Towers, masts and chimneys;*

EN 1993-4, *Design of Steel Structures — Part 4: Silos and tanks;*

EN 1993-5, *Design of Steel Structures — Part 5: Piling;*

EN 1993-6, *Design of Steel Structures — Part 6: Crane supporting structures;*

EN 1993-7, *Design of steel structures — Part 7: Sandwich panels.*

EN 1993-1 in itself does not exist as a physical document, but comprises the following 14 separate parts, the basic part being EN 1993-1-1:

EN 1993-1-1, *Design of Steel Structures — Part 1-1: General rules and rules for buildings;*

EN 1993-1-2, *Design of Steel Structures — Part 1-2: Structural fire design;*

EN 1993-1-3, *Design of Steel Structures — Part 1-3: Cold-formed members and sheeting;*

NOTE Cold formed hollow sections supplied according to EN 10219 are covered in EN 1993-1-1.

EN 1993-1-4, *Design of Steel Structures — Part 1-4: Stainless steel structures*;

EN 1993-1-5, *Design of Steel Structures — Part 1-5: Plated structural elements*;

EN 1993-1-6, *Design of Steel Structures — Part 1-6: Strength and stability of shell structures*;

EN 1993-1-7, *Design of Steel Structures — Part 1-7: Plate assemblies with elements under transverse loads*;

EN 1993-1-8, *Design of Steel Structures — Part 1-8: Joints*;

EN 1993-1-9, *Design of Steel Structures — Part 1-9: Fatigue*;

EN 1993-1-10, *Design of Steel Structures — Part 1-10: Material toughness and through-thickness properties*;

EN 1993-1-11, *Design of Steel Structures — Part 1-11: Tension components*;

EN 1993-1-12, *Design of Steel Structures — Part 1-12: Additional rules for steel grades up to S960*;

EN 1993-1-13, *Design of Steel Structures — Part 1-13: Beams with large web openings*;

EN 1993-1-14, *Design of Steel Structures — Part 1-14: Design assisted by finite element analysis*.

All subsequent parts EN 1993-1-2 to EN 1993-1-14 treat general topics that are independent from the structural type such as structural fire design, cold-formed members and sheeting, stainless steels, plated structural elements, etc.

All subsequent parts numbered EN 1993-2 to EN 1993-7 treat topics relevant for a specific structural type such as steel bridges, towers, masts and chimneys, silos and tanks, piling, crane supporting structures, etc. EN 1993-2 to EN 1993-7 refer to the generic rules in EN 1993-1 and supplement, modify or supersede them.

### 0.3 Introduction to EN 1993-4-2

EN 1993-4-2 gives design requirements for the structural design of tanks for the storage of liquid and liquified gas products. It gives design rules that supplement the generic rules in the many parts of EN 1993-1. This document is intended for clients, designers, contractors and relevant authorities.

### 0.4 Verbal forms used in the Eurocodes

The verb “shall” expresses a requirement strictly to be followed and from which no deviation is permitted in order to comply with the Eurocodes.

The verb “should” expresses a highly recommended choice or course of action. Subject to national regulation and/or any relevant contractual provisions, alternative approaches could be used/adopted where technically justified.

The verb “may” expresses a course of action permissible within the limits of the Eurocodes.

The verb “can” expresses possibility and capability; it is used for statements of fact and clarification of concepts.

### 0.5 National Annex for EN 1993-4-2

National choice is allowed in this standard where explicitly stated within notes. National choice includes the selection of values for Nationally Determined Parameters (NDPs).

The national standard implementing EN 1993-4-2 can have a National Annex containing all national choices to be used for the design of buildings and civil engineering works to be constructed in the relevant country.

When no national choice is given, the default choice given in this standard is to be used.

When no national choice is made and no default is given in this standard, the choice can be specified by a relevant authority or, where not specified, agreed for a specific project by appropriate parties.

National choice is allowed in EN 1993-4-2 through notes to the following clauses:

|          |          |          |          |
|----------|----------|----------|----------|
| 4.3.2(3) | 4.3.3(2) | 4.4.1(3) | 4.4.2(4) |
| 4.4.3(2) | 4.11(4)  | 7.1.3(1) | 8.4.7(1) |
| 10.2(1)  | 10.2(9)  | 10.3(2)  |          |

National choice is allowed in EN 1993-4-2 on the application of the following informative annexes:

None

The National Annex can contain, directly or by reference, non-contradictory complementary information for ease of implementation, provided it does not alter any provisions of the Eurocodes.

# 1 Scope

## 1.1 Scope of EN 1993-4-2

(1) EN 1993-4-2 provides rules for structural design of vertical cylindrical, conical and pedestal above-ground steel tanks for the storage of liquid and liquified gas products.

(2) EN 1993-4-2 is applicable to the design for resistance of cylindrical walls and flat bottoms constructed using unstiffened plates. The design of conical and dome roofs as shell structures (unsupported) or as supported on a structural framework (supported) are also covered.

(3) EN 1993-4-2 is only applicable to the requirements for resistance and structural stability of steel tanks.

(4) EN 1993-4-2 only covers steel tank structures in Tank Groups 1, 2 and 3, as defined in this document.

NOTE Tank Group 4 is not defined in this standard (see 3.1.41).

(5) This document is applicable to tanks within the following dimensional limits (see EN 1991-4):

Tank aspect ratio  $h_s/d < 10$

Tank total height  $h_s < 70$  m

Tank diameter  $d < 100$  m

(6) This standard includes suitable rules for the design of tanks intended to store solids suspended in a liquid, where the appropriate global density of the mixture is used.

NOTE Tanks used for the separation of mineral particles of different density fall into this category.

(7) EN 1993-4-2 does not apply to the following:

- a) tanks with gross capacity less than 5 m<sup>3</sup> (5 000 l);
- b) dished-end tanks that have a diameter less than 5 m;
- c) tanks with characteristic internal pressures above the liquid surface greater than 50 kPa (500 mbar)<sup>1</sup> (see pressure equipment directive);
- d) design metal temperatures outside the ranges defined in Clause 5, with -50 °C being the lowest temperature for the application of this document;
- e) tanks of rectangular and other non-circular planforms;
- f) tanks exposed to fire;
- g) floating roofs and floating covers;
- h) ancillary structures such as stairways, platforms, nozzles, piping and access doors.

(8) This document does not cover

- a) the special requirements for seismic design of tanks,

<sup>1</sup> All pressures are in bar gauge unless otherwise specified.

- b) the design of a supporting structure,
- c) the design of ancillary structures such as stairways, platforms, pipe racks and ladders,
- d) the design of an aluminium roof structure on a steel tank,
- e) reinforced concrete foundations for steel tanks,
- f) the design of a conical hopper,
- g) the design of a transition junction between the base of a cylindrical shell wall and a conical hopper,
- h) the design of a supporting ring girder in an elevated tank.

## 1.2 Assumptions

- (1) Unless specifically stated, EN 1990, the EN 1991 series and the EN 1993-1 series apply.
- (2) The design methods given in this document apply if:
  - the execution quality is as specified in EN 1090-2, and
  - the construction materials and products used are as specified in the relevant parts of the EN 1993 series, or in the relevant material and product specifications.
- (3) This standard applies to axisymmetric structures, but includes the effects of unsymmetrical actions (e.g. wind), and unsymmetrically supported tanks (e.g. on discrete supports).
- (4) EN 1993-4-2 is intended to be used in conjunction with EN 1990, with EN 1991-4, with the other Parts of EN 1991, with EN 1993-1-6 and EN 1993-4-1, with the other Parts of EN 1993, with EN 1992 and with the other Parts of EN 1994 to EN 1999 relevant to the design of tanks. Matters that are already covered in those documents are not repeated.
- (5) Numerical values for partial factors and other reliability parameters are recommended as basic values that provide an acceptable level of reliability. They have been selected assuming that an appropriate level of workmanship and quality management applies.

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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.

EN 1090-2, *Execution of steel structures and aluminium structures — Part 2: Technical requirements for steel structures*

EN 1990:2023,<sup>2</sup> *Eurocode — Basis of structural and geotechnical design*

EN 1991 (all parts), *Eurocode 1 — Actions on structures*

EN 1993 (all parts), *Eurocode 3 — Design of steel structures*

---

<sup>2</sup> As impacted by EN 1990:2023/prA1:2024

### 3 Terms, definitions, symbols, sign conventions and units

#### 3.1 Terms and definitions

For the purposes of this document, the terms and definitions from EN 1990, ISO 8930 and the following apply.

##### 3.1.1

##### **axial direction**

**$x$**

vertical direction on the shell wall

Note 1 to entry: For a cylindrical wall, the axial and meridional directions are identical.

##### 3.1.2

##### **axisymmetric shell**

shell structure whose geometry is defined by rotation of a meridional line about a central axis

##### 3.1.3

##### **base ring or annular plate**

structural member that passes around the circumference of the structure beneath the cylindrical shell wall and is required to ensure that the assumed boundary conditions are achieved in practice

##### 3.1.4

##### **catch basin**

external tank structure to contain liquid that could escape by leakage or accident from the primary tank

Note 1 to entry: This type of structure is usually used where the primary tank contains toxic or hazardous liquids. A catch basin also effectively reduces the requirement for an extensive area of liquid containment around the tank.

##### 3.1.5

##### **circumferential direction**

**$\theta$**

horizontal tangent to the shell wall at any point

Note 1 to entry: It varies around the tank, lies in the horizontal plane and is tangential to the shell wall.

##### 3.1.6

##### **continuously supported tank**

tank in which all positions around the circumference are supported in an identical manner

Note 1 to entry: Minor departures from this condition (e.g. a small opening) need not affect the applicability of the definition.

##### 3.1.7

##### **course**

section of the height of a cylindrical wall constructed from a single plate thickness or between ring stiffeners, usually made up of several strakes (see 3.1.39)

Note 1 to entry: The cylindrical shell wall of the tank is formed by making horizontal joints between a series of short cylindrical sections, termed strakes, each formed by making vertical joints between individual curved plates.

##### 3.1.8

##### **curb angle**

light ring attached to the top of the cylindrical shell wall of a tank

### 3.1.9

#### **discrete support**

situation in which a tank is supported using a local bracket or column, giving a limited number of narrow supports around the tank circumference

### 3.1.10

#### **eaves junction**

joint between a cylindrical wall and a roof structure

Note 1 to entry: See also curb angle and primary ring.

### 3.1.11

#### **externally stiffened wall**

tank wall with stiffeners attached to the outside of the tank wall

### 3.1.12

#### **fixed shell roof**

roof structure that is attached to the top of the cylindrical wall

Note 1 to entry: This term includes both roofs supported on rafters or a structural frame and an unstiffened shell roof (sometimes referred to as unsupported).

### 3.1.13

#### **floating roof**

roof structure that floats on the surface of the stored liquid, sliding up and down within the tank as the liquid level varies

### 3.1.14

#### **gas/vapour pressure**

pressure in the space above the surface of the stored liquid

### 3.1.15

#### **ground supported tank**

tank where the shell structure is uniformly supported on a horizontal foundation supported directly by the ground

### 3.1.16

#### **hopper**

converging section towards the bottom of a tank

Note 1 to entry: It is used to channel liquids towards a gravity discharge outlet (usually when they contain suspended solids).

### 3.1.17

#### **horizontally corrugated wall**

shell wall constructed from corrugated steel sheets where the troughs pass around the circumference of the tank

### 3.1.18

#### **internally stiffened wall**

tank wall with stiffeners attached to the inside of the tank wall

**3.1.19****isotropic wall**

shell wall of a tank constructed from flat rolled steel sheet

**3.1.20****joint efficiency factor**

ratio of the membrane resistance of a welded or bolted joint to the yield membrane resistance of the parent plate

**3.1.21****junction**

point at which any two or more shell segments are connected

Note 1 to entry: It can include a stiffener or can have no stiffener: the point of attachment of a ring stiffener to the shell is treated as a junction.

**3.1.22****maximum design liquid level**

MDLL

highest liquid level in a tank which is used as an accidental load design situation

Note 1 to entry: This is higher than the maximum normal operating level (see Figure 3.1).

**3.1.23****maximum normal operating liquid level**

MNOL

highest liquid level in a tank under normal operating conditions and used in load combinations according to EN 1990:2023, Clause A.4

Note 1 to entry: This is lower than the maximum design liquid level (see Figure 3.1)

**3.1.24****meridional direction**

$\phi$

tangent to the shell wall at any point in a plane that passes through the axis of the tank

Note 1 to entry: It varies according to the structural element being considered. For a cylindrical wall, the axial and meridional directions are identical, and axial is generally the preferred term.

**3.1.25****middle surface**

middle of the shell wall at any point, such that under elastic conditions, this surface is stress free when the shell is subject only to bending in any direction

**3.2.26****minimum operating liquid level**

min NOL

lowest liquid level in a tank under normal operations

Note 1 to entry: See Figure 3.1.

**3.1.27****purlin**

circumferentially oriented structural member supporting a roof and supported itself on rafters

### 3.1.28

#### **primary ring**

ring located near the top of the cylindrical wall or at the eaves junction

Note 1 to entry: It can also be referred to as the top ring or wind girder. Where there is a roof, the primary ring also serves the purpose of forming the junction between the roof and cylindrical wall.

### 3.1.29

#### **rafter**

radially oriented structural member supporting a roof structure

### 3.1.30

#### **rib**

local member that provides a primary load-carrying path for loads causing bending down the meridian of a shell, representing a generator of the shell of revolution

Note 1 to entry: It is used to distribute transverse loads on the structure by bending action.

### 3.1.31

#### **ring girder or ring beam**

circumferential stiffener which has bending stiffness and strength normal to the plane of the circular section of a shell as well as in that plane

Note 1 to entry: It is a primary load-carrying element, used to distribute local vertical loads into the shell.

### 3.1.32

#### **ring stiffener**

local stiffening member that passes around the circumference of the structure at a given point on the meridian

Note 1 to entry: It is assumed to have no stiffness in the meridional plane of the structure. It is provided to increase the stability or to introduce local loads, not as a primary load-carrying element.

### 3.1.33

#### **RLG**

refrigerated liquefied gas

### 3.1.34

#### **secondary ring stiffener**

ring stiffener on a tank wall located on the cylindrical wall below the primary ring

Note 1 to entry: There can be multiple secondary rings. The purpose of the secondary ring is to increase the buckling resistance of the cylindrical shell under external pressure and wind.

### 3.1.35

#### **separation of ring stiffeners**

centre to centre distance between the circumferential axes of two adjacent ring stiffeners

**3.1.36****shell**

vertical wall of a ground-supported cylindrical tank

Note 1 to entry: The term shell is often used in the tank industry to refer to the vertical wall of a ground-supported cylindrical tank. This usage is slightly confusing when compared with the general definition of a shell (see EN 1993-1-6) which has more general application. To avoid confusion, the term “shell” is used in this standard where appropriate to the needs of the tank industry, but the term “cylindrical wall” is more generally used.

**3.1.37****shell-roof junction**

junction between a cylindrical shell wall and the roof

Note 1 to entry: Alternatively known as the top angle or eaves junction, is the junction between the vertical wall and the roof.

**3.1.38****sketch plate or bottom plate**

plating used to form the internal bottom of a ground-supported tank

**3.1.39****strake**

single row of plates of a given thickness

Note 1 to entry: The cylindrical shell wall of a tank is formed by making horizontal circumferential joints between a group of short cylindrical sections, each termed a strake, formed by making vertical joints between individual curved plates. Several strakes normally form one course (see 3.1.7).

**3.1.40****tank**

vessel for storing liquid products

Note 1 to entry: In this standard it is assumed to be circular in plan.

**3.1.41****Tank Group**

TG

classification of a tank to identify the sophistication of its design requirements, according to its size, form and usage, placing it into Tank Group 0, 1, 2 or 3

Note 1 to entry: Tanks in Consequence Class 4 are in Tank Group 4. For these tanks additional considerations are necessary.

Note 2 to entry: The provisions of this standard are not required for TG0. All the provisions are intended to apply to TGs 1, 2 and 3, except where exemptions are specifically made for TG1 or TG2.

**3.1.42****shell wall**

metal plate elements forming the vertical walls, roof or a hopper bottom of a tank

Note 1 to entry: This term is not restricted to the vertical walls.

### 3.1.43

#### **Structural Complexity Class**

SCC

classification of a tank to address the complexity of the structural form, insofar as is necessary to meet the susceptibility to different failure modes

### 3.1.44

#### **test pressure**

pressure in the space above the test liquid during the test procedure

### 3.1.45

#### **transition junction**

junction between the vertical shell wall and a conical hopper

Note 1 to entry: The junction can be at the base of the vertical wall or part way down it.

### 3.1.46

#### **unsupported shell roof structure**

shell roof that has no truss or rafter structural framework beneath it, but relies on the resistance of the shell alone to carry loads and transfer them to the cylindrical wall of the tank

### 3.1.47

#### **vertical stiffener**

stiffener attached to the cylindrical shell wall in the axial direction

Note 1 to entry: It is sometimes used on elevated tanks to enhance the axial buckling resistance.

### 3.1.48

#### **wind girder**

substantial primary ring near the top of the cylindrical shell to provide both stiffness against buckling and strength against induced stresses under wind loading

## 3.2 Symbols

For the purposes of this document, the following symbols apply.

The symbols used are based on ISO 3898.

### 3.2.1 Roman upper-case letters

$A$  area of structural member cross-section;

$A_1, A_2$  area of top, bottom flange of roof centre ring;

$E$  Young's modulus of elasticity;

$E_{\text{red}}$  reduced elastic modulus to account for thermal effects;

$F$  force;

$F_A$  maximum vertical downward design distributed load on a roof including the weight of the plating, supporting structure and external vertical loads;

$F_B$  maximum vertical downward design distributed load on a roof including the weight of the plating, supporting structure and external vertical loads;

$I$  second moment of area of cross-section;

$K_a$  reduction factor for the effect of axial compression on buckling under external pressure;

|              |                                                      |
|--------------|------------------------------------------------------|
| $M$          | bending moment in a structural member;               |
| $N$          | axial force in a structural member;                  |
| $N_f$        | minimum number of load cycles relevant for fatigue;  |
| $P_r$        | vertical load on a roof rafter;                      |
| $R_{cr}$     | linear elastic buckling resistance (see EN 1993-1-6) |
| $T$          | temperature;                                         |
| $T_{Ed}$     | reference temperature for design;                    |
| $T_{LODMAT}$ | lowest one-day mean ambient temperature (see 5.4.2); |
| $T_{MDMT}$   | minimum design metal temperature (see 5.4.2);        |
| $W$          | elastic section modulus.                             |

### 3.2.2 Roman lower-case letters

|          |                                                                                                                                                                                   |
|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $a$      | is the horizontal side length of a rectangular opening in a cylindrical shell wall;                                                                                               |
| $a_j$    | vertical distance from secondary ring $j$ to the next secondary ring ( $j+1$ ) below it, or else where there is no lower secondary ring, to the bottom of the cylindrical wall;   |
| $b$      | is the vertical height of a rectangular opening in a cylindrical shell wall;                                                                                                      |
| $b_k$    | is the radial width of the centre ring in a roof;                                                                                                                                 |
| $b_r$    | is the local distance between two rafters or purlins when designing a roof (nonlinear theory);                                                                                    |
| $c_p$    | coefficient for wind pressure loading;                                                                                                                                            |
| $d$      | diameter of cylindrical shell wall of a tank;                                                                                                                                     |
| $d_n$    | diameter of reinforcement around a manhole or nozzle;                                                                                                                             |
| $d_o$    | diameter of opening of a manhole or nozzle;                                                                                                                                       |
| $e$      | distance of outer fibre of beam to beam axis;                                                                                                                                     |
| $f_r$    | replacement factor at a nozzle used in design of reinforced openings;                                                                                                             |
| $f_s$    | stress concentration factor at a nozzle;                                                                                                                                          |
| $f_q$    | axial buckling resistance reduction factor for fabrication quality class;                                                                                                         |
| $f_{yd}$ | design value of yield strength of steel;                                                                                                                                          |
| $f_u$    | ultimate strength of steel;                                                                                                                                                       |
| $h_{co}$ | rise of roof (height of apex of a conical roof above the plane of its junction to a cylindrical wall), see Figure 3.1 and 8.1;                                                    |
| $h_s$    | rise of roof (height of apex of a dome or dished end above the plane of its junction to a cylindrical wall), see Figure 3.1 and 8.1;                                              |
| $h_b$    | height of an unstiffened cylindrical shell that can be stable against buckling measured from the top of the cylindrical wall, curb angle or primary wind girder (as appropriate); |
| $h_{bm}$ | height of a potential buckle extending down from the curb angle or primary wind girder down to the base of the $m^{\text{th}}$ course ( $i = 1$ for the top course);              |
| $h_{co}$ | rise of roof (height of apex of a conical roof above the plane of its junction to a cylindrical wall), see Figures 3.1 and 8.1;                                                   |

|            |                                                                                                                                                                                                                                |
|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $h_F$      | freeboard or height of the top of the shell above the maximum design liquid level (MDLL), see Figure 3.1;                                                                                                                      |
| $h_g$      | height above the base of the centre of mass of the liquid in a pedestal tank (Figure 3.2);                                                                                                                                     |
| $h_i$      | depth of the base of the $i^{\text{th}}$ course below the top of a cylindrical shell wall ( $i = 1$ at the top);                                                                                                               |
| $h_k$      | vertical distance between the flanges of the centre ring (Figure 8.2);                                                                                                                                                         |
| $h_L$      | liquid level above the base in the considered design situation;                                                                                                                                                                |
| $h_{PR}$   | height of the primary ring / primary wind girder from the base, see Figure 3.1;                                                                                                                                                |
| $h_{rj}$   | depth to the $j^{\text{th}}$ secondary ring below the primary ring (Figure 7.5);                                                                                                                                               |
| $h_S$      | rise of roof (height of apex of a dome or dished end above the plane of its junction to a cylindrical wall), see Figures 3.1 and 8.1;                                                                                          |
| $h_T$      | height of the cylindrical shell from the base to the top of the cylindrical wall (Figure 3.1);                                                                                                                                 |
| $h_V$      | height of cylindrical wall of thickness $t_i$ needed to resist the internal vapour pressure (transformed into equivalent liquid); $i$ the assigned number to a shell wall course, measured from the top (roof or wind girder); |
| $j$        | the assigned number to a secondary ring, measured from the top;                                                                                                                                                                |
| $j_{ef}$   | joint efficiency factor;                                                                                                                                                                                                       |
| $k_a$      | coefficient for axial compression in buckling resistance under external pressure;                                                                                                                                              |
| $k_w$      | coefficient for buckling resistance under wind;                                                                                                                                                                                |
| $l_S$      | height of shell segment or stiffener shear length;                                                                                                                                                                             |
| $m$        | bending moment per unit width of plate;                                                                                                                                                                                        |
| $m$        | the number of courses in a group being assessed for buckling under external pressure;                                                                                                                                          |
| $n$        | membrane stress resultant per unit width of plate;                                                                                                                                                                             |
| $n$        | number of rafters in circular tank roof;                                                                                                                                                                                       |
| $p$        | distributed loading of any kind (not necessarily normal to the wall);                                                                                                                                                          |
| $p_n$      | internal pressure normal to a tank wall surface (acting outward);                                                                                                                                                              |
| $p_{V,Ed}$ | design value of the vapour pressure above the liquid surface;                                                                                                                                                                  |
| $q$        | external pressure or wind pressure normal to a tank wall or roof (acting inward);                                                                                                                                              |
| $r$        | radial coordinate of any point;                                                                                                                                                                                                |
| $r_{CO}$   | radius of curvature of a conical roof (see Formula (8.22));                                                                                                                                                                    |
| $r_S$      | radius of curvature of a spherical dome roof;                                                                                                                                                                                  |
| $r_T$      | radius of middle surface of a cylindrical tank wall (shell);                                                                                                                                                                   |
| $t$        | shell wall thickness;                                                                                                                                                                                                          |
| $t_{AP}$   | thickness of the annular plate or base ring;                                                                                                                                                                                   |
| $t_{BP}$   | thickness of the bottom plate, sketch plate or bottom central plate;                                                                                                                                                           |
| $t_{CO}$   | thickness of the roof plate of a conical roof;                                                                                                                                                                                 |
| $t_{eq,m}$ | equivalent thickness of a potential external pressure buckle;                                                                                                                                                                  |
| $t_i$      | shell wall thickness in the $i^{\text{th}}$ course below the top of the tank wall;                                                                                                                                             |
| $t_S$      | thickness of the roof plate of a spherical dome roof;                                                                                                                                                                          |

|                |                                                                                                                             |
|----------------|-----------------------------------------------------------------------------------------------------------------------------|
| $w_g$          | size parameter used in defining the Structural Complexity Class;                                                            |
| $w_{AP}$       | width of annular plate or base ring;                                                                                        |
| $w_{APlim}$    | minimum width of annular plate or base ring;                                                                                |
| $w_{AP,i,min}$ | minimum exposed inside width (distance from the inner edge of the annular base plate to the inner edge of the shell plate); |
| $x$            | vertical coordinate of any point in a tank;                                                                                 |
| $x_{CO}$       | local vertical coordinate of a point on a conical tank roof (Figure 8.1);                                                   |
| $x_L$          | global vertical coordinate measured down from the liquid surface level $h_L$ .                                              |
| $x_S$          | local vertical coordinate of a point on a spherical tank roof (Figure 8.1);                                                 |
| $x_T$          | local vertical coordinate measured from the top of shell downwards (Figure 3.1);                                            |

### 3.2.3 Greek letters

|                     |                                                                                         |
|---------------------|-----------------------------------------------------------------------------------------|
| $\alpha$            | slope of the outer edge of a roof relative to the horizontal (see Figures 3.1 and 8.1); |
| $\alpha_{\theta I}$ | imperfection reduction factor under external pressure or wind;                          |
| $\beta$             | inclination of a conical segment relative to the vertical (see Figure 13.1);            |
| $\beta_r$           | rafter spacing parameter = $\pi/n$ where $n$ is the number of rafters;                  |
| $\gamma_U$          | upper characteristic value of the unit weight (specific weight) of a liquid;            |
| $\gamma_F$          | partial factor for actions (see EN 1990:2023, Clause A.4);                              |
| $\gamma_{FL}$       | partial factor for liquid pressure actions;                                             |
| $\gamma_{FV}$       | partial factor for vapour pressure actions;                                             |
| $\gamma_M$          | partial factor for resistance;                                                          |
| $\delta$            | deflection;                                                                             |
| $\eta$              | dimensionless size of a circular opening in a cylindrical shell;                        |
| $\Delta$            | change in a variable;                                                                   |
| $\nu$               | Poisson's ratio;                                                                        |
| $\rho$              | upper characteristic value of the mass density of a liquid;                             |
| $\theta$            | circumferential coordinate around a shell;                                              |
| $\sigma$            | direct stress;                                                                          |
| $\tau$              | shear stress.                                                                           |

### 3.2.4 Subscripts

|   |                                                                |
|---|----------------------------------------------------------------|
| E | value of stress or displacement (arising from design actions); |
| F | at half span;                                                  |
| F | action;                                                        |
| a | annular;                                                       |
| d | design value;                                                  |
| f | fatigue;                                                       |
| i | inside;                                                        |

|          |                                                                                      |
|----------|--------------------------------------------------------------------------------------|
| i        | inward directed;                                                                     |
| i        | counting variable;                                                                   |
| i        | the course number, counting from the primary ring or curb angle or roof;             |
| j        | the secondary ring number, counting from the primary ring or roof to shell junction; |
| k        | roof centre ring;                                                                    |
| k        | characteristic value;                                                                |
| m        | mean value;                                                                          |
| min      | minimum allowed value;                                                               |
| n        | nominal;                                                                             |
| n        | normal to the wall;                                                                  |
| o        | outside;                                                                             |
| o        | outward directed;                                                                    |
| p        | pressure;                                                                            |
| r        | radial;                                                                              |
| r        | ring;                                                                                |
| R        | resistance;                                                                          |
| s        | at support;                                                                          |
| s        | shell wall;                                                                          |
| T        | tank cylindrical shell wall;                                                         |
| x        | axial (meridional in a cylinder);                                                    |
| $\theta$ | circumferential;                                                                     |
| z        | transverse;                                                                          |
| y        | yield;                                                                               |
| 0        | reference value;                                                                     |
| 1        | upper;                                                                               |
| 2        | lower;                                                                               |
| $\theta$ | circumferential;                                                                     |
| $\phi$   | meridional.                                                                          |

### **3.3 Sign conventions**

#### **3.3.1 Conventions for global tank structure axis system**

(1) The sign convention given here is for the complete circular tank structure, and recognizes that the tank is not a structural member. Care with coordinate systems is required to ensure that local coordinates associated with members attached to the shell wall and loadings given in local coordinate directions but defined by a global coordinate are not confused.

(2) In general, the convention for the global tank structure axis system is in cylindrical coordinates (see Figure 3.1b) as follows:

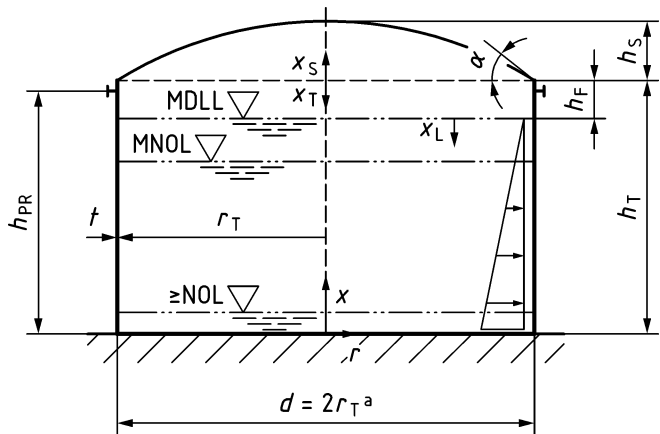
Coordinate system

- Coordinate on the central axis of a shell of revolution  $x$
- Radial coordinate  $r$
- Circumferential coordinate  $\theta$

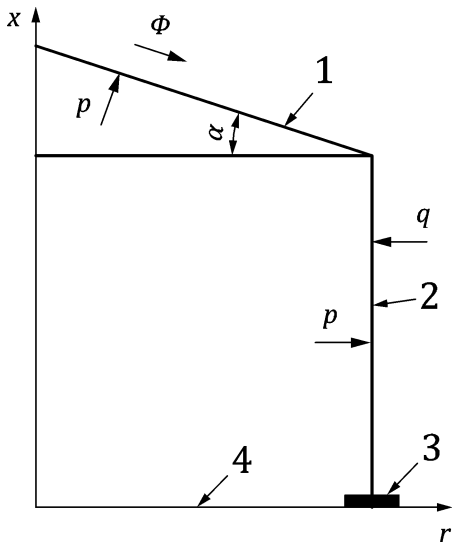
(3) The convention for positive directions is:  
Outward direction positive (internal pressure positive, outward displacements positive)  
Tensile stresses positive (except in buckling equations where compression is positive)

(4) The convention for distributed actions on the tank wall surface is:

- Pressure normal to surface (outward pressure positive)  $p$
- Pressure normal to surface (inward pressure positive)  $q$



a) Ground-supported cylindrical tank with spherical dome roof, showing important levels



b) Vertical section through circular tank with conical roof: coordinates and loading

**Key**

- <sup>a</sup> planform diameter
- 1 roof
- 2 cylindrical shell
- 3 annular plate
- 4 bottom

**Figure 3.1 — Circular tanks: general descriptors**

NOTE For simplicity and clarity in Figure 3.1, only the liquid level MDLL has been identified by its dimensional location with the corresponding coordinate  $x_L$ . The other defined liquid levels MNOL and min. NOL are marked but their locations are not identified.

### 3.3.2 Conventions for structural element axes in circular tanks

(1) The notation and sign convention for ring stiffeners and wind girders attached to the tank wall (Figure 3.2) is:

- Circumferential coordinate axis (curved)  $\theta$
- Bending moments  $M_\theta$  and section modulus  $I_\theta$  for circumferential stresses  $\sigma_\theta$

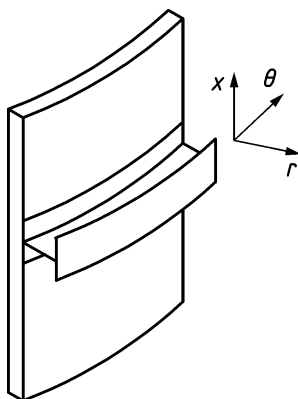


**Figure 3.2 — Local coordinate system for ring stiffeners, wind girders or circumferential stiffeners on a cylindrical shell**

### 3.3.3 Conventions for stress resultants for circular tanks

(1) The convention used for subscripts indicating membrane forces is:

“The subscript derives from the direction in which direct stress is induced by the force” for direct stress resultants. For membrane shears and twisting moments, the sign convention is shown in Figure 3.3.

Membrane stress resultants:

- $n_x$  axial membrane stress resultant in a cylindrical shell
- $n_\phi$  meridional membrane stress resultant in a conical or spherical shell
- $n_\theta$  circumferential membrane stress resultant in shells
- $n_{x\theta}$  membrane shear stress resultant in a cylindrical shell
- $n_{\phi\theta}$  membrane shear stress resultant in a conical or spherical shell

Membrane stresses:

- $\sigma_{mx}$  axial membrane stress in a cylindrical shell
- $\sigma_{m\phi}$  meridional membrane stress in a conical or spherical shell
- $\sigma_{m\theta}$  circumferential membrane stress in shells
- $\tau_{mx\theta}$  membrane shear stress in a cylindrical shell
- $\tau_{m\phi\theta}$  membrane shear stress in a conical or spherical shell

(2) The convention used for subscripts indicating moments is:

The subscript derives from the direction in which direct stress is induced by the moment. For twisting moments, the sign convention is shown in Figure 3.3.

NOTE 1 This plate and shell convention is at variance with beam and column conventions used in EN 1993-1-1 and EN 1993-1-3. Care is needed when using them in conjunction with these provisions.

NOTE 2 To match bending terminology for shell structures, the vertical stresses in both the shell and any vertical stiffener are denoted  $\sigma_x$ . The bending moments inducing vertical stresses in a vertical stiffener are denoted as  $M_x$ , and the second moment of area of a stiffener bending in the vertical direction (stresses in the vertical direction) (Figure 3.3a) is denoted as  $I_x$  (not  $I_\theta$  as would be the case for a structural member according to EN 1993-1-1). Similarly, the circumferential stresses in both the shell and any ring stiffener are denoted  $\sigma_\theta$ . The bending moments inducing circumferential stresses in a ring stiffener are denoted as  $M_\theta$ , and the second moment of area of a ring (Figure 3.2) bending in the plane of the ring (stresses in the circumferential direction) is denoted by  $I_\theta$ . This last notation is important for the required stiffness of ring stiffeners to assist in resisting buckling under external pressure or wind.

Bending stress resultants:

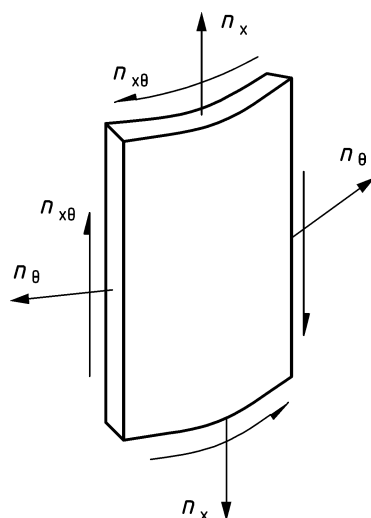
- $m_x$  axial bending moment per unit width in a cylindrical shell
- $m_\phi$  meridional bending moment per unit width in a conical or spherical shell
- $m_\theta$  circumferential bending moment per unit width in shells
- $m_{x\theta}$  twisting shear moment per unit width in a cylindrical shell
- $m_{\phi\theta}$  twisting shear moment per unit width in a conical or spherical shell

Bending stresses:

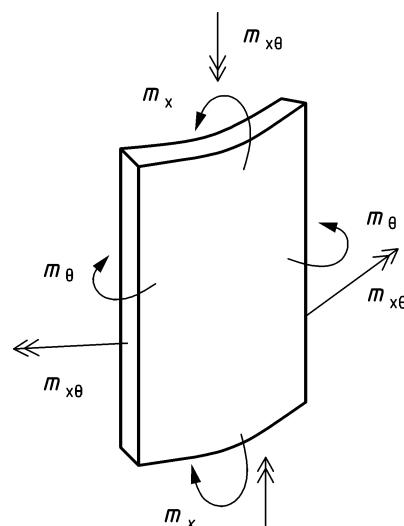
- $\sigma_{bx}$  axial bending stress in a cylindrical shell
- $\sigma_{b\phi}$  meridional bending stress in a conical or spherical shell
- $\sigma_{b\theta}$  circumferential bending stress in shells
- $\tau_{bx\theta}$  twisting shear stress in a cylindrical shell
- $\tau_{b\phi\theta}$  twisting shear stress in a conical or spherical shell

Inner and outer surface stresses:

- $\sigma_{six}, \sigma_{sox}$  axial inner, outer surface stress
- $\sigma_{si\phi}, \sigma_{so\phi}$  meridional inner, outer surface stress
- $\sigma_{si\theta}, \sigma_{so\theta}$  circumferential inner, outer surface stress in shells



a) Membrane stress resultants



b) Bending stress resultants

Figure 3.3 — Stress resultants in a cylindrical shell wall