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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 Please indicate if you are aware of any reason why this draft standard should not be published as a British Standard.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
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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 4-1: Silos

Eurocode 3 - Calcul des structures en acier - Partie 4-1:
Silos

Eurocode 3 - Bemessung und Konstruktion von
Stahlbauten - Teil 4-1: Silos

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.

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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.



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COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

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European foreword

This document (prEN 1993-4-1:2024), has been prepared by Technical Committee CEN/TC250 “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 EN1993-4-1:2007 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 EN 1993 (all parts)

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 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 of the structural type such as structural fire design, cold-formed members and sheeting, stainless steels, plated structural elements, shell structures, 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 prEN 1993-4-1

prEN 1993-4-1 gives design guidance for the structural design of silos and design rules that supplement the generic rules in the parts of EN 1993-1.

prEN 1993-4-1 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 prEN 1993-4-1

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 prEN 1993-4-1 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 prEN 1993-4-1 through notes to the following clauses:

4.3.2(4)	4.3.3(1)	4.3.3(3)	4.3.3(8)
4.4.1.2(3)	4.4.2(2)	4.5.3(1)	5.4(1)
6.1.4(6)	7.5.4(3)	12.5.2(9)	

National choice is allowed in prEN 1993-4-1 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 1993-4-1

(1) prEN 1993-4-1 provides rules for the structural design of steel silos of circular or rectangular plan-form, being free-standing (on ground) or supported on a structural framework (elevated).

(2) prEN 1993-4-1 is applicable to silos constructed from isotropic rolled plates that are stiffened or unstiffened, from corrugated sheeting that is stiffened or unstiffened and from flat or corrugated plates assembled into box structures of different geometries. It applies to vertical walls, hoppers, roof structures, transition junctions and support structures.

(3) prEN 1993-4-1 does not apply to storage vessels for silage and haylage, or to the storage of materials that are not free-flowing (see EN 1991-4). This Part 4-1 also does not cover:

- resistance to fire;
- cylindrical silos with internal subdivisions;
- internal structures within a single silo (except for internal ties, as defined in 12.5);
- silos with capacity less than 100 kN (10 tonnes);
- hoppers that are supported on a structural framework;
- cases where special measures are necessary to limit the consequences of accidents.

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

- Silo aspect ratio $h_b/d_c < 10$
- Silo total height $h_b < 70$ m
- Silo equivalent diameter $d_c < 60$ m

NOTE These dimensional limitations are more limited than those of EN 1991-4 which also applies to silos constructed from other materials.

(5) Where this standard applies to circular planform silos, the geometric form is restricted to axisymmetric structures, but unsymmetrical actions on them and supports that induce forces in the silo structure that are not axisymmetric are included.

(6) This part is concerned only with the requirements for resistance and stability of steel silos. For other requirements (such as operational safety, functional performance, fabrication and erection, quality control, details like man-holes, flanges, filling devices, outlet gates and feeders, etc.), see other relevant standards and information.

(7) This part is concerned with both isolated silo structures and silos that are connected to others to form a battery of silos, but throughout this document the term silo refers to a single cell within a battery.

(8) Provisions relating to special requirements of seismic design are provided in EN 1998-4, which complements or adapts the provisions of Eurocode 3 specifically for this purpose.

(9) The structural design of supporting structures for the silo are dealt with in EN 1993-1-1. The supporting structure is deemed to consist of all structural elements beneath the bottom flange of the lowest ring of the silo (see Figure 1.1), though information on some forms of support structure is given in Clause 8 of this document.

(10) Foundations in reinforced concrete for steel silos are dealt with in EN 1992 (all parts) and EN 1997 (all parts).

1.2 Assumptions

- (1) Unless specifically stated, the provisions of EN 1990, EN 1991 (all parts) and EN 1993-1 (all parts) apply.
- (2) The design methods given in EN 1993-4-1 are applicable 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 EN 1993 (all parts), or in the relevant material and product specifications.

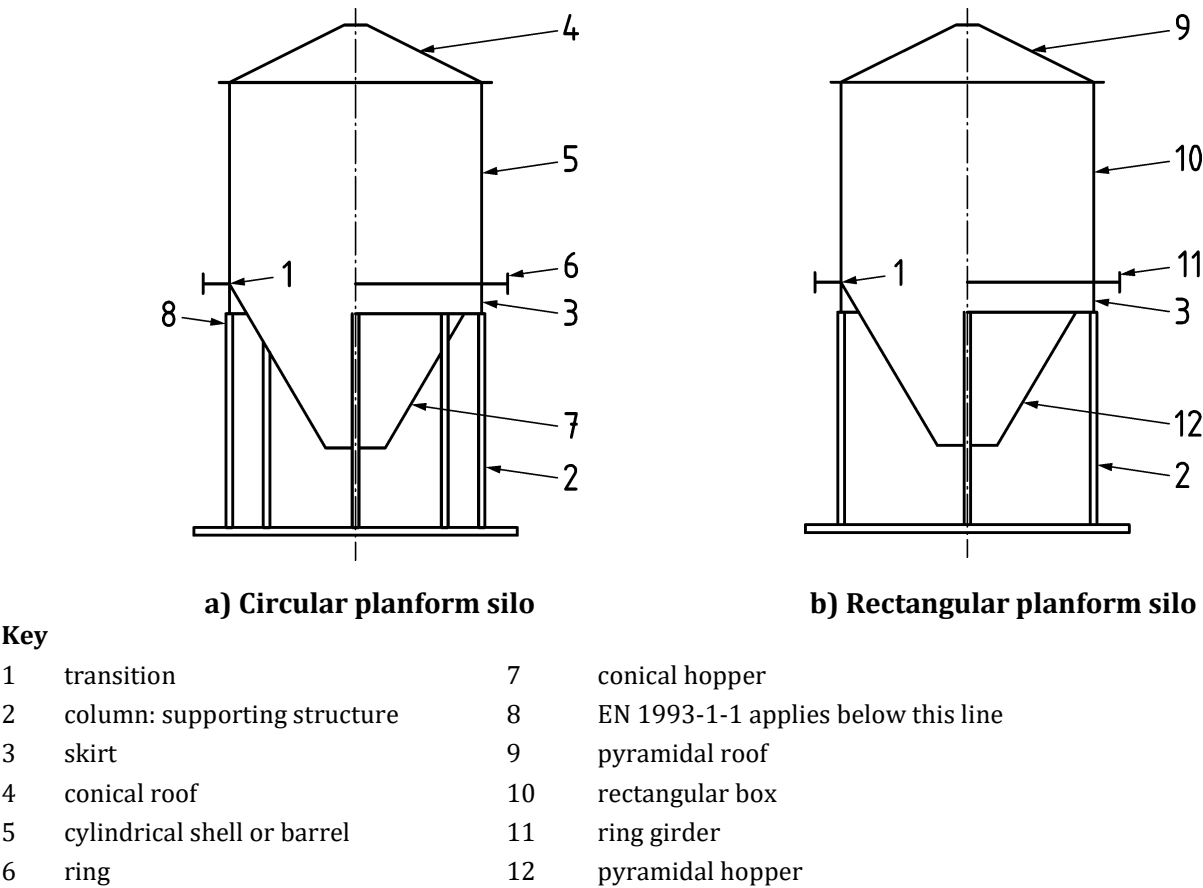


Figure 1.1 — Terminology used in silo structures

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 1990:2023¹, *Eurocode — Basis of structural and geotechnical design*¹

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

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

ISO 8930, *General principles on reliability for structures — Vocabulary*

3 Terms, definitions, symbols, sign conventions and units

3.1 Terms and definitions

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

3.1.1

axial direction

vertical tangent to a cylindrical silo wall

Note 1 to entry: For the cylinder alone, it coincides with the meridional direction.

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

structural member that passes around the circumference of the structure at the base and provides means of attachment of the structure to a foundation or other element

Note 1 to entry: It is required that the assumed boundary conditions are achieved in practice.

3.1.4

box

structure formed from an assembly of flat plates into a three-dimensional enclosed form

Note 1 to entry: For the purposes of this Standard, the box has dimensions that are generally comparable in all directions.

3.1.5

circumferential direction

horizontal tangent to the silo wall at any point

Note 1 to entry: The circumferential direction varies around the silo, lies in the horizontal plane and is tangential to the silo wall irrespective of whether the silo is circular or rectangular in plan.

¹ As impacted by EN 1990:2023/prA1:2024.

3.1.6

continuously supported silo

silo 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

corrugated silo wall

shell strake of a circular silo that is formed from sheet that has been rolled before construction into a corrugated form (rounded or trapezoidal undulations) that provides enhanced bending resistance in one direction

Note 1 to entry: See 6.5. This term also refers to a wall in a rectangular or polygonal silo where trapezoidal undulations are used to enhance the bending resistance.

3.1.8

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

Note 1 to entry: See 3.1.32.

3.1.9

cylindrical shell

vertical walled section of a circular planform silo

Note 1 to entry: See Figure 1.1.

3.1.10

discrete support

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

Note 1 to entry: Four or six discrete supports are commonly used, but three or more than six are also found.

3.1.11

hopper

converging section towards the bottom of a silo, normally conical in form

Note 1 to entry: It is used to channel solids towards a gravity discharge outlet.

3.1.12

isotropic conical hopper

conical hopper that is formed from rolled flat sheets

Note 1 to entry: These sheets can be welded or bolted together.

3.1.13

isotropic shell

shell segment of a silo that is formed from rolled flat sheets

Note 1 to entry: These sheets can be welded or bolted together.

3.1.14**isotropic shell with vertical stiffeners**

isotropic shell segment with attached vertical stiffeners that can be rolled or cold-formed sections and can be external or internal to the shell

3.1.15**joint efficiency factor**

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

3.1.16**junction**

point at which any two or more shell segments, or two or more flat plate elements of a box, meet

Note 1 to entry: The junction can include a ring stiffener or can be unstiffened.

Note 2 to entry: The point of attachment of a ring stiffener to the shell or box can be treated as a junction.

3.1.17**meridional direction**

tangent at any point to the silo wall in a vertical plane

Note 1 to entry: The meridional direction varies according to the structural element being considered (cylindrical, conical or spherical). Alternatively, it is the vertical or inclined direction on the surface of the structure that a raindrop would take in sliding down the surface.

3.1.18**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

Note 1 to entry: This term can also refer to the middle plane of a flat plate that forms part of a box.

3.1.19**pyramidal hopper**

converging section towards the bottom of a silo, inverted pyramidal in form

Note 1 to entry: In EN 1993-4-1, it is assumed that the geometry is simple, consisting of only four planar elements of trapezoidal shape.

3.1.20**rib**

local member that provides a primary load-carrying path for loads causing bending down the meridian of a shell or flat plate, representing a generator of the shell of revolution or a vertical stiffener on a box

Note 1 to entry: A rib is used to distribute transverse loads on a shell structure by bending action.

3.1.21**ring girder or ring beam**

circumferential stiffener which has bending stiffness and strength both normal to the plane of the circular section of a shell or the plan section of a rectangular structure and also in that plane

Note 1 to entry: This ring beam is a primary load-carrying element, used to distribute local vertical support forces into the shell or box structure.

3.1.22

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 that the ring stiffener has no effective 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. In a shell of revolution, it is circular, but in rectangular structures it takes the rectangular form of the plan section.

3.1.23

separation of stiffeners

centre to centre distance between the longitudinal centroidal axes of two adjacent parallel stiffeners

3.1.24

shell

structure formed from a curved, thin plate, made from either a flat or a corrugated plate

Note 1 to entry: The shell can be stiffened with discrete external or internal structural members. Its shape can be cylindrical, conical or spherical.

3.1.25

shell segment

component part of a shell structure that consists of separate pieces, each of which is formed from a curved, thin plate

Note 1 to entry: The segment is the full zone that is cylindrical, conical or spherical even when composed of multiple plates.

3.1.26

silo

vessel for storing particulate granular solids

Note 1 to entry: In this document, the silo is assumed to have a vertical form with solids being added by gravity at the top. The term silo includes all forms of structure to store particulate solids and is sometimes referred to as a bin, hopper, grain tank or bunker.

3.1.27

silo fundamental loading case

SFLC

loading derived from the stored solid that is close to symmetrical under all conditions leading to simpler situations for structural design

Note 1 to entry: These load cases are defined in EN 1991-4.

3.1.28

silo group

SG

categorization of each silo in terms of complexity of the structural design requirements, based on its size, form and usage

Note 1 to entry: Each silo is identified as belonging to one of the Silo Groups 0, 1, 2 and 3 according to the sophistication of the structural design requirements

Note 2 to entry: This standard does not cover silos in Consequence Class 4, so SG4 is not defined. The provisions of this standard are not required for SG0. The provisions are all intended for SGs 1, 2 and 3, except where exemptions are specifically made for SG1 or SG2.

3.1.29**silo special load case**

SSLC

loading condition derived from the stored solid that is unsymmetrical to the structure, leading to more complicated design load cases for structural design

Note 1 to entry: These load cases are defined in prEN 1991-4:2024, 3.1.30.

skirt

part of the cylindrical shell that lies below the transition junction

Note 1 to entry: The skirt differs from the higher part in that it has no contact with the stored bulk solid.

3.1.31**smeared stiffener analysis**

analysis of the shell in which stiffeners are treated as integral to the wall leading to the shell wall properties being a composite section

Note 1 to entry: A width of shell equal to an integer multiple of the separation of the stiffeners is used to define the smeared shell properties. The stiffness properties of a smeared shell wall are orthotropic with eccentric terms leading to coupling between bending and stretching behaviour.

3.1.32**strake**

single row of plates of a given thickness

Note 1 to entry: The cylindrical shell wall of a silo is formed by making horizontal circumferential joints between a set of short cylindrical sections, each termed a strake, and formed by making vertical joints between individual curved plates. Several strakes normally form one course (see 3.1.8)

3.1.33**stringer stiffener**

local stiffening member that follows the meridian of a shell, representing a generator of the shell of revolution

Note 1 to entry: It is provided to increase the stability, or to assist with the introduction of local loads or to carry axial loads. It is not intended to provide a primary load-carrying capacity for bending due to transverse loads.

3.1.34**Structural Complexity Class**

SCC

classification of a silo to address the complexity of the structural form, insofar as a different precision in the definition of actions is needed to meet the susceptibility to different failure modes

3.1.35**transition junction**

junction between the cylindrical wall of a silo and a hopper beneath it

Note 1 to entry: The junction can be at the base of the cylinder or part way down it if the cylinder includes a skirt.

3.2 Symbols used in Part 4.1 of Eurocode 3

The symbols used are based on ISO 3898.

3.2.1 Roman upper-case letters

A	area of cross-section;
C	membrane stretching stiffness;
C	buckling coefficient;
D	bending flexural rigidity;
E	Young's modulus of elasticity;
E_{red}	reduced elastic modulus to account for thermal effects;
F	force;
G	shear modulus;
H	height of structure;
I	second moment of area of a cross-section;
I_{r}	second moment of area of a ring cross-section;
I_{x}	second moment of area of cross-section for bending in the axial direction;
I_{θ}	second moment of area of cross-section for bending in the circumferential direction;
J	uniform torsion constant;
K	flexural stiffness of wall panel;
L	height of shell segment or length of vertical stiffener;
M	bending moment;
N	axial force;
P	force per unit circumference;
Q	fabrication tolerance quality of construction of a shell susceptible to buckling;
V	force per unit length on a tie;
W	vertical force on a hopper.

NOTE The coordinate x is used in EN 1993-1-6 for the axial direction (also termed meridional) in cylindrical shells. If x is used as the meridional coordinate in all cases, a problem arises where conical roofs and hoppers are involved, since x is strictly the axial coordinate in the global system. For cylinders, the meridional and axial coordinates coincide, but in EN 1993-4-1 it is important to make the key distinction between the axial and meridional directions, so x is used exclusively for axial. The treatment of hoppers and conical roofs uses the meridional coordinate ϕ as shown in Figure 3.1 and Figure 3.3.

3.2.2 Roman lower-case letters

a	coefficient;
b	width of plate or stiffener;
d_{c}	silo equivalent diameter (see EN 1991-4);
d_{cr}	crest to crest dimension of a corrugation;
d_{s}	circumferential distance between adjacent axial stiffeners;
e	eccentricity of force or stiffener;
f_{y}	yield strength of steel;

f_u	ultimate strength of steel;
g_r	ring beam unsymmetrical deformation stiffness parameter;
g_s	shell unsymmetrical deformation stiffness parameter;
h	separation of flanges of ring girder;
h_b	silo overall height (see EN 1991-4);
j	joint efficiency factor for welded lap joints assessed using membrane stresses;
j	equivalent harmonic of the design stress variation;
ℓ	effective length of shell in linear stress analysis;
ℓ	half wavelength of a potential buckle (height to be considered in calculation);
l	wavelength (pitch) of a corrugation in corrugated sheeting;
m	bending moment per unit width;
m_x	axial or meridional bending moment in a cylinder per unit circumference;
m_ϕ	meridional bending moment in a conical shell per unit circumference;
m_y	circumferential bending moment per unit height of box;
m_θ	circumferential bending moment per unit height of shell;
m_{xy}	twisting shear moment per unit width of plate;
$m_{x\theta}$	twisting shear moment in a cylinder per unit width of shell;
$m_{\phi\theta}$	twisting shear moment in a conical shell per unit width of shell;
n	membrane stress resultant;
n	number of discrete supports around silo circumference;
n_x	axial or meridional membrane stress resultant in a cylinder per unit circumference;
n_ϕ	meridional membrane stress resultant in a conical shell per unit circumference;
n_y	horizontal membrane stress resultant per unit height of box;
n_θ	circumferential membrane stress resultant per unit height of shell;
n_{xy}	membrane shear stress resultant per unit width of flat plate;
$n_{x\theta}$	membrane shear stress resultant in a cylinder per unit width of shell;
$n_{\phi\theta}$	membrane shear stress resultant in a conical shell per unit width of shell;
p	pressure distributed loading;
p_h	internal pressure normal to cylindrical shell (outward);
p_n	internal pressure normal to conical hopper (outward);
p_t	meridional surface traction tangential to hopper shell (downward);
p_w	meridional surface traction tangential to cylindrical shell (downward);

p_x	meridional surface loading tangential to shell (downward);
p_x	meridional surface loading tangential to shell (downward);
p_θ	circumferential surface loading tangential to shell (anticlockwise in plan);
q	external pressure normal to a shell (inward);
r	radial coordinate in a circular plan-form silo;
r	radius of the middle surface of an axisymmetric shell;
r_ϕ	local radius of curvature at the crest or trough of a corrugation;
s	meridional coordinate;
t	wall thickness;
t_x, t_y	equivalent wall thickness of corrugated sheet for stretching in the x, y directions;
w	radial or normal deflection;
x	local axial coordinate in a cylinder;
y	local circumferential coordinate;
z	global axial coordinate;
z	coordinate along the vertical axis of an axisymmetric silo (shell of revolution).

3.2.3 Greek letters

α	elastic buckling imperfection factor (knock-down factor);
α	coefficient of thermal expansion;
β	hopper apex half angle;
γ_F	partial factor for actions;
γ_M	partial factor for resistance;
δ	imperfection amplitude;
Δ	increment;
Δt_a	abrasion loss of wall thickness at points in contact with moving solid during discharge
ζ	stress amplification factor above the ring girder at a support;
ζ_r	reduced stress amplification ratio above an intermediate ring;
θ	circumferential coordinate;
κ_g	shell to girder stiffness ratio (girder transverse stiffness);
κ_r	shell to ring stiffness ratio (ring circumferential bending stiffness);
λ	shell symmetrical meridional bending half-wavelength (short wave);
$\bar{\lambda}$	relative slenderness of a shell;
μ	wall friction coefficient;
μ	shell unsymmetrical meridional bending half-wavelength (long wave);

ν	Poisson's ratio;
θ	circumferential coordinate around shell;
σ	direct stress;
σ_{bx}	axial or meridional bending stress in a cylindrical shell;
$\sigma_{b\phi}$	meridional bending stress in a conical shell;
σ_{by}	circumferential bending stress in box;
$\sigma_{b\theta}$	circumferential bending stress in curved shell;
τ_{bxy}	twisting shear stress in box;
$\tau_{bx\theta}$	twisting shear stress in cylindrical shell;
$\tau_{b\phi\theta}$	twisting shear stress in conical shell;
σ_{mx}	axial or meridional membrane stress in a cylindrical shell;
$\sigma_{m\phi}$	meridional membrane stress in a conical shell;
σ_{my}	circumferential membrane stress in box;
$\sigma_{m\theta}$	circumferential membrane stress in curved shell;
τ_{mxy}	membrane shear stress in box;
$\tau_{mx\theta}$	membrane shear stress in curved shell;
σ_{sox}	axial or meridional outer surface stress in a cylindrical shell;
$\sigma_{so\phi}$	meridional outer surface stress in a conical shell;
σ_{soy}	circumferential outer surface stress in box;
$\sigma_{so\theta}$	circumferential outer surface stress in curved shell;
τ_{soxy}	outer surface shear stress in box;
$\tau_{sox\theta}$	outer surface shear stress in a cylindrical shell;
$\tau_{so\phi\theta}$	outer surface shear stress in a conical shell;
τ	shear stress;
ϕ	local meridional coordinate in a conical shell;
χ	reduction factor for flexural column buckling;
χ	shell buckling stress reduction factor;
ψ	stress non-uniformity parameter
ω	dimensionless parameter in buckling calculation;
ω	inclination to vertical of a hopper whose axis is not vertical.

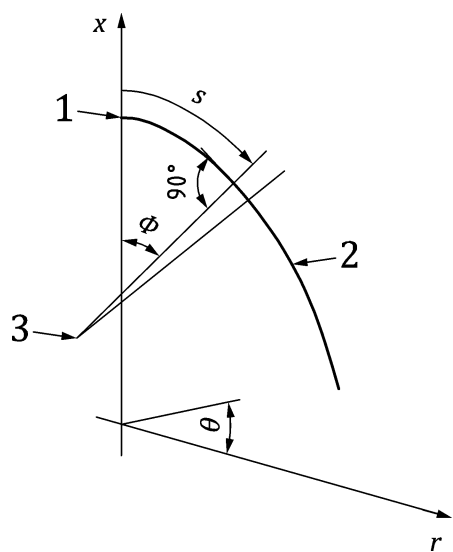
3.2.4 Subscripts

E	value of stress or displacement (arising from design actions);
F	actions;
M	material;
R	resistance;
S	value of stress resultant (arising from design actions);
b	bending;
c	cylinder;
cr	critical buckling value (linear eigenvalue);
d	design value;
eff	effective;
eq	equivalent;
h	hopper;
m	membrane, midspan;
min	minimum allowed value;
n	normal to the wall;
p	pressure;
r	radial;
s	skirt, support;
s	surface stress (o... outer surface, i... inner surface)
u	ultimate;
w	meridional and parallel to the wall (wall friction);
x	axial or meridional;
y	circumferential (box structures), yield;
z	axial direction;
θ	circumferential (axisymmetric shells);
ϕ	meridional in conical shells.

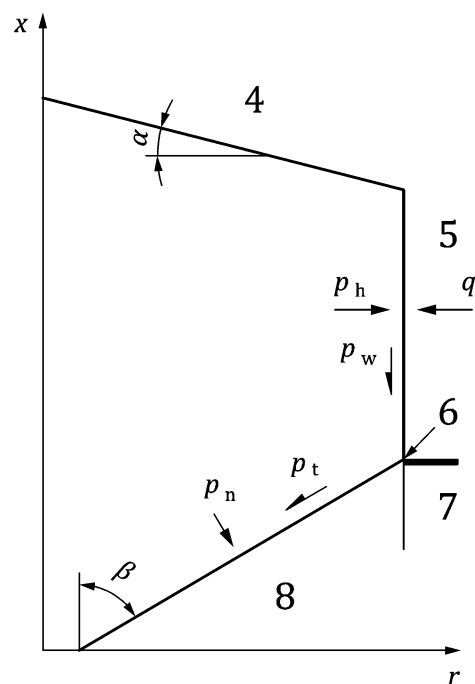
3.3 Sign conventions

3.3.1 Conventions for global silo structure axis system for circular silos

(1) The sign convention given here is for the complete silo structure and recognizes that the silo is not a structural member.



a) Global coordinate system



b) Vertical section through silo axisymmetric shell

Key

- 1 pole
- 2 shell meridian
- 3 instantaneous centre of meridional curvature
- 4 conical roof
- 5 cylinder
- 6 transition
- 7 skirt
- 8 conical hopper

Figure 3.1 — Global coordinate system and loadings on a circular silo

NOTE The notation for loads on the cylindrical and conical walls of a silo are consistent with the notation used for these specific loads in EN 1991-4. More general notations used in EN 1993-1-6 are different.

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

Coordinate system

- coordinate on the central axis of a shell of revolution x
- radial coordinate r
- circumferential coordinate θ
- local meridional angular coordinate in a roof or hopper ϕ

(3) The convention for positive directions is: Outward direction positive (internal pressure positive, outward displacements positive, except for wind and external pressure which is external pressure positive) Tensile stresses positive (except in buckling formulae where compression is positive as noted in the text).

(4) The convention for distributed actions on the silo wall surfaces is:

- pressure normal to cylindrical shell (outward positive) p_h
- pressure normal to cylindrical shell (inward positive) q
- meridional surface loading parallel to cylindrical shell (downward positive) p_w
- pressure normal to hopper (outward positive) p_n
- meridional surface loading parallel to hopper (downward positive) p_t
- circumferential surface loading parallel to shell (anticlockwise positive in plan) p_θ

3.3.2 Conventions for global silo structure axis system for rectangular silos

(1) The sign convention given here is for the complete silo structure and recognizes that the silo is not a structural member.

NOTE 1 In general, the convention for the global silo structure axis system is in Cartesian coordinates x, y, z , where the vertical direction is taken as z , see Figure 3.2 a).

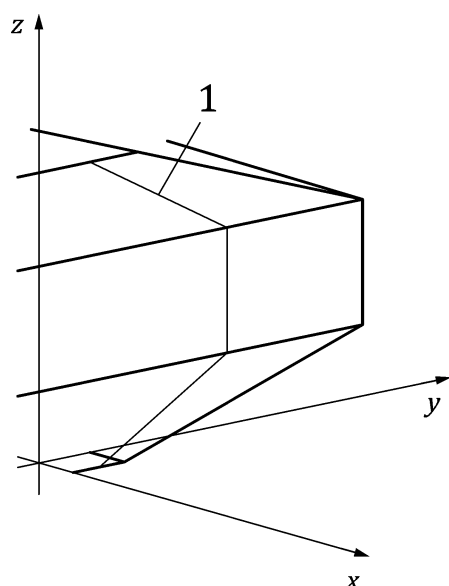
NOTE 2 The angles α and β in a rectangular silo are defined as the steepest slopes on the planar surface, see Figure 3.2 b).

(2) The convention for positive directions is:

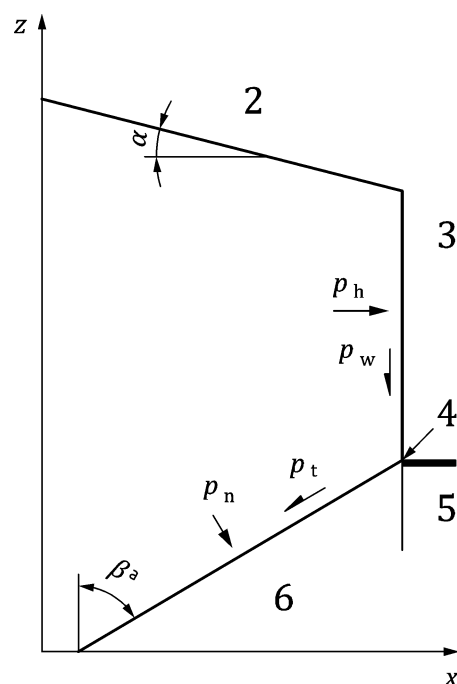
- outward direction positive (internal pressure positive, outward displacements positive);
- tensile stresses positive (except in buckling formulae where compression is positive);
- bending stresses tensile on the outer surface.

(3) The convention for distributed actions on the silo wall surface is:

- pressure normal to vertical box wall (outward positive) p_h
- meridional surface loading parallel to vertical box wall (downward positive) p_w
- pressure normal to hopper on steepest slope (outward positive) p_n
- meridional surface loading parallel to hopper on steepest slope (downward positive) p_t
- circumferential surface loading in the plane of the box plan cross-section (anticlockwise positive) p_y



a) global coordinate system



b) silo box coordinates and loading: section

Key

- 1 box meridian
- 2 pyramidal roof
- 3 vertical wall
- 4 transition
- 5 skirt
- 6 pyramidal hopper
- ^a steepest slope

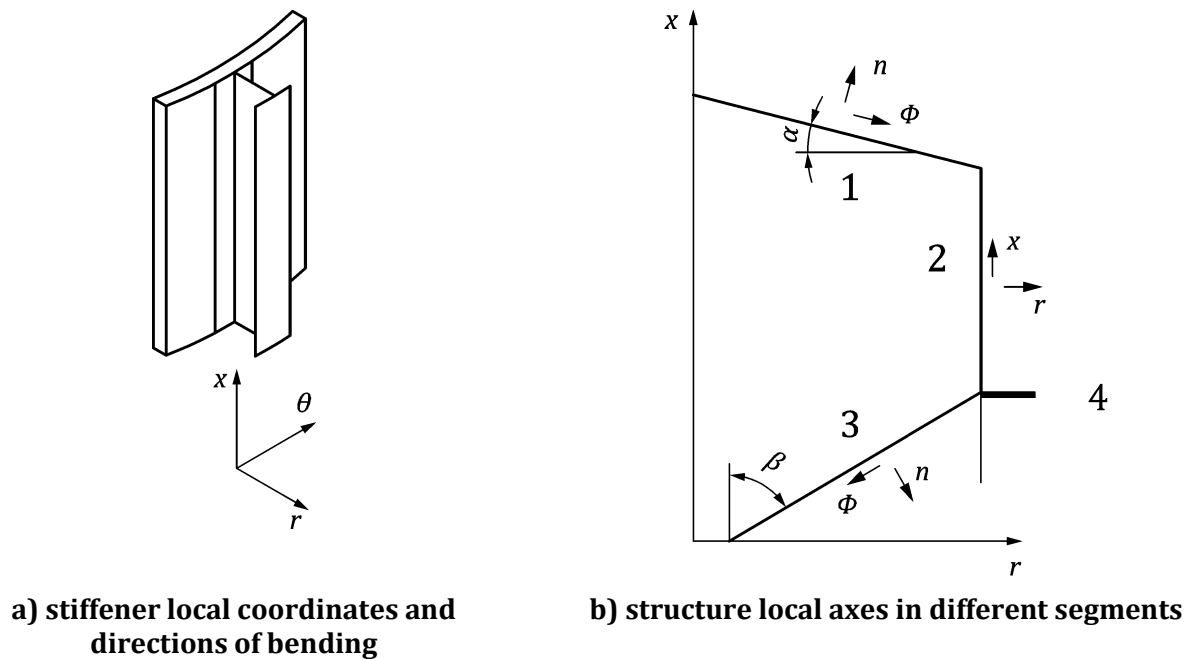
Figure 3.2 — Global coordinate system and loadings on a rectangular silo**3.3.3 Conventions for structural element axes in both circular and rectangular silos**

(1) The convention for structural elements attached to the silo wall (see Figure 3.3 and Figure 3.4) is different for meridional and circumferential members.

(2) The local axis convention for meridional straight structural elements (see Figure 3.3a) attached to the silo wall (shells and boxes) is:

- axial or meridional coordinate for cylindrical shell or vertical box wall x
- axial coordinate for vertical box wall z
- normal coordinate for cylindrical shell r
- normal coordinate for vertical box wall n
- meridional coordinate for conical hopper and conical roof ϕ
- normal coordinate for hopper and roof n

NOTE 1 A meridional stiffener bending in a manner that is compatible with meridional bending (m_x) in the cylinder bends about the θ axis of the stiffener but its second moment of area is denoted I_x .



Key

- 1 roof
- 2 vertical wall
- 3 hopper
- 4 skirt

Figure 3.3 — Local coordinate systems for walls and meridional stiffeners on a shell

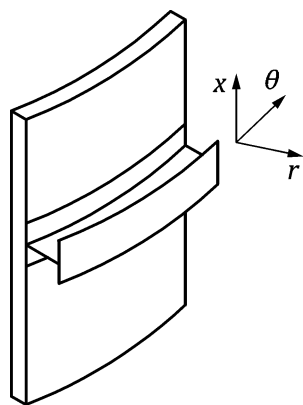


Figure 3.4 — Local coordinate system for circumferential ring stiffeners on a shell for directions of bending

NOTE 2 To match bending terminology for shell structures, the vertical stresses in both the shell and any vertical stiffener are denoted σ_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 3.3 a) is denoted as I_x (not I_θ 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 σ_θ . The bending moments inducing circumferential stresses in a ring stiffener are denoted as M_θ , and the second moment of area of a ring (Figure 3.4 a)) bending in the plane of the ring (stresses in the circumferential direction) is denoted by I_θ . This last notation is important for the required stiffness of ring stiffeners to assist in resisting buckling under external pressure or wind.

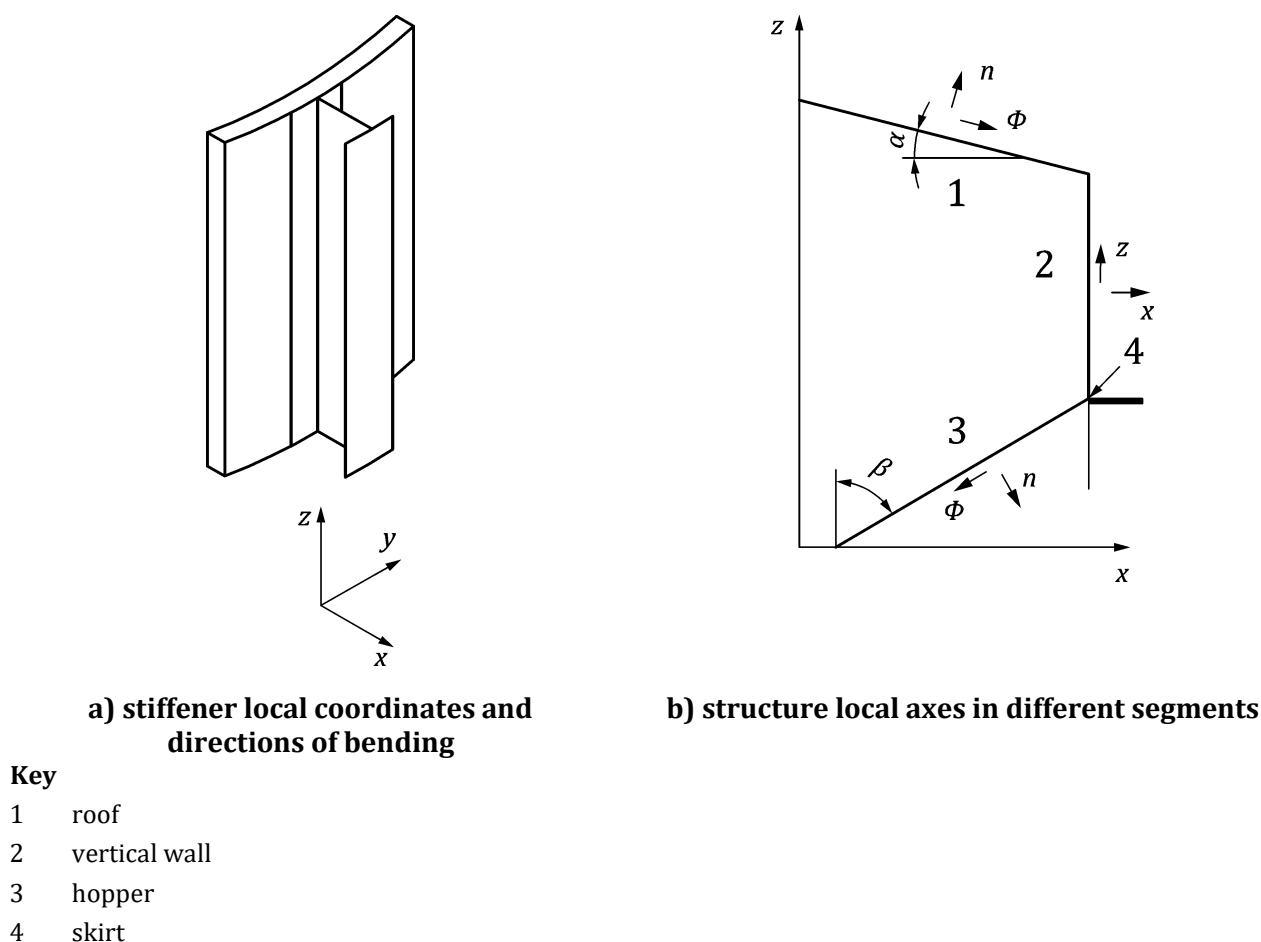


Figure 3.5 — Local coordinate systems for walls and meridional stiffeners on a box

(3) The local axis convention for circumferential curved structural elements (see Figure 3.4 a)) attached to a shell wall is:

- Circumferential coordinate axis (curved) θ
- Radial axis (axis for bending in a tangential vertical plane) r
- Subscript for circumferential bending θ
- Subscript for axial bending x

NOTE A circumferential ring under a bending moment m_θ is subject to bending about its vertical axis x and the bending is compatible with circumferential bending in the cylinder (m_θ). The second moment of area of this ring is defined as I_θ . When the ring is subject to bending moments (m_r) about its radial axis r when either acting as a ring girder, or when subject to radial forces acting at a point eccentric to the ring centroid. These bending moments also induce stresses σ_θ and $\tau_{r\theta}$ in the ring. The second moment of area of this ring is defined as I_r .

(4) The local axis convention for circumferential straight structural elements attached to a box is:

- circumferential axis y
- outward axis x
- vertical axis z

NOTE A circumferential straight stiffener on a box is subject to bending about its vertical axis z when the bending is out of the plane of the box wall, which is the normal condition.

3.3.4 Conventions for stress resultants for circular silos and rectangular silos

(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."

Membrane stress resultants:

- n_x axial membrane stress resultant in a cylindrical shell
- n_ϕ meridional membrane stress resultant in a conical or spherical shell
- n_θ circumferential membrane stress resultant in a shell
- n_z vertical membrane stress resultant in a rectangular box
- n_y circumferential membrane stress resultant in a rectangular box
- n_{yz} or $n_{x\theta}$ membrane shear stress resultant

Membrane stresses:

- σ_{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 a shell
- σ_{mz} vertical membrane stress in a rectangular box
- σ_{my} circumferential membrane stress in a rectangular box
- τ_{myz} or $\tau_{mx\theta}$ membrane shear stress

(2) The convention used for subscripts indicating moments is: The subscript derives from the direction in which direct stress is induced by the moment.

NOTE This plate and shell convention differs from that for beams and columns as used in EN 1993-1-1 and EN 1993-1-3. Care is to be exercised when using those documents in conjunction with these rules.

Bending stress resultants:

- m_x meridional or axial bending moment per unit width
- m_θ circumferential bending moment per unit width in shells
- m_y circumferential bending stress resultant in rectangular boxes
- m_{xy} or $m_{x\theta}$ twisting shear moment per unit width

Bending stresses:

- σ_{bx} meridional or axial bending stress
- $\sigma_{b\theta}$ circumferential bending stress in shells
- σ_{by} circumferential bending stress in rectangular boxes
- τ_{bxy} or $\tau_{bx\theta}$ twisting shear stress

Inner and outer surface stresses:

- $\sigma_{six}, \sigma_{sox}$ meridional or axial inner, outer surface stress for boxes and shells
- $\sigma_{si\theta}, \sigma_{so\theta}$ circumferential inner, outer surface stress in shells
- $\tau_{six\theta}, \tau_{sox\theta}$ inner, outer surface shear stress in shells
- $\sigma_{siy}, \sigma_{soy}$ circumferential inner, outer surface stress in rectangular boxes
- τ_{sixy}, τ_{soxy} inner, outer surface shear stress in rectangular boxes

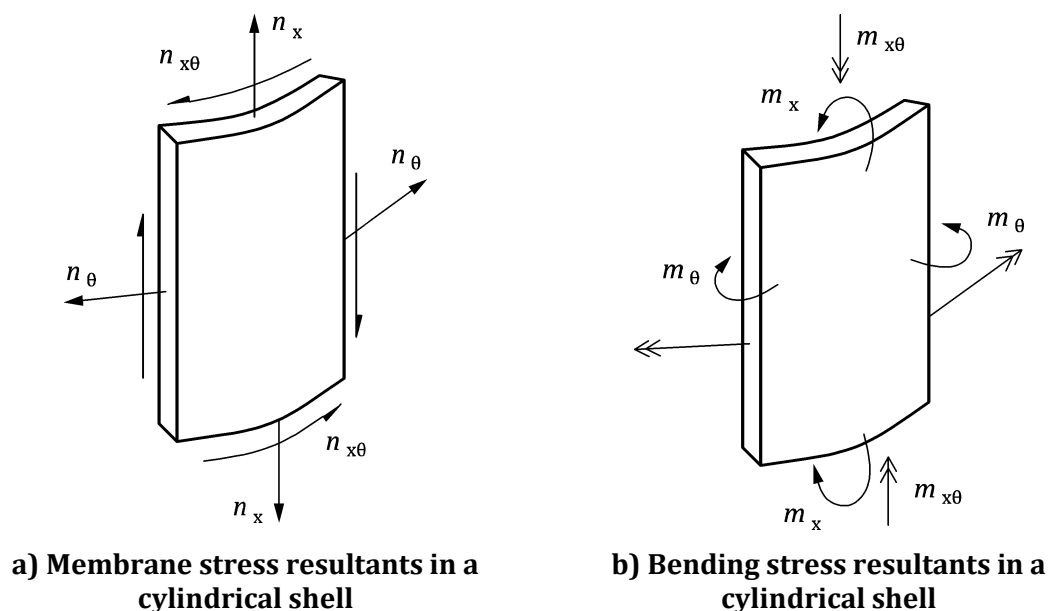


Figure 3.6 — Stress resultants in the shell silo wall

4 Basis of design

4.1 Basic requirements

- (1) The design of silos shall be in accordance with the general rules given in EN 1990 and EN 1991 (all parts) and the specific design provisions for steel structures given in EN 1993-1 (all parts).
- (2) Numerical values of the specific actions on steel silos shall be taken from EN 1991-4.
- (3) Silos designed according to this document shall be executed according to EN 1090-2 with construction materials and products used as specified in the relevant parts of the EN 1993 series, or in the relevant material and product specifications.
- (4) Where the buckling resistance is critical, the fabrication tolerances defined in EN 1993-1-6 should be adopted.
- (5) The design of the silo structure should consider all shell and plated sections of the structure, including stiffeners, ribs, rings and attachments.
- (6) The supporting structure should not be treated as part of the silo structure. The boundary between the silo and its supports should be taken as indicated in Figure 1.1. Similarly, other structures supported by the silo should be treated as beginning where the silo wall or attachment ends.
- (7) Silos should be designed to be damage-tolerant where appropriate, considering the use of the silo.
- (8) Particular requirements for special applications can be specified by the relevant authority, or where not specified, can be agreed for a specific project by the relevant parties.
- (8) This document 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 1993-4-2, 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 silos. Matters that are already covered in those documents are not repeated.
- (9) 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.
- (10) Safety factors for 'product type' silos (factory production) can be specified by the appropriate authorities. When applied to 'product type' silos, the factors in 4.3 are for guidance purposes only. They are provided to show the likely levels needed to achieve consistent reliability with other designs.

4.2 Units

- (1) For the application of this standard S.I. units are used in accordance with ISO 1000.
- (2) For calculations, the following consistent units are recommended:

dimensions and thicknesses:	m	mm
unit weight:	kN/m ³	N/mm ³
forces and loads:	kN	N
line forces and line loads:	kN/m	N/mm
pressures and area distributed actions:	kPa	MPa
unit mass:	t/m ³	t/mm ³

acceleration:	m/s^2	mm/s^2
membrane stress resultants:	kN/m	N/mm
bending stress resultants:	kNm/m	Nmm/mm
stresses and elastic moduli:	kPa	$\text{MPa (N/mm}^2\text{)}$

4.3 Silo classifications

4.3.1 Consequence Classification for silos

- (1) For reliability differentiation by Consequence Class, see EN 1990:2023, A.4.
- (2) The classification of each silo into a Consequence Class is given in EN 1990:2023, A.4, based on the consequences of failure. The classification for structural design rules combines the Consequence Class with the Structural Complexity Class into a single classification as a Silo Group.

4.3.2 Structural Complexity Classification for silos

- (1) The Structural Complexity Class for a silo shall be determined by the conditions of the individual silo.
- (2) The dimensions of the silo should be used as a critical part of the evaluation of the Structural Complexity Class.
- (3) The effect of silo size on selection of the Structural Complexity Class should be determined according to the parameter w , associated with the potential energy of the stored solid using Formula (4.1).

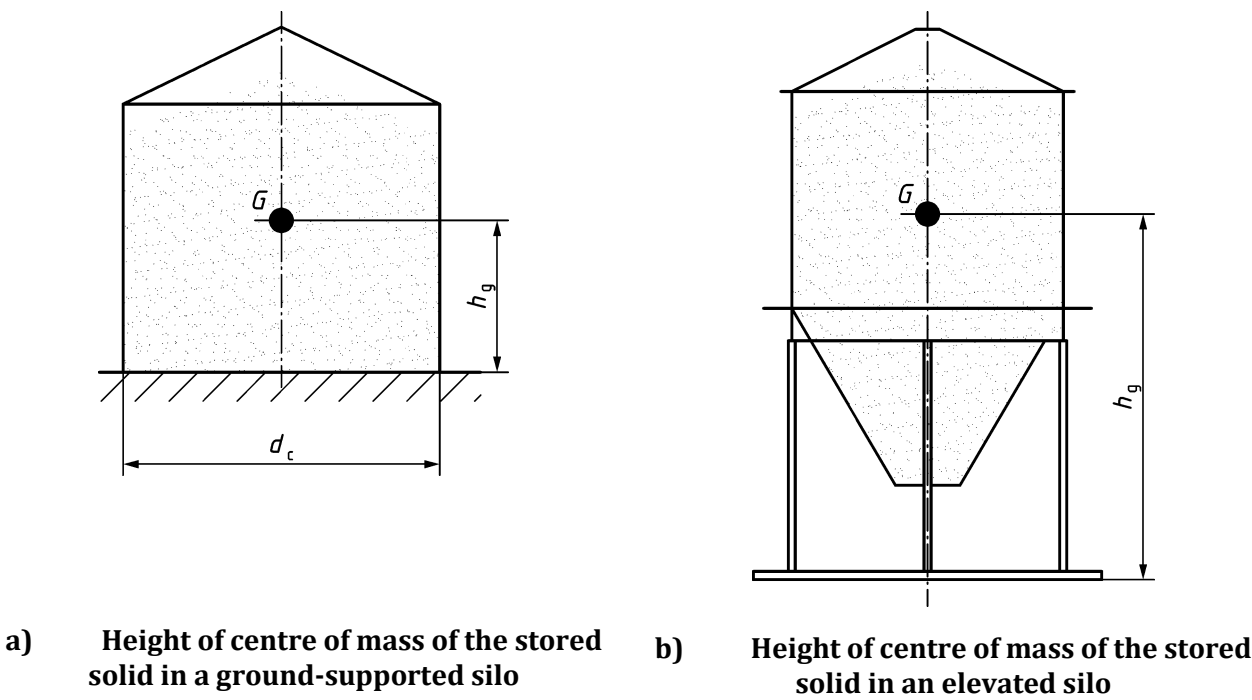


Figure 4.1 — Dimensions used to define Structural Complexity Classes

(4) The effect of silo size on the selection of the Structural Complexity Class should be determined according to the parameter w , calculated from Formula (4.1):

$$w = \sqrt{h_g \times \min(h_g, d_c)} \quad (4.1)$$

where

d_c is the characteristic dimension of the silo cross-section (see prEN 1991-4:2024, Figure 1.1c)

h_g is the height of the centre of mass of the stored solid above the ground (see Figure 4.1)

NOTE 1 The parameter w provides a simple understandable single dimension that is related to the potential energy of the stored solid, though the unit weight is omitted.

NOTE 2 Quantified limits of the parameter w for each Structural Complexity Class for silos are given in Table 4.1 (NDP), unless the National Annex gives different quantified limits.

Table 4.1 (NDP) — Descriptions and quantified limits for parameter w for Structural Complexity Classes for silos

Structural Complexity Class	Descriptions and values of parameter w
Structural Complexity Class 3	a) Elevated discretely-supported silos $w > 20$ m b) Silos designed to resist unsymmetrical loads with $w > 15$ m
Structural Complexity Class 2	Silos with $10 < w \leq 15$ m
Structural Complexity Class 1	Ground-supported silos with $2 < w \leq 10$ m
Structural Complexity Class 0	Silos with $w \leq 2$ m

4.3.3 Silo Group Categorisation

(1) Different levels of rigour should be used in the design of silo structures, depending on the Silo Group to which the silo belongs, the structural arrangement and the susceptibility to different failure modes.

NOTE The National Annex can define the conditions to distinguish between Silo Groups as a function of the location, the size, the structural form and internal structures, the stored solid and loading, and the type of operation, noting the definitions and classifications given in EN 1990:2023, Clause A.4 and EN 1991-4. It can also provide additional information on other issues associated with the choice of Silo Group.

(2) Classification into a Silo Group should be determined by the conditions of the individual silo.

(3) Four Silo Groups are used in this standard, with requirements that produce designs with essentially comparable demands on the design assessment and considering the expense and procedures necessary to ensure the safety of different structures: Silo Groups 0, 1, 2 and 3 as indicated in Table 4.2.

NOTE 1 The classification of a silo into a Silo Group is given in Table 4.2, unless the National Annex gives a different classification.

NOTE 2 Silos that could be classified as Silo Group 4 correspond to structures in Consequence Class 4 (EN 1990), which are outside the scope of the Eurocodes since additional information is required for their design.

Table 4.2 — Silo Group (SG) (NDP) defined by the Structural Complexity Class (SCC), and Consequence Class (CC)

Structural Complexity Class (SCC)	Higher (CC3)	Normal (CC2)	Lower (CC1)	Lowest (CC0)
Higher (SCC3)	SG3	SG3	SG2	SG1
Normal (SCC2)	SG3	SG2	SG2	SG0
Lower (SCC1)	SG3	SG2	SG1	SG0
Lowest (SCC0)	SG2	SG2	SG1	SG0

(4) The structural design should be carried out according to the provisions for the relevant Silo Group given in this part.

(5) The provisions for a higher Silo Group than that required may always be adopted for the design.

(6) The provisions for a lower Silo Group than that defined shall not be adopted for the design.

(7) Silos that are used to store materials that can induce vibrations, oscillations and shocks (quaking, honking, banging; see prEN 1991-4:2024, D.3 and Table C.2) require special load assessments and design considerations that are outside the scope of this document.

(8) A higher Silo Group than that defined by Table 4.2 may be adopted. Any part of the procedures for a higher Silo Group may be adopted whenever it is appropriate.

NOTE Other requirements can be specified in the National Annex in reference to each Silo Group. These relate to:

- Design qualification and experience levels (DQLs);
- Design Check Levels (DCLs), Execution Classes (EXC);
- Inspection Levels (ILs);
- Minimum validation of stored materials behaviour;
- Specification of assumptions concerning differential settlements;
- Minimum validation of calculation models used in the design.

(9) Silo Group 3 should be used for all Special Silo Load Cases (SSLC) which refer to a stored solid load case associated with unsymmetrical conditions on the wall of the silo, as defined in EN 1991-4.

(10) For silos in Silo Groups 0 and 1, simplified provisions may be adopted.

NOTE Appropriate provisions for silos in Silo Group 1 (and Silo Group 0) are set out in Annex A.

4.4 Verification by the partial factor method

4.4.1.1 Partial factors for actions on silos

(1) For persistent, transient and accidental design situations, the partial factors γ_F shall be taken from EN 1990:2023, A.4.

(2) Partial factors for 'product-type' silos (factory production) may be specified by the appropriate authorities.

NOTE When applied to 'product-type' silos, the values of the partial factors given in Table 4.4 are for guidance purposes only. They are provided to show the likely levels needed to achieve consistent reliability with other designs.

4.4.1.2 Partial factors for resistances

(1) Where structural properties are determined by testing, the requirements and procedures of EN 1990 should be adopted.

(2) Fatigue verifications should satisfy Clause 10 of prEN 1993-1-6:2023 and EN 1993-1-9.

(3) The partial factors γ_{Mi} for different limit states shall be taken from Table 4.3. The specific values for those factors are recommended as given in Table 4.4.

Table 4.3 — Partial factors for resistance

Resistance to failure mode	Relevant γ
Resistance of welded or bolted shell or box wall to plastic limit state	γ_{M0}
Resistance of shell or box wall to stability	γ_{M1}
Resistance of welded or bolted shell or box wall to rupture	γ_{M2}
Resistance of shell or box wall to cyclic plasticity	γ_{M4}
Resistance of connections	γ_{M5}
Resistance of shell or box wall to fatigue	γ_{Mf}

NOTE 1 The numerical values in Table 4.4 are given for silo structures, unless the National Annex gives different values.

Table 4.4 (NDP) — Numerical values for partial factors for resistance for silo structures

$\gamma_{M0} = 1,00$	$\gamma_{M1} = 1,10$	$\gamma_{M2} = 1,25$
$\gamma_{M4} = 1,00$	γ_{M5} see EN 1993-1-8	γ_{Mf} see EN 1993-1-9

NOTE 2 The required partial factor for shell buckling γ_{M1} depends quite strongly on the structural form, the slenderness of the shell, the load case and the buckling mode, since the imperfection sensitivity and the consequent variability of the buckling resistance varies considerably with these factors. Due to lack of reliable data relevant to practical construction, the drafting committee chose to retain the historically accepted value of γ_{M1} .

(4) Where hot-rolled steel sections are used as part of a silo structure, the relevant partial factors for their resistance should be taken from EN 1993-1-1.

(5) Where cold-formed steel sections are used as part of a silo structure, the relevant partial factors for their resistance should be taken from EN 1993-1-3.

4.4.2 Serviceability limit states

(1) Where simplified compliance rules are given in the relevant provisions dealing with characteristic serviceability limit states, detailed calculations using combinations of actions need not be carried out.

(2) For all serviceability limit states the values of γ_{Mser} should be specified.

NOTE The partial factor for serviceability $\gamma_{Mser} = 1,0$, unless the National Annex gives a different value.

(3) The limit states defined in EN 1993-1-6 and EN 1993-1-7, as appropriate, should be adopted.

- Global stability and static equilibrium as a rigid body;
- LS1: plastic limit;
- LS2: cyclic plasticity;
- LS3: buckling;
- LS4: fatigue.

4.5 Actions and environmental effects

4.5.1 General

(1) The general requirements set out in Clause 4 of EN 1990:2023 shall be satisfied.

4.5.2 Wind action

(1) For specifications of wind actions not set out in EN 1991-1-4 for the design of silos either in isolation or in a GROUP, appropriate additional information should be agreed.

(2) Because these large light structures are sensitive to the detailed wind pressure distribution on the wall, both with respect to the buckling resistance when empty and the holding down details required at the foundation, additional information may be used to augment the wind data provided in EN 1991-1-4 for the specific needs of an individual construction.

4.5.3 Combination of solids pressures with other actions

(1) The combination factors on actions in silos set out in EN 1990:2023, A.4 should be used.

NOTE The National Annex can specify different combination factors on actions.

4.6 Geometrical data

(1) The provisions concerning geometrical data given in Clause 6 of EN 1990:2023 shall be followed.

(2) The additional information specific to shell structures given in EN 1993-1-6 should also be applied.

(3) The shell plate thickness should be taken as the nominal thickness. In the case of hot-dipped galvanised metal-coated steel sheet conforming with EN 10346, the nominal thickness should be taken as the nominal core thickness, obtained as the nominal external thickness less the total thickness of zinc coating on both surfaces.

(4) The effects of corrosion and abrasion on the thickness of silo wall plates should be included in the design, in accordance with 6.1.4.

4.7 Modelling of the silo for determining action effects

- (1) The general requirements set out in EN 1990 shall be followed.
- (2) The specific requirements for structural analysis in relation to serviceability, set out in Clause 13 of this document for each structural segment, should be followed.
- (3) The specific requirements for structural analysis in relation to ultimate limit states, set out in Clauses 6 to 12 of this document and in more detail in EN 1993-1-6 and EN 1993-1-7, should be followed.

4.8 Design assisted by testing

- (1) The general requirements set out in EN 1990:2023, Annex D should be followed.
- (2) For 'product-type' silos (factory production) which are subject to full-scale testing, 'deemed-to-satisfy' criteria may be adopted for design purposes.

4.9 Action effects for limit state verifications

- (1) The general requirements set out in EN 1990 shall be satisfied.

4.10 Durability

- (1) The general requirements set out in EN 1990:2023, 4.6 should be followed.

4.11 Fire resistance

- (1) The provisions set out in EN 1993-1-2 for fire resistance should be met.

5 Properties of materials

5.1 General

- (1) All steels used for silos should be suitable for welding to permit later modifications when necessary.
- (2) All steels used for silos of circular planform should be suitable for cold forming into curved sheets or curved members.
- (3) The material properties given in EN 1993-1-1 (see Table 5.1 and Table 5.2 in EN 1993-1-1:2022) and EN 1993-1-3 (see Table 5.2 in FprEN 1993-1-3:2023) as appropriate, should be treated as nominal values to be adopted as characteristic values in design calculations, except as defined in 5.2.
- (4) Other material properties are given in the relevant Reference Standards defined in EN 1993-1-1.
- (5) Where the silo can be filled with hot solids, the values of the material properties should be appropriately reduced to values corresponding to the maximum temperatures to be encountered.
- (6) The variation in the material properties of structural steels at temperatures above 100 °C should be obtained from EN 1993-1-2. Where these are adopted, the reduced yield stress may be conservatively taken as the temperature-dependent proportionality limit $f_{p\theta}$. The mechanical properties for steel grades not represented in EN 1993-1-2 should be based on reliable information.

5.2 Structural steels

(1) The methods for design by calculation given in this document may be used for structural steels as defined in EN 1993-1-1, which conform with the European Standards and International Standards listed in Table 5.1 and Table 5.2 of EN 1993-1-1:2022.

(2) The mechanical properties of structural steels, according to EN 10025 series or EN 10149 series should be obtained from EN 1993-1-1 and EN 1993-1-3, as appropriate.

(3) Corrosion and abrasion allowances are given in 6.1.4.

(4) For the steels covered by this document, the design value of Poisson's ratio should be taken as $\nu = 0,3$. The characteristic value of the elastic modulus for structural steel should be taken as $E = 200\,000\text{ N/mm}^2$, in accordance with the value defined for stability calculations in EN 1993-1-14.

NOTE Elastic buckling is often critical in silo structures, so a conservative estimate of the elastic modulus is required, since the partial factor for buckling γ_M has been made consistent throughout all the EN 1993 standards.

(5) Where the design involves a stability calculation, appropriate reduced properties should be used either as appropriate to the operating temperature (see EN 1993-1-2) or as appropriate to the stress-strain curve higher stresses (see EN 1993-1-6 and EN 1993-1-14). For stability calculations, the reduced elastic modulus E_{red} should be adopted under these conditions.

5.3 Stainless steels

(1) The mechanical properties of stainless steels should be established according to the provisions of Clause 5 in prEN 1993-1-6:2023.

(2) Guidance for the selection of stainless steels in view of corrosion and abrasion actions of stored solids may be obtained from appropriate sources (see also 6.1.4).

(3) Where the design involves a buckling calculation, appropriate reduced properties should be used (see EN 1993-1-6).

5.4 Special alloy steels

(1) For non-standardised alloy steels, appropriate values of relevant mechanical properties should be chosen. The properties of steels should fulfil the general requirements given in EN 1993-1-1.

NOTE Further information on the application of non-standardized alloy steels can be given in the National Annex.

(2) Guidance for the selection of non-standardised alloy steels with respect to the corrosion and abrasion actions of stored solids should be obtained from appropriate sources.

(3) Where the design involves a buckling calculation, appropriate reduced properties should be used (see EN 1993-1-6 and EN 1993-1-14).

5.5 Toughness requirements

(1) The provisions in this standard apply to materials that satisfy the brittle fracture provisions given in EN 1993-1-4, EN 1993-1-10 and EN 1993-1-12.

6 Basis for structural analysis

6.1 Ultimate limit states

6.1.1 Basis

(1) Steel structures and components should be so proportioned that the basic design requirements given in Clause 4 are satisfied.

6.1.2 Required checks

(2) For every relevant limit state, the design shall satisfy the condition:

$$S_d \leq R_d \quad (6.1)$$

where

S and R represent any appropriate parameter.

6.1.3 Fatigue and cyclic plasticity — low cycle fatigue

(1) Parts of the structure subject to severe local bending should be checked against the fatigue and cyclic plasticity limit states using the procedures of EN 1993-1-6 and EN 1993-1-7 as appropriate.

NOTE The term “severe local bending” refers to locations where the local bending stress exceeds twice the local membrane stress.

(2) The number of cycles for a particular fatigue load case should be determined as defined in prEN 1991-4:2023, 5.2.3(6). Consideration should also be given to the conditions identified in prEN 1991-4:2023, 5.2.3(11).

(3) The number of cycles involved in either the cyclic plasticity or fatigue limit states are defined in prEN 1993-1-6:2023, 6.3.2 and 6.3.4.

(4) It is not necessary to check silos in Silo Groups 0 and 1 for fatigue or cyclic plasticity.

6.1.4 Allowance for corrosion and abrasion

(1) The effects of abrasion of the stored solid on the walls of the container over the life of the structure should be included in determining the effective thickness of the wall for analysis. Solids identified as potentially leading to abrasion of steel are given in prEN 1991-4:2024, Table C.2.

(2) Where no specific information is available, the wall should be assumed to lose an amount Δt_a of its thickness due to abrasion at all points that can be in contact with moving solid during discharge.

(3) Where the stored material is a cereal grain, the value of Δt_a may be taken to be $\Delta t_a = 0$.

(4) Where the stored material is identified as potentially abrasive in EN 1991-4, the value of Δt_a may be taken to be $\Delta t_a = 2$ mm.

NOTE Alternative recommendations for the abrasion caused by different stored solids in contact with different surfaces over different periods can be found in the literature.

(5) The effects of corrosion of the wall in contact with the stored solid over the life of the structure should be included in determining the effective thickness of the wall for analysis.

NOTE Recommendations for the corrosion caused by different stored solids in contact with different surfaces over different periods can be found in the literature.

(6) For the specification of specific values for corrosion and abrasion losses, the intended use and the nature of the solids to be stored should be taken into account. These values should be stated in the execution specification.

NOTE 1 The National Annex can choose appropriate values for corrosion and abrasion losses for particular solids in frictional contact with defined silo wall materials, recognising the mode of solids flow and the abrasive or corrosive potential of the solid as defined in EN 1991-4.

NOTE 2 Appropriate inspection measures are needed to ensure that the design assumptions are met in service.

6.1.5 Allowance for temperature effects

(1) Where hot solids are stored in the silo, the effects of differential temperature between parts of the structure in contact with hot material and those that have cooled should be included in determining the stress distribution in the wall.

6.2 Serviceability limit states

(1) Deformations should be limited to avoid:

- 2nd order deformation problems, when they are not taken into account in the analysis;
- problems associated with the attachment of, or proximity to, adjacent structures (e.g. feeders, chutes, conveyors, pipelines, etc.);
- limitations required for the individual project by the relevant authority or client.

(2) Where no limits are defined by the relevant authority or client, see Clause 13.

6.3 Analysis of the structure of a shell silo

6.3.1 Modelling of the structural shell

(1) The modelling of the structural shell should follow the requirements of EN 1993-1-6. They may be deemed to be satisfied by using the following provisions.

- (2) The modelling of the structural shell should include all stiffeners, large openings and attachments.
- (3) The design should ensure that the assumed boundary conditions are achievable in execution.
- (4) A shell formed from corrugated plate (vertically or horizontally) may be treated as an orthotropic uniform shell provided that the corrugation full wavelength is less than $0,5\sqrt{rt}$ where t is the local plate thickness.

6.3.2 Methods of analysis

6.3.2.1 General

- (1) The analysis of the silo shell should be carried out according to the requirements of EN 1993-1-6.
- (2) An analysis type defined for a higher Silo Group than the subject silo may always be used.
- (3) Where the silo is subject to any form of unsymmetrical bulk solids loading (proxy loads, eccentric discharge, unsymmetrical filling etc., see EN 1991-4), the structural model should be designed to capture the membrane shear transmission within the silo wall and between the wall and rings.

NOTE The shear transmission between parts of the wall and rings has special importance in construction using bolts or other discrete connectors (e.g. between the wall and hopper, between the cylinder wall and vertical stiffeners or support, and between different courses in the cylinder).

(4) Where a ring girder is used to redistribute silo wall forces into discrete supports, and where bolts or discrete connectors are used to join the structural elements, the shear transmission between the parts of the ring due to shell bending and ring girder bending phenomena should be determined.

(5) The stiffness of the stored bulk solid in resisting wall deformations or in increasing the buckling resistance of the shell structure should only be considered where a rational analysis is used and there is clear evidence that the solid against the wall is not in motion at the specified location during discharge. In such situations, the relevant information on the flow pattern, the pressure in the solid and the properties of the specific stored bulk solid should be determined from EN 1991-4.

(6) Where a corrugated silo exhibits mass flow (see EN 1991-4), the solid held stationary only within the corrugations should not be considered as stationary when evaluating the support provided by internal pressure to resist buckling (see 7.9.4.3(11)).

6.3.2.2 Silo Group 3

(1) For silos in Silo Group 3, the internal forces and moments should be determined using a validated numerical analysis (e.g. computational shell analysis, as defined in EN 1993-1-6). Plastic collapse strengths under primary stress states may be used in relation to the plastic limit state as defined in EN 1993-1-6.

6.3.2.3 Silo Group 2

(1) For silos in Silo Group 2 under conditions of axisymmetric actions and support conditions, one of two alternative analyses may be used:

- Membrane theory may be used to determine the primary stresses. Bending theory elastic formulae may be used to describe all local bending effects (see EN 1993-1-6 for definitions);
- A validated numerical analysis may be used (e.g. computational shell analysis, as defined in EN 1993-1-6).

(2) Where the design loading from stored solids cannot be treated as axisymmetric, a validated numerical analysis should be used.

(3) Notwithstanding (2), where the loading varies smoothly around the shell causing global bending only (i.e. in the form of circumferential harmonic 1), membrane theory may be used to determine the primary stresses.

(4) For analyses of actions due to wind loading and/or foundation settlement and/or smoothly varying proxy loads (see EN 1991-4 for thin walled silos), the semi-membrane theory or the membrane theory of shells may be used.

(5) Where membrane theory is used to find the primary stresses in the shell:

- a) Discrete rings attached to an isotropic cylindrical silo shell under internal pressure may be deemed to have an effective area which includes a length of shell above and below the ring of $0,78\sqrt{rt}$ except where the ring is at a transition junction;
- b) The effect of local bending stresses at discontinuities in the shell surface and supports should be evaluated separately.

(6) Where an isotropic shell wall is discretely stiffened by vertical stiffeners, the stresses in the stiffeners and the shell wall may be calculated by treating the stiffeners as smeared on the shell wall, provided the spacing of the stiffeners is not wider than $5\sqrt{rt}$.

(7) Where smeared stiffeners are used on an isotropic shell, the stress in the stiffener should be determined making proper allowance for compatibility between the stiffener and the wall and including the effect of the wall membrane stress in the orthogonal direction (see 7.8.3).

NOTE Internal pressure causes circumferential stresses which induce vertical strains (shortening) of the shell wall, but this does not apply to vertical stiffeners. Compatibility between the shell and the stiffeners then increases the axial compression in stiffeners.

(8) Where a ring girder is used above discrete supports, membrane theory may be used to determine the primary stresses, but the requirements of 7.8 and 10.1.4 concerning the evaluation of additional non-axisymmetric primary stresses should be followed.

(9) Where a ring girder is used above discrete supports, compatibility of the deformations between the ring and adjacent shell segments should be considered, see Figure 6.1. Particular attention should be paid to compatibility of the axial deformations, as the induced stresses penetrate far up the shell. Where such a ring girder is used, the eccentricity of the ring girder centroid and shear centre relative to the shell wall and the support centreline should be considered, see 10.1.4 and 10.2.3.

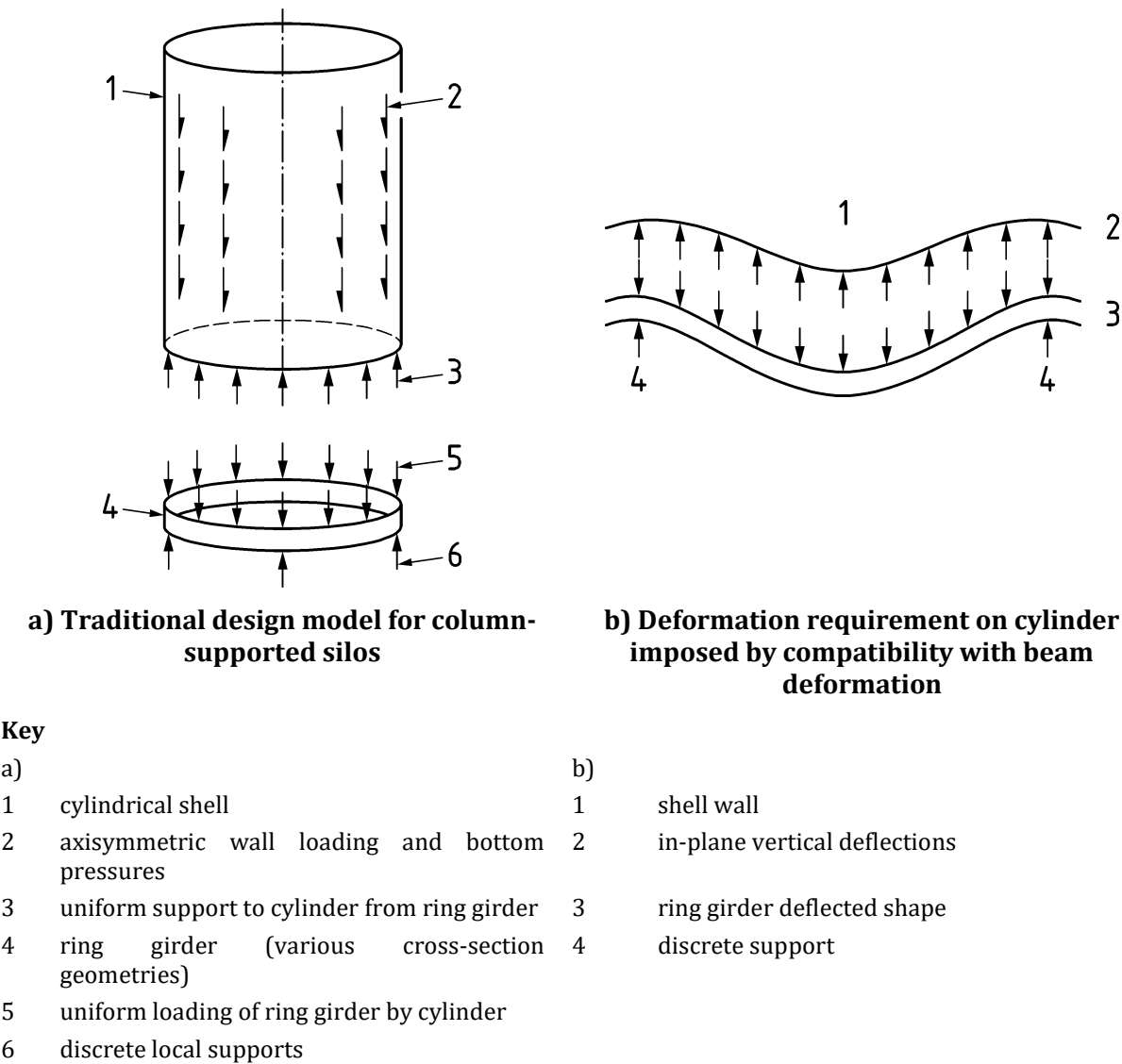


Figure 6.1 — Axial deformation compatibility between ring girder and shell

6.3.2.4 Silo Group 1

(1) For silos in Silo Group 1, membrane theory may be used to determine the primary stresses, with factors and simplified formulae to describe local bending effects and unsymmetrical actions.

6.3.2.5 Silo Group 0

(1) Silos in Silo Group 0 may be designed to the provisions defined for Silo Group 1, but they strictly lie outside the scope of this document.

6.3.3 Geometric imperfections

(1) Geometric imperfections in the shell should satisfy the tolerance requirements defined in EN 1993-1-6.

(2) For silos in Silo Groups 2 and 3, the geometric imperfections should, where possible, be measured following construction to ensure that the assumed fabrication tolerance quality has been achieved.

(3) Geometric imperfections in the shell need not be explicitly included in determining the internal forces and moments, except where a GNIA or GMNIA analysis is used, as defined in EN 1993-1-6.

6.4 Analysis of the box structure of a plate assembly silo

6.4.1 Modelling of the structural box formed by an assembly of plates

(1) The modelling of the structural box should follow the requirements of EN 1993-1-7, but they may be deemed to be satisfied by the following provisions.

(2) The modelling of the structural box should include all stiffeners, large openings and attachments.

(3) The design should ensure that the assumed boundary conditions are satisfied.

(4) The joints between segments of the box should satisfy the modelling assumptions for strength and stiffness.

(5) Each panel of the box may be treated as an individual plate segment provided that both:

a) the forces and moments introduced into each panel by its neighbours are included;

b) the flexural stiffness of adjacent panels is included.

(6) Where corrugated wall panels are used, the bending stresses in each panel or plate segment may be calculated by treating the plate as acting in one-way bending.

(7) Where an isotropic plate wall panel is discretely stiffened with horizontal stiffeners, the stresses in the stiffeners and the box wall may be calculated by treating the stiffeners as smeared on the wall to produce an orthotropic plate, provided that the spacing of the stiffeners is no wider than $30t$.

NOTE For further information, see EN 1993-1-7.

(8) Where a smeared stiffener treatment is used, the stress in the stiffener should be determined making proper allowance for the eccentricity of the stiffener from the wall plate, and for the wall stress in the direction orthogonal to the axis of the stiffener.

(9) The effective width of plate on each side of a stiffener may be taken as $15 \varepsilon t$, where $\varepsilon = \sqrt{235/f_y}$ and f_y is in N/mm². For more detailed information see EN 1993-1-5 and EN 1993-1-7.

NOTE The simple value $15 \varepsilon t$ is chosen a safe value.

6.4.2 Geometric imperfections

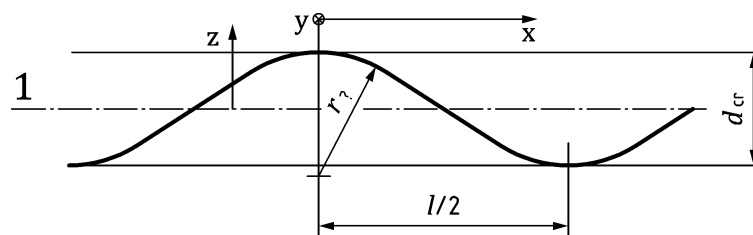
- (1) Where geometric imperfections in the box are relevant to buckling ultimate limit states, their amplitudes should satisfy the limitations defined in EN 1993-1-7.
- (2) Geometric imperfections in the box need not be explicitly included in determining the internal forces and moments.

6.4.3 Methods of analysis

- (1) The internal forces in the plate segments of the box wall may be determined using either:
 - a) static equilibrium for membrane forces and beam theory for bending (see prEN 1993-1-7:2023, Annex A);
 - b) an analysis based on linear plate bending and stretching theory (see prEN 1993-1-7:2023, Annex B);
 - c) an analysis based on nonlinear plate bending and stretching theory.
- (2) For silos in Silo Group 1, method a) in (1) may be used.
- (3) Where the design loading condition is symmetric relative to each plate segment and the silo is in Silo Group 2, method a) in (1) may be used.
- (4) Where the design loading condition is not symmetric and the silo is in Silo Group 2, either method b) or method c) in (1) should be used.
- (5) For silos in Silo Group 3, the internal forces and moments should be determined using either method b) or method c) in (1) (as defined in EN 1993-1-7).

6.5 Analysis treatment of corrugated sheeting

- (1) Where corrugated sheeting is used as part of the silo structure, the analysis may be carried out treating the sheeting as an equivalent uniform orthotropic wall.
- (2) The following properties may be used in a stress analysis and in a buckling analysis of the structure, provided that the corrugation profile has either an arc-and-tangent or a sinusoidal shape. Where other corrugation profiles are used, the corresponding properties should be calculated from first principles.



Key

- 1 effective middle surface of the corrugated shell wall

Figure 6.2 — Corrugation profile and geometric parameters

- (3) The properties of the corrugated sheeting should be defined in terms of an x, y coordinate system in which the y axis runs parallel to the corrugations (straight lines on the surface) whilst x runs normal to the corrugations (troughs and peaks). The corrugation should be defined in terms of the following parameters, irrespective of the actual corrugation profile, see Figure 6.2:

where

- d_{cr} is the crest to crest transverse dimension;
- L is the wavelength (pitch) of the corrugation;
- r_{ϕ} is the local radius of curvature at the crest or trough.

(4) The equivalent properties of the sheeting in each of the two principal directions may be treated as independent, so that strains in one direction do not produce stresses in the orthogonal direction (i.e. no Poisson effects).

(5) The equivalent membrane properties (stretching stiffnesses) may be taken as:

$$C_1 = Et_1 \quad (6.2)$$

$$C_2 = Et_2 \quad (6.3)$$

$$C_{12} = Gt_{12} \quad (6.4)$$

where

- t_1 is the equivalent thickness for the smeared membrane stiffness parallel to the corrugations, given by:

$$t_1 = t \left(1 + \frac{\pi^2 d_{cr}^2}{4l^2} \right) \quad (6.5)$$

- t_2 is the equivalent thickness for the smeared membrane stiffness normal to the corrugations, given by:

$$t_2 = \frac{2t^3}{3d_{cr}^2} \quad (6.6)$$

- t_{12} is the equivalent thickness for the smeared membrane shear stiffness, given by:

$$t_{12} = \frac{t}{\left(1 + \frac{\pi^2 d_{cr}^2}{4l^2} \right)} \quad (6.7)$$

NOTE The surface length of one corrugation wave is given by $l(t_1/t)$.

(6) The equivalent bending properties (flexural stiffnesses) are defined in terms of the flexural rigidity for moments causing bending stresses in that direction, and may be taken as:

$$D_1 = EI_1 \quad (6.8)$$

$$D_2 = EI_2 \quad (6.9)$$

$$D_{12} = GI_{12} \quad (6.10)$$

where

I_1 is the equivalent second moment of area per unit width for the smeared bending stiffness parallel to the corrugations. For the corrugated profiles described in (2), it may be taken as:

$$I_1 = \frac{td_{cr}^2}{8} \left(1 + \frac{\pi^2 d_{cr}^2}{8l^2} \right) \quad (6.11)$$

I_2 is the equivalent second moment of area per unit width for the smeared bending stiffness perpendicular to the corrugations, given by:

$$I_2 = \frac{t^3}{12(1-\nu^2)} \frac{1}{\left(1 + \frac{\pi^2 d_{cr}^2}{4l^2} \right)} \quad (6.12)$$

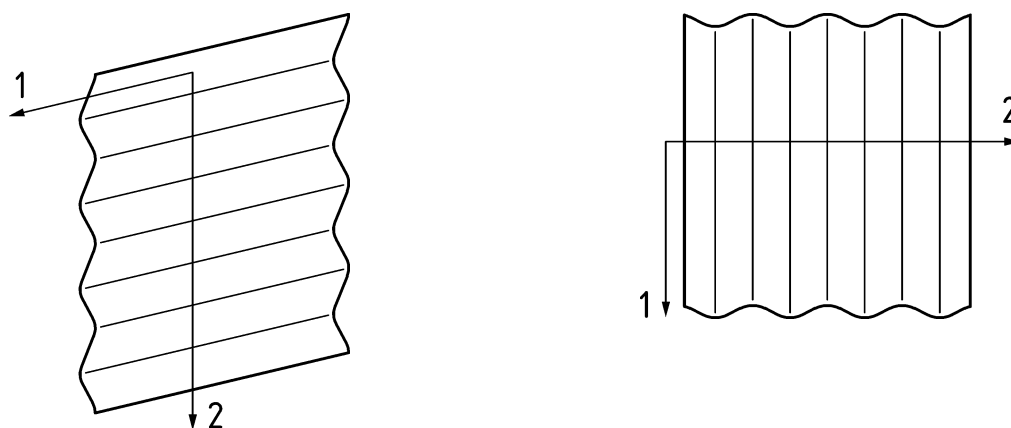
I_{12} is the equivalent second moment of area per unit width for the smeared twisting stiffness:

$$I_{12} = \frac{t^3}{12} \left(1 + \frac{\pi^2 d_{cr}^2}{4l^2} \right) \quad (6.13)$$

NOTE The convention for bending moments in plates relates to the direction in which the plate becomes curved, so is contrary to the convention used for beams. Bending parallel to the corrugation engages the bending stiffness of the corrugated profile, induces stresses parallel to the corrugation, and is the chief reason for using corrugated construction.

(7) In circular silos, the corrugations are commonly arranged to run circumferentially. In this arrangement, the directions 1 and 2 in the above formulae should be taken as the circumferential θ and vertical x directions respectively, see Figures 3.1a and 6.3a. In the less common arrangement in which the corrugations run vertically, the directions 1 and 2 in the above formulae should be taken as the vertical x and circumferential θ directions respectively, see Figures 3.1a and 6.3b.

NOTE For circular silos, the above formulae provide values for C_x , C_θ , $C_{x\theta}$, D_x , D_θ and $D_{x\theta}$. These can be used in treating cylindrical corrugated walls as orthotropic (see 7.9).



a) Corrugations running horizontally

b) Corrugations running vertically

Figure 6.3 — Corrugated sheeting and silo wall orientations

(8) The shearing properties should be taken as independent of the corrugation orientation. The value of G may be taken as $E / \{2(1+\nu)\} = 80\,800 \text{ MPa}$.

(9) In rectangular silos, the corrugations are commonly arranged to run horizontally. In this arrangement, the directions 1 and 2 in the above formulae should be taken as the horizontal y and vertical z directions respectively, see Figures 3.2a and 6.3a. In the less common arrangement where the corrugations run vertically, the directions 1 and 2 in the above formulae should be interchanged on the real structure and taken as the vertical z and horizontal y directions respectively, see Figures 3.2a and 6.3b.

7 Ultimate limit state design of cylindrical shell walls

7.1 Basis

7.1.1 General

(1) Cylindrical steel silo walls should be so proportioned that the basic design requirements for the ultimate limit states given in 7.1.2 are satisfied.

(2) The safety assessment of an isotropic walled cylindrical shell should be conducted using the provisions of EN 1993-1-6, which may be deemed to be satisfied by the provisions of this clause.

(3) Where a silo has either corrugated or stiffened walls, the provisions of 7.4, 7.5 or 7.6 should be adopted as appropriate.

7.1.2 Silo wall design

(1) The cylindrical wall of the silo should be checked for the following phenomena under the limit states defined in EN 1993-1-6:

- global stability and static equilibrium.

LS1: plastic limit state covering:

- resistance to bursting or rupture or plastic mechanism collapse (excessive yielding) under internal pressures or other actions;
- resistance of joints (connections).

LS2: cyclic plastification covering:

- resistance to local yielding in bending;
- local effects.

LS3: buckling covering:

- resistance to buckling under axial compression (meridional compression);
- resistance to buckling under external pressure (wind or vacuum);
- resistance to buckling under shear from unsymmetrical actions;
- resistance to buckling under shear near engaged columns;
- resistance to local failure above supports;
- resistance to local crippling near openings;
- resistance to local buckling under unsymmetrical actions.

LS4: fatigue covering:

- resistance to high cycle fatigue failure at locations where high elastic stresses are often repeated.

(2) The shell wall should satisfy the provisions of EN 1993-1-6, except where 7.3 to 7.6 provide conditions that are deemed to satisfy the provisions of that standard.

(3) For silos in Silo Groups 0 and 1, the cyclic plasticity and fatigue limit states may be ignored.

7.2 Distinctions between cylindrical shell forms

(1) For a shell wall constructed from flat rolled steel sheet, termed 'isotropic' (see Figure 7.1a), the resistances should be determined as defined in 7.3.

(2) For an isotropic shell wall with lap joints formed by connecting adjacent plates with overlapping sections, termed 'lap-jointed' (see Figure 7.1b), the resistances should be determined as defined in 7.3.6.

(3) For an isotropic shell wall with vertical stiffeners attached to the outside, termed 'externally stiffened' irrespective of the spacing of the stiffeners (see Figure 7.1c), the resistances should be determined as defined in 7.4.

NOTE The use of internal stiffeners in silos is not encouraged, since the surface of contact with the stored solid is increased, increasing vertical forces in the wall and permitting stored solid to be trapped, and also because internal stiffeners lead to a lower axial compression buckling resistance in a cylindrical shell than external stiffeners.

(4) For a shell wall constructed from corrugated steel sheets where the troughs run around the silo circumference, termed 'horizontally corrugated' (see Figure 7.1d), the resistances should be determined as defined in 7.5. For a shell wall with the troughs running up the meridian, termed 'vertically corrugated', the resistances should be determined as defined in 7.6.