



BSI Standards Publication

Eurocode 3 - Design of steel structures

Part 4-1: Silos

National foreword

This British Standard is the UK implementation of EN 1993-4-1:2007+A1:2017. It supersedes BS EN 1993-1-4:2007, which is withdrawn.

The start and finish of text introduced or altered by corrigendum is indicated in the text by tags. Text altered by CEN corrigendum April 2009 is indicated in the text by AC1 AC1.

The start and finish of text introduced or altered by amendment is indicated in the text by tags. Tags indicating changes to CEN text carry the number of the CEN amendment. For example, text altered by CEN amendment A1 is indicated by A1 A1.

Following publication of the EN, there is a period allowed for national calibration during which the National Annex is issued, followed by a co-existence period of a maximum three years. During the co-existence period Member States are encouraged to adapt their national provisions. At the end of this co-existence period, the conflicting parts of national standard(s) will be withdrawn.

In the UK there are no conflicting national standards.

The UK participation in its preparation was entrusted to Technical Committee CB/203, Design & execution of steel structures.

A list of organizations represented on this committee can be obtained on request to its secretary.

Where a normative part of this EN allows for a choice to be made at the national level, the range and possible choice will be given in the normative text as Recommended Values, and a note will qualify it as a Nationally Determined Parameter (NDP). NDPs can be a specific value for a factor, a specific level or class, a particular method or a particular application rule if several are proposed in the EN.

UK National Annex to BS EN 1993-4-2

To enable EN 1993-4-2 to be used in the UK, the committee has decided that no National Annex will be issued and recommend the following:

- all the Recommended Values should be used;
- all Informative Annexes may be used; and
- no NCCI have currently been identified.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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28 February 2010	Implementation of CEN corrigendum April 2009
31 January 2011	Correction to equation (8.27) in 8.3.2.3
31 December 2017	Implementation of CEN amendment A1:2017

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 European Standard was approved by CEN on 12 June 2006.

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Foreword

This European Standard EN 1993-4-1, “Eurocode 3: Design of steel structures – Part 4-1: Silos”, has been prepared by Technical Committee CEN/TC250 « Structural Eurocodes », the Secretariat of which is held by BSI. CEN/TC250 is responsible for all Structural Eurocodes.

This European Standard shall be given the status of a National Standard, either by publication of an identical text or by endorsement, at the latest by August 2007 and conflicting National Standards shall be withdrawn at latest by March 2010.

This Eurocode supersedes ENV 1993-4-1:1999.

According to the CEN-CENELEC Internal Regulations, the National Standard Organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

Foreword to amendment A1

This document (EN 1993-4-1:2007/A1:2017) has been prepared by Technical Committee CEN/TC 250 “Structural Eurocodes”, the secretariat of which is held by BSI.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by June 2018, and conflicting national standards shall be withdrawn at the latest by June 2018.

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

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

According to the CEN-CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

Background of the Eurocode programme

In 1975, the Commission of the European Community decided on an action programme in the field of construction, based on article 95 of the Treaty. The objective of the programme was the elimination of technical obstacles to trade and the harmonisation of technical specifications.

Within this action programme, the Commission took the initiative to establish a set of harmonized technical rules for the design of construction works which, in a first stage, would serve as an alternative to the national rules in force in the Member States and, ultimately, would replace them.

For fifteen years, the Commission, with the help of a Steering Committee with Representatives of Member States, conducted the development of the Eurocodes programme, which led to the first generation of European codes in the 1980's.

In 1989, the Commission and the Member States of the EU and EFTA decided, on the basis of an agreement¹⁾ between the Commission and CEN, to transfer the preparation and the publication of the Eurocodes to the CEN through a series of Mandates, in order to provide them with a future status of European Standard (EN). This links de facto the Eurocodes with the provisions of all the Council's Directives and/or Commission's Decisions dealing with European standards (e.g. the Council Directive 89/106/EEC on construction products - CPD - and Council Directives 93/37/EEC, 92/50/EEC and 89/440/EEC on public works and services and equivalent EFTA Directives initiated in pursuit of setting up the internal market).

¹⁾ Agreement between the Commission of the European Communities and the European Committee for Standardisation (CEN) concerning the work on EUROCODES for the design of building and civil engineering works (BC/CEN/03/89).

The Structural Eurocode programme comprises the following standards generally consisting of a number of Parts:

EN1990	Eurocode: Basis of structural design
EN1991	Eurocode 1: Actions on structures
EN1992	Eurocode 2: Design of concrete structures
EN1993	Eurocode 3: Design of steel structures
EN1994	Eurocode 4: Design of composite steel and concrete structures
EN1995	Eurocode 5: Design of timber structures
EN1996	Eurocode 6: Design of masonry structures
EN1997	Eurocode 7: Geotechnical design
EN1998	Eurocode 8: Design of structures for earthquake resistance
EN1999	Eurocode 9: Design of aluminium structures

Eurocode standards recognise the responsibility of regulatory authorities in each Member State and have safeguarded their right to determine values related to regulatory safety matters at national level where these continue to vary from State to State.

Status and field of application of Eurocodes

The Member States of the EU and EFTA recognise that EUROCODES serve as reference documents for the following purposes:

- as a means to prove compliance of building and civil engineering works with the essential requirements of Council Directive 89/106/EEC, particularly Essential Requirement N°1 - Mechanical resistance and stability - and Essential Requirement N°2 - Safety in case of fire ;
- as a basis for specifying contracts for construction works and related engineering services ;
- as a framework for drawing up harmonised technical specifications for construction products (ENs and ETAs)

The Eurocodes, as far as they concern the construction works themselves, have a direct relationship with the Interpretative Documents²⁾ referred to in Article 12 of the CPD, although they are of a different nature from harmonised product standards³⁾. Therefore, technical aspects arising from the Eurocodes work need to be adequately considered by CEN Technical Committees and/or EOTA Working Groups working on product standards with a view to achieving full compatibility of these technical specifications with the Eurocodes.

The Eurocode standards provide common structural design rules for everyday use for the design of whole structures and component products of both a traditional and an innovative nature. Unusual forms of construction or design conditions are not specifically covered and additional expert consideration will be required by the designer in such cases.

National Standards implementing Eurocodes

The National Standards implementing Eurocodes will comprise the full text of the Eurocode (including any annexes), as published by CEN, which may be preceded by a National title page and National foreword, and may be followed by a National Annex.

The National Annex may only contain information on those parameters which are left open in the Eurocode for national choice, known as Nationally Determined Parameters, to be used for the design of buildings and civil engineering works to be constructed in the country concerned, i.e. :

²⁾ According to Art. 3.3 of the CPD, the essential requirements (ERs) shall be given concrete form in interpretative documents for the creation of the necessary links between the essential requirements and the mandates for harmonised ENs and ETAGs/ETAs.

³⁾ According to Art. 12 of the CPD the interpretative documents shall :

- a) give concrete form to the essential requirements by harmonising the terminology and the technical bases and indicating classes or levels for each requirement where necessary ;
- b) indicate methods of correlating these classes or levels of requirement with the technical specifications, e.g. methods of calculation and of proof, technical rules for project design, etc. ;
- c) serve as a reference for the establishment of harmonised standards and guidelines for European technical approvals.

The Eurocodes, de facto, play a similar role in the field of the ER 1 and a part of ER 2.

- values and/or classes where alternatives are given in the Eurocode,
- values to be used where a symbol only is given in the Eurocode,
- country specific data (geographical, climatic, etc), e.g. snow map,
- the procedure to be used where alternative procedures are given in the Eurocode.

It may also contain:

- decisions on the application of informative annexes,
- references to non-contradictory complementary information to assist the user to apply the Eurocode.

Links between Eurocodes and harmonised technical specifications (ENs and ETAs) for products

There is a need for consistency between the harmonised technical specifications for construction products and the technical rules for works⁴⁾. Furthermore, all the information accompanying the CE Marking of the construction products which refer to Eurocodes should clearly mention which Nationally Determined Parameters have been taken into account.

Additional information specific to EN1993-4-1

EN 1993-4-1 gives design guidance for the structural design of silos.

EN 1993-4-1 gives design rules that supplement the generic rules in the many parts of EN 1993-1.

EN 1993-4-1 is intended for clients, designers, contractors and relevant authorities.

EN 1993-4-1 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.

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.

Safety factors for ‘product type’ silos (factory production) can be specified by the appropriate authorities. When applied to ‘product type’ silos, the factors in 2.9 are for guidance purposes only. They are provided to show the likely levels needed to achieve consistent reliability with other designs.

National Annex for EN1993-4-1

This standard gives alternative procedures, values and recommendations for classes with notes indicating where national choices may have to be made. Therefore the National Standard implementing EN 1993-4-1 should have a National Annex containing all Nationally Determined Parameters to be used for the design of buildings and civil engineering works to be constructed in the relevant country.

National choice is allowed in EN 1993-4-1 through:

- 2.2 (1)
- 2.2 (3)

⁴⁾ see Art.3.3 and Art.12 of the CPD, as well as clauses 4.2, 4.3.1, 4.3.2 and 5.2 of ID 1.

- 2.9.2.2 (3)
- 3.4 (1)
- 4.1.4 (2) and (4)
- 4.2.2.3 (6)
- 4.3.1 (6) and (8)
- 5.3.2.3 (3)
- 5.3.2.4 (10), (12) and (15)
- 5.3.2.5 (10) and (14)
- 5.3.2.6 (3) and (6)
- 5.3.2.8 (2)
- 5.3.3.5 (1) and (2)
- 5.3.4.3.2 (2)
- 5.3.4.3.3 (2) and (5)
- 5.3.4.3.4 (5)
- 5.3.4.5 (3)
- 5.4.4 (2), (3)b and (3)c)
- 5.4.7 (3)
- 5.5.2 (3)
- 5.6.2 (1) and (2)
- 6.1.2 (4)
- 6.3.2.3 (2) and (4)
- **A1** 6.3.2.7 (4) **A1**
- 7.3.1 (4)
- 8.3.3 (4)
- 8.4.1 (6)
- 8.4.2 (5)
- 8.5.3 (3)
- 9.5.1 (3) and (4)
- 9.5.2 (5)
- 9.8.2 (1) and (2)
- A.2 (1) and (2)
- A.3.2.1 (6)
- A.3.2.2 (6)
- A.3.2.3 (2)
- A.3.3 (1), (2) and (3)
- A.3.4 (4)

1 General

1.1 Scope

- (1) Part 4.1 of Eurocode 3 provides principles and application rules for the structural design of steel silos of circular or rectangular plan-form, being free standing or supported.
- (2) The provisions given in this Part supplement modify or supersede the equivalent provisions given in EN 1993-1.
- (3) 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 the relevant standards.
- (4) 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.
- (5) The 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.
- (6) Foundations in reinforced concrete for steel silos are dealt with in EN 1992 and EN 1997.
- (7) Numerical values of the specific actions on steel silos to be taken into account in the design are given in EN 1991-4 Actions in Silos and Tanks.
- (8) This Part 4.1 does not cover:
 - resistance to fire;
 - silos with internal subdivisions and internal structures;
 - AC1** – silos with capacity less than 100 kN (10 tonnes); **AC1**
 - cases where special measures are necessary to limit the consequences of accidents.
- (9) Where this standard applies to circular planform silos, the geometric form is restricted to axisymmetric structures, but the actions on them may be unsymmetrical, and their supports may induce forces in the silo that are not axisymmetrical.

1.2 Normative references

This European Standard incorporates, by dated and undated reference, provisions from other standards. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to, or revisions of, any of these publications apply to the European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

EN 1090	<i>Execution of steel structures;</i>
A1 EN 1990:2002	<i>Eurocode – Basis of Structural Design; A1</i>
EN 1991	<i>Eurocode 1: Actions on structures;</i>
Part 1.1	<i>Actions on structures – Densities, self-weight and imposed loads for buildings;</i>
Part 1.2:	<i>Actions on structures – Actions on structures exposed to fire;</i>
Part 1.3:	<i>Actions on structures – Snow loads;</i>
Part 1.4:	<i>Actions on structures – Wind loads;</i>
Part 1.5:	<i>Actions on structures – Thermal loads;</i>

Part 1.6:	<i>Actions on structures – Construction loads;</i>
⌈AC1⌋ Part 1.7:	<i>Actions on structures – Accidental actions;</i> ⌈AC1⌋
Part 4:	<i>Actions on silos and tanks;</i>
EN 1993	<i>Eurocode 3: Design of steel structures;</i>
Part 1.1:	<i>General rules and rules for buildings;</i>
Part 1.3:	<i>Cold formed thin gauge members and sheeting;</i>
Part 1.4:	<i>Stainless steels;</i>
⌈A1⌋ Part 1.6:2007: ⌈A1⌋	<i>Strength and stability of shell structures;</i>
Part 1.7:	<i>Planar plated structures loaded transversely;</i>
Part 1.8:	<i>Design of joints;</i>
Part 1.9:	<i>Fatigue strength of steel structures;</i>
Part 1.10:	<i>Selection of steel for fracture toughness and through-thickness properties;</i>
Part 4.2:	<i>Tanks;</i>
EN 1997	<i>Eurocode 7: Geotechnical design;</i>
EN 1998	<i>Eurocode 8: Design provisions for earthquake resistance of structures;</i>
Part 4:	<i>Silos, tanks and pipelines;</i>
⌈AC1⌋ EN 10025	<i>Hot rolled products of structural steels</i>
EN 10149	<i>Hot-rolled flat products made of high yield strength steels for cold forming;</i> ⌈AC1⌋
ISO 1000	<i>SI Units;</i>
ISO 3898	<i>Bases for design of structures - Notation - General symbols;</i>
ISO 4997	<i>Cold reduced steel sheet of structural quality;</i>
ISO 8930	<i>General principles on reliability for structures - List of equivalent terms.</i>

1.3 Assumptions

- (1) In addition to the general assumptions of EN 1990 the following assumptions apply:
- fabrication and erection complies with EN 1090-2

1.4 Distinction between principles and application rules

- (1) See 1.4 in EN 1990.

1.5 Terms and definition

- (1) The terms that are defined in 1.5 in EN 1990 for common use in the Structural Eurocodes and the definitions given in ISO 8930 apply to this Part 4.1 of EN 1993, unless otherwise stated, but for the purposes of this Part 4.1 the following supplementary definitions are given:

1.5.1 shell. A structure formed from a curved thin plate.

1.5.2 axisymmetric shell. A shell structure whose geometry is defined by rotation of a meridional line about a central axis.

1.5.3 box. A structure formed from an assembly of flat plates into a three-dimensional enclosed form. For the purposes of this Standard, the box has dimensions that are generally comparable in all directions.

1.5.4 meridional direction. The tangent to the silo wall in a vertical plane at any point. It varies according to the structural element being considered. Alternatively, it is the vertical or inclined direction on the surface of the structure that a rain drop would take in sliding down the surface.

1.5.5 circumferential direction. The horizontal tangent to the silo wall at any point. It 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.

1.5.6 middle surface. This term is used to refer to both the stress-free middle surface when a shell is in pure bending and the middle plane of a flat plate that forms part of a box.

1.5.7 separation of stiffeners. The centre to centre distance between the longitudinal axes of two adjacent parallel stiffeners.

Supplementary to Part 1 of EN 1993 (and Part 4 of EN 1991), for the purposes of this Part 4.1, the following terminology applies, see figure 1.1:

1.5.8 silo: A silo is a vessel for storing particulate granular solids. In this Standard, it is assumed to have a vertical form with solids being added by gravity at the top. The term silo includes all forms of particulate solids storage structure, that might otherwise be referred to as a bin, hopper, grain tank or bunker.

1.5.9 barrel: The barrel is the vertical walled section of a silo.

1.5.10 hopper: A hopper is a converging section towards the bottom of a silo. It is used to channel solids towards a gravity discharge outlet.

1.5.11 junction: A junction is the point at which any two or more shell segments, or two or more flat plate elements of a box meet. It can include a stiffener or not: the point of attachment of a ring stiffener to the shell or box may be treated as a junction.

1.5.12 transition junction: The transition junction is the junction between the barrel and hopper. The junction can be at the base of the barrel or part way down it.

1.5.13 skirt: The skirt is that part of the barrel which lies below the transition junction: it differs from the higher part in that it has no contact with the stored bulk solids.

1.5.14 strake: A strake or course is a single layer of steel plates used to form one level of the cylindrical barrel of a silo.

1.5.15 stringer stiffener: A stringer stiffener is a local stiffening member that follows the meridian of a shell, representing a generator of the shell of revolution. 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.

1.5.16 rib: A rib is a 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. It is used to distribute transverse loads on the structure by bending action.

1.5.17 ring stiffener: A ring stiffener is a local stiffening member that passes around the circumference of the structure at a given point on the meridian. 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. In a shell of revolution it is circular, but in rectangular structures it takes the rectangular form of the plan section.

1.5.18 smeared stiffeners: Stiffeners are said to be smeared when the properties of the shell wall and the individual stiffeners are treated as a composite section using a width equal to an integer multiple of the separation of the stiffeners. The stiffness properties of a shell wall with smeared stiffeners are orthotropic with eccentric terms leading to coupling between bending and stretching behaviour.

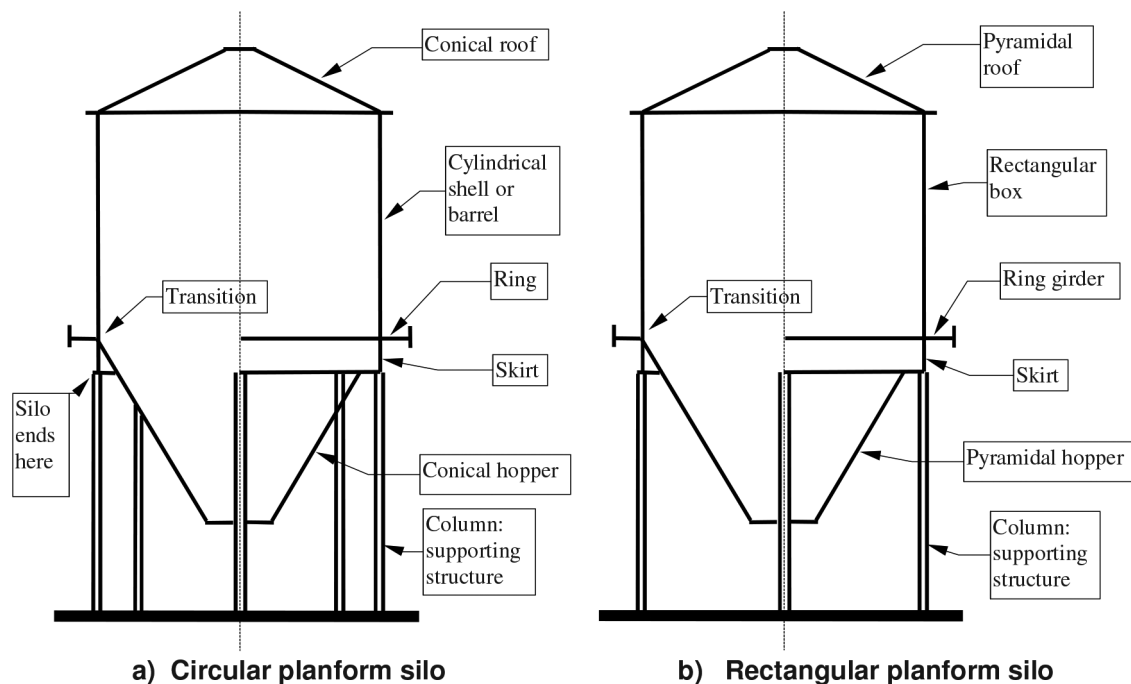


Figure 1.1: Terminology used in silo structures

1.5.19 base ring: A base ring is a 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. It is required to ensure that the assumed boundary conditions are achieved in practice.

1.5.20 ring girder or ring beam: A ring girder or ring beam is a circumferential stiffener which has bending stiffness and strength both in the plane of the circular section of a shell or the plan section of a rectangular structure and also normal to that plane. It is a primary load-carrying element, used to distribute local loads into the shell or box structure.

1.5.21 continuous support: A continuously supported silo is one in which all positions around the circumference are supported in an identical manner. Minor departures from this condition (e.g. a small opening) need not affect the applicability of the definition.

1.5.22 discrete support: A discrete support is a position in which a silo is supported using a local bracket or column, giving a limited number of narrow supports around the silo circumference. Four or six discrete supports are commonly used, but three or more than six are also found.

1.5.23 pyramidal hopper: A pyramidal hopper is used for the hopper section of a rectangular silo, in the form of an inverted pyramid. In this Standard, it is assumed that the geometry is simple, consisting of only four planar elements of trapezoidal shape.

1.6 Symbols used in Part 4.1 of Eurocode 3

The symbols used are based on ISO 3898: 1987.

1.6.1 Roman upper case letters

A	area of cross-section;
C	membrane stretching stiffness;
C	buckling coefficient;
D	bending flexural rigidity;
E	Young's modulus;
F	force;
G	shear modulus;
H	height of structure;
I	second moment of area of cross-section;
I_t	uniform torsion constant;
K	flexural stiffness of wall panel;
L	height of shell segment or stiffener;
M	bending moment;
N	axial force;
Q	fabrication tolerance quality of construction of a shell susceptible to buckling;
$\sqrt{A_1} r \phi \sqrt{A_1}$	local radius at the crest or trough of a corrugation.

1.6.2 Roman lower case letters

a	coefficient;
b	width of plate or stiffener;
d	crest to crest dimension of a corrugation;
e	eccentricity of force or stiffener;
f_y	yield strength of steel;
f_u	ultimate strength of steel;
h	separation of flanges of ring girder;
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;
$\sqrt{A_1} \ell \sqrt{A_1}$	wavelength of a corrugation in corrugated sheeting;
ℓ	half wavelength of a potential buckle (height to be considered in calculation);
m	bending moment per unit width;
m_x	meridional bending moment 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 per unit width of shell;
n	membrane stress resultant;
n	number of discrete supports around silo circumference;
n_x	meridional membrane stress resultant per unit circumference;
n_y	circumferential 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 plate;
$n_{x\theta}$	membrane shear stress resultant per unit width of shell;

p	pressure distributed loading;
p_n	pressure normal to shell (outward);
p_x	meridional surface loading parallel to shell (downward);
p_θ	circumferential surface loading parallel to shell (anticlockwise in plan);
q	transverse force per unit length acting on a tie;
r	radial coordinate in a circular plan-form silo;
r	radius of shell middle surface;
s	circumferential separation of stiffeners;
t	wall thickness;
t_x, t_y	equivalent wall thickness of corrugated sheet for stretching in the x, y directions;
w	imperfection amplitude;
w	radial deflection;
x	local meridional coordinate;
y	local circumferential coordinate;
z	global axial coordinate;
z	coordinate along the vertical axis of an axisymmetric silo (shell of revolution).

1.6.3 Greek letters

α	elastic buckling imperfection factor (knock-down factor);
α	coefficient of thermal expansion;
β	hopper apex half angle;
χ_F	partial factor for actions;
χ_M	partial factor for resistance;
δ	limiting deflection;
Δ	increment;
χ	reduction factor for flexural column buckling;
χ	shell buckling stress reduction factor;
λ	shell meridional bending half-wavelength;
$\bar{\lambda}$	relative slenderness of a shell;
μ	wall friction coefficient;
ν	Poisson's ratio;
θ	circumferential coordinate around shell;
σ	direct stress;
σ_{bx}	meridional bending stress;
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 curved shell;
σ_{mx}	meridional membrane stress;
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}	meridional outer surface stress;
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 curved shell;
τ	shear stress;
ω	dimensionless parameter in buckling calculation;

ω	inclination to vertical of a hopper whose axis is not vertical;
ψ	stress non-uniformity parameter.

1.6.4 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;
d	design value;
eff	effective;
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	meridionally parallel to the wall (wall friction);
x	meridional;
y	circumferential (box structures), yield;
z	axial direction;
θ	circumferential (shells of revolution).

1.7 Sign conventions

1.7.1 Conventions for global silo structure axis system for circular silos

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

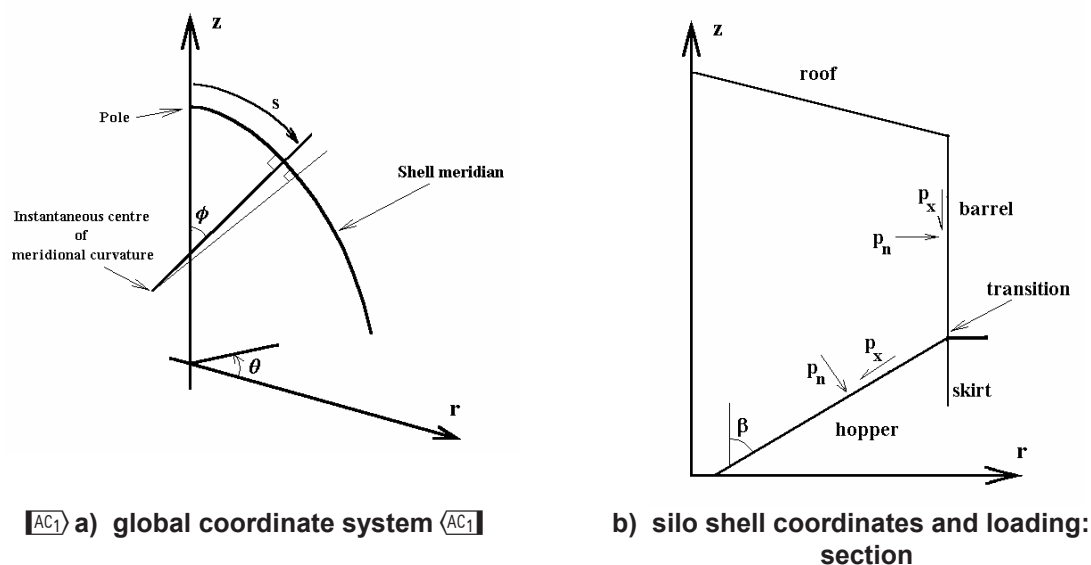


Figure 1.2: Coordinate systems for a circular silo

- (2) In general, the convention for the global silo structure axis system is in cylindrical coordinates (see figure 1.2) as follows:

Coordinate system

Coordinate along the central axis of a shell of revolution	z
Radial coordinate	r
Circumferential coordinate	θ

- (3) The convention for positive directions is:

Outward direction positive (internal pressure positive, outward displacements positive)

Tensile stresses positive (except in buckling expressions where compression is positive)

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

Pressure normal to shell (outward positive)	p_n
Meridional surface loading parallel to shell (downward positive)	p_x
Circumferential surface loading parallel to shell (anticlockwise positive in plan)	p_θ

1.7.2 Conventions for global silo structure axis system for rectangular silos

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

- (2) 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 1.3.

- (3) The convention for positive directions is:

Outward direction positive (internal pressure positive, outward displacements positive)

Tensile stresses positive (except in buckling expressions where compression is positive)

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

Pressure normal to box (outward positive)	p_n
Meridional surface loading parallel to box surface (downward positive)	p_x
Circumferential surface loading in the plane of the box plan cross-section (anticlockwise positive)	p_y

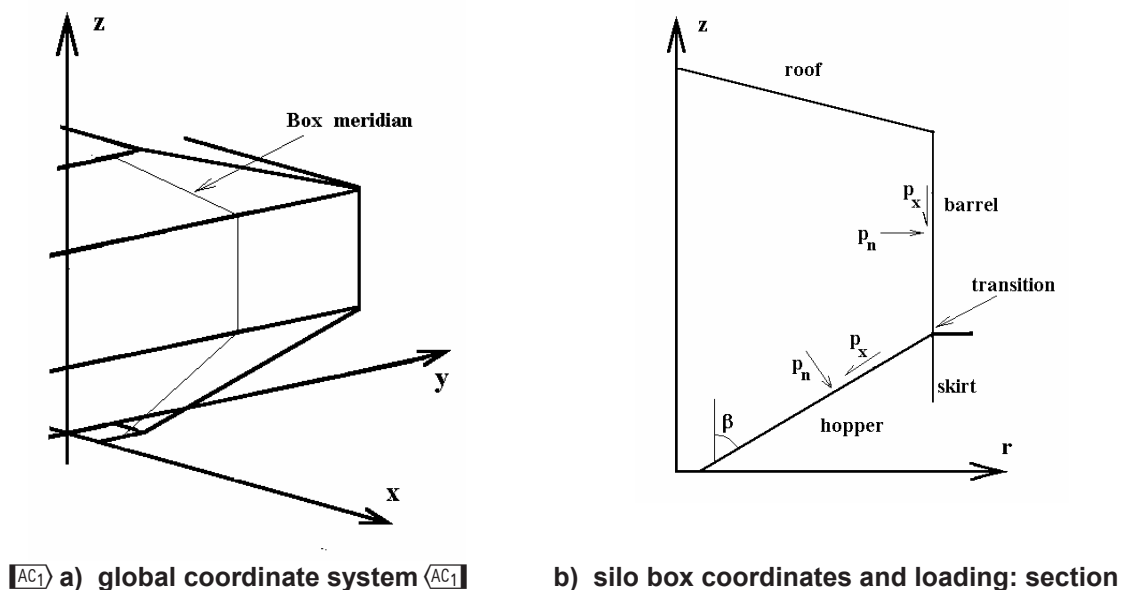


Figure 1.3: Coordinate systems for a rectangular silo

1.7.3 Conventions for structural element axes in both circular and rectangular silos

- (1) The convention for structural elements attached to the silo wall (see figures 1.4 and 1.5) is different for meridional and circumferential members.
- (2) The convention for meridional straight structural elements (see figure 1.4a) attached to the silo wall (shells and boxes) is:

Meridional coordinate for barrel, hopper and roof attachment	x
Strong bending axis (parallel to flanges: axis for meridional bending)	y
Weak bending axis (perpendicular to flanges)	z

NOTE: A meridional stiffener bending in a manner that is compatible with meridional bending (m_x) in the cylinder bends about the y axis of the stiffener.

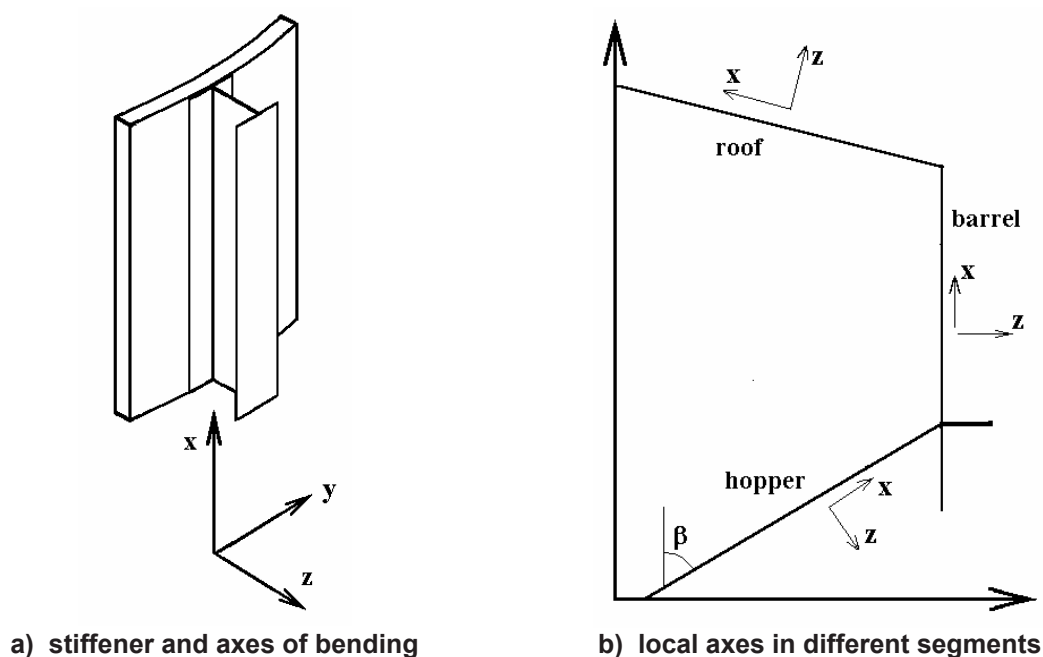


Figure 1.4: Local coordinate systems for meridional stiffeners on a shell or box

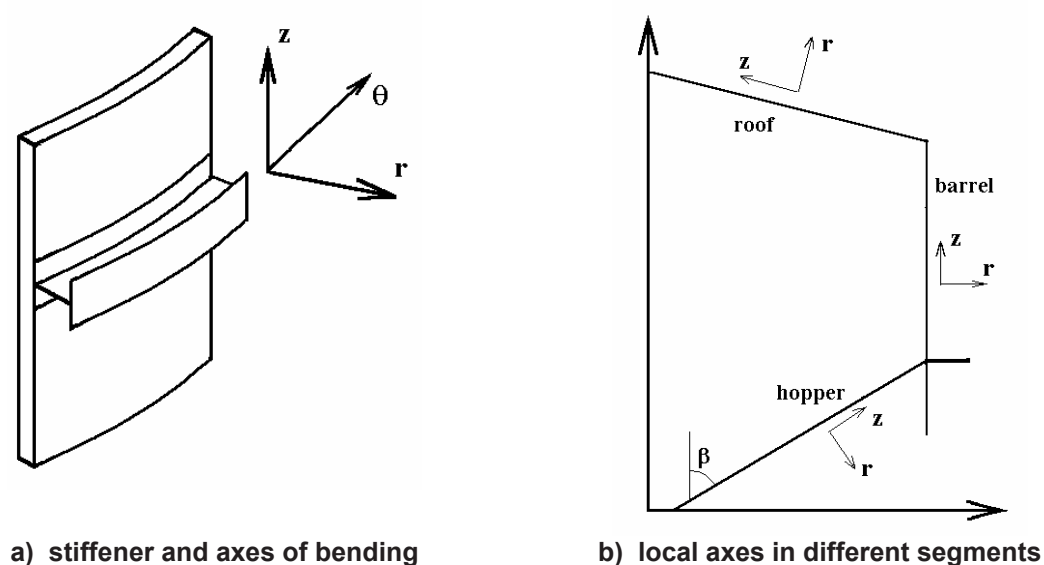


Figure 1.5: Local coordinate systems for circumferential stiffeners on a shell or box

(3) The convention for circumferential curved structural elements (see figure 1.5a) attached to a shell wall is:

Circumferential coordinate axis (curved)	θ
Radial axis (axis for bending in the vertical plane)	r
Vertical axis (axis for circumferential bending)	z

NOTE: A circumferential stiffener or ring is subject to bending about its vertical axis z when the bending is compatible with circumferential bending in the cylinder (m_θ). It is subject to bending moments 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.

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

Circumferential axis	x
Horizontal axis	y
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.

1.7.4 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	meridional membrane stress resultant
n_θ	circumferential membrane stress resultant in shells
n_y	circumferential membrane stress resultant in rectangular boxes
n_{xy} or $n_{x\theta}$	membrane shear stress resultant

Membrane stresses:

σ_{mx}	meridional membrane stress
$\sigma_{m\theta}$	circumferential membrane stress in shells
σ_{my}	circumferential membrane stress in rectangular boxes
τ_{mxy} 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 Eurocode 3 Parts 1.1 and 1.3. Care must be exercised when using Parts 1.1 and 1.3 in conjunction with these rules.

Bending stress resultants:

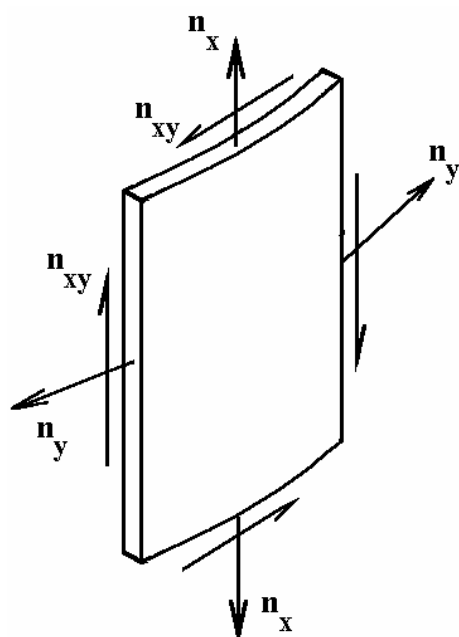
m_x	meridional bending moment per unit width
m_θ	circumferential bending moment per unit width in shells
m_y	circumferential bending stress resultant in rectangular boxes
m_{xy} or $m_{x\theta}$	twisting shear moment per unit width

Bending stresses:

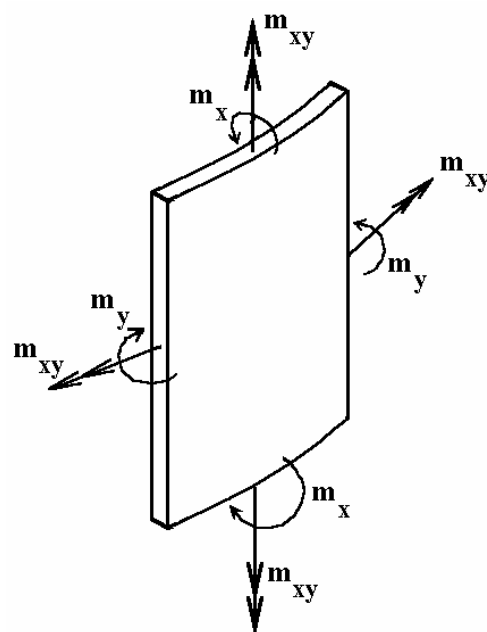
σ_{bx}	meridional bending stress
$\sigma_{b\theta}$	circumferential bending stress in shells
σ_{by}	circumferential bending stress in rectangular boxes
τ_{bxy} or $\tau_{bx\theta}$	twisting shear stress

Inner and outer surface stresses:

$\sigma_{six}, \sigma_{sox}$	meridional 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



a) Membrane stress resultants



b) Bending stress resultants

Figure 1.6: Stress resultants in the silo wall (shells and boxes)

1.8 Units

(1)P S.I. units shall be 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	:	kg/m ³	kg/mm ³
– acceleration	:	km/s ²	m/s ²
– membrane stress resultants	:	kN/m	N/mm
– bending stress resultants	:	kNm/m	Nmm/mm
– stresses and elastic moduli	:	kPa	MPa (=N/mm ²)

2 Basis of design

2.1 Requirements

- (1)P A silo shall be designed, constructed and maintained to meet the requirements of section 2 of EN 1990 as supplemented by the following.
- (2) The silo structure should include all shell and plated sections of the structure, including stiffeners, ribs, rings and attachments.
- (3) 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.
- (4) Silos should be designed to be damage-tolerant where appropriate, considering the use of the silo.
- (5) Particular requirements for special applications may be agreed between the designer, the client and the relevant authority.

2.2 Reliability differentiation

- (1) For reliability differentiation, see EN 1990.

NOTE: The national annex may define consequence classes for silos as a function of the location, type of infill and loading, the structural type, size and type of operation.

- (2) Different levels of rigour should be used in the design of silo structures, depending on the consequence class chosen, the structural arrangement and the susceptibility to different failure modes.
- (3) For this standard, 3 consequence classes are used, with requirements which produce designs with essentially equal risk in the design assessment and considering the expense and procedures necessary to reduce the risk of failure for different structures: Consequence Classes 1, 2 and 3.

NOTE 1: The national annex may provide information on the consequence classes. Table 2.1 gives an example for the classification of two parameters, the size and the type of operation into consequence classes when all other parameters result in medium consequences, see EN 1990, B.3.1.

Table 2.1: Consequence classes depending on size and operation

Consequence Class	Design situations
Consequence Class 3	Ground supported silos or silos supported on a complete skirt extending to the ground with capacity in excess of W_{3a} tonnes Discretely supported silos with capacity in excess of W_{3b} tonnes Silos with capacity in excess of W_{3c} tonnes in which any of the following design situations occur: a) eccentric discharge b) local patch loading c) unsymmetrical filling
Consequence Class 2	All silos covered by this Standard and not placed in another class
Consequence Class 1	Silos with capacity between W_{1a} tonnes [†] and W_{1b} tonnes
[†] Silos with capacity less than W_{1a} tonnes are not covered by this standard.	

The recommended values for class boundaries are as follows:

Class boundary	Recommended value (tonnes)
W_{3a}	5000
W_{3b}	1000
W_{3c}	200
W_{1b}	100
W_{1a}	10

NOTE 2: For the classification into action assessment classes, see EN 1991-4

- (4) A higher Consequence Class may always be adopted than that required.
- (5)P The choice of relevant Consequence Class shall be agreed between the designer, the client and the relevant authority.
- (6) Consequence Class 3 should be used for local patch loading, which refers to a stored solids loading case causing a patch load which extends round less than half the circumference of the silo, as defined in EN 1991-4.
- (7) For Consequence Class 1, simplified provisions may be adopted.

NOTE: Appropriate provisions for silos in Consequence Class 1 are set out in Annex A.

2.3 Limit states

- (1) The limit states defined in EN 1993-1-6 should be adopted for this Part.

2.4 Actions and environmental effects

2.4.1 General

- (1)P The general requirements set out in section 4 of EN 1990 shall be satisfied.

2.4.2 Wind action

- (1) For specifications of wind actions not set down in EN 1991-1-4 for the design of silos in isolation and in groups, 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 basic wind data provided in EN 1991-1-4 for the specific needs of individual constructions.

NOTE: Appropriate additional information on wind pressure distributions is set out in Annex C.

2.4.3 Combination of solids pressures with other actions

- (1)P The partial factors on actions in silos set out in 2.9.2 shall be used.

2.5 Material properties

- (1) The general requirements for material properties set out in EN 1993-1-1 should be followed.
- (2) The specific properties of materials for silos given in section 3 of this Part should be used.

2.6 Geometrical data

- (1)P The provisions concerning geometrical data given in section 6 of EN 1990 shall be followed.
- (2) The additional information specific to shell structures given in EN 1993-1-6 should also be applied.

AC1(3) The shell plate thickness should be taken as the nominal thickness. In the case of hot-dipped metal coated steel sheet conforming with EN 10149, 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. **AC1**

- (4) The effects of corrosion and abrasion on the thickness of silo wall plates should be included in the design, in accordance with 4.1.4.

2.7 Modelling of the silo for determining action effects

- (1)P 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 sections 4 to 9 of this Part for each structural segment, should be followed.
- (3) The specific requirements for structural analysis in relation to ultimate limit states, set out in sections 4 to 9 of this Part and in more detail in EN 1993-1-6 and EN 1993-1-7, should be followed.

2.8 Design assisted by testing

- (1) The general requirements set out in Annex D of EN 1990 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.

2.9 Action effects for limit state verification

2.9.1 General

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

2.9.2 Partial factors for ultimate limit states

2.9.2.1 Partial factors for actions on silos

- (1)P For persistent, transient and accidental design situations, the partial factors γ_F shall be taken from EN 1990 and EN 1991-4.

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

NOTE: When applied to 'product type' silos, the factors in (1) are for guidance purposes only. They are provided to show the likely levels needed to achieve consistent reliability with other designs.

2.9.2.2 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 section 9 of EN 1993-1-6.

- (3)P The partial factors γ_{Mi} for different limit states shall be taken from table 2.2.

- [A1]** (4) Where hot rolled steel sections are used as part of a silo structure, the relevant partial factors for 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 resistance should be taken from EN 1993-1-3. **[A1]**

Table 2.2: Partial factors for resistance

Resistance to failure mode	Relevant γ
Resistance of welded or bolted shell wall to plastic limit state	γ_{M0}
Resistance of shell wall to stability	γ_{M1}
Resistance of welded or bolted shell wall to rupture	γ_{M2}
Resistance of shell wall to cyclic plasticity	γ_{M4}
Resistance of connections	γ_{M5}
Resistance of shell wall to fatigue	γ_{M6}

NOTE: Partial factors γ_{Mi} for silos may be defined in the National Annex. For values of γ_{M5} , further information may be found in EN 1993-1-8. For values of γ_{M6} , further information may be found in EN 1993-1-9. The following numerical values are recommended for silos:

$\gamma_{M0} = 1,00$	$\gamma_{M1} = 1,10$	$\gamma_{M2} = 1,25$
$\gamma_{M4} = 1,00$	$\gamma_{M5} = 1,25$	$\gamma_{M6} = 1,10$

For further differentiation, see 2.2(1) and 2.2(3)

2.9.3 Serviceability limit states

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

2.10 Durability

A1 (1) The general requirements set out in 2.4 of EN 1990:2002 should be followed. **A1**

2.11 Fire resistance

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

3 Properties of materials

3.1 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 this section, see Table 3.1 in EN 1993-1-1 and Table 3.1b in EN 1993-1-3, should be treated as nominal values to be adopted as characteristic values in design calculations.
- (4) Other material properties are given in the relevant Reference Standards defined in EN 1993-1-1.
- (5) Where the silo may 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) Where the temperature exceeds 100°C, the material properties should be obtained from EN 13084-7.

3.2 Structural steels

- (1) The methods for design by calculation given in this Part 4.1 of EN 1993 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 3.1.
- (2) The mechanical properties of structural steels, according to EN 10025 or EN 10149 should be obtained from EN 1993-1-1, EN 1993-1-3 and EN 1993-1-4.
- (3) Corrosion and abrasion allowances are given in section 4 of this Part 4.1.
- (4) It should be assumed that the properties of steel in tension are the same as those in compression.
- (5) For the steels covered by this Part 4.1 of EN 1993, the design value of the modulus of elasticity should be taken as $E = 210\,000$ MPa and Poisson's ratio as $\nu = 0,3$.

3.3 Stainless steels

- (1) The mechanical properties of stainless steels should be obtained from EN 1993-1-4.
- (2) Guidance for the selection of stainless steels in view of corrosion and abrasion actions of stored solids may be obtained from appropriate sources.
- (3) Where the design involves a buckling calculation, appropriate reduced properties should be used (see EN 1993-1-6).

3.4 Special alloy steels

- (1) For non-standardised alloy steels, appropriate values of relevant mechanical properties should be defined.

NOTE: The National Annex may give information on appropriate values.

- (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).

3.5 Toughness requirements

- (1) The toughness requirements for the steels should be determined according to EN 1993-1-10.

4 Basis for structural analysis

4.1 Ultimate limit states

4.1.1 Basis

(1) Steel structures and components should be so proportioned that the basic design requirements given in section 2 are satisfied.

4.1.2 Required checks

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

$$S_d < R_d$$

... (4.1)

where S and R represent any appropriate parameter.

4.1.3 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.

(2) Silos in Consequence Class 1 need not be checked for fatigue or cyclic plasticity.

4.1.4 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.

(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 on contact with moving solid.

NOTE: The National Annex may choose the value of Δt_a . The value $\Delta t_a = 2\text{mm}$ is recommended.

(3) 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.

(4) Specific values for corrosion and abrasion losses, appropriate to the intended use, should be agreed between the designer, the client and the relevant authority, taking account of the intended use and the nature of the solids to be stored.

NOTE 1: The National Annex may 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 defined in EN 1991-4.

NOTE 2: To ensure that the design assumptions are met in service, appropriate inspection measures have to be instituted.

4.1.5 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.

4.2 Analysis of the structure of a shell silo

4.2.1 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 the following provisions.

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

A1 (3) Where the silo is subject to any form of unsymmetrical bulk solids loading (patch loads, eccentric discharge, unsymmetrical filling etc.), 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 strakes of 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, the solid held stationary within the corrugations should not be considered as stationary in (5). **A1**

4.2.2 Methods of analysis

4.2.2.1 General

(1) The analysis of the silo shell should be carried out according to the requirements of EN 1993-1-6.

(2) A higher class of analysis may always be used than that defined for the Consequence Class.

4.2.2.2 Consequence Class 3

(1) For silos in Consequence Class 3 (see 2.3), the internal forces and moments should be determined using a validated numerical analysis (finite element 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.

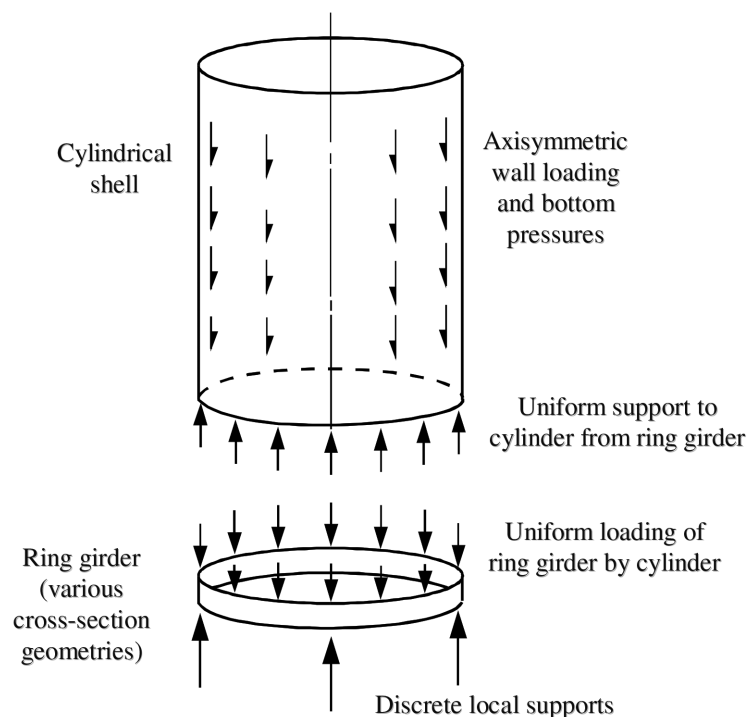
4.2.2.3 Consequence Class 2

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

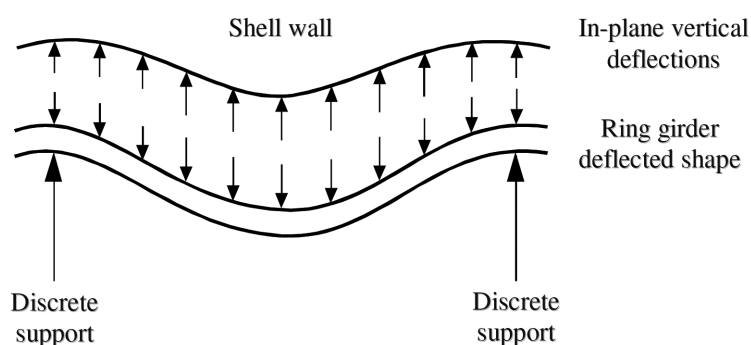
- a) Membrane theory may be used to determine the primary stresses. Bending theory elastic expressions may be used to describe all local bending effects.
- b) A validated numerical analysis may be used (e.g. finite element shell analysis) (as defined in EN 1993-1-6).

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

- (3) Notwithstanding paragraph (2), where the loading varies smoothly around the shell causing global bending only (i.e. in the form of 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 patch loads (see EN 1991-4 for thin walled silos), semi-membrane theory or membrane theory 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 no wider than $n_{vs}\sqrt{rt}$.
- NOTE:** The National Annex may choose the value of n_{vs} . The value $n_{vs} = 5$ is recommended.
- (7) Where smeared stiffeners are used, 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.
- (8) Where a ring girder is used above discrete supports, membrane theory may be used to determine the primary stresses, but the requirements of 5.4 and 8.1.4 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 4.1. 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 8.1.4 and 8.2.3.



a) Traditional design model for column-supported silos



b) Deformation requirement on cylinder imposed by compatibility with beam deformation

Figure 4.1: Axial deformation compatibility between ring girder and shell

4.2.2.4 Consequence Class 1

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

4.2.3 Geometric imperfections

- (1) Geometric imperfections in the shell should satisfy the limitations defined in EN 1993-1-6.
- (2) For silos in Consequence Classes 2 and 3, the geometric imperfections should 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.

4.3 Analysis of the box structure of a rectangular silo

4.3.1 Modelling of the structural box

- (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 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 $n_s t$.

NOTE: The National Annex may choose the value of n_s . The value $n_s = 40$ is recommended.

- (7) Where smeared stiffeners are 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.
- (8) The effective width of plate on each side of a stiffener should be taken as not greater than $n_{ew} t$, where t is the local plate thickness.

NOTE: The National Annex may choose the value of n_{ew} . The value $n_{ew} = 15$ is recommended.

4.3.2 Geometric imperfections

- (1) Geometric imperfections in the box 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.

4.3.3 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;
 - b) an analysis based on linear plate bending and stretching theory;
 - c) an analysis based on nonlinear plate bending and stretching theory.
- (2) For silos in Consequence Class 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 Consequence Class 2, method (a) in (1) may be used.
- (4) Where the design loading condition is not symmetric and the silo is in Consequence Class 2, either method (b) or method (c) in (1) should be used.
- AC1 (5) For silos in Consequence Class 3 (see 2.), the internal forces and moments should be determined using either method (b) or method (c) in (1) (as defined in EN 1993-1-7). AC1

4.4 Equivalent orthotropic properties 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.

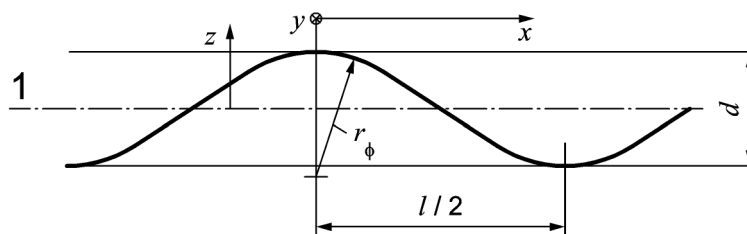


Figure 4.2: Corrugation profile and geometric parameters

(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 4.2:

where:

- d is the crest to crest dimension;
- A1 l A1 is the wavelength of the corrugation;
- A1 r_ϕ A1 is the local radius at the crest or trough.

A1 (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:

$$C_x = Et_x \quad \dots (4.2)$$

$$C_y = Et_y \quad \dots (4.3)$$

$$C_{xy} = Gt_{xy} \quad \dots (4.4)$$

where:

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

$$t_x = \frac{2t^3}{3d^2} \quad \dots (4.5)$$

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

$$t_y = \left(1 + \frac{\pi^2 d^2}{4l^2} \right) \quad \dots (4.6)$$

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

$$t_{xy} = \frac{t}{\left(1 + \frac{\pi^2 d^2}{4l^2} \right)} \quad \dots (4.7)$$

(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:

$$D_x = EI_x \quad \dots (4.8)$$

$$D_y = EI_y \quad \dots (4.9)$$

$$D_{xy} = GI_{xy} \quad \dots (4.10)$$

where: