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Evrokod 3: Projektiranje jeklenih konstrukcij - 1-6.del: Trdnost in stabilnost lupinastih konstrukcij

Eurocode 3 - Design of steel structures - Part 1-6: Strength and Stability of Shell Structures

Eurocode 3 - Bemessung und Konstruktion von Stahlbauten - Teil 1-6: Festigkeit und Stabilität von Schalen

Eurocode 3 - Calcul des structures en acier - Partie 1-6: Résistance et stabilité des structures en coque

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ICS:

91.010.30	Tehnični vidiki	Technical aspects
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Eurocode 3 - Design of steel structures - Part 1-6: Strength and Stability of Shell Structures

Eurocode 3 - Calcul des structures en acier - Partie 1-6: Résistance et stabilité des structures en coque

Eurocode 3 - Bemessung und Konstruktion von Stahlbauten - Teil 1-6: Festigkeit und Stabilität von Schalen

This European Standard was approved by CEN on 12 June 2006.

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Contents **Page**

Foreword

This European Standard EN 1993-1-6, Eurocode 3: Design of steel structures: Part 1-6 Strength and stability of shell structures, 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of an identical text or by endorsement, at the latest by August 2007, and conflicting National Standards shall be withdrawn at latest by March 2010.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 1993-1-6.

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.

National annex for EN 1993-1-6

This standard gives alternative procedures, values and recommendations with notes indicating where national choices may have to be made. Therefore the National Standard implementing EN 1993-1-6 should have a National Annex containing all Nationally Determined Parameters to be used for the design of steel structures to be constructed in the relevant country.

National choice is allowed in EN 1993-1-6 through:

- 3.1.(4)
- 4.1.4 (3)
- 5.2.4 (1)
- 6.3 (5)
- 7.3.1 (1)
- 7.3.2 (1)
- 8.4.2 (3)
- 8.4.3 (2)
- 8.4.3 (4)
- 8.4.4 (4)
- 8.4.5 (1)
- 8.5.2 (2)
- 8.5.2 (4)
- 8.7.2 (7)
- 8.7.2 (16)
- 8.7.2 (18) (2 times)
- 9.2.1 (2)P

1. General

1.1 Scope

(1) EN 1993-1-6 gives basic design rules for plated steel structures that have the form of a shell of revolution.

(2) This Standard is intended for use in conjunction with EN 1993-1-1, EN 1993-1-3, EN 1993-1-4, EN 1993-1-9 and the relevant application parts of EN 1993, which include:

Part 3.1 for towers and masts;
Part 3.2 for chimneys;
Part 4.1 for silos;
Part 4.2 for tanks;
Part 4.3 for pipelines.

(3) This Standard defines the characteristic and design values of the resistance of the structure.

(4) This Standard is concerned with the requirements for design against the ultimate limit states of:

plastic limit;
cyclic plasticity;
buckling;
fatigue.

(5) Overall equilibrium of the structure (sliding, uplifting, overturning) is not included in this Standard, but is treated in EN 1993-1-1. Special considerations for specific applications are included in the relevant application parts of EN 1993.

(6) The provisions in this Standard apply to axisymmetric shells and associated circular or annular plates and to beam section rings and stringer stiffeners where they form part of the complete structure. General procedures for computer calculations of all shell forms are covered. Detailed expressions for the hand calculation of unstiffened cylinders and cones are given in the Annexes.

(7) Cylindrical and conical panels are not explicitly covered by this Standard. However, the provisions can be applicable if the appropriate boundary conditions are duly taken into account.

(8) This Standard is intended for application to steel shell structures. Where no standard exists for shell structures made of other metals, the provisions of this standards may be applied provided that the appropriate material properties are duly taken into account.

(9) The provisions of this Standard are intended to be applied within the temperature range defined in the relevant EN 1993 application parts. The maximum temperature is restricted so that the influence of creep can be neglected if high temperature creep effects are not covered by the relevant application part.

(10) The provisions in this Standard apply to structures that satisfy the brittle fracture provisions given in EN 1993-1-10.

(11) The provisions of this Standard apply to structural design under actions that can be treated as quasi-static in nature.

(12) In this Standard, it is assumed that both wind loading and bulk solids flow can, in general, be treated as quasi-static actions.

(13) Dynamic effects should be taken into account according to the relevant application part of EN 1993, including the consequences for fatigue. However, the stress resultants arising from dynamic behaviour are treated in this part as quasi-static.

(14) The provisions in this Standard apply to structures that are constructed in accordance with EN 1090-2.

(15) This Standard does not cover the aspects of leakage.

(16) This Standard is intended for application to structures within the following limits:

design metal temperatures within the range −50°C to +300°C;
radius to thickness ratios within the range 20 to 5000.

NOTE: It should be noted that the stress design rules of this standard may be rather conservative if applied to some geometries and loading conditions for relatively thick-walled shells.

1.2 Normative references

(1) This European Standard incorporates, by dated or undated reference, provisions from other publications. 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 this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

EN 1090-2	*Execution of steel structures and aluminium structures – Part 2: Technical requirements for steel structures;*
EN 1990	*Basis of structural design;*
EN 1991	*Eurocode 1: Actions on structures ;*
EN 1993	*Eurocode 3: Design of steel structures:*
Part 1.1:	*General rules and rules for buildings;*
Part 1.3:	*Cold formed thin gauged members and sheeting;*
Part 1.4:	*Stainless steels;*
Part 1.5:	*Plated structural elements;*
Part 1.9:	*Fatigue strength of steel structures;*
Part 1.10:	*Selection of steel for fracture toughness and through-thickness properties;*
Part 1.12:	*Additional rules for the extension of EN 1993 up to steel grades S 700*
Part 2:	*Steel bridges;*
Part 3.1:	*Towers and masts;*
Part 3.2:	*Chimneys;*
Part 4.1:	*Silos;*
Part 4.2:	*Tanks;*
Part 4.3:	*Pipelines;*
Part 5:	*Piling.*

1.3 Terms and definitions

The terms that are defined in EN 1990 for common use in the Structural Eurocodes apply to this Standard. Unless otherwise stated, the definitions given in ISO 8930 also apply in this Standard. Supplementary to EN 1993-1-1, for the purposes of this Standard, the following definitions apply:

1.3.1 Structural forms and geometry

1.3.1.1 shell

A structure or a structural component formed from a curved thin plate.

1.3.1.2 shell of revolution

A shell whose geometric form is defined by a middle surface that is formed by rotating a meridional generator line around a single axis through 2π radians. The shell can be of any length.

1.3.1.3 complete axisymmetric shell

A shell composed of a number of parts, each of which is a shell of revolution.

1.3.1.4 shell segment

A shell of revolution in the form of a defined shell geometry with a constant wall thickness: a cylinder, conical frustum, spherical frustum, annular plate, toroidal knuckle or other form.

1.3.1.5 shell panel

An incomplete shell of revolution: the shell form is defined by a rotation of the generator about the axis through less than 2π radians.

1.3.1.6 middle surface

The surface that lies midway between the inside and outside surfaces of the shell at every point. Where the shell is stiffened on either one or both surfaces, the reference middle surface is still taken as the middle surface of the curved shell plate. The middle surface is the reference surface for analysis, and can be discontinuous at changes of thickness or at shell junctions, leading to eccentricities that may be important to the shell structural behaviour.

1.3.1.7 junction

The line at which two or more shell segments meet: it can include a stiffener. The circumferential line of attachment of a ring stiffener to the shell may be treated as a junction.

1.3.1.8 stringer stiffener

A local stiffening member that follows the meridian of the 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. It is not intended to provide a primary resistance to bending effects caused by transverse loads.

1.3.1.9 rib

A local member that provides a primary load carrying path for bending down the meridian of the shell, representing a generator of the shell of revolution. It is used to transfer or distribute transverse loads by bending.

1.3.1.10 ring stiffener

A local stiffening member that passes around the circumference of the shell of revolution at a given point on the meridian. It is normally assumed to have no stiffness for deformations out of its own plane (meridional displacements of the shell) but is stiff for deformations in the plane of the ring. It is provided to increase the stability or to introduce local loads acting in the plane of the ring.

1.3.1.11 base ring

A structural member that passes around the circumference of the shell of revolution at the base and provides a means of attachment of the shell to a foundation or other structural member. It is needed to ensure that the assumed boundary conditions are achieved in practice.

1.3.1.12 ring beam or ring girder

A circumferential stiffener that has bending stiffness and strength both in the plane of the shell circular section and normal to that plane. It is a primary load carrying structural member, provided for the distribution of local loads into the shell.

1.3.2 Limit states

1.3.2.1 plastic limit

The ultimate limit state where the structure develops zones of yielding in a pattern such that its ability to resist increased loading is deemed to be exhausted. It is closely related to a small deflection theory plastic limit load or plastic collapse mechanism.

1.3.2.2 tensile rupture

The ultimate limit state where the shell plate experiences gross section failure due to tension.

1.3.2.3 cyclic plasticity

The ultimate limit state where repeated yielding is caused by cycles of loading and unloading, leading to a low cycle fatigue failure where the energy absorption capacity of the material is exhausted.

1.3.2.4 buckling

The ultimate limit state where the structure suddenly loses its stability under membrane compression and/or shear. It leads either to large displacements or to the structure being unable to carry the applied loads.

1.3.2.5 fatigue

The ultimate limit state where many cycles of loading cause cracks to develop in the shell plate that by further load cycles may lead to rupture.

1.3.3 Actions

1.3.3.1 axial load

Externally applied loading acting in the axial direction.

1.3.3.2 radial load

Externally applied loading acting normal to the surface of a cylindrical shell.

1.3.3.3 internal pressure

Component of the surface loading acting normal to the shell in the outward direction. Its magnitude can vary in both the meridional and circumferential directions (e.g. under solids loading in a silo).

1.3.3.4 external pressure

Component of the surface loading acting normal to the shell in the inward direction. Its magnitude can vary in both the meridional and circumferential directions (e.g. under wind).

1.3.3.5 hydrostatic pressure

Pressure varying linearly with the axial coordinate of the shell of revolution.

1.3.3.6 wall friction load

Meridional component of the surface loading acting on the shell wall due to friction connected with internal pressure (e.g. when solids are contained within the shell).

1.3.3.7 local load

Point applied force or distributed load acting on a limited part of the circumference of the shell and over a limited height.

1.3.3.8 patch load

Local distributed load acting normal to the shell.

1.3.3.9 suction

Uniform net external pressure due to the reduced internal pressure in a shell with openings or vents under wind action.

1.3.3.10 partial vacuum

Uniform net external pressure due to the removal of stored liquids or solids from within a container that is inadequately vented.

1.3.3.11 thermal action

Temperature variation either down the shell meridian, or around the shell circumference or through the shell thickness.

1.3.4 Stress resultants and stresses in a shell

1.3.4.1 membrane stress resultants

The membrane stress resultants are the forces per unit width of shell that arise as the integral of the distribution of direct and shear stresses acting parallel to the shell middle surface through the thickness of the shell. Under elastic conditions, each of these stress resultants induces a stress state that is uniform through the shell thickness. There are three membrane stress resultants at any point (see figure 1.1(e)).

1.3.4.2 bending stress resultants

The bending stress resultants are the bending and twisting moments per unit width of shell that arise as the integral of the first moment of the distribution of direct and shear stresses acting parallel to the shell middle surface through the thickness of the shell. Under elastic conditions, each of these stress resultants induces a stress state that varies linearly through the shell thickness, with value zero and the middle surface. There are two bending moments and one twisting moment at any point.

1.3.4.3 transverse shear stress resultants

The transverse stress resultants are the forces per unit width of shell that arise as the integral of the distribution of shear stresses acting normal to the shell middle surface through the thickness of the shell. Under elastic conditions, each of these stress resultants induces a stress state that varies parabolically through the shell thickness. There are two transverse shear stress resultants at any point (see figure 1.1(f)).

1.3.4.4 membrane stress

The membrane stress is defined as the membrane stress resultant divided by the shell thickness (see figure 1.1(e)).

1.3.4.5 bending stress

The bending stress is defined as the bending stress resultant multiplied by 6 and divided by the square of the shell thickness. It is only meaningful for conditions in which the shell is elastic.

1.3.5 Types of analysis

1.3.5.1 global analysis

An analysis that includes the complete structure, rather than individual structural parts treated separately.

1.3.5.2 membrane theory analysis

An analysis that predicts the behaviour of a thin-walled shell structure under distributed loads by assuming that only membrane forces satisfy equilibrium with the external loads.

1.3.5.3 linear elastic shell analysis (LA)

An analysis that predicts the behaviour of a thin-walled shell structure on the basis of the small deflection linear elastic shell bending theory, related to the perfect geometry of the middle surface of the shell.

1.3.5.4 linear elastic bifurcation (eigenvalue) analysis (LBA)

An analysis that evaluates the linear bifurcation eigenvalue for a thin-walled shell structure on the basis of the small deflection linear elastic shell bending theory, related to the perfect geometry of the middle surface of the shell. It should be noted that, where an eigenvalue is mentioned, this does not relate to vibration modes.

1.3.5.5 geometrically nonlinear elastic analysis (GNA)

An analysis based on the principles of shell bending theory applied to the perfect structure, using a linear elastic material law but including nonlinear large deflection theory for the displacements that accounts full for any change in geometry due to the actions on the shell. A bifurcation eigenvalue check is included at each load level.

1.3.5.6 materially nonlinear analysis (MNA)

An analysis based on shell bending theory applied to the perfect structure, using the assumption of small deflections, as in 1.3.4.3, but adopting a nonlinear elasto-plastic material law.

1.3.5.7 geometrically and materially nonlinear analysis (GMNA)

An analysis based on shell bending theory applied to the perfect structure, using the assumptions of nonlinear large deflection theory for the displacements and a nonlinear elasto-plastic material law. A bifurcation eigenvalue check is included at each load level.

1.3.5.8 geometrically nonlinear elastic analysis with imperfections included (GNIA)

An analysis with imperfections explicitly included, similar to a GNA analysis as defined in 1.3.4.5, but adopting a model for the geometry of the structure that includes the imperfect shape (i.e. the geometry of the middle surface includes unintended deviations from the ideal shape). The imperfection may also cover the effects of deviations in boundary conditions and / or the effects of residual stresses. A bifurcation eigenvalue check is included at each load level.

1.3.5.9 geometrically and materially nonlinear analysis with imperfections included (GMNIA)

An analysis with imperfections explicitly included, based on the principles of shell bending theory applied to the imperfect structure (i.e. the geometry of the middle surface includes unintended deviations from the ideal shape), including nonlinear large deflection theory for the displacements that accounts full for any change in geometry due to the actions on the shell and a nonlinear elasto-plastic material law. The imperfections may also include imperfections in boundary conditions and residual stresses. A bifurcation eigenvalue check is included at each load level.

1.3.6 Stress categories used in stress design

1.3.6.1 Primary stresses

The stress system required for equilibrium with the imposed loading. This consists primarily of membrane stresses, but in some conditions, bending stresses may also be required to achieve equilibrium.

1.3.6.2 Secondary stresses

Stresses induced by internal compatibility or by compatibility with the boundary conditions, associated with imposed loading or imposed displacements (temperature, prestressing, settlement, shrinkage). These stresses are not required to achieve equilibrium between an internal stress state and the external loading.

1.3.7 Special definitions for buckling calculations

1.3.7.1 critical buckling resistance

The smallest bifurcation or limit load determined assuming the idealised conditions of elastic material behaviour, perfect geometry, perfect load application, perfect support, material isotropy and absence of residual stresses (LBA analysis).

1.3.7.2 critical buckling stress

The membrane stress associated with the critical buckling resistance.

1.3.7.3 plastic reference resistance

The plastic limit load, determined assuming the idealised conditions of rigid-plastic material behaviour, perfect geometry, perfect load application, perfect support and material isotropy (modelled using MNA analysis).

1.3.7.4 characteristic buckling resistance

The load associated with buckling in the presence of inelastic material behaviour, the geometrical and structural imperfections that are inevitable in practical construction, and follower load effects.

1.3.7.5 characteristic buckling stress

The membrane stress associated with the characteristic buckling resistance.

1.3.7.6 design buckling resistance

The design value of the buckling load, obtained by dividing the characteristic buckling resistance by the partial factor for resistance.

1.3.7.7 design buckling stress

The membrane stress associated with the design buckling resistance.

1.3.7.8 key value of the stress

The value of stress in a non-uniform stress field that is used to characterise the stress magnitudes in a buckling limit state assessment.

1.3.7.9 fabrication tolerance quality class

The category of fabrication tolerance requirements that is assumed in design, see 8.4.

1.4 Symbols

(1) In addition to those given in EN 1990 and EN 1993-1-1, the following symbols are used:

(2) Coordinate system, see figure 1.1:

- r radial coordinate, normal to the axis of revolution;
- x meridional coordinate;
- z axial coordinate;
- θ circumferential coordinate;
- ϕ meridional slope: angle between axis of revolution and normal to the meridian of the shell;

(3) Pressures:

- p_n normal to the shell;
- p_x meridional surface loading parallel to the shell;
- p_θ circumferential surface loading parallel to the shell;

(4) Line forces:

- P_n load per unit circumference normal to the shell;
- P_x load per unit circumference acting in the meridional direction;
- P_θ load per unit circumference acting circumferentially on the shell;

(5) Membrane stress resultants:

- n_x meridional membrane stress resultant;
- n_θ circumferential membrane stress resultant;
- $n_{x\theta}$ membrane shear stress resultant;

(6) Bending stress resultants:

- m_x meridional bending moment per unit width;

m_θ circumferential bending moment per unit width;

$m_{x\theta}$ twisting shear moment per unit width;

q_{xn} transverse shear force associated with meridional bending;

$q_{\theta n}$ transverse shear force associated with circumferential bending;

(7) Stresses:

σ_x meridional stress;

σ_θ circumferential stress;

σ_{eq} von Mises equivalent stress (can also take negative values during cyclic loading);

τ, $\tau_{x\theta}$ in-plane shear stress;

τ_{xn}, $\tau_{\theta n}$ meridional, circumferential transverse shear stresses associated with bending;

(8) Displacements:

u meridional displacement;
v circumferential displacement;
w displacement normal to the shell surface;
β_ϕ meridional rotation, see 5.2.2;

(9) Shell dimensions:

d internal diameter of shell;
L total length of the shell;
ℓ length of shell segment;
ℓ_g gauge length for measurement of imperfections;

$\ell_{g\theta}$ gauge length in circumferential direction for measurement of imperfections;

ℓ_{gw} gauge length across welds for measurement of imperfections;

ℓ_{gx} gauge length in meridional direction for measurement of imperfections;

ℓ_R limited length of shell for buckling strength assessment;
r radius of the middle surface, normal to the axis of revolution;
t thickness of shell wall;
t_{max} maximum thickness of shell wall at a joint;
t_{min} minimum thickness of shell wall at a joint;
t_{ave} average thickness of shell wall at a joint;
β apex half angle of cone;

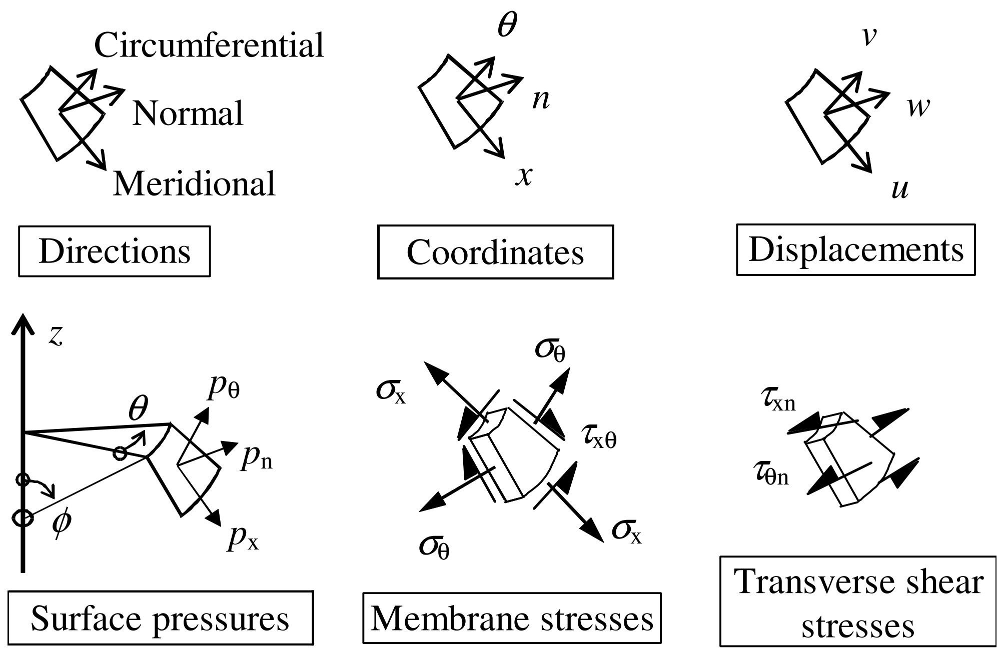

Figure 1.1: Symbols in shells of revolution

(10) Tolerances, see 8.4:

- e eccentricity between the middle surfaces of joined plates;
- U_e accidental eccentricity tolerance parameter;
- U_r out-of-roundness tolerance parameter;
- U_n initial dimple imperfection amplitude parameter for numerical calculations;
- U_0 initial dimple tolerance parameter;
- Δw_0 tolerance normal to the shell surface;

(11) Properties of materials:

- E Young's modulus of elasticity;
- f_{eq} von Mises equivalent strength;
- f_y yield strength;
- f_u ultimate strength;
- ν Poisson's ratio;

(12) Parameters in strength assessment:

- C coefficient in buckling strength assessment;
- D cumulative damage in fatigue assessment;
- F generalised action;
- F_{Ed} action set on a complete structure corresponding to a design situation (design values);
- F_{Rd} calculated values of the action set at the maximum resistance condition of the structure (design values);
- r_{Rk} characteristic reference resistance ratio (used with subscripts to identify the basis): defined as