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

This draft amendment A1, if approved, will modify the European Standard EN 1993-1-6:2007. If this draft becomes an amendment, CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for inclusion of this amendment into the relevant national standard without any alteration.

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

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Contents

European foreword

This document (EN 1993-1-6:2007/prA1:2016) has been prepared by Technical Committee CEN/TC 250 “Structural Eurocodes”, the secretariat of which is held by BSI.

This document is currently submitted to the CEN Enquiry.

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

1 Modifications to the Foreword

In the Foreword, in the section "National Annex for EN 1993-1-6", *add the following entries into the list at the appropriate places:*

"

– 6.2.1(6);"

and

"

– 8.6.3(5);".

In the Foreword, in the section "National Annex for EN 1993-1-6", *replace:*

"

– 8.7.2 (7)
– 8.7.2 (16)
– 8.7.2 (18) (2 times)"

with:

"

– 8.8.2 (9)
– 8.8.2 (18)
– 8.8.2 (20) (2 times)".

2 Modification throughout the whole standard

Replace "r_R" *with* "R".

3 Modification to 1.2, Normative references

In the list of the parts of EN 1993, replace "Part 1.1:" *with* "Part 1.1:2005:".

4 Modifications to 1.3, Terms and definitions

Replace the whole Entry 1.3.2.1 with:

"1.3.2.1 plastic failure limit state (LS1)
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".

Add a new Entry 1.3.5.3:

"1.3.5.3 semi-membrane theory analysis
analysis that predicts the behaviour of an unsymmetrically loaded or supported thin-walled cylindrical shell structure by assuming that only membrane forces and circumferential bending moments satisfy equilibrium with the external loads"

and renumber accordingly the former Entry 1.3.5.3 (as 1.3.5.4) and the following subclauses in 1.3.5.

Replace the former Subclause 1.3.5.6 (newly renumbered as 1.3.5.7) with:

"1.3.5.7 materially nonlinear analysis (MNA)
analysis based on shell bending theory applied to the perfect structure, using the assumption of small deflections, as in 1.3.5.4, but adopting an ideal elastic plastic material law (idealised perfectly plastic response after yield)".

Replace the former Subclause 1.3.5.7 (newly renumbered as 1.3.5.8) with:

"1.3.5.8 geometrically and materially nonlinear analysis (GMNA)
analysis based on shell bending theory applied to the perfect structure, using the assumptions of nonlinear large deflection theory for the displacements and a fully nonlinear elastic-plastic-hardening material law, where appropriate, and in which a bifurcation eigenvalue check is included at each load level".

Replace the former Subclause 1.3.5.9 (newly renumbered as 1.3.5.10) with:

"1.3.5.10 geometrically and materially nonlinear analysis with imperfections included (GMNIA)
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 fully for any change in geometry due to the actions on the shell and a fully nonlinear elastic-plastic-hardening material law, where appropriate

Note 1 to entry: The imperfections may also include imperfections in boundary conditions and residual stresses. A bifurcation eigenvalue check is included at each load level.".

5 Modifications to 1.4, Symbols

In Paragraph (12), replace the following line:

"α elastic imperfection reduction factor in buckling strength assessment;"

with:

"α elastic buckling reduction factor in buckling strength assessment;

α_G geometric reduction factor;

α_I imperfection reduction factor;".

In Paragraph (12), replace the following line:

"χ buckling reduction factor for elastic-plastic effects in buckling strengths assessment;"

with:

"χ elastic-plastic buckling reduction factor for elastic-plastic effects in buckling strength assessment;".

In Paragraph (12) , replace:

"χ_{ov} overall buckling resistance reduction factor for complete shell;"

with:

"χ_{ov} overall elastic-plastic buckling reduction factor for a complete shell;".

Delete the NOTE in Paragraph (12).

6 Modification to 2.2.5, Linear elastic bifurcation analysis (LBA)

In Paragraph (1), replace "8.6 and 8.7" *with* "8.7 and 8.8".

7 Modification to 2.2.6, Geometrically nonlinear elastic analysis (GNA)

In Paragraph (2), replace "8.6 and 8.7" *with* "8.7 and 8.8".

8 Modification to 2.2.7, Materially nonlinear analysis (MNA)

In Paragraph (1), replace "8.7" *with* "8.8".

9 Modification to 2.2.8, Geometrically and materially nonlinear analysis (GMNA)

Replace Paragraphs (1) and (2) with the following ones:

"(1) The result of a GMNA analysis, analogously to 2.2.7, gives the geometrically nonlinear plastic failure load of the perfect structure and the plastic strain increment, that may be used for checking the limit states LS1 and LS2.

(2) Where compression or shear stresses are predominant in some part of the shell, a GMNA analysis gives the elasto-plastic buckling load of the perfect structure. This perfect shell buckling load should always be determined when the limit state LS3 is verified using GMNIA analysis, see 8.8.".

10 Modification to 2.2.9, Geometrically nonlinear elastic analysis with imperfections included (GNIA)

In Paragraph (1), replace "8.7" *with* "8.8".

11 Modification to 2.2.10, Geometrically and materially nonlinear analysis with imperfections included (GMNIA)

In Paragraph (1), replace "8.7" *with* "8.8".

12 Modification to 3.3, Geometrical tolerances and geometrical imperfections

In Paragraph (3), replace twice "8.7" *with* "8.8".

13 Modifications to 4.1.1, LS1: Plastic limit

Replace the title itself of Subclause 4.1.1 with "LS1: Plastic failure limit state".

Replace Paragraph (1) with:

"(1) The limit state of the plastic failure should be taken as the condition in which the capacity of the structure to resist the actions on it is exhausted by plasticity in the material.

The plastic failure resistance should be distinguished from the plastic reference resistance which is derived as the plastic collapse load obtained from a mechanism based on small displacement theory using an ideal elastic-plastic material law.".

Replace Paragraph (3) with:

"(3) In the absence of fastener holes, verification at the limit state of tensile rupture may be assumed to be covered by the check for the plastic failure limit state. However, where holes for fasteners occur, a supplementary check in accordance with 6.2 of EN 1993-1-1:2005 should be carried out.".

Replace Paragraph (4) with:

"(4) In verifying the plastic failure limit state, plastic or partially plastic behaviour of the structure may be assumed (i.e. elastic compatibility considerations may be neglected).

NOTE Since the plastic failure limit state includes change of geometry, it may be noted that this limit state may also capture snap-through buckling, which may occur in the elastic state. The plastic reference resistance does not include change of geometry, so this apparent anomaly does not occur.".

14 Modification to 4.2.2.2,Primary stresses

Replace Paragraphs (1) and (2) with:

"(1) The primary stresses should be taken as the stress system required for equilibrium with the imposed loading. They may be calculated from any realistic statically admissible determinate system. The plastic failure limit state (LS1) should be deemed to be reached when the primary stress reaches the yield strength throughout the full thickness of the wall at a sufficient number of points, such that only the strain hardening reserve or a change of geometry would lead to an increase in the resistance of the structure.

(2) The calculation of primary stresses should be based on any system of stress resultants, consistent with the requirements of equilibrium of the structure. It may also take into account the benefits of plasticity theory. Alternatively, since linear elastic analysis satisfies equilibrium requirements, its predictions may also be used as a safe representation of the plastic failure limit state (LS1). Any of the analysis methods given in 5.3 may be applied.".

15 Modification to 4.2.4, Design by global numerical analysis

In Paragraph (6), replace "8.7" *with* "8.8".

16 Modification to 5.3, Types of analysis

In Table 5.2, replace the row:

"

Materially non-linear analysis (MNA)	linear	non-linear	perfect

"

with:

"

Materially non-linear analysis (MNA)	linear	ideal elastic-plastic	perfect

".

17 Modification to Clause 6, Plastic limit state (LS1)

Replace the title itself with "Plastic failure limit state (LS1)".

18 Modifications to 6.2.1, Design values of stresses

Replace Paragraph (1) with:

"(1) Although stress design is based on an elastic analysis and therefore cannot accurately predict the plastic failure limit state, it may be used, on the basis of the lower bound theorem, to provide a conservative assessment of the plastic collapse resistance which is used to represent the plastic failure limit state, see 4.1.1.".

Replace Paragraphs (5) and (6) with:

"(5) Where a membrane theory analysis is used, or where a linear bending theory analysis (LA) is used subject to the conditions defined in (6), the resulting two-dimensional field of stress resultants $n_{x,\,Ed}$, $n_{\theta,\,Ed}$ and $n_{x\theta,\,Ed}$ may be represented by the equivalent design stress $\sigma_{eq,\,Ed}$ obtained from:

$$\sigma_{\mathrm{eq,Ed}} = \frac{1}{t}\sqrt{n_{\mathrm{x,Ed}}^2 + n_{\theta,\mathrm{Ed}}^2 - n_{\mathrm{x,Ed}} \cdot n_{\theta,\mathrm{Ed}} + 3n_{\mathrm{x}\theta,\mathrm{Ed}}^2} \tag{6.1}$$

(6) Where an LA or GNA analysis is used, and the magnitude of the largest von Mises surface stress found using Formulae (6.2) to (6.4) exceeds n times the von Mises membrane stress found using Formula (6.1) at the same location, the equivalent stress should be taken as the value determined using Formulae (6.2) to (6.4).

$$\sigma_{\mathrm{eq,Ed}} = \sqrt{\sigma_{\mathrm{x,Ed}}^2 + \sigma_{\theta,\mathrm{Ed}}^2 - \sigma_{\mathrm{x,Ed}} \cdot \sigma_{\theta,\mathrm{Ed}} + 3\tau_{\mathrm{x}\theta,\mathrm{Ed}}^2} \tag{6.2}$$

in which:

$$\sigma_{\mathrm{x,Ed}} = \frac{n_{\mathrm{x,Ed}}}{t} \pm \frac{m_{\mathrm{x,Ed}}}{\left(t^2/4\right)} \qquad \sigma_{\theta,\mathrm{Ed}} = \frac{n_{\theta,\mathrm{Ed}}}{t} \pm \frac{m_{\theta,\mathrm{Ed}}}{\left(t^2/4\right)} \tag{6.3}$$

$$\tau_{\mathrm{x}\theta,\mathrm{Ed}} = \frac{n_{\mathrm{x}\theta,\mathrm{Ed}}}{t} \pm \frac{m_{\mathrm{x}\theta,\mathrm{Ed}}}{\left(t^2/4\right)} \tag{6.4}$$

NOTE 1 Formulae (6.2) to (6.4) give a simplified conservative equivalent stress for design purposes.

NOTE 2 The National Annex may choose the value of n. The recommended value is 3.".

19 Modifications to 6.3, Design by global numerical MNA or GMNA analysis

Replace Paragraph (1)P with:

"(1)P The design plastic failure resistance shall be determined as a load factor R_{pl} applied to the design values F_{Ed} of the combination of actions for the relevant load case.".

Replace Paragraph (3) with:

"(3) In an MNA or GMNA analysis based on the design yield strength f_{yd}, the shell should be subject to the design values of the load cases detailed in (2), progressively increased by the load ratio R until the plastic failure condition at the load ratio R_{pl} is reached.".

In Paragraph (4), replace "8.7" *with* "8.8".

Replace Paragraph (5) with:

"(5) Where a GMNA analysis is used, if the analysis predicts a maximum load followed by a descending path, the maximum value should be used to determine the load ratio R_{GMNA}. Where a GMNA analysis does not predict a maximum load, but produces a progressively rising action-displacement relationship without strain hardening of the material, the load ratio R_{GMNA} should be taken as no larger than the value at which the maximum von Mises equivalent plastic strain in the structure attains the value $\varepsilon_{\mathrm{mps}}=n_{\mathrm{mps}}\cdot(f_{\mathrm{yd}}/E)$.

NOTE The National Annex may choose the value of n_{mps}. The value $n_{\mathrm{mps}}=(66\text{-}f_{\mathrm{yd}}/15)$, where f_{yd} is in MPa, is recommended.".

Add a new Paragraph (6):

"(6) A GMNA analysis may not be used to establish the plastic reference resistance R_{pl}, which is used in Clause 8 as part of the LBA-MNA design method.".

Renumber accordingly Paragraph (6) (as Paragraph (7)) along with the following paragraphs.

Replace the former Paragraph (6) (new Paragraph (7)) with:

"(7) The characteristic plastic failure resistance $R_{\mathrm{pl,k}}$ should be taken as either R_{MNA} or R_{GMNA} according to the analysis that has been used.".

Replace the former Paragraph (7)P (new paragraph (8)P) with:

"(8)P The design plastic failure resistance F_{Rd} shall be obtained from:

$$F_{\mathrm{Rd}}=\frac{F_{\mathrm{Rk}}}{\gamma_{\mathrm{M0}}}=\frac{R_{\mathrm{k}}\cdot F_{\mathrm{Ed}}}{\gamma_{\mathrm{M0}}}=R_{\mathrm{d}}\cdot F_{\mathrm{Ed}} \tag{6.7}$$ ".

20 Modification to 8.2, Special definitions and symbols

Replace Paragraph (1) with:

"(1) Reference should be made to the special definitions of terms concerning buckling in 1.3.7.".

21 Modifications to 8.5.2, Design resistance (buckling strength)

Replace the first sentence of Paragraph (1) with "The buckling resistance should be represented by the buckling stresses as defined in 1.3.7.".

Replace Paragraph (3) with:

"(3) The characteristic buckling stresses should be obtained by multiplying the characteristic yield strength by the elastic-plastic buckling reduction factors χ:

$$\sigma_{\mathrm{x,Rk}} = \chi_{\mathrm{x}} f_{\mathrm{yk}}, \qquad \sigma_{\theta,\mathrm{Rk}} = \chi_{\theta} f_{\mathrm{yk}}, \qquad \tau_{\mathrm{x}\theta,\mathrm{Rk}} = \chi_{\tau} f_{\mathrm{yk}} / \sqrt{3} \tag{8.12}$$

Replace Paragraph (4) with:

"(4) The elastic-plastic buckling reduction factors χ_{x}, χ_{θ} and χ_{τ} should be determined as a function of the relative slenderness of the shell $\overline{\lambda}$ from:

$$\chi = \chi_{\mathrm{h}} - \left(\frac{\overline{\lambda}}{\overline{\lambda}_0}\right)(\chi_{\mathrm{h}} - 1) \quad \text{when} \quad \overline{\lambda} \le \overline{\lambda}_0 \tag{8.13}$$

$$\chi = 1 - \beta\left(\frac{\overline{\lambda} - \overline{\lambda}_0}{\overline{\lambda}_{\mathrm{p}} - \overline{\lambda}_0}\right)^{\eta} \quad \text{when} \quad \overline{\lambda}_0 < \overline{\lambda} < \overline{\lambda}_{\mathrm{p}} \tag{8.14}$$

$$\chi = \frac{\alpha}{\overline{\lambda}^2} \quad \text{when} \quad \overline{\lambda}_{\mathrm{p}} \le \overline{\lambda} \tag{8.15}$$

where:

α is the elastic buckling reduction factor;
β is the plastic range factor;
η is the interaction exponent;
$\overline{\lambda}_0$ is the squash limit relative slenderness;
χ_{h} is the hardening limit.".

In Paragraph (8), replace "8.6.2" *with* "8.7.2".

22 Addition of a new Subclause 8.6, Design using reference resistances

Add the following new Subclause 8.6; then have the former Subclauses 8.6 and 8.7 automatically renumbered as 8.7 and 8.8 and renumber all the formulae in the latter subclauses accordingly:

"

8.6 Design using reference resistances

8.6.1 Principle

(1) Because buckling is not controlled by a single membrane stress at a single location, but depends on the development of a zone of high stress that may include significant plasticity, the buckling limit state, within this section, is represented by the design value of the actions, augmented to the point of buckling and applied to the specific defined conditions.

(2) The influence of membrane and bending effects, of plasticity and geometric imperfections are all included in the use of the two reference resistances and the buckling parameters.

8.6.2 Design value of actions

(1) The design values of actions should be taken as in 8.1(1)P.

8.6.3 Design value of resistance

(1) The design buckling resistance should be determined from the reference elastic critical resistance R_{cr} and the reference plastic resistance R_{pl} for the geometry and load case, together with the capacity parameters α, β, η, λ_0 and χ_h as defined in Annex E.

(2) The plastic reference resistance R_{pl} may be taken from Annex B. The value of R_{pl} for a given load case, involving as appropriate the loading $P_{n,Ed}$, $P_{x,Ed}$, $p_{n,Ed}$, F_{Ed}, etc. should be obtained as follows. Where there is more than one loading component, the ratios between different loading components should be retained in fixed proportions, with one nominated as the leading load F_{Ed}. The plastic collapse load should then be determined for the magnitude of the leading load as F_R. The plastic reference resistance should then be found as the ratio

$$R_{pl} = \frac{F_R}{F_{Ed}} \tag{8.24}$$

(3) The elastic critical reference resistance R_{cr} is defined in Annex E for specific geometries, load cases, and boundary conditions and may only be used for these specific cases.

(4) The relative slenderness of the shell should be found as

$$\bar{\lambda} = \sqrt{\frac{R_{pl}}{R_{cr}}} \tag{8.25}$$

(5) The elastic-plastic buckling reduction factor χ should be determined as a function of the relative slenderness of the shell $\bar{\lambda}$ from:

$$\chi = \chi_h - \left(\bar{\lambda} / \bar{\lambda}_0\right)(\chi_h - 1) \quad \text{when} \quad \bar{\lambda} \le \bar{\lambda}_0 \tag{8.26}$$

$$\chi = 1 - \beta\left(\frac{\bar{\lambda} - \bar{\lambda}_0}{\bar{\lambda}_p - \bar{\lambda}_0}\right)^{\eta} \quad \text{when} \quad \bar{\lambda}_0 < \bar{\lambda} < \bar{\lambda}_p \tag{8.27}$$

$$\chi = \frac{\alpha}{\bar{\lambda}^2} \quad \text{when} \quad \bar{\lambda}_p \le \bar{\lambda} \tag{8.28}$$

where:

α is the elastic buckling reduction factor;
β is the plastic range factor;
η is the interaction exponent;
$\bar{\lambda}_0$ is the squash limit relative slenderness;
χ_h is the hardening limit.".

NOTE The values of these parameters should be taken from Annex E. Where Annex E does not define the values of these parameters, they may be given by the National Annex.

Formula (8.28) describes the elastic buckling condition, accounting for geometric nonlinearity and geometric imperfections. In this case, where the behaviour is entirely elastic, the characteristic buckling resistance may alternatively be determined directly from $R_k = \alpha R_{cr}$.

(6) The value of the plastic limit relative slenderness $\bar{\lambda}_p$ should be determined from:

$$\bar{\lambda}_p = \sqrt{\frac{\alpha}{1-\beta}} \tag{8.29}$$

(7) The characteristic resistance of the shell should be determined from:

$$R_k = \chi R_{pl} \tag{8.30}$$

(8) The design resistance of the shell should then be determined from:

$$R_d = R_k / \gamma_{M1} \tag{8.31}$$

8.6.4 Buckling strength verification

(1) The following verification of the resistance of the shell structure to the defined loading should be undertaken:

$$R_d \ge 1 \tag{8.32}$$

23 Modifications to 8.6.2 (new subclause number: 8.7.2), Design value of resistance

Replace Paragraph (3) itself with:

"(3) The plastic reference resistance ratio R_{pl} (see figure 8.5) should be obtained by materially non-linear analysis (MNA) as the plastic limit load under the applied combination of actions. This load ratio R_{pl} may be taken as the largest value attained in the analysis, using an ideal elastic-plastic material law.".

In Paragraph (4), replace the whole Formula (8.24) (to be renumbered as (8.33)):

"

$$r_{\mathrm{Rpl}} = \frac{t \cdot f_{\mathrm{yk}}}{\sqrt{n_{\mathrm{x,Ed}}^2 - n_{\mathrm{x,Ed}} \cdot n_{\theta,\mathrm{Ed}} + n_{\theta,\mathrm{Ed}}^2 + n_{\mathrm{x}\theta,\mathrm{Ed}}^2}} \tag{8.24}$$

with:

$$R_{\mathrm{pl}} = \frac{t \cdot f_{\mathrm{y,k}}}{\sqrt{n_{\mathrm{x,Ed}}^2 - n_{\mathrm{x,Ed}} \cdot n_{\theta,\mathrm{Ed}} + n_{\theta,\mathrm{Ed}}^2 + 3n_{\mathrm{x}\theta,\mathrm{Ed}}^2}} \tag{8.33}$$

In Paragraph (4), in the NOTE, replace "expression (8.24)" *with* "Formula (8.33)".

Replace Paragraph (8) with:

"(8) The overall elastic-plastic buckling reduction factor χ_{ov} should be determined as $\chi_{\mathrm{ov}} = f\left(\bar{\lambda}_{\mathrm{ov}}, \bar{\lambda}_{\mathrm{ov,0}}, \alpha_{\mathrm{ov,}} \beta_{\mathrm{ov,}}\ \eta_{\mathrm{ov,}} \chi_{\mathrm{ov,h}}\right)$ using 8.5.2(4), in which α_{ov} is the overall elastic imperfection reduction factor, β_{ov} is the plastic range factor, η_{ov} is the interaction exponent, $\chi_{\mathrm{ov,h}}$ is the hardening limit and $\bar{\lambda}_{ov,0}$ is the squash limit relative slenderness.".

Replace Paragraph (9) with:

"(9) The evaluation of the factors $\bar{\lambda}_{\mathrm{ov,0}}$, α_{ov}, β_{ov}, η_{ov} and $\chi_{\mathrm{ov,h}}$ should take account of the imperfection sensitivity, geometric nonlinearity and other aspects of the particular shell buckling case. Conservative values for these parameters should be determined by comparison with known shell buckling cases (see Annex D) that have similar buckling modes, similar imperfection sensitivity, similar geometric nonlinearity, similar yielding sensitivity and similar postbuckling behaviour. The value of α_{ov} should also take account of the appropriate fabrication tolerance quality class.

Care should be taken in choosing an appropriate value of α_{ov} when this approach is used on shell geometries and loading cases where snap-through buckling may occur. Such cases include conical and spherical caps and domes under external pressure or on supports that can displace radially. The appropriate value of α_{ov} should also be chosen with care when the shell geometry and load case produce conditions that are highly sensitive to changes of geometry, such as at unstiffened junctions between cylindrical and conical shell segments under meridional compressive loads (e.g. in chimneys).

The commonly reported elastic shell buckling loads for these special cases are normally based on geometrically nonlinear analysis applied to a perfect or imperfect geometry, which predicts the snap-through buckling load. By contrast, the methodology used here adopts the linear bifurcation load as the reference elastic critical buckling resistance, and this is often much higher than the snap-through load. The design calculation must account for these two sources of reduced resistance by an appropriate choice of the overall elastic buckling reduction factor α_{ov}. This choice shall include the effect of both the geometric nonlinearity (that can lead to snap-through) and the additional strength reduction caused by geometric imperfections.".

Replace Paragraph (11) with:

"(11) If specific values of α_{ov}, β_{ov}, η_{ov}, $\overline{\lambda}_{\mathrm{ov,0}}$ and $\chi_{\mathrm{ov,h}}$ are not available according to (9) or (10), the values for an axially compressed unstiffened cylinder may be adopted, see D.1.2.2. Where snap-through is known to be a possibility, appropriate further reductions in α_{ov} should be considered.".

24 Modifications to 8.7.2 (new subclause number: 8.8.2), Design value of resistance

Replace Paragraph (4) with:

"(4) An LBA analysis should first be performed on the perfect structure to determine the elastic critical buckling resistance ratio R_{cr} of the perfect shell.

(5) An MNA analysis, adopting a perfect elastic-plastic material representation, should next be performed on the perfect structure to determine the perfect plastic reference resistance ratio R_{pl}.

(6) The LBA and MNA resistance ratios should then be used to establish the overall relative slenderness $\overline{\lambda}_{\mathrm{ov}}$ for the complete shell according to Formula (8.25).".

Renumber accordingly the following Paragraphs (5) to (27).

In Paragraph (15) (to be renumbered as (17)), replace "(13) and (14)" *with* "(15) and (16)".

In Paragraph (20) (to be renumbered as (22)), replace "(18) and (20)".

Replace the NOTE beneath Paragraph (22) (to be renumbered as (24)) with the following paragraph:

"Where the resistance is dominated by plasticity effects, the ratio ($R_{\mathrm{GMNIA}}/R_{\mathrm{GMNA}}$) will be much larger than the elastic buckling reduction factor α, and no close comparison can be expected. However, where the resistance is controlled by buckling phenomena that are substantially elastic, the ratio ($R_{\mathrm{GMNIA}}/R_{\mathrm{GMNA}}$) should be only a little higher than the value determined by hand calculation, and the factors that have led to any substantially higher value should be examined carefully.".

25 Modification to Annex B (normative), Additional expressions for plastic collapse resistances

Replace the title "Additional expressions for plastic collapse resistances" *with* "Additional expressions for plastic reference resistances".

26 Modification to C.3.3, Cylinder, pinned: uniform internal pressure with axial loading

Replace the formula itself for the maximum equivalent stress:

"
$$\text{Maximum}\,\sigma_{\mathrm{eq,m}} = \sigma_{\mathrm{MTx}}\sqrt{1-\left(\frac{\sigma_{\mathrm{MTx}}}{\sigma_{\mathrm{MT\theta}}}\right)+\left(\frac{\sigma_{\mathrm{MTx}}}{\sigma_{\mathrm{MT\theta}}}\right)^2}$$
"

with:

" $$\text{Maximum}\,\sigma_{\text{eq,m}} = \sigma_{\text{MT}\theta}\sqrt{1-\left(\frac{\sigma_{\text{MTx}}}{\sigma_{\text{MT}\theta}}\right)+\left(\frac{\sigma_{\text{MTx}}}{\sigma_{\text{MT}\theta}}\right)^2}$$ ".

27 Modifications to D.1.2.2, Meridional buckling parameters

Replace Paragraph (1) with:

"(1) The meridional elastic buckling reduction factor $\alpha_x = \alpha_{xG}\alpha_{xI}$ should be obtained from:

$$\alpha_{xG} = 0{,}83 \tag{D.14a}$$

$$\alpha_{xI} = \frac{1}{1+2{,}2\left(\Delta w_k / t\right)^{0{,}88}} \tag{D.14b}$$

The plastic range factor β_x should be obtained from:

$$\beta_x = 1-\frac{0{,}95}{1+1{,}2\left(\Delta w_k / t\right)} \tag{D.14c}$$

The interaction exponent η_x and the hardening limit χ_{xh} should be obtained from:

$$\eta_x = \frac{5{,}4}{1+4{,}6\left(\Delta w_k / t\right)} \qquad \textit{and} \qquad \chi_{xh}=1{,}0 \tag{D.14d}$$

where Δw_k is the characteristic imperfection amplitude:

$$\Delta w_k = \frac{1}{Q}\sqrt{rt} \tag{D.14e}$$

where Q is the meridional compression fabrication quality parameter.".

Replace Paragraph (3) with:

"(3) The meridional squash limit slenderness $\bar{\lambda}_{x0}$ should be taken as:

$$\bar{\lambda}_{x0} = 0{,}20 \tag{D.16}$$

28 Modification to D.1.3.2, Circumferential buckling parameters

Replace Paragraph (1) with:

"(1) The circumferential elastic buckling reduction factor should be taken from Table D.5 for the specified fabrication tolerance quality class.".

29 Modification to D.1.4.2, Shear buckling parameters

Replace Paragraph (1) with:

"(1) The shear elastic buckling reduction factor should be taken from Table D.6 for the specified fabrication tolerance quality class.".

30 Modifications to D.1.5.2, Pressurised meridional buckling parameters

Replace Paragraph (1) with:

"(1) The pressurised meridional buckling stress should be verified analogously to the unpressurised meridional buckling stress as specified in 8.5 and D.1.2.2. However, the unpressurised elastic buckling reduction factor α_x should be replaced by the pressurised elastic buckling factor α_{xp}.".

In Paragraph (2), replace the first sentence with:

"The pressurised elastic buckling reduction factor α_{xp} should be taken as the smaller of the two following values:".

In Paragraph (3), replace the notation beneath Formula (D.42):

"α_x is the unpressurised meridional elastic imperfection reduction factor according to D.1.2.2, and"

with:

"α_x is the unpressurised meridional elastic buckling reduction factor according to D.1.2.2, and".

31 Modification to D.1.6, Combinations of meridional (axial) compression, circumferential (hoop) compression and shear

In Paragraph (1), replace the notation beneath Formula (D.49):

"χ_x, χ_θ, χ_τ are the buckling reduction factors defined in 8.5.2, using the buckling parameters given in D.1.2 to D.1.4."

with:

"χ_x, χ_θ, χ_τ are the elastic-plastic buckling reduction factors defined in 8.5.2, using the buckling parameters given in D.1.2 to D.1.4.".

32 Modifications to D.4.2.2, Meridional compression

Add a new Paragraph (3):

"(3) The characteristic imperfection amplitude Δw_k, which may be needed for tolerance controls, should be taken as:

$$\Delta w_k = \left(\frac{22}{Q}\right)\lambda \cdot t \tag{D.70a}$$

in which Q is the meridional compression fabrication quality parameter, t is the local thickness and λ is the shell slenderness.".

33 Addition of a new Annex E (normative), Expressions for reference resistance design

Add the following new Annex E at the end of the document:

Annex E
(normative)

Expressions for reference resistance design

E.1 Cylindrical shells under uniform global bending

E.1.1 General

E.1.1.1 Scope

(1) The following rules apply to uniform unstiffened cylindrical shells subjected to uniform global bending.

(2) The rules are limited to the ranges given by

$$25 \leq \frac{r}{t} \leq 3000 \tag{E.1}$$

E.1.1.2 Notation

In this subclause the following notation is used (Figure E.1):

- r is the radius of the cylinder middle surface;
- t is the uniform thickness of the cylinder;
- L is the length of the cylinder;
- M is the uniform bending moment acting on the cylinder.

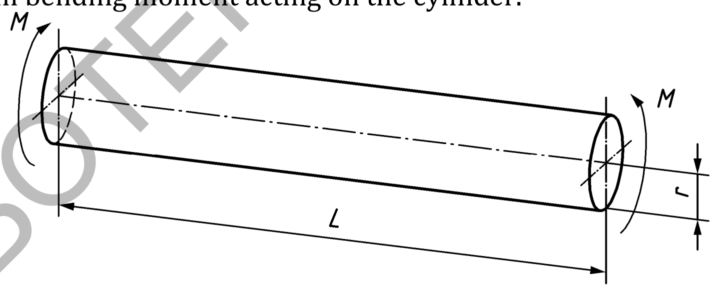


Figure E.1 — Cylinder under global bending

E.1.1.3 Boundary conditions

(1) The rules given here are strictly applicable to cylinders with fixed end boundary conditions BC1r. Cylinders with BC1f may also be treated if the dimensionless length ω is greater than 5.

E.1.1.4 Loading conditions

(1) The following rules apply to uniform global bending characterised by the moment M (Figure E.1).

E.1.2 Buckling resistances

E.1.2.1 Plastic reference resistance

(1) The plastic reference moment should be obtained from:

$$M_{\mathrm{R,pl}} = 4 r^2 t\, f_{\mathrm{y,k}} \tag{E.2}$$

E.1.2.2 Elastic critical buckling resistance

(1) The elastic critical buckling moment $M_{\mathrm{R,cr}}$ is given by:

$$M_{\mathrm{R,cr}} = 1{,}813\, C_{\mathrm{m}} \frac{E}{\sqrt{1-\nu^2}} r t^2 \approx 1{,}90\, C_{\mathrm{m}} E r t^2 \tag{E.3}$$

where the factor C_{m} accounts for the difference between the linear bifurcation bending moment and the classical elastic critical bending moment.

(2) The value of C_{m} may be taken conservatively as:

$$C_{\mathrm{m}} = 1 + \frac{4}{\omega^2} \tag{E.4}$$

where the first dimensionless length is given by:

$$\omega = \frac{L}{\sqrt{rt}} \tag{E.5}$$

E.1.2.3 Buckling parameters

(1) The geometrical reduction factor α_{G} depends on the second dimensionless length of the cylinder Ω, which should be determined as:

$$\Omega = \frac{L}{r}\sqrt{\frac{t}{r}} = \frac{t}{r}\omega \tag{E.6}$$

The value of α_{G} should be determined according to Tables E.1 and E.2.

Table E.1 — Length classes and values of α_{G}

Length class	Range of ω	Range of Ω	Expression for α_{G}
Short	$3 \le \omega < 4{,}8$		$1{,}93 - 0{,}5(\omega - 3{,}8)^2 - 0{,}44(\omega - 3{,}8)^3$
Medium	$4{,}8 \le \omega < 0{,}5\left(\frac{r}{t}\right)$		See Table E.2
Transitional		$0{,}5 \le \Omega < 7{,}0$	$1{,}07\left(\frac{1 - 0{,}22\Omega + 0{,}061\,\Omega^{2{,}94}}{1 + 0{,}12\Omega^{2{,}94}}\right)$
Long		$\Omega \ge 7{,}0$	0,516

Table E.2 — Values of α_G for medium length cylinders

Range of ω	Expression for α_G
$4,8 \le \omega < 8,6$	$0,85 + 0,029(\omega - 7,1)^2$
$8,6 \le \omega < 0,5\left(\frac{r}{t}\right)$	0,92

(2) The imperfection reduction factor α_I should be obtained from:

$$\alpha_I = \frac{1}{1 + 2,00(\Delta w_k / t)^{0,8}} \tag{E.7}$$

where Δw_k is the characteristic imperfection amplitude:

$$\Delta w_k = \frac{1}{Q}\sqrt{rt} \tag{E.8}$$

in which Q is the fabrication quality parameter given in (3).

(3) The fabrication quality parameter Q should be taken from Table E.3 for the specified fabrication tolerance quality.

Table E.3 — Values of fabrication quality parameter Q

Quality Class	Description	Q
Class A	excellent	40
Class B	high	25
Class C	normal	16

NOTE For manufactured tubes, tests may show that the relevant value of Q may be different from the above. The National Annex may define an appropriate value of Q.

(4) The elastic buckling reduction factor α should be found as:

$$\alpha = \alpha_G \alpha_I \tag{E.9}$$

(5) The plastic range factor β should be found as:

$$\beta = 1 - \frac{0,60}{1 + 1,2(\Delta w_k / t)^{0,8}} \tag{E.10}$$

(6) The interaction exponent η and the hardening limit χ_h should be found as:

$$\eta = 0,65 + 0,2(\Delta w_k / t) \quad \text{and} \quad \chi_h = 1,0 \tag{E.11}$$

(7) The squash limit relative slenderness λ_0 should be taken as:

$$\lambda_0 = 0,30 \tag{E.12}$$

E.1.2.4 Characteristic buckling resistance

(1) The characteristic buckling resistance should be determined according to 8.6.3, with the leading load F_{Ed} taken as the applied bending moment M_{Ed}, the reference plastic resistance $F_{R,pl}$ taken as $M_{R,pl}$ (Formula (E.2)) and the reference elastic critical resistance $F_{R,cr}$ taken as $M_{R,cr}$ (Formula (E.3)).

(2) This leads to the resistances evaluated as:

$$R_{pl} = \frac{M_{R,pl}}{M_{Ed}} \quad \text{and} \quad R_{cr} = \frac{M_{R,cr}}{M_{Ed}} \tag{E.13}$$

(3) The relative slenderness $\overline{\lambda}$ is then:

$$\overline{\lambda} = \sqrt{\frac{R_{pl}}{R_{cr}}} = \sqrt{\frac{M_{R,pl}}{M_{R,cr}}} \tag{E.14}$$

(4) The characteristic buckling resistance or the buckling moment is then found as:

$$R_k = \chi R_{pl} \quad \text{or} \quad M_{R,k} = \chi M_{R,pl} \tag{E.15}$$

in which:

χ = the elastic-plastic buckling reduction factor according to 8.6.3 (5).

E.1.3 Buckling strength verification

(1) The buckling verification is then simply:

$$R_d = \frac{R_k}{\gamma_{M1}} \geq 1 \tag{E.16}$$

where the safety factor γ_{M1} should be taken from the appropriate application standard.

E.2 Complete and partial spherical shells

E.2.1 General

E.2.1.1 Scope

(1) The following rules apply to spherical shells and spherical caps under internal vacuum or uniform external pressure with different boundary conditions. The wall thickness of the spherical shell should not vary significantly. The shell is unstiffened.

(2) The rules are limited to the ranges given by:

$$100 \leq \frac{r_s}{t} \leq 3000 \tag{E.17}$$

$\phi \leq 135°$ (spherical caps) with the special addition of

$$\phi \leq 180° \text{ (complete sphere)} \tag{E.18}$$

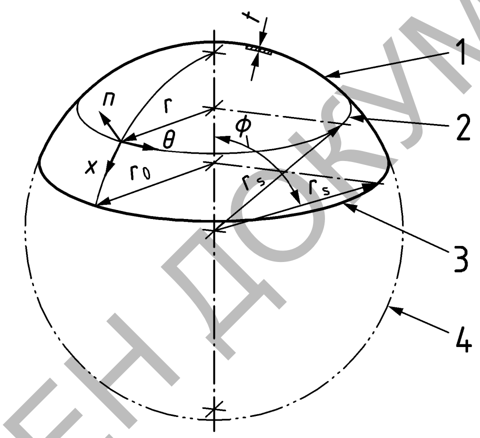
No lower limit on the range of ϕ is given, but very flat spherical caps should be checked by means of plate bending analysis. The test of Formula (E.20) defines the corresponding limit of application.

(3) The shell segments should be connected by welded butt-joints or by bolted symmetrical double-lap-joints or the shell should consist of a single spherical element without any interior joints.

E.2.1.2 Notation

In this subclause the following notation is used (Figure E.2):

- r_s is the radius of the sphere (shell middle surface);
- r is the simple radius of the shell middle surface = $r(x)$, perpendicular to the axis of rotation;
- r_0 is the radius of the base circle of the spherical cap;
- t is the thickness of the shell;
- ϕ is the semi-angle of the spherical cap.



Key
1 spherical cap
2 circumference
3 base circle
4 complete sphere

Figure E.2 — Spherical shell geometry

E.2.1.3 Support and boundary conditions

(1) The rules given here are applicable only to shells that are supported as indicated in Figure E.3 with the following boundary conditions:

SC 1: complete sphere without support or complete sphere with meridional support around a complete circumference;

SC 2: spherical cap with clamped edges;

SC 3: spherical cap with edges with displacement restraint in both the meridional direction and normal to the shell middle surface, and flexurally pinned;

SC 4: spherical cap with edges with displacement restraint in the meridional direction, but free normal to the shell middle surface, and flexurally pinned;

SC 5: spherical cap with edges free to displace in the plane of the base circle.

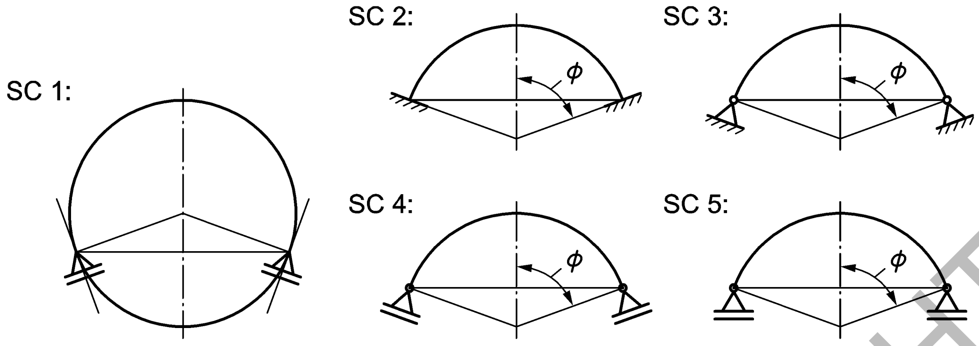


Figure E.3 — Illustrations of the different support conditions

E.2.1.4 Loading conditions

(1) The following apply only to uniform internal vacuum or external pressure loading p perpendicular to the shell wall (Figure E.4).

The design value of the pressure difference between the inside and outside surfaces p_{Ed} should be taken as the key value.

a) Complete sphere subjected to internal vacuum or external pressure

b) Spherical cap subjected to external pressure

Figure E.4 — Loading on spherical shells and caps

(2) For the loading cases of self-weight or snow, the procedures here may be used to obtain a conservative estimate of resistance if the value of the pressure load p is taken as the maximum surface load normal to the middle surface of the shell.

E.2.2 Tolerances for spherical shells

(1) The geometrical tolerances are classified into three Fabrication Tolerance Quality Classes A to C.

(2) For the buckling relevant tolerances, the provisions of Subclause 8.4 apply by taking the radius r_s of the spherical shell in place of the cylinder radius r and the diameter $2r_s$ instead of the diameter d of the cylinder. The measurement of dimples (8.4.4) should be performed in both the meridional and circumferential

directions using the stick lengths ℓ_{gx} given by Formula (8.6) and ℓ_{gw} given by Formula (8.8). It is not necessary to use the stick length $\ell_{g\theta}$ given by Formula (8.7) at all.

(3) The tolerance limits for each fabrication tolerance quality class given in 8.4 should be used.

E.2.3 Buckling design

E.2.3.1 Limitation on buckling calculations

(1) It is not necessary to check the resistance to buckling in shells that satisfy the following conditions:

Spherical shells that satisfy the condition:

$$\frac{r_s}{t} \le \frac{E}{20 f_{y,k}} \cdot C_c \tag{E.19}$$

and very flat spherical caps that satisfy the condition:

$$\frac{r_0}{r_s} \le \frac{1,1}{\sqrt{r_s / t}} \tag{E.20}$$

E.2.3.2 Elastic critical buckling resistance

(1) The elastic critical buckling pressure $p_{R,cr}$ is given by:

$$p_{R,cr} = \frac{2}{\sqrt{3(1-\upsilon^2)}} C_c \cdot E \cdot \left(\frac{t}{r_s}\right)^2 \tag{E.21}$$

where the factor C_c depends on the support conditions and should be taken from Table E.4.

Table E.4 — Values of C_c for different support conditions

Support condition SC	SC 1	SC 2	SC 3	SC 4	SC 5
C_c	1,0	0,8	0,7	0,4	0,1
Applicable for	complete sphere	$\phi \le 135°$			

E.2.3.3 Plastic reference resistance

(1) The plastic reference resistance should be obtained from:

$$p_{R,pl} = f_{y,k} \cdot C_{pl} \cdot \frac{2t}{r_s} \tag{E.22}$$

in which the factor C_{pl} is a function of the support conditions and should be taken from Table E.5.

Table E.5 — Values of C_{pl} for different support conditions

Support condition SC	SC 1	SC 2	SC 3	SC 4	SC 5
C_{pl}	1,0	0,9	0,9	0,8	0,2
Applicable for	complete sphere	$\phi \leq 135°$			

E.2.3.4 Buckling parameters

(1) The geometric reduction factor α_G is given as:

$$\alpha_G = 0,70 \tag{E.23}$$

(2) The imperfection reduction factor α_I should be obtained from:

$$\alpha_I = \frac{1}{1 + 1,90\left(\Delta w_k / t\right)^{0,75}} \tag{E.24}$$

where Δw_k is the characteristic imperfection amplitude:

$$\Delta w_k = \frac{1}{Q}\sqrt{r_s t} \tag{E.25}$$

in which Q is the fabrication quality parameter given in (3).

(3) The fabrication quality parameter Q should be taken from Table E.6 for the specified fabrication tolerance quality.

Table E.6 — Values of fabrication quality parameter Q

Quality class	Description	Q
Class A	excellent	40
Class B	high	25
Class C	normal	16

(4) The elastic buckling reduction factor α should be found as:

$$\alpha = \alpha_G \alpha_I \tag{E.26}$$

(5) The squash limit relative slenderness λ_0, the plastic range factor β, the interaction exponent η and the hardening limit χ_h should be taken as:

$$\lambda_0 = 0,20 \qquad \beta = 0,70 \qquad \eta = 1,0 \qquad \chi_h = 1,0 \tag{E.27}$$

E.2.3.5 Characteristic buckling resistance

(1) The characteristic buckling resistance should be determined according to 8.6.3, with the leading load F_{Ed} taken as the applied external pressure p_{Ed}, the reference plastic resistance $F_{R,pl}$ taken as $p_{R,pl}$ (Formula (E.22)) and the reference elastic critical resistance $F_{R,cr}$ taken as $p_{R,cr}$ (Formula (E.21)).

(2) This leads to the resistances evaluated as:

$$R_{pl} = \frac{p_{R,pl}}{p_{Ed}} \quad \text{and} \quad R_{cr} = \frac{p_{R,cr}}{p_{Ed}} \tag{E.28}$$

(3) The relative slenderness $\overline{\lambda}$ is then:

$$\overline{\lambda} = \sqrt{\frac{p_{R,pl}}{p_{R,cr}}} = \sqrt{\frac{R_{pl}}{R_{cr}}} \tag{E.29}$$

(4) The characteristic buckling resistance or the buckling pressure is then found as:

$$R_k = \chi R_{pl} \quad \text{or} \quad p_{R,k} = \chi\, p_{R,pl} \tag{E.30}$$

in which:

χ = the elastic-plastic buckling reduction factor according to 8.6.3(5).

E.2.4 Buckling strength verification

(1) The buckling verification is then:

$$R_d = \frac{R_k}{\gamma_{M1}} \geq 1 \tag{E.31}$$

where the safety factor γ_{M1} should be taken from the appropriate application standard.".