

AENOR

EUROPEAN STANDARD
NORMA EUROPEA
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1992-3

Junio 2006

ICS 91.010.30; 91.080.40

English version

Eurocode 2: Design of concrete structures
Part 3: Liquid retaining and containment structures

Eurocódigo 2: Proyecto de estructuras de hormigón. Parte 3: Depósitos y estructuras de contención.

Eurocode 2: Calcul des structures en béton. Partie 3: Silos et réservoirs.

Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken. Teil 3: Stütz- und Behälterbauwerke aus Beton.

This European Standard was approved by CEN on 2005-11-24.

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FOREWORD

This European Standard (EN 1992-3:2006) 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of an identical text or by endorsement, at the latest by December 2006, and conflicting national standards shall be withdrawn at the latest by March 2010.

This Eurocode supersedes ENV 1992-4.

CEN/TC 250 is responsible for all Structural Eurocodes.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, 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 the United Kingdom.

Background of the Eurocode programme

See EN 1992-1-1.

Eurocode programme

See EN 1992-1-1.

Status and Field of application of Eurocodes

See EN 1992-1-1.

National Standards implementing Eurocodes

See EN 1992-1-1.

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

See EN 1992-1-1.

Additional information specific to EN 1992-3 and link to EN 1992-1-1

The scope of Eurocode 2 is defined in 1.1.1 of EN 1992-1-1 and the scope of this Part of Eurocode 2 is defined in 1.1.2. Other Additional Parts of Eurocode 2 which are planned are indicated in 1.1.3 of EN 1992-1-1; these will cover additional technologies or applications, and will complement and supplement this Part. It has been necessary to introduce into EN 1992-3 a few clauses which are not specific to liquid retaining or containment structures and which strictly belong to Part 1-1. These are deemed valid interpretations of Part 1-1 and design complying with the requirements of EN 1992-3 are deemed to comply with the principles of EN 1992-1-1.

It should be noted that any product, such as concrete pipes, which are manufactured and used in accordance with a product standard for a watertight product, will be deemed to satisfy the requirements, including detailing, of this code without further calculation.

There are specific regulations for the surfaces of storage structures which are designed to contain foodstuffs or potable water. These should be referred to as necessary and their provisions are not covered in this code.

In using this document in practice, particular regard should be paid to the underlying assumptions and conditions given in 1.3 of EN 1992-1-1.

The nine chapters of this document are complemented by four Informative Annexes. These Annexes have been introduced to provide general information on material and structural behaviour which may be used in the absence of information specifically related to the actual materials used or actual conditions of service.

As indicated above, reference should be made to National annexes which will give details of compatible supporting standards to be used. For this Part of Eurocode 2, particular attention is drawn to EN 206-1 (Concrete - performance, production, placing and compliance criteria).

For EN 1992-3, the following additional sub-clauses apply.

This Part 3 of Eurocode 2 complements EN 1992-1-1 for the particular aspects of liquid retaining structures and structures for the containment of granular solids.

The framework and structure of this Part 3 correspond to EN 1992-1-1. However, Part 3 contains Principles and Application Rules which are specific to liquid retaining and containment structures.

Where a particular sub-clause of EN 1992-1-1 is not mentioned in this EN 1992-3, that sub-clause of EN 1992-1-1 applies as far as deemed appropriate in each case.

Some Principles and Application Rules of EN 1992-1-1 are modified or replaced in this Part, in which case the modified versions supersede those in EN 1992-1-1 for the design of liquid retaining or containment structures.

Where a Principle or Application Rule in EN 1992-1-1 is modified or replaced, the new number is identified by the addition of 100 to the original number. Where a new Principle or Application Rule is added, it is identified by a number which follows the last number in the appropriate clause in EN 1992-1-1 with 100 added to it.

A subject not covered by EN 1992-1-1 is introduced in this Part by a new sub-clause. The sub-clause number for this follows the most appropriate clause number in EN 1992-1-1.

The numbering of equations, figures, footnotes and tables in this Part follow the same principles as the clause numbering as described above.

National annex for EN 1992-3

This standard gives values with notes indicating where national choices may have to be made. Therefore the national Standard implementing EN 1992-3 should have a National annex containing all Nationally Determined Parameters to be used for the design of liquid retaining and containment structures to be constructed in the relevant country.

National choice is allowed in EN 1992-3 through the following clauses:

7.3.1 (111)

7.3.1 (112)

7.3.3

8.10.3.3 (102) and (103)

9.11.1 (102)

SECTION 1 GENERAL

1.1 Scope

Replacement of clause 1.1.2 in EN 1992-1-1 by:

1.1.2 Scope of Part 3 of Eurocode 2

(101)P Part 3 of EN 1992 covers additional rules to those in Part 1 for the design of structures constructed from plain or lightly reinforced concrete, reinforced concrete or prestressed concrete for the containment of liquids or granular solids.

(102)P Principles and Application Rules are given in this Part for the design of those elements of structure which directly support the stored liquids or materials (i.e. the directly loaded walls of tanks, reservoirs or silos). Other elements which support these primary elements (for example, the tower structure which supports the tank in a water tower) should be designed according to the provisions of Part 1-1.

(103)P This part does not cover:

- Structures for the storage of materials at very low or very high temperatures.
- Structures for the storage of hazardous materials the leakage of which could constitute a major health or safety risk.
- The selection and design of liners or coatings and the consequences of the choice of these on the design of the structure.
- Pressurised vessels.
- Floating structures.
- Large dams
- Gas tightness.

(104) This code is valid for stored materials which are permanently at a temperature between -40°C and $+200^{\circ}\text{C}$.

(105) For the selection and design of liners or coatings, reference should be made to appropriate documents.

(106) It is recognised that, while this code is specifically concerned with structures for the containment of liquids and granular materials, the clauses covering design for liquid tightness may also be relevant to other types of structure where liquid tightness is required.

(107) In clauses relating to leakage and durability, this code mainly covers aqueous liquids. Where other liquids are stored in direct contact with structural concrete, reference should be made to specialist literature.

1.2 Normative references

The following normative documents contain provisions that, though referenced in this text, constitute provisions of this European Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this European Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies.

EN 1990, *Eurocode, Basis of structural design*.

EN 1991-1-5, *Eurocode 1, Actions on structures. Part 1-5: General Actions. Thermal actions*.

EN 1991-4, *Eurocode 1, Actions on structures. Part 4: Silos and tanks.*

EN 1992-1-1, *Eurocode 2, Design of concrete structures. Part 1.1: General rules and rules for buildings.*

EN 1992-1-2, *Eurocode 2, Design of concrete structures – Part 1.2: General rules – Structural fire design*

EN 1997, *Eurocode 7: Geotechnical design*

1.6 Symbols

Addition after 1.6.

1.7 Special symbols used in Part 3 of Eurocode 2

Latin upper case symbols

R_{ax} factor defining the degree of external axial restraint provided by elements attached to the element considered

R_m factor defining the degree of moment restraint provided by elements attached to the element considered

Latin lower case symbols

f_{ctx} tensile strength, however defined

f_{ckT} characteristic compressive strength of the concrete modified to take account of temperature

Greek symbols

ε_{av} average strain in the element

ε_{az} actual strain at level z

ε_{iz} imposed intrinsic strain at level z

ε_{Tr} transitional thermal strain

ε_{Th} free thermal strain in the concrete

SECTION 2 BASIS OF DESIGN

2.1 Requirements

2.1.1 Basic requirements

Addition following (3):

(104) The design situations to be considered should comply with EN 1990, EN 1991-4 and EN 1991-1-5, chapter 3. In addition, for liquid retaining and containment structures made with concrete, the following special design situations may be relevant:

- operating conditions implying patterns of discharge and filling;
- dust explosions;
- thermal effects caused, for example, by stored materials or environmental temperature;
- requirements for testing of reservoirs for watertightness.

2.3 Basic variables

2.3.1 Actions and environmental influences

2.3.1.1 General

Addition after (1):

(102)P The partial safety factors for the actions for liquid retaining and containment structures are set out in Normative Annex B of EN 1991-4.

(103) Actions resulting from soil or water within the ground should be obtained in accordance with EN 1997.

2.3.2 Material and product properties

2.3.2.3 Properties of concrete with respect to watertightness

(101) If the minimum thicknesses of the member given in 9.11 (102) are used then a lower water-cement ratio may be required and, consideration should be given to a limitation to the maximum aggregate size.

SECTION 3 MATERIALS

3.1 Concrete

3.1.1 General

(103) The effect of temperature on the properties of concrete should be taken into consideration in design.

NOTE Further information may be found in informative Annex K.

3.1.3 Elastic deformation

Replace (5) by:

(105) Unless more accurate information is available, the linear coefficient of thermal expansion may be taken as equal to $10 \times 10^{-6} \text{K}^{-1}$. It should be noted, however, that coefficients of thermal expansion of concrete vary considerably depending on the aggregate type and the moisture conditions within the concrete.

3.1.4 Creep and Shrinkage

Addition after application rule (5)

(106) Where the elements are exposed for substantial periods to high temperature ($> 50^\circ\text{C}$), creep behaviour is substantially modified. Where this is likely to be significant, appropriate data should generally be obtained for the particular conditions of service envisaged.

NOTE Guidance is given in Informative Annex K on the estimation of creep effects at elevated temperatures.

3.1.11 Heat evolution and temperature development due to hydration

(101) Where conditions during the construction phase are considered to be significant, the heat evolution characteristics for a particular cement should generally be obtained from tests. The actual heat evolution should be determined taking account of the expected conditions during the early life of the member (e.g. curing, ambient conditions). The maximum temperature rise and the time of occurrence after casting should be established from the mix design, the nature of the formwork, the ambient conditions and the boundary conditions.

3.2 Reinforcing steel

3.2.2 Properties

(107) For reinforcing steels subjected to temperatures in the range -40 to +100 °C (if no special investigation is made) reference should be made to 1992-1-1, clause 3.2.2. For higher temperature, information is given in 3.2.3 of EN 1992-1-2. For relaxation at temperatures above 20 °C, see 10.3.2.2 in EN 1992-1-2.

3.3 Prestressing steel

3.3.2 Properties

(110) For prestressing strands subjected to temperatures in the range -40 to +100 °C (if no special investigation is made) the same values for strength and relaxation apply as for "normal temperatures". For higher temperatures, information is given in 3.2.4 of EN 1992-1-2.

SECTION 4 DURABILITY AND COVER TO REINFORCEMENT

4.3 Requirements for durability

Addition after 4.4.1.2 (13)

(114) Abrasion of the inner face of the walls of a silo may cause contamination of the stored material or lead to significant loss of cover. Three mechanisms of abrasion may occur:

- mechanical attack due to the filling and discharging process;
- physical attack due to erosion and corrosion with changing temperature and moisture conditions;
- chemical attack due to reaction between the concrete and the stored material.

(115) Appropriate measures should be taken to ensure that the elements subject to abrasion will remain serviceable for the design working life.

SECTION 5 STRUCTURAL ANALYSIS

Addition after 5.11

5.12 Determination of the effects of temperature

5.12.1 General

(101) Rigorous analyses may be carried out using the provisions of 3.1.4 and Annex B of EN 1992-1-1 for creep and shrinkage.

(102) In storage structures, high temperature gradients may occur where the stored material is either self heating or is put into the structure at high temperature. In such circumstances calculation of the resulting temperature gradients and the consequent internal forces and moments will be necessary.

5.13 Calculation of the effects of internal pressure

(101) The internal pressure from solid materials acts directly upon the inner surface of the concrete. In the absence of a more rigorous analysis, internal pressure from liquids may be assumed to act at the centre of the retaining members.

SECTION 6 ULTIMATE LIMIT STATES

Addition after 6.2.3 (8)

(109) The choice of strut angle in 6.2.3(2) for shear resistance should take into account the influence of any significant applied tension. Conservatively, $\cot \theta$ may be taken as 1,0. The procedure in Annex QQ of EN1992-2 may also be used.

Addition after 6.8

6.9 Design for dust explosions

6.9.1 General

(101)P Where silos are designed to contain materials which may pose a risk of dust explosions, the structure shall either be designed to withstand the resulting expected maximum pressures or be provided with suitable venting which will reduce the pressure to a supportable level. The appropriate loads resulting from dust explosions are dealt with in EN 1991-4 and general considerations relating to design for explosions in 1991-1-7 however, the points in 6.9.2 (101) to (105) should be noted.

(102)P Fire expelled through a venting outlet shall not cause any impairment of the surroundings nor cause explosions in other sections of the silo. Risks to people due to flying glass or other debris shall be minimised.

(103) Vent openings should lead directly to open air through planned venting outlets, which reduce the explosion pressure.

(104) Venting systems should be initiated at low pressure and have low inertia.

(105) Actions due to dust explosions should be treated as accidental actions.

6.9.2 Design of structural elements

(101) The maximum pressures due to explosions occur in empty silo bins, however, the pressures in a partly filled silo bin combined with the corresponding pressures from the bulk material may lead to a more critical design condition.

(102) When inertia forces arise due to a rapid discharge of gas followed by cooling of the hot smoke, a pressure below atmospheric may occur. This should be taken into account when designing the encasing structure and members in the flow path.

(103) The elements forming a venting device should be secured against flying off and adding to the risks from flying debris.

(104) As pressure relief due to venting occurs, reaction forces are generated which should be taken into account in the design of structural members.

(105) Specialist assistance should be sought where complex installations are contemplated or where explosions might pose a high risk of injury.

SECTION 7 SERVICEABILITY LIMIT STATES

7.3 Cracking

7.3.1 General considerations

Addition after (9)

(110) It is convenient to classify liquid retaining structures in relation to the degree of protection against leakage required. Table 7.105 gives the classification. It should be noted that all concrete will permit the passage of small quantities of liquids and gasses by diffusion.

Table 7.105 – Classification of tightness

Tightness Class	Requirements for leakage
0	Some degree of leakage acceptable, or leakage of liquids irrelevant
1	Leakage to be limited to a small amount. Some surface staining or damp patches acceptable
2	Leakage to be minimal. Appearance not to be impaired by staining
3	No leakage permitted

(111) Appropriate limits to cracking depending on the classification of the element considered should be selected, paying due regard to the required function of the structure. In the absence of more specific requirements, the following may be adopted.

Tightness Class 0. – the provisions in 7.3.1 of EN 1992-1-1 may be adopted.

Tightness Class 1. – any cracks which can be expected to pass through the full thickness of the section should be limited to w_{kl} . The provisions in 7.3.1 of EN 1992-1-1 apply where the full thickness of the section is not cracked and where the conditions in (112) and (113) below are fulfilled.

Tightness Class 2. – cracks which may be expected to pass through the full thickness of the section should generally be avoided unless appropriate measures (e.g. liners or water bars) have been incorporated.

Tightness Class 3. – generally, special measures (e.g. liners or prestress) will be required to ensure watertightness.

NOTE The value of w_{kl} for use in a country may be found in its National Annex. The recommended values for structures retaining water are defined as a function of the ratio of the hydrostatic pressure, h_D to the wall thickness of the containing structure, h . For $h_D/h \leq 5$, $w_{kl} = 0,2$ mm while for $h_D/h \geq 35$, $w_{kl} = 0,05$ mm. For intermediate values of h_D/h , linear interpolation between 0,2 and 0,05 may be used. Limitation of the crack widths to these values should result in the effective sealing of the cracks within a relatively short time.

(112) To provide adequate assurance for structures of classes 2 or 3 that cracks do not pass through the full width of a section, the design value of the depth of the compression zone should be at least x_{min} calculated for the quasi-permanent combination of actions. Where a section is subjected to alternate actions, cracks should be considered to pass through the full thickness of the section unless it can be shown that some part of the section thickness will always remain in compression. This thickness of concrete in compression should normally be at least x_{min} under all appropriate combinations of actions. The action effects may be calculated on the assumption of linear elastic material behaviour. The resulting stresses in a section should be calculated assuming that concrete in tension is neglected.

NOTE The values of x_{min} for use in a country may be found in its National Annex. The recommended value for x_{min} is the lesser of 50 mm or $0,2 h$ where h is the element thickness.

(113) If the provisions of 7.3.1 (111) for tightness class 1 are met then cracks through which water flows may be expected to heal in members which are not subjected to significant changes of loading or temperature during service. In the absence of more reliable information, healing may be assumed where the expected range of strain at a section under service conditions is less than 150×10^{-6} .

(114) If self-healing is unlikely to occur, any crack which passes through the full thickness of the section may lead to leakage, regardless of the crack width.

(115) Silos holding dry materials may generally be designed as Class 0 however it may be appropriate for Class 1, 2 or 3 to be used where the stored material is particularly sensitive to moisture.

(116) Special care should be taken where members are subject to tensile stresses due to the restraint of shrinkage or thermal movements.

(117) Acceptance criteria for liquid retaining structures may include maximum level of leakage.

7.3.3 Control of cracking without direct calculation

Replace note in Application Rule (2):

NOTE Where the minimum reinforcement given by 7.3.2 is provided, Figures 7.103N and 7.104N give values of maximum bar diameters and bar spacings for various design crack widths for sections totally in tension.

The maximum bar diameter given by Figure 7.103N should be modified using Expression 7.122 below rather than Expression 7.7 which applies where ϕ_s^* has been calculated for pure flexure:

$$\phi_s = \phi_s^* \left(\frac{f_{ct,eff}}{2,9} \right) \frac{h}{10(h-d)} \quad [7.122]$$

where

ϕ_s is the adjusted maximum bar diameter;

ϕ_s^* is the maximum bar diameter obtained from Figure 7.103N;

h is the overall thickness of the member;

d is the depth to the centroid of the outer layer of reinforcement from the opposite face of the concrete (see Figure 7.1(c) in Part 1).

$f_{ct,eff}$ is the effective mean value of the tensile strength of the concrete as defined in Part 1 where $f_{ct,eff}$ is in MPa.

For cracking caused dominantly by restraint, the bar sizes given in Figure 7.103N should not be exceeded where the steel stress is the value obtained immediately after cracking (i.e. σ_s in Expression 7.1)

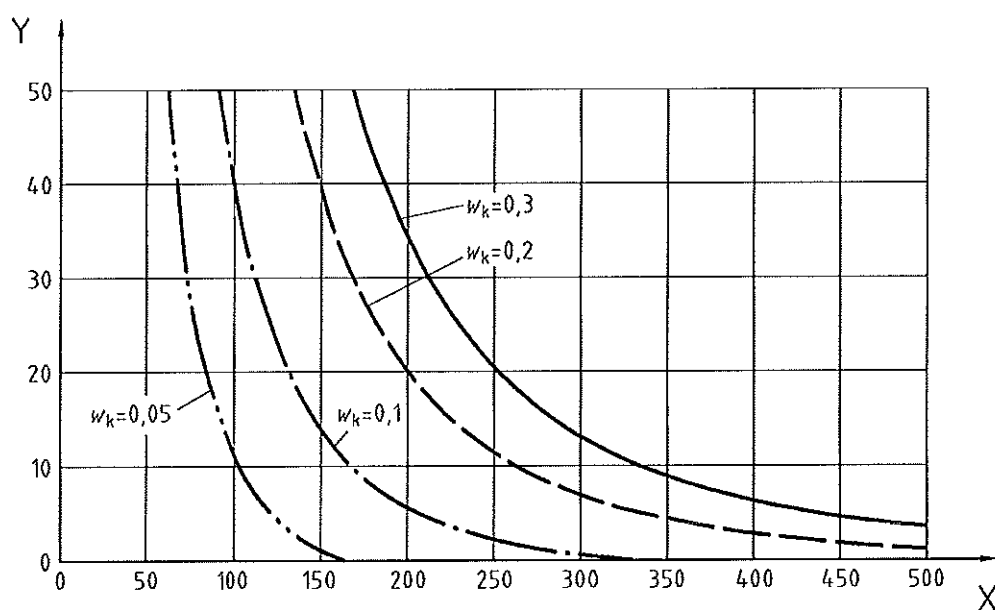
For cracks caused dominantly by loading, either the maximum bar sizes from Figure 7.103N or the maximum bar spacings from Figure 7.104N may be complied with. The steel stress should be calculated on the basis of a cracked section under the relevant combination of actions.

For intermediate values of design crack width, values may be interpolated.

7.3.4 Calculation of crack width

Addition after Application Rule (5)

(106) Information on the calculation of crack widths in members subjected to restrained thermal or shrinkage strains is given in Informative Annexes L and M.

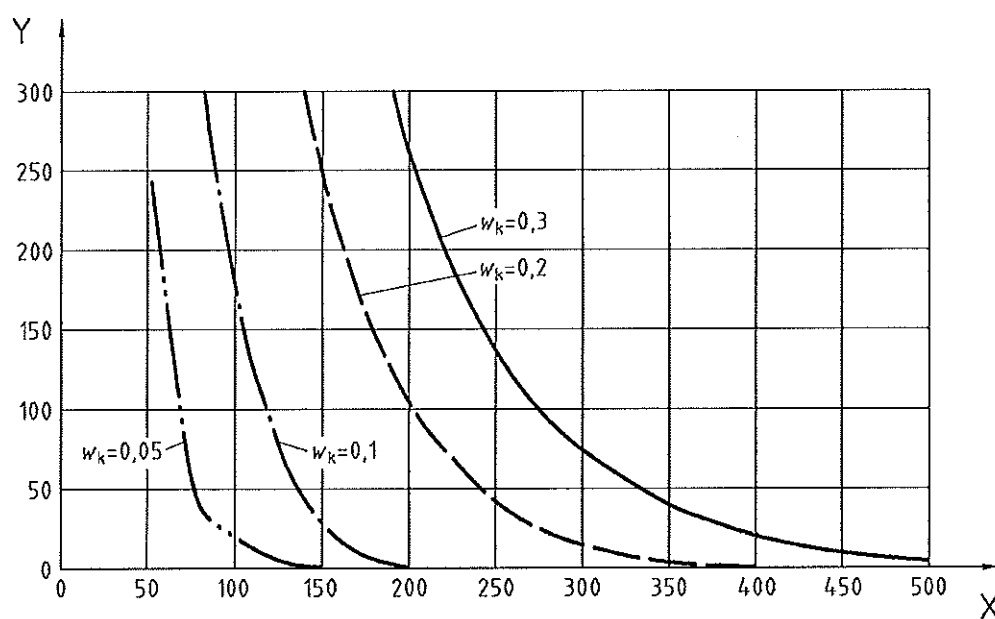


Key

X Reinforcement stress, σ_s (N/mm²)

Y Maximum bar diameter (mm)

Figure 7.103N – Maximum bar diameters for crack control in members subjected to axial tension



Key

X Reinforcement stress, σ_s (N/mm²)

Y Maximum bar spacing (mm)

Figure 7.104N – Maximum bar spacings for crack control in members subjected to axial tension

Addition after 7.3.4

7.3.5 Minimising cracking due to restrained imposed deformations

(101) Where it is desirable to minimise the formation of cracks due to restrained imposed deformations resulting from temperature change or shrinkage, this may be achieved for Class 1 structures (see Table 7.105) by ensuring that the resulting tensile stresses do not exceed the available tensile strength $f_{ctk,0.05}$ of the concrete, adjusted, if appropriate, for the two-dimensional state of stress (see Annex QQ of EN 1992-2) and, for Class 2 or Class 3 structures where a liner is not used, by ensuring that the whole section remains in compression. This may be achieved by:

- limiting the temperature rise due to hydration of the cement;
- removing or reducing restraints;
- reducing the shrinkage of the concrete;
- using concrete with a low coefficient of thermal expansion;
- using concrete with a high tensile strain capacity (Class 1 structures only);
- application of prestressing.

(102) It will generally be sufficiently accurate to calculate the stresses assuming the concrete to be elastic and to allow for the effects of creep by use of an effective modulus of elasticity for the concrete. Informative Annex L provides a simplified method of assessing stresses and strains in restrained concrete members which may be used in the absence of more rigorous calculation.

SECTION 8 DETAILING PROVISIONS

8.10.1 Arrangement of prestressing tendons and ducts

8.10.1.3 Post-tension ducts

Addition after Application Rule (1)

(102) In the case of circular tanks with internal prestressing, care needs to be taken to avoid the possibility of local failures due to the tendons breaking out through the inside cover. In general, this will be avoided if the theoretical centroid of the horizontal cables lies in the outer third of the wall. Where the cover provisions make this impossible, this requirement may be relaxed provided the tendon duct remains within the outer half of the wall.

(103) The diameter of a duct within a wall should generally not exceed κ times the wall thickness.

NOTE The value of κ for use in a country may be found in its National Annex. The recommended value is $\kappa = 0,25$.

(104) The prestressing force on a wall should be distributed as evenly as possible. Anchorages or buttresses should be so arranged as to reduce the possibilities of uneven force distribution unless specific measures are taken to take the effects into account.

(105) Where structures subjected to elevated temperatures containing vertical unbonded tendons are used, it has been found that the protective grease is liable to run out. To avoid this, it is better to avoid the use of unbonded prestressing tendons as vertical prestress. If they are used, means should be provided to enable the presence of protective grease to be checked and renewed if necessary.

8.10.4 Anchorages and couplers for prestressing tendons

Addition after Application Rule (5)

(106) If anchorages are located on the inside of tanks, particular care should be taken to protect them against possible corrosion.

SECTION 9 DETAILING OF MEMBERS AND PARTICULAR RULES

9.6 Reinforced concrete walls

Addition after 9.6.4

9.6.5 Corner connections between walls

(101) Where walls are connected monolithically at a corner and are subjected to moments and shears which tend to open the corner (i.e. the inner faces of the walls are in tension), care is required in detailing the reinforcement to ensure that the diagonal tension forces are adequately catered for. A strut and tie system as covered in 5.6.4 of EN 1992-1-1 is an appropriate design approach.

9.6.6 Provision of movement joints

(101) If effective and economic means cannot otherwise be taken to limit cracking, liquid retaining structures should be provided with movement joints. The strategy to be adopted will depend on the conditions of the structure in service and the degree of risk of leakage which is acceptable. Different procedures for the satisfactory design and construction of joints have been developed in different countries. It should be noted that the satisfactory performance of joints requires that they are formed correctly. Furthermore, the sealants to joints frequently have a life considerably shorter than the design working life of the structure and therefore in such cases joints should be constructed so that they are inspectable and repairable or renewable. Further information on the provision of movement joints is given in Informative Annex N. It is also necessary to ensure that the sealant material is appropriate for the material or liquid to be retained.

9.11 Prestressed walls

9.11.1 Minimum area of passive reinforcement and cross-sectional dimensions

(101) Where there is no vertical prestressing (or no inclined prestressing in inclined walls), vertical (or inclined) reinforcement should be provided on the basis of reinforced concrete design.

(102) The thickness of walls forming the sides of reservoirs or tanks should generally not be less than t_1 mm for class 0 or t_2 mm for classes 1 or 2. Slipformed walls should not be thinner than t_2 mm whatever the class and the holes left by the lifting rods should be filled with a suitable grout.

NOTE The values of t_1 and t_2 for use in a country may be found in its National Annex. The recommended value for t_1 is 120 mm and for t_2 is 150 mm.

ANNEX K (Informative)

EFFECT OF TEMPERATURE ON THE PROPERTIES OF CONCRETE

K.1 General

(101) This Annex covers the effects on the material properties of concrete of temperatures in the range -25 °C to +200 °C. Properties covered are: strength and stiffness, creep and transitional thermal strain.

(102) In all cases the changes in properties are strongly dependant on the particular type of concrete used and the Annex should not be considered to provide more than general guidance.

K.2 Material properties at sub-zero temperatures

(101) When concrete is cooled to below zero, its strength and stiffness increase. This increase depends mainly on the moisture content of the concrete: the higher the moisture content, the greater is the increase in strength and stiffness. It should be noted that the enhancement in properties would apply only to structures, which would be permanently below -25 °C.

(102) Cooling concrete to -25 °C leads to increases in the compressive strength of:

- around 5 MPa for partially dry concrete;
- around 30 MPa for saturated concrete.

(103) The expressions given in Table 3.1 for tensile strength may be modified to give the effect of temperature as follows:

$$f_{ctx} = \alpha f_{ckT}^{2/3} \quad [K.1]$$

where

f_{ctx} = tensile strength, however defined (see Table K.1);

α = a coefficient taking account of the moisture content of the concrete. Values of α are given in Table K.1;

f_{ckT} = the characteristic compressive strength of the concrete modified to take account of temperature according to (102) above.

Table K.1 – Values of α for saturated and dry concrete

Definition of tensile strength (f_{ctx})	Saturated concrete	Dry concrete
f_{ctm}	0,47	0,30
$f_{ctk} 0,05$	0,27	0,21
$f_{ctk} 0,95$	0,95	0,39

(104) Cooling concrete to -25 °C leads to increases in the modulus of elasticity of:

- around 2 000 MPa for partially dry concrete;
- around 8 000 MPa for saturated concrete.

(105) Creep at sub-zero temperatures may be taken to be 60 % to 80 % of the creep at normal temperatures. Below -20 °C creep may be assumed to be negligible.

K.3 Material properties at elevated temperatures

(101) Information on the compressive strength and tensile strength of concrete at temperatures above normal may be obtained from 3.2.2 of EN 1992-1-2.

(102) The modulus of elasticity of concrete may be assumed to be unaffected by temperature up to 50 °C. For higher temperatures, a linear reduction in modulus of elasticity may be assumed up to a reduction of 20 % at a temperature of 200 °C.

(103) For concrete heated prior to loading, the creep coefficient may be assumed to increase with increase in temperature above normal (assumed as 20 °C) by the appropriate factor from Table K.2.

Table K.2 – Creep coefficient multipliers to take account of temperature where the concrete is heated prior to loading

Temperature (°C)	Creep coefficient multiplier
20	1,00
50	1,35
100	1,96
150	2,58
200	3,20
NOTE The values in the table have been deduced from CEB Bulletin 208 and are in good agreement with multipliers calculated on the basis of an activation energy for creep of 8 kJ/mol.	

(104) In cases where the load is present during the heating of the concrete, deformations will occur in excess of those calculated using the creep coefficient multipliers given in (103) above. This excess deformation, the transitional thermal strain, is an irrecoverable, time-independent strain which occurs in concrete heated while in a stressed condition. The maximum transitional thermal strain may be calculated approximately from the expression:

$$\varepsilon_{Tr} = \kappa \sigma_c \varepsilon_{Th} / f_{cm} \quad [K.2]$$

where

κ = a constant obtained from tests. The value of κ will be within the range $1,8 \leq \kappa \leq 2,35$;

f_{cm} = the mean compressive strength of the concrete;

ε_{Tr} = the transitional thermal strain;

ε_{Th} = the free thermal strain in the concrete (= temperature change \times the coefficient of expansion);

σ_c = the applied compressive stress.

ANNEX L (Informative)

CALCULATION OF STRAINS AND STRESSES IN CONCRETE SECTIONS
SUBJECTED TO RESTRAINED IMPOSED DEFORMATIONS

L.1 Expressions for the calculation of stress and strain in an uncracked section

(101) The strain at any level in a section is given by:

$$\varepsilon_{az} = (1 - R_{ax}) \varepsilon_{iav} + (1 - R_m)(1/r)(z - \underline{z}) \quad [L.1]$$

and the stress in the concrete may be calculated from:

$$\sigma_z = E_{c,eff}(\varepsilon_{iz} - \varepsilon_{az}) \quad [L.2]$$

where

R_{ax} = factor defining the degree of external axial restraint provided by elements attached to the element considered;

R_m = factor defining the degree of moment restraint provided by elements attached to the element considered. In most common cases R_m may be taken as 1,0;

$E_{c,eff}$ = effective modulus of elasticity of the concrete allowing for creep as appropriate;

ε_{iav} = average imposed strain in the element (i.e. the average strain which would occur if the member was completely unrestrained);

ε_{iz} = imposed strain at level z ;

ε_{az} = actual strain at level z ;

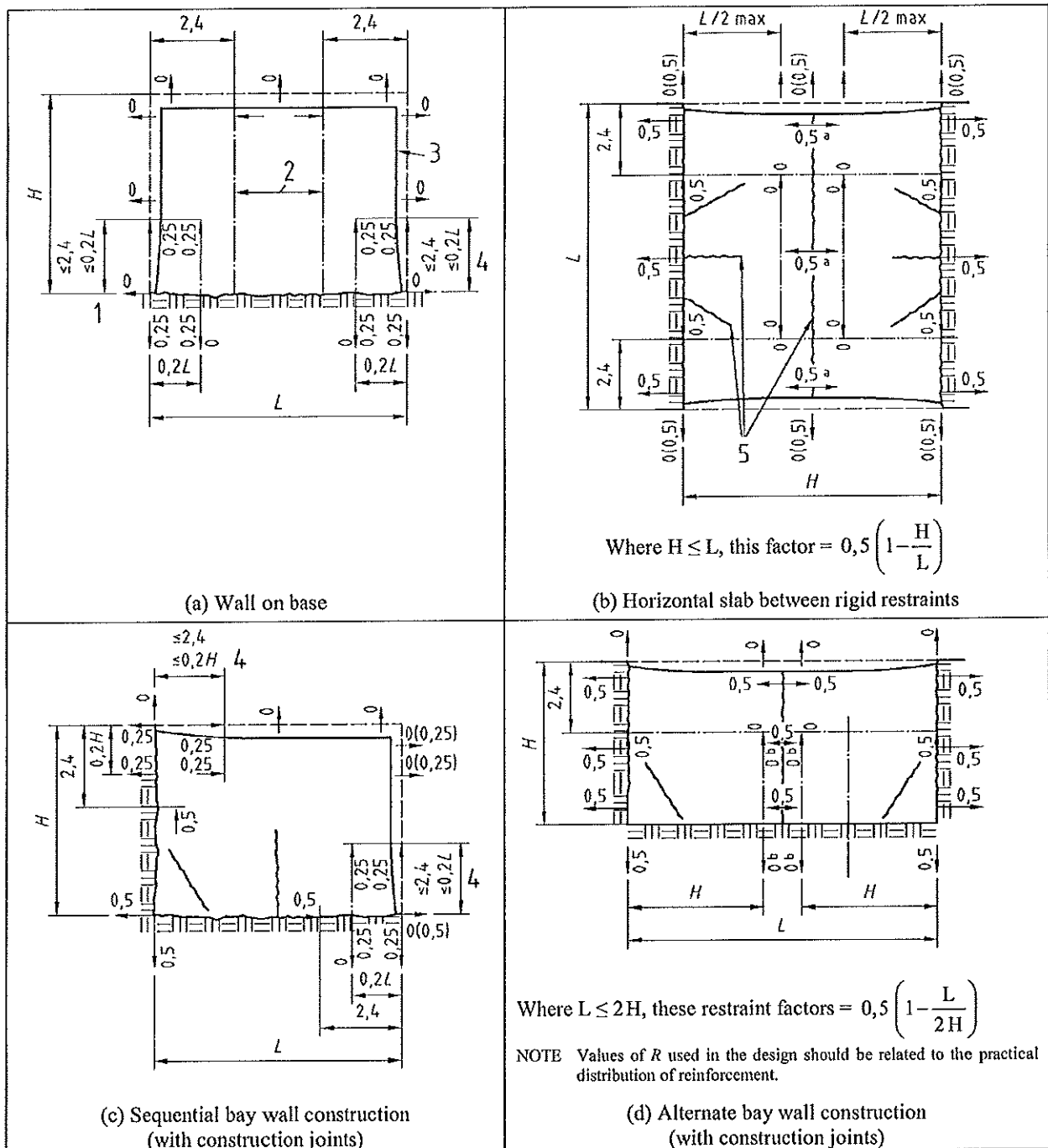
z = height to section;

\underline{z} = height to section centroid;

$1/r$ = curvature.

L.2 Assessment of restraint

(101) The restraint factors may be calculated from a knowledge of the stiffnesses of the element considered and the members attached to it. Alternatively, practical axial restraint factors for common situations may be taken from Figure L.1 and Table L.1. In many cases (e.g. a wall cast onto a heavy pre-existing base) it will be clear that no significant curvature could occur and a moment restraint factor of 1,0 will be appropriate.



Key

- 1 Vertical restraint factors
- 2 Horizontal restraint factor (obtain from table L.1 for this central zone)
- 3 Expansion or free contraction joints
- 4 (whichever is the greater)
- 5 Potential primary cracks

Figure L.1 – Restraint factors for typical situations

Table L.1 – Restraint factors for central zone of walls shown in Figure L.1

Ratio L/H (see Fig L.1)	Restraint factor at base	Restraint factor at top
1	0,5	0
2	0,5	0
3	0,5	0,05
4	0,5	0,3
> 8	0,5	0,5

ANNEX M (Informative)

CALCULATION OF CRACK WIDTHS DUE TO RESTRAINT OF IMPOSED DEFORMATIONS

M.1 General

(101) The forms of imposed deformation covered in this Annex are shrinkage and early thermal movements due to cooling of members during the days immediately after casting.

There are two basic practical problems which need to be addressed. These relate to different forms of restraint and are as sketched below.

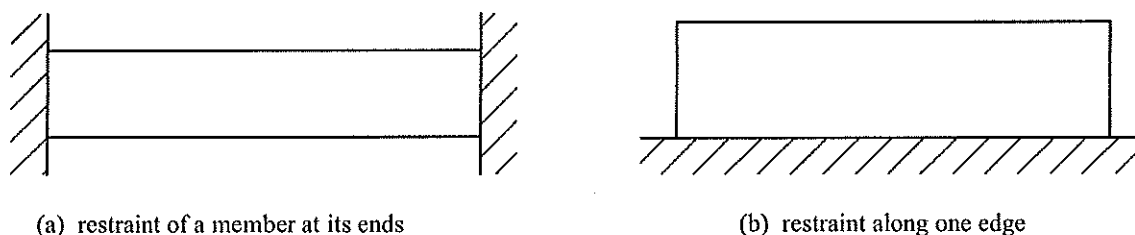


Figure M.1 – Types of restraint to walls

The factors controlling the cracking in these two cases are rather different; and both are of real practical significance. (a) occurs when a new section of concrete is cast between two pre-existing sections. (b) is particularly common and arises where a wall is cast onto a pre-existing stiff base. (a) has been researched extensively over the past few decades years and is reasonably well understood. (b) has not been studied so systematically and there appears to be little published guidance.

M.2 Restraint of a member

(a) Restraint of member at its end

The maximum crack width may be calculated using Expression 7.8 in EN 1992-1-1 where $(\epsilon_{sm} - \epsilon_{cm})$ is calculated from expression M.1

$$(\epsilon_{sm} - \epsilon_{cm}) = 0,5 \alpha_e k_c k_{f_{ct,eff}} (1 + 1/(\alpha_e \rho)) / E_s \quad [M.1]$$

For checking cracking without direct calculation, σ_s may be calculated from Expression M.2 which may then be used with Figures 7.103N and 7.104N to obtain a suitable arrangement of reinforcement.

$$\sigma_s = k_c k_{f_{ct,eff}} / \rho \quad [M.2]$$

where ρ is A_s/A_{ct} and A_{ct} is the area of concrete in tension as defined in 7.3.2.

(b) A long wall restrained along one edge

Unlike the end restrained situation, the formation of a crack in this case only influences the distribution of stresses locally and the crack width is a function of the restrained strain rather than the tensile strain capacity of the concrete. A reasonable estimate of the crack width can be made by taking the value of $(\epsilon_{sm} - \epsilon_{cm})$ given by expression M.3 in expression 7.8 in EN 1992-1-1.

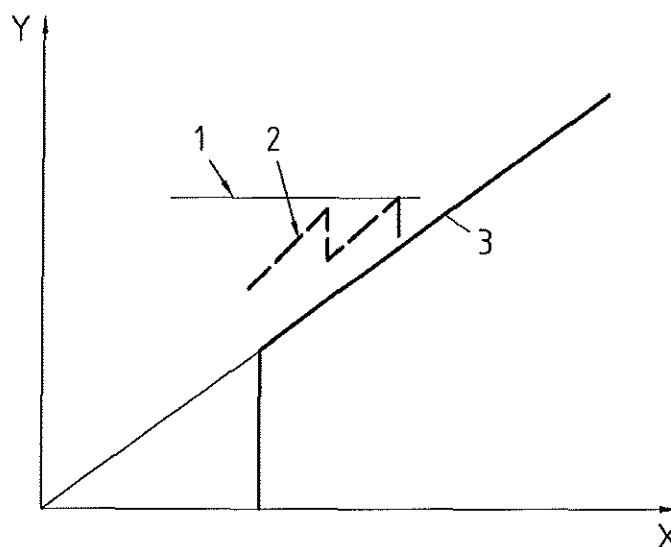
$$(\varepsilon_{sm} - \varepsilon_{cm}) = R_{ax} \varepsilon_{free} \quad [M.3]$$

where

R_{ax} = the restraint factor. This is considered in Informative Annex L;

ε_{free} = the strain which would occur if the member was completely unrestrained.

Figure M.2 illustrates the difference between the cracking in the two restraint situations.



- Key
- X Imposed deformation
 - Y Crack width
 - 1 Expression M.1
 - 2 Cracking due to end restraint
 - 3 Cracking due to edge restraint (expression [M.3])

Figure M.2 – Relation between crack width and imposed strain for edge and end restrained walls

ANNEX N (Informative)**PROVISION OF MOVEMENT JOINTS**

(101) There are two main options available:

- a) Design for full restraint. In this case, no movement joints are provided and the crack widths and spacings are controlled by the provision of appropriate reinforcement according to the provisions of 7.3.
- b) Design for free movement. Cracking is controlled by the proximity of joints. A moderate amount of reinforcement is provided sufficient to transmit any movements to the adjacent joint. Significant cracking between the joints should not occur. Where restraint is provided by concrete below the member considered, a sliding joint may be used to remove or reduce the restraint.

Table N.1 indicates the recommendations for the options.

Table N.1 – Design of joints for the control of cracking

Option	Method of control	Movement joint spacing	Reinforcement
(a)	Continuous – full restraint	Generally no joints, though some widely spaced joints may be desirable where a substantial imposed deformation (temperature or shrinkage) is expected.	Reinforcement in accordance with Chapters 6 and 7.3
(b)	Close movement joints – minimum restraint	Complete joints at greater of 5 m or 1.5 times wall height	Reinforcement in accordance with Chapter 6 but not less than minimum given in 9.6.2 to 9.6.4

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