CHAPTER 11

SERVICEABILITY LIMIT STATE DESIGN

Article 49. Cracking Limit State

49.1 General considerations

In the case of verifications relating to Cracking Limit State, the effects of actions comprise the tensions in the sections (σ) and the crack openings (w) that they cause, as applicable.

Generally, both σ and w are calculated from the design actions and the combinations indicated in Chapter 3 for Limit Serviceability States.

The stresses shall be obtained from the actions, as indicated in Chapter 5. The tensions, crack openings and other verifying criteria, shall be calculated in accordance with the requirements indicated in the following paragraphs.

49.2 Cracking due to perpendicular stresses

49.2.1 Appearance of compression cracks

In all persistent situations and in temporary situations with the least favourable combination of actions corresponding to the phase considered, the compressive stresses in the concrete shall satisfy the following:

$$\sigma_c \leq 0.60\, f_{ck,j}$$

in which:

σ_c Compressive stress of the concrete in the verifying situation.

$f_{ck,j}$ Assumed value in the design for characteristic strength at j days (age of the concrete and the phase considered).

49.2.2 Decompression Limit State

The calculations for the Decompression Limit State comprise verifying that under the combination of actions corresponding to the phase being studied, decompression does not occur in the concrete in any fibre in the section.

49.2.3 Cracking due to tension. Verifying criteria

The general verifying of the Cracking Limit State due to tension comprises satisfying the following inequality:

$$w_k \leq w_{max}$$

in which:

w_k Characteristic crack opening.

w_{max} Maximum crack opening defined in table 5.1.1.2.

This verification only needs to be undertaken if the stress in the most tensioned fibre exceeds the mean bending tensile strength, $f_{ctm,fl}$ in accordance with 39.1.

49.2.4 Assessment of crack width

The characteristic crack opening shall be calculated using the following expression:

$$w_k = \beta s_m \ \varepsilon_{sm}$$

in which:

β Coefficient which relates the mean crack opening to the characteristic value and is equal to1.3 in the case of cracking caused by indirect actions only, and 1.7 in other cases.

s_m Median crack spacing expressed in mm.

$$s_m = 2\,c + 0{,}2\,s + 0{,}4\,k_1 \frac{\phi\, A_{c,eficaz}}{A_s}$$

ε_{sm} Mean elongation of reinforcements taking account of the collaboration of the concrete between cracks.

$$\varepsilon_{sm} = \frac{\sigma_s}{E_s}\left[1 - k_2\left(\frac{\sigma_{sr}}{\sigma_s}\right)^2\right] \geq 0{,}4\,\frac{\sigma_s}{E_s}$$

c Cover of tensioned reinforcements.

s Distance between longitudinal bars. If $s > 15\,Ø$, s shall be taken to equal 15 $Ø$.
In the case of beams reinforced with end bars, s shall be taken to = b/n, with b being the width of the beam.

k_1 Coefficient representing the effect of the tension diagram in the section, with a value of:

$$k_1 = \frac{\varepsilon_1 + \varepsilon_2}{8\,\varepsilon_1}$$

in which ε_1 and ε_2 are the maximum and minimum deformations calculated in the cracked section at the limits of the tensioned zone (figure 49.2.4.a).

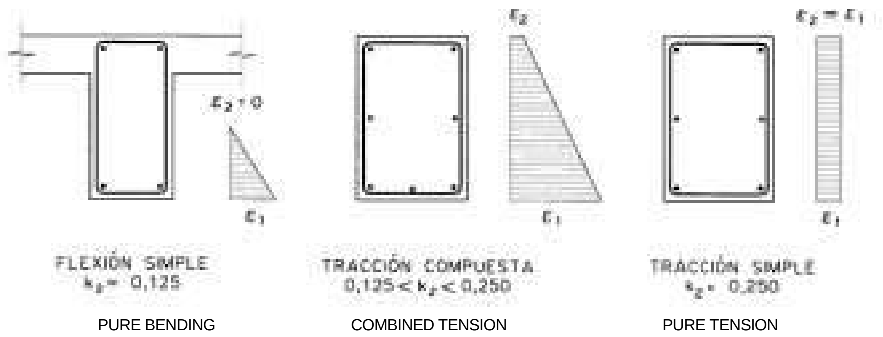


Figure 49.2.4.a

$Ø$ Diameter of the thickest tensioned bar or equivalent diameter in the case of bundled bars.

$A_{c,eficaz}$ Area of concrete of the cover zone, defined in figure 49.2.4.b, in which the tension bars effectively influence the crack opening.

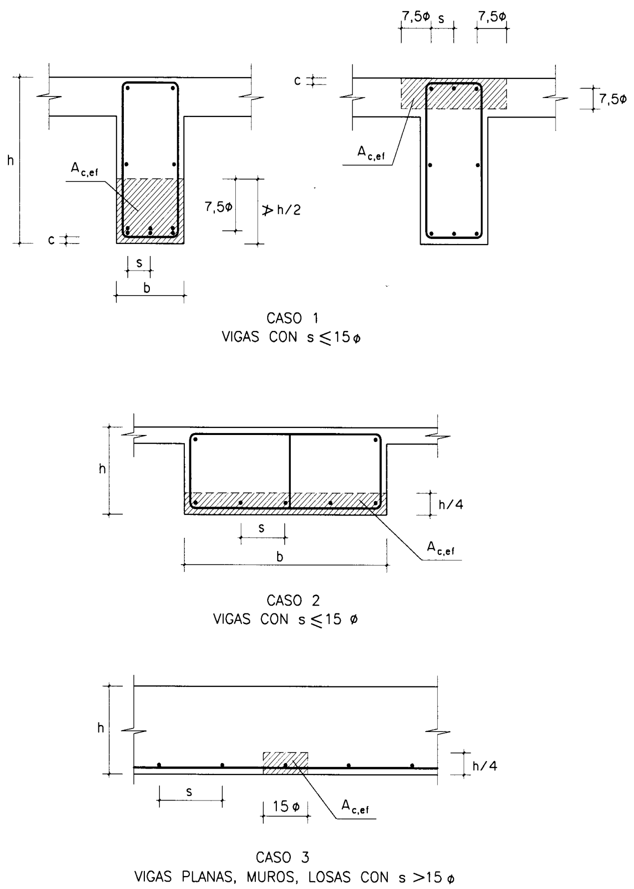
A_s Total section of the reinforcements located in the area $A_{c,eficaz}$.

σ_s Service stress of the passive reinforcement in the cracked section hypothesis.

E_s Modulus of longitudinal deformation of the steel.

K_2 Coefficient of value 1.0 in the case of non-repeating temporary load and 0.5 in other cases.

σ_{sr} Stress in the reinforcement in the cracked section at the moment when the concrete cracks, which is assumed to happen when the tensile stress in the most tensioned fibre in the concrete reaches a value of $f_{ctm,fl}$ (paragraph 39.1).



CASE 1
BEAMS WITH …S≤15 Φ

CASE 2
BEAMS WITH S≤15 Φ

CASE 3
PLANE BEAMS, WALLS, SLABS WITH S>15 Φ

Figure 49.2.4.b

In the case of members concreted against the ground, the normal cover corresponding to the exposure class, in accordance with table 37.2.4.1.a, b, and c, may be adopted when calculating the crack width.

49.3 Limitation of cracking due to shear stress

Generally, if the criteria in Article 44, Ultimate Limit State in Shear are satisfied, cracking will be controlled in service without the need for any additional verifications.

49.4 Limitation of cracking due to torsion

Generally, if the criteria in Article 45, Ultimate Limit State in Torsion in linear elements are satisfied, cracking will be controlled in service without the need for any additional verifications.

Article 50. Deformation Limit State

50.1 General considerations

The Deformation Limit State shall be satisfied if the movements (deflections or rotations) in the structure or structural element are less than specific maximum limit values.

The Deformation Limit State shall be verified in cases where deformation can cause the structure or structural element to be taken out of service for functional, aesthetic or other reasons.

Deformations shall be studied for service conditions which correspond, depending on the problem to be examined, in accordance with the combination criteria, set out in 13.3.

The total deformation produced in a concrete element is a sum of the various partial deformations that occur over time due to the loads that are applied, the creep and shrinkage of the concrete and the relaxation of the active reinforcements.

Deflections shall be maintained within the limits set out by the specific regulations in force, or failing this, by the limits indicated in this Code. The designer shall therefore design the structure with sufficient rigidity, and in extreme cases, shall require that a building procedure is used that minimises the part of total deflection that could damage non-structural elements.

50.2 Elements subjected to pure or combined bending stress

50.2.1 General method

The most common calculation method for deflection comprises a step by step structural analysis over time, in accordance with the criteria in Article 25, in which for each instant, the deformations are calculated by double integration of the curves along the length of the member.

50.2.2 Simplified method

This method applies to beams, reinforced concrete slabs and one-way slabs. The deflection shall be considered to comprise the sum of a temporary deflection and a time-dependent deflection, due to permanent loads.

50.2.2.1 Minimum depths

Deflections will not need to be verified in beams and slabs in which the span/effective depth ratio of the element under study does not exceed the value indicated in table 50.2.2.1.a. The slenderness ratios L/d shall be multiplied by 0.8 in beams or hollow core slabs comprising T-beams in which the ratio between the width of their flanges and webs exceeds 3.

Table 50.2.2.1.a *L/d* ratios in reinforced concrete beams and slabs subjected to simple bending

STRUCTURAL SYSTEM *L/d*	*K*	Highly reinforced elements: *p= 1.5%*	Slightly reinforced elements *p=0.*5%
Simply supported beam Simply supported one or two way slab	1.00	14	20
Beam[1] continuous at one end. One way slab [1,2] continuous on one side only.	1.30	18	26
Beam [1] continuous at both ends. Continuous one way or two way slab [1,2]	1.50	20	30
Edge and corner panels in flat slab on point supports	1.15	16	23
Inner panels in flat slab on point supports	1.20	17	24
Cantilever	0.40	6	8

[1] *An end shall be considered continuous if the corresponding moment is 85% or m ore of the perfect embedding moment.*
[2] *In one way slabs, the given slenderness values refer to the smaller span.*
[3] *In slabs on point supports (columns), the slenderness values relate to the larger spans.*

In the particular case of slabs comprising joists with spans of less than 7 m, and hollow core pre-stressed slabs with spans less than 12 m, where the imposed loads do not exceed 4 kN/m^2, no verification needs to be made as to whether the deflection satisfies the restriction of 50.1, if the total depth h is more than the minimum $h_{mín}$ given by:

$$h_{mín} = \delta_1 \ \delta_2 L / C$$

in which:

- δ_1 Factor which depends on the total load and which has the value of $\sqrt{q/7}$, with q being the total load in kN/m^2;
- δ_2 Factor which has a value of $(L/6)^{1/4}$;
- L The design span of the slab in m;
- C Coefficient whose value is taken from Table 50.2.2.1.b:

Table 50.2.2.1.b

C Coefficients				
Type of slab	Type of load	Type of span		
		Isolated	End	Internal
Reinforced beams	With partitions or walls Roofs	17 20	21 24	24 27
Pre-stressed breams	With partitions or walls Roofs	19 22	23 26	26 29
Pre-stressed hollow core slabs (*)	With partitions or walls Roofs	36 45		

(*) Pre-stressed members designed so that the moment of cracking is not exceeded with the rare combination,.

50.2.2.2 Calculation of instantaneous deflection

When calculating instantaneous deflections in cracked members of constant cross-section, in the absence of more rigorous methods, the following simplified method may be used at any construction stage:

1. The equivalent moment of inertia of a section is defined as the value I_e obtained from:

$$I_e = \left(\frac{M_f}{M_a}\right)^3 I_b + \left[1 - \left(\frac{M_f}{M_a}\right)^3\right] I_f \leq I_b$$

in which:

- M_a Maximum bending moment applied to the section until the instant when the deflection is calculated.
- M_f Nominal cracking moment of the section, which is calculated using the following expression:

$$M_f = f_{ctm,fl} W_b$$

- $f_{ctm,fl}$ Mean flexural tensile strength of the concrete, according to 39.1.
- W_b Strength modulus of the gross section relative to the end fibre tensioned.
- I_b Moment of inertia of the gross section.
- I_f Moment of inertia of the simply bent cracked section, which is obtained by disregarding the tensioned concrete zone and homogenising the areas of the active and passive reinforcements and multiplying these by the coefficient of equivalence.

2. The maximum deflection of a member may be obtained from the Materials' Strength Formulae, and using as the modulus of longitudinal deformation in the concrete the modulus defined in 39.6, and using as the constant moment of inertia for the entire member the moment corresponding to the reference section which is defined below:

a) In simply supported members: the central section.
b) In cantilevered members: the initial section.
c) On internal spans of continuous members.

$$I_e = 0.50\, I_{ec} + 0.25\, I_{ee1} + 0.25\, I_{ee2}$$

in which:

I_{ec} Equivalent inertia of the span's centre section.
I_{ee} Equivalent inertia of the support section.

d) In end spans, with continuity only on one of the supports,

$$I_e = 0.75\, I_{ec} + 0.25\, I_{ee}$$

When calculating instantaneous deflections in non-cracked members of constant cross-section, the gross inertia of the section shall be used.

50.2.2.3 Calculation of time-dependent deflection

Additional time-dependent deflections, produced by persistent loads resulting from the deformations due to creep and shrinkage, may be calculated unless greater accuracy is required, by multiplying the corresponding instantaneous deflection by the factor λ.

$$\lambda = \frac{\xi}{1 + 50\rho'}$$

in which:

p' Geometric ratio of the compression reinforcement, A_s' with reference to the area of the effective section, $b_0\, d$, in the reference section.

$$\rho' = \frac{A_s'}{b_0\, d}$$

ξ Coefficient that is a function of the duration of the load which shall be taken from one of the following values:

5 or more years	2.0
1 year	1.4
6 months	1.2
3 months	1.0
1 month	0.7
2 weeks	0.5

For age j of the load, and t for the deflection calculation, the value of ξ to be used for the calculation of λ is $\xi_{(t)} - \xi_{(j)}$.

If the load is applied in fractions, P_1, P_2...., P_n, the following value of ξ may be adopted:

$$\xi = (\xi_1 P_1 + \xi_2 P_2 + ... + \xi_n P_n) / (P_1 + P_2 + ... + P_n)$$

50.3 Elements subjected to torsional stress

The rotation of linear members or elements subjected to torsion may be calculated by simple integration of the rotations per unit length obtained from the following expression:

$$\theta = \frac{T}{0{,}3\ E_c\ I_j} \qquad \text{In the case of non-cracked sections}$$

$$\theta = \frac{T}{0{,}1\ E_c\ I_j} \qquad \text{In the case of cracked sections}$$

in which:

T Torsional moment in service.
E_c Secant modulus of longitudinal deformation defined in 39.6.
I_j Moment of torsional inertia of the gross concrete section.

50.4 Elements subjected to pure tension

Deformations in members subjected to pure tension may be calculated by multiplying the mean elongation per unit of the reinforcements ε_{sm}, obtained in accordance with 49.2.5, by the member's length.

Article 51. Vibration Limit State

51.1 General considerations

Vibrations may affect the service performance of structures for functional reasons. Vibrations may be uncomfortable for occupants and users, may affect the operating of equipment sensitive to this type of phenomenon, for example.

51.2 Dynamic performance

Generally, in order to satisfy the Vibration Limit State, the structure must be designed for natural vibration frequencies being sufficiently different of definite critical values.