Disponible en **www.hormigonyacero.com**
Hormigón y Acero 2023; 74(299-300):223-234
https://doi.org/10.33586/hya.2023.3096

Some Highlights on the New Version of EN 1992-1-2 (Eurocode 2, Fire part).

Algunos aspectos destacados de la nueva versión de la norma EN 1992-1-2 (Eurocódigo 2, parte de fuego)

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Recibido el 3 de agosto de 2022; aceptado el 31 de marzo de 2023

SUMMARY

The revision process of Eurocode 2 relating to concrete structural design is ready for the final step, the Formal Vote in CEN TC 250 Structural Eurocodes at the beginning of 2023. This paper summarizes the main changes and new developments presented by this revision in FprEN 1992-1-2 regarding the version currently in force. It's mainly focused in the introduction on some changes in the structure of the document and the reduction of the number of Nationally Determined Parameters (NDPs). Additionally, some changes and novelties in the properties of concrete, reinforcing and prestressing steel with temperature are commented. Another important point is the novelties in the design and verification methods (tables, simplified and advanced), focusing on the simplified methods and an analytical formulation to find the temperature in rectangular and circular cross-sections. Finally, the new approach in the treatment of concrete spalling that simplifies and clarifies the measures to avoid it and new developments in the Annexes section are discussed.

KEYWORDS: EN 1992-1-2, concrete structures, fire design, design methods, spalling.

RESUMEN

El proceso de revisión del Eurocódigo 2 relativo al diseño estructural de hormigón está listo para el último paso, la votación formal en el CEN TC 250 *Structural Eurocodes* a principios de 2023. Este documento resume los principales cambios y novedades que presenta esta revisión de FprEN 1992-1-2 con respecto a la versión actualmente en vigor. Se centrará principalmente en la introducción en algunos cambios en la estructura del documento y en la reducción del número de Parámetros de Determinación Nacional (PDN). Además, se comentan algunos cambios y novedades en las propiedades del hormigón, las armaduras y el acero de pretensado con la temperatura. Otro punto importante son las novedades en los métodos de diseño y verificación (tablas, simplificado y avanzado), centrándose en los métodos simplificados y en una formulación analítica para hallar la temperatura en secciones rectangulares y circulares. Por último, se discute el nuevo enfoque en el tratamiento del desconchado del hormigón (spalling) que simplifica y aclara las medidas para evitarlo y las novedades en la sección de Anexos.

PALABRAS CLAVE: EN 1992-1-2, estructuras de hormigón, diseño frente a incendio, métodos de cálculo, spalling.

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How to cite this article: Carrascón, S., Robert, F., & Villagrá, C. (2023) Some Highlights on the New Version of EN 1992-1-2 (Eurocode 2, Fire Part), *Hormigón y Acero* 74(299-300):223-234, https://doi.org/10.33586/hya.2023.3096

1 INTRODUCTION

The revision process of Eurocode 2 [1] relating to concrete structural design is ready for the final step, the Formal Vote in CEN TC 250 Structural Eurocodes at the beginning of 2023. This paper summarizes the main changes and new developments presented by this revision in prEN 1992-1-2 [2] about the version currently in force.

2 STRUCTURE AND GENERAL ISSUES OF prEN 1992-1-2

It has a structure very similar to the rest of the Eurocodes, with the particularities of the design of concrete structures against fire. It can be summarized in the following sections:

- Chapter 1. Introduction.
- Chapter 2. Scope.
- Chapter 3. Normative references.
- Chapter 4. Terms, definitions and symbols.
- Chapter 5. Basis of design.
- Chapter 6. Material properties.
- Chapter 7. Tabulated design data.
- Chapter 8. Simplified design methods.
- Chapter 9. Advanced design methods.
- Chapter 10. Detailing.
- Chapter 11. Rules of spalling.
- Annex A (normative): Lightweight aggregate concrete.
- Annex B (informative): Properties at high temperature of steel fibres reinforced concrete.
- Annex C (informative): Recycled aggregate concrete structures.
- Annex D (normative): Buckling of columns under fire conditions.
- Annex E (informative): Load-bearing solid walls – complementary tables.
- Bibliography.

One of the premises to be fulfilled in this revision of the Eurocodes was the reduction of Nationally Determined Parameters (NPDs) to a minimum. In the introduction, the parameters of national determination that are contemplated in [2] are defined, having been reduced from eighteen to four as could see in Table 1.

3 CHANGES CONCERNING BASIS OF DESIGN AND MATERIAL PROPERTIES

In the next bullet list, the main changes in basis of design and materials properties are listed:

- In Chapter 4, one important change should be highlighted: the introduction in the project guidelines of a section on spalling where a definition of severe spalling is introduced and reference is made to chapter 10 where rules to avoid it are given.
- Chapter 5, in its general section, introduces lightweight aggregates (material properties and specific rules for spalling in Annex A), steel fibres for concrete reinforcement (design rules in Annex B) and recycled aggregates (design rules in Annex C).
- In [1], for the evaluation of the characteristic strength of normal concrete as a function of temperature and for application in the simplified methods at sectional level,

No.	Clause in EN 1992-1-2:2004	Corresponding clause in prEN 1992-1-2:2023	Parameter	Recommended value	Category of NDP	Status
	e.g. 2.3(1)	e.g. 4.3(1)	e.g. characteristic values of self-weight	e.g. nominal value	Essential NDP	Retained
					Other NDP	Removed
						New
1	2.1.3 (2)	4.3 (2)	values of D_{q1} and D_{q2}		Other NDP	Removed
2	2.3 (2)	4.5 (1)	partial safety factor for the material properties	Recommended value $\gamma_{M,fi}$=1	Essential NDP	Retained
					Other NDP	Removed
3	3.2.3 (5)	5.3.2.1	class N and class X reduction factor for steel		Other NDP	Removed
4	3.2.4 (2)	5.3.3.1	Class A or B for prestressing steel		Other NDP	Removed
5	3.3.3 (1)	5.2.2	thermal conductivity of concrete		Other NDP	Removed
6	4.1 (1)		use of advanced calculation method		Other NDP	Removed
7	4.5.1 (2)	section 10	moisture content		Other NDP	Removed
8	5.2 (3)[refers to (2.4.2 note 2)]	6.2(1)	partial factor for combinaison of actions	Recommended value η_{fi}=0,7	Essential NDP	Retained
9	5.3.2 (2)	6.3.2	first order eccentricity max		Other NDP	Removed
10	5.6.1 (1)	6.6.1 (1)	class WA, WB, WC		Other NDP	Removed
11	5.7.3 (2)	6.7.3	plastic rotation		Other NDP	Removed
12	6.1 (5)	5.3.1.1	reduction factor HSC		Other NDP	Removed
13	6.2 (2)	new section 10	methods against spalling		Other NDP	Removed
14	6.3.1 (1)	5.2.2	thermal conductivity for HSC		Other NDP	Removed
15	6.4.2.1.(3)		k factor		Other NDP	Removed
16	6.4.2.2 (2)		k factor		Other NDP	Removed
17		9.2(1)	coefficient anchorage length		Essential NDP	New
18		10 (10)	minimum content of kpp monofilament fibres	k_{pp} = 2 kg/m^3	Other NDP	New

Table 1. Former and current NPD.

Concrete temp. θ	$k_{c,\theta} = f_{c,\theta}/f_{ck}$			$\varepsilon_{c1,\theta}$	$\varepsilon_{cu1,\theta}$
	f_{ck} < 70 MPa		$f_{ck} \geq$ 70 MPa		
	Siliceous aggregates	**Calcareous aggregates**	**any type of aggregates**		
[°C]	[–]	[–]	[–]	[–]	[–]
1	**2**	**3**	**4**	**5**	**6**
20	1.00	1.00	1.00	0.0025	0.0200
100	1.00	1,00	1.00	0.0040	0.0225
200	0.95	0.97	0.75	0.0055	0.0250
300	0.85	0.91	0.75	0.0070	0.0275
400	0.75	0.85	0.75	0.0100	0.0300
500	0.60	0.74	0.60	0.0150	0.0325
600	0.45	0.60	0.45	0.0250	0.0350
700	0.30	0.43	0.30	0.0250	0.0375
800	0.15	0.27	0.15	0.0250	0,0400
900	0.08	0.15	0.08	0.0250	0.0425
1 000	0.04	0.06	0.04	0,0250	0.0450
1 100	0.01	0.02	0.01	0.0250	0.0475
1 200	0.00	0.00	0.00	–	–

Table 2: New version of reduction factor for concrete strength in compression. Reproduction of Table 5.1 of FprEN1992-1-2:2023 [2].

there is a curve that represents the coefficient as a function of the type of aggregate.

On the other hand, there is a table giving the reduction strength factor for High Strength Concrete (HSC) for the three different classes of HSC. In the new version there is only one table (Table 2) for the reduction factor $k_{c,\theta}$, and other parameters of stress-strain relationship with two columns for normal concrete (under 70 MPa) for calcareous aggregates and for siliceous aggregates and the third column is for HSC (from 70 to 100 MPa).

One reference for these changes, could be [3].

- In [4], a specific informative annex is provided specifying the strength of concrete during its cooling phase. To harmonize the different parts of Eurocodes, the Horizontal Fire Group has suggested incorporating the informative annex in EN1992-1-2 [1]. This one has been adapted to cover both siliceous and calcareous aggregates and has been simplified to become one unique clause. The decision was taken by an agreement between the members of the Horizontal Fire Group.
- Another interesting new feature is the introduction of values for the concrete strength in the cooling phase, depending on the maximum temperature reached during the heating phase (Extract 1 in Appendix to this paper).
- In [1] two different curves for thermal conductivity at elevated temperatures are provided and finally an interval of values is adopted but giving the possibility to take any specific curve within the interval in the scope of national annex (NDP). This situation has led to many curves across Europe. The new curve presented as an analytical expression is included in Extract 2 of the Appendix to this paper. For further information, see 5.2.2 in the Background Document for prEN 1992-1-2:2022.[5]

4 CHANGES CONCERNING TABULATED DATA

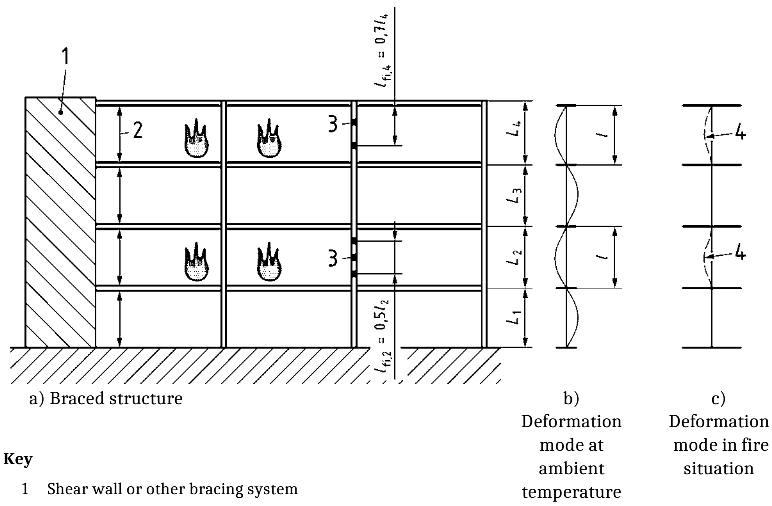
In chapter 6, new tables have been introduced for ease of use. The following general rules are given:

Concretes of usual density between 2000 and 2600 kg/m³.

- If the cross-section is variable along length, the minimum dimensions and axis distance of reinforcement shall be applied for the most unfavourable cross-section.
- For concretes with $f_{ck} \geq$ 70MPa, they should only be checked for R-values up to R120.
- There is a risk of severe spalling if the limitation rules to avoid spalling (Chapter 10) are not complied with.
- If the minimum values of the tabulated data are taken, no additional checks for torsion, shear, and reinforcement anchorage should be carried out.
- All tables in Chapter 6 are calculated with a load level $\eta_{fi} = 0.7$.

The design Table 5.2a in EN1992-1-2 [1] gives in some cases results on the unsafe side compared to advance design method, see explanations according to Method A. Thus the table is restricted to columns with $l_{0,fi} / l_0 = 0.5$. To increase the ease of use for designing columns, a rule defining a fictitious replacement effective length is established and the tables and Formula (6.7) in [2] may be used for other values of this ratio. Then, should be calculated according to Formula (6.6) in [2] using the value of axial resistance of the column at ambient temperature conditions N_{Rd} for a modified effective length $l_{0'} = 2l_{0,fi}$.

For columns, there is a definition of the effective column lengths to consider second order effects in case of fire (Figure 1).



Key

1 Shear wall or other bracing system
2 height of separate fire compartments in each storey
3 effective length of column exposed to fire
4 deformation mode in fire

Figure 1. Effective length $l_{0,fi}$ for columns. Reproduction of Figure 6.3 [2].

According to 6.1 (2) of [2], Tabulated design data is considered to generally give conservative results compared to relevant tests or simplified or advanced design methods. This is in line with the concept of Levels-of-Approximation, presented e.g. in FIB Model Code 2010 in the Section "Basic Principles" [6]. Several studies with comparing calculations indicate that Method A in tendency leads to less conservative results than other design methods for $l_{0,fi} = l_0$, and also for $l_{0,fi}= l_0$. Furthermore, the extensively validated Annex D is available for columns with $l_{0,fi} = l_0$, and for $l_{0,fi} = 0.7l_0$.

In method A, two tables are provided (one for columns with fire exposure on four faces and one for a single exposed face) for $l_{0,fi} / l_0 = 0.5$, the number of μ_{fi} values having been increased for ease of use (Table 3).

A new methodology has been set up to develop tables for braced or unbraced columns given in Annex D when $l_{0,fi} = 0$ or $l_{0,fi} = 0.7l_0$.

To increase the ease of use for designing load bearing walls exposed to fire, the tabulated data for load bearing walls were extended. The table for load bearing walls in [1] contains three load degrees and two different maximum lengths at ambient temperature linked to different maximum lengths in case of fire. The table was transferred from DIN 4102-4 [7] without justifying the load degrees. For further information, see 6.4 in the Background Document for prEN 1992-1-2:2022 [5].

In walls, the table for solid load-bearing walls exposed to fire on one or two sides has been modified, increasing the values of μ_{fi} for ease of use (Tables 4 and 5) and splitting the table according to the effective length.

5
CHANGES CONCERNING THE TREATMENT OF SPALLING

A new chapter 10 has been added which clarifies the rules to assess spalling.

Many tests have been performed on concrete structural elements these last decades. However test reports on fire resistance tests on structural elements with detailed concrete mix and characteristic strength are not so well documented or publicly available. Further to a state of the art performed within CEN TC 250/SC2/WG1/TG5 and then the threshold of concrete strength for which no experimental evidence or addition of polypropylene is asked, is switched from C80 to C60.

In [1], moisture content is a key parameter to consider the occurrence of explosive spalling. Moisture content is undeniably one of the main parameters influencing fire spalling of concrete, but it cannot be taken as the only parameter and many arguments are in favour of eliminating the moisture threshold:

- It is controversial, below which moisture content spalling is "unlikely to occur". Since a European agreement for the value of could not be reached, the decision was left to national annexes (in the present version of EN1992-1-2 [1], varies from 2% to 4%).
- Scientific results indicate that spalling may appear from different moisture content values depending on the concrete composition, strength, section geometry, load… At first glance, a general fixed moisture limit for spalling seems like a good idea but this is not supported by the literature as so many inter-dependent factors are involved in the phenomenon. For further information, see chapter 10 in the Background Document for prEN 1992-1-2:2022 [5].
- Even if the temperature, relative humidity (climate history) and age of concrete are known, it is a very difficult task to determine the moisture content of the concrete.
- While moisture gradients do appear instead of uniform moisture contents, nothing is said about where (at the surface, in depth…) and when (3 months after casting, at equilibrium?) the moisture content should be measured or estimated.
- The designer has difficulties predicting what will be the moisture content in the built element, and cannot influence it.

Standard fire resistance	Minimum dimensions (mm) Column width b_{min}/axis distance a of the main reinforcement		
	μ_{fi} = 0,2	μ_{fi} = 0,5	μ_{fi} = 0,7
1	2	3	4
R 30	200/25	200/25	200/32 300/27
R 60	200/25	200/36 300/31	250/46 350/40
R 90	200/31 300/25	300/45 400/38	350/53 450/40[a]
R 120	250/40 350/35	350/45[a] 450/40[a]	350/57[a] 450/51[a]
R 180	350/45[a]	350/63[a]	450/70[a]
R 240	350/61[a]	450/75[a]	–

NOTE 1 For prestressed columns, the increase of axis distance according to 6.2 (2) should be noted.
NOTE 2 Table 6.1 has been generated from Formula (6.6) with $l_{0,fi}$ = 3 m.
NOTE 3 Table 6.1 can be used for columns exposed on two parallel sides

[a] Minimum 8 bars

Standard fire resistance	Minimum dimensions (mm) Column width b_{min}/axis distance a of the main reinforcement		
	$\mu_{fi} = 0,2$	$\mu_{fi} = 0,5$	$\mu_{fi} = 0,7$
1	2	3	4
R 30	100/10	120/15	130/25
R 60	110/10	130/15	140/25
R 90	120/20	140/25	155/25
R 120	150/25	160/30	175/35
R 180	185/45	200/50	230/55
R 240	230/60	240/65	290/70

Table 3. Tables of method A for columns exposed to fire on four sides (upper table) and one side (lower table). Reproduction of Tables 6.1 and 6.2 [2].

Standard fire resistance	Minimum dimensions (mm) Wall thickness h_w/axis distance a			Standard fire resistance	Minimum dimensions (mm) Wall thickness h_w/axis distance a		
	$\mu_{fi} = 0,2$	$\mu_{fi} = 0,5$	$\mu_{fi} = 0,7$		$\mu_{fi} = 0,2$	$\mu_{fi} = 0,5$	$\mu_{fi} = 0,7$
Exposed on one side				Exposed on both sides			
1	2	3	4	5	6	7	8
REI 30	100/10	110/10	120/10	R 30	100/10	120/10	130/10
REI 60	110/10	120/15	130/20	R 60	120/15	155/20	170/25
REI 90	120/20	135/25	140/30	R 90	140/20	185/30	210/35
REI 120	135/25	150/30	160/35	R 120	165/30	210/40	240/45
REI 180	155/35	170/40	180/45	R 180	200/45	250/50	280/55
REI 240	180/40	200/45	210/50	R 240	250/50	305/55	340/60

Table 4. Minimum dimensions and axis distances for load-bearing reinforced concrete walls exposed on one long side (left) or on both sides (right) with $l_0 \leq 4.5$ m for ambient temperature conditions and $l_{0,fi} \leq 2.5$ m for fire situations. Reproduction of Table 6.4 [2].

It is favoured to delete the moisture content threshold and to give general recommendations when a high moisture content is expected.

Firstly, Table 6 shows the spalling verification rules according to the requested fire resistance, the environmental circumstances of the structure and the compressive strength of the concrete and the types of concrete additions.

Standard fire resistance	Minimum dimensions (mm) Wall thickness h_w/axis distance a			Standard fire resistance	Minimum dimensions (mm) Wall thickness h_w/axis distance a		
	$\mu_{fi} = 0,2$	$\mu_{fi} = 0,5$	$\mu_{fi} = 0,7$		$\mu_{fi} = 0,2$	$\mu_{fi} = 0,5$	$\mu_{fi} = 0,7$
Exposed on one side				Exposed on both sides			
1	2	3	4	5	6	7	8
REI 30	80/10	90/10	100/10	R 30	90/10	100/10	110/10
REI 60	90/10	100/10	110/15	R 60	110/10	125/15	140/20
REI 90	100/10	110/15	120/20	R 90	125/15	155/25	170/30
REI 120	120/15	120/20	130/25	R 120	140/25	175/35	200/40
REI 180	150/20	150/25	150/30	R 180	175/30	215/40	240/45
REI 240	170/25	175/30	175/35	R 240	200/35	250/45	280/50

Table 5. Minimum dimensions and axis distances for load-bearing reinforced concrete walls exposed on one long side (left) or on both sides (right) with $l_0 \leq 2.5$ m for ambient temperature conditions and $l_{0,fi} \leq 1.25$ m for fire situations. Reproduction of table 6.6 [2].

Verification for spalling	
R15	Verification of spalling may be omitted except Clause 10(2)
— structures in a water saturated environment — insulating permanent formwork which prevents concrete from drying	Specific assessment of spalling should be undertaken or polypropylene fibres should be specified See Clause 10(7), (8), (9) or (10)
$f_{ck} < 70$ MPa and silica fume content < 6 % by weight of cement	Verification of spalling may be omitted except Clause 10(3) and (5)
$f_{ck} < 70$ MPa and silica fume content ≥ 6 % by weight of cement or $f_{ck} \geq 70$ MPa	Specific assessment of spalling should be undertaken or polypropylene fibres should be specified See Clause 10(7), (8), (9) or (10)

Table 6. Overview of the rules for spalling. Reproduction of Table 10.1 [2].

Standard fire resistance	Minimum web thickness $b_{w,min}$ (mm)	Minimum web thickness $b_{w,min}$ for a distance of $2h$ from an intermediate support in continuous isolated members
R 30	80	80
R ≥ 60	100	120

Table 7. Special rules for isolated members with thin web. Reproduction of Table 10.2 [2].

In Extract 3 of the Appendix to this paper, content from [2] is included that is referred to Table 6.

In a second table (Table 7), the specific cases in which special measures have to be taken for beams with small web dimensions are shown.

6 CHANGES CONCERNING SIMPLIFIED DESIGN METHODS

The major change in chapter 7 related to simplified design method is that the Isotherm 500 method disappears as such. However, an improved version of the "zone method" is given.

In [1], the zone method consists of dividing the section into strips of equal width (zones), determining the average temperature of each zone and, from this, determining the strength of the concrete. From the contributions of each zone, the resistance capacity of the section is determined, disregarding a rim zone, determined by the parameter a_z. The contribution of the reinforcement is evaluated considering the exact temperatures in the rebars.

The major drawback of this method is the determination of the section temperatures. In [1], different temperature profiles at different time instants are given for several typical cross-section profiles. Some of these profiles are shown in Figure 2. The problem with this method is that the determination of the temperatures at each point is not very precise, which leads to some uncertainty in the calculation of the temperature of the reinforcement, for example. On the other hand, if the section considered in the project does not coincide exactly with one of those recorded in the current Annex A, it is difficult to make an accurate estimate of the temperature and the associated

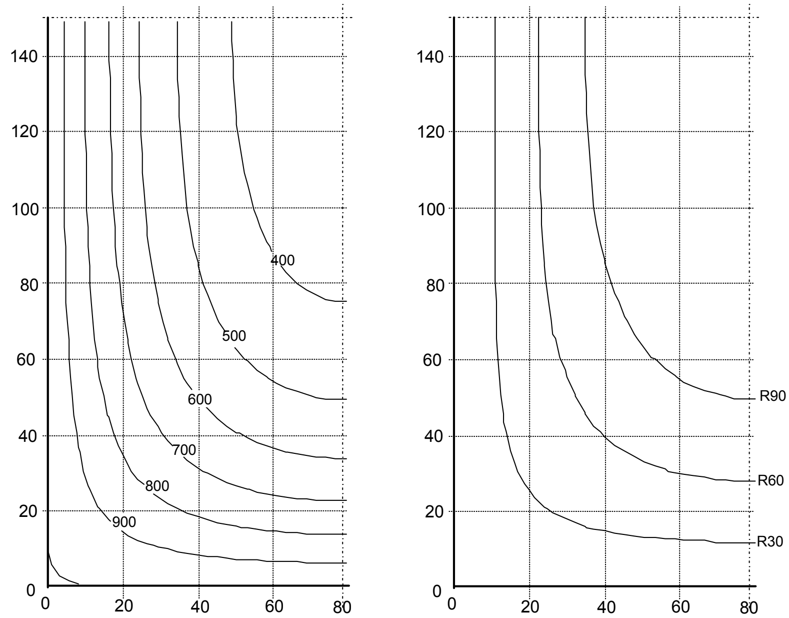


Figure 2. Isotherms (t =90min) and Isotherm 500 positions for different times. Reproduction of Figures A5 and A6 [1].

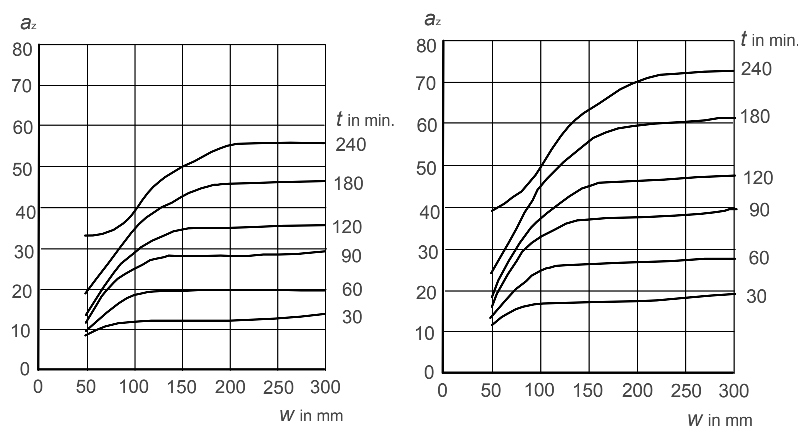


Figure 3. Reduction in cross-section a_z, of a beam or slab using siliceous aggregate concrete (left). Reduction in cross section a_z, of a column or wall using siliceous aggregate concrete (right). Reproduction of Figure B.5 [1].

resistance. With this approach, the calculation using the zone method is really laborious.

This is where one of the most important changes of [2] appears. Now, the calculation of the temperature is done employing analytical expressions. The proposed models allow the most common cases to be solved: rectangular section elements, cylindrical section elements, walls and slabs… The other major change is the determination of the parameter a_z, which is used in the improved zone method. Previously it was done from a series of abacuses (Figure 3), while now it is calculated from analytical expressions[1].

Although the a_z parameter is also defined in [2], it appears that its definition is a bit different from [1]. In the current version, it simply appears as a parameter in the calculation. In [2] it is called "rim zone" and, according to [5], for a wall of thickness $2w$ with both sides exposed, a_z can be determined with the following expression:

$$(2w - 2a_z)\cdot f_c(\theta_M) = \int_{-w}^{w} f_c(\theta(x))\, dx \qquad (1)$$

The idea behind equation (1) is that a_z gives the thickness of a strength-equivalent element with reduced cross-section, by deducting the thickness a_z from the original cross-section. For supports exposed on all four sides, [5] gives an analogous expression. Equations (8) and (9) are the analytical approximation of (1).

6.1. *Calculation procedure in the new Eurocode [2]*

In the new Eurocode, for the verification of the fire resistance, the following procedures are given:

- Tabulated methods (chapter 6).
- Simplified methods (chapter 7), which are divided for the cases of bending and bending and axial load in:
    - Simplified verification.

1 Strictly speaking, in [1] the calculation of a_z is already done using analytical expressions (from which come those of [2]). However, these expressions depend on the terms $k_c(\theta_i)$, the reduction coefficients for concrete. The calculation of $k_c(\theta_i)$ is complex because it depends on the temperature in the centre of the zone, which, as mentioned above, must be calculated graphically.

- Refined verification.
- Advanced methods (chapter 8).

The changes in the tabulated methods have already been listed in section 4.

As indicated in the introduction, the most significant change has been in the simplified methods. What used to be the Isotherm 500 method and the zone method have converged into analytical methods, with two levels of complexity.

Finally, the changes in advanced methods are mainly due to changes in material models. As in [1], what is set out in Chapter 8 are general guidelines for the calculation of temperatures and structural response by numerical methods, based on the models established in Chapter 5.

Assessment by simplified methods

The new Eurocode, as in the current version, considers the cases of bending, bending and axial load, shear and torsion. However, it focuses on bending and bending-compression behaviour, leaving shear and torsional verification as a series of additional checks.

The procedure is almost the same for both bending and bending and axial load checks:

1. Determination of temperatures
2. Structural analysis
   1. Calculation of the reduced cross-section (determination of the parameter a_z). In the case of bending, the a_z parameter is determined by dividing the section into parallel zones of equal width, while in the case of bending and axial loading, the cross-section of the member should be discretized into a grid of small elemental zones (see Figure 7.9 of [2]) each characterized by area A_{cij}.
   2. Verification of the structural behaviour:
      - Simplified verification
      - Refined verification

This procedure is basically the same as the one to be followed in [1]; the key changes are in how both the temperatures and the rim zone are determined. In both cases, there has been a move from graphical methods to analytical methods.

Calculation of section temperature

In [2], it is now possible to calculate the temperature of each point of the section utilizing a series of analytical expressions.

Equations (2) to (7), which reproduce part of equations (7.1) to (7.11) of [2], do not actually have a physical meaning, but are mathematical expressions that try to adjust the temperature values of a section to those calculated by numerical methods from the material models of [2]. In particular, according to the background document [5], the conditions adopted are:

- emissivity of concrete surfaces, 0.7 (5.2.1 of [2])
- convection factor of exposed surfaces, 25W/(m²K) (7.2.1.(3) of [2])
- thermal conductivity of concrete is as given in 5.2.2 of [2]
- specific heat of concrete is as given in 5.2.3 of [2] with moisture content 1.5%.
- density of concrete is as indicated in 5.2.4 of [2]; the reference value at 20°C is 2300 kg/m³.

In addition, in [5], it can be seen that the fit between the numerical and the analytical model is rather good, with an error threshold for both concrete and steel strength of 0.1. Temperature deviations, when they occur, are always on the safe side.

For sections with a rectangular cross-section[2]:

- Unidirectional temperature distribution:

$$\theta_1(x,t) = 345\cdot\log_{10}\left(\frac{7(t-\Delta t)}{60}+1\right)\cdot \text{expo}\left(-x\sqrt{\frac{k}{t}}\right) \tag{2}$$

where:

- t is the duration of the standard fire (in seconds), $t \geq 1800$ s;
- x is the distance from the exposed surface (in m);
- Δt represents a delay between the temperature in the fire compartment and the concrete surface temperature as an approximation for the effects of convection and radiation, Δt=720 s;
- k is an adjust coefficient as a function of density of concrete. It should be taken as k=3×10⁶ s/m². Additional information is given in the background document [6].
- Fire on two opposite sides:

$$\theta_2\,(y,t) = \theta_1(y,t)+\theta_1(b-y,t) \tag{3}$$

$$\theta_2\,(z,t) = \theta_1(z,t)+\theta_1(h-z,t) \tag{4}$$

In these equations, x and z refer to the two directions (horizontal or vertical, respectively) of the section under consideration. Each equation therefore represents the temperature distribution in each direction (cases A and B of [2], 7.2.3 (1)).

- Four-sided fire:

$$\theta\,(y,z,t) = \theta_2(y,t)+\theta_2(z,t)-\frac{\theta_2(y,t)\cdot\theta_2(z,t)}{\theta_1(0,t)}+\Delta\theta(y',z',t)+20°\text{C} \tag{5}$$

- Three-sided fire:

$$\theta\,(y,z,t) = \theta_2(y,t)+\theta_1(z,t)-\frac{\theta_2(y,t)\cdot\theta_1(z,t)}{\theta_1(0,t)}+\Delta\theta(y',z',t)+20°\text{C} \tag{6}$$

In the above equations, the term $\Delta\theta$ considers the increase in temperatures due to the effect of the corners:

$$\Delta\theta(y',z',t)=\left(345\,\log_{10}\left(\frac{8t}{60}+1\right)-\theta_1(0,t)\right)\frac{(a_c-y')(a_c-z')}{a_c^2} \tag{7}$$

where the term a_c is a parameter that depends on the duration of the fire under consideration.

Calculation of the reduced cross-section

In this part, there are also considerable changes compared to [1]. On the one hand, what has been done is a generalization of the zone method of [1]. On the other hand, the parameter a_z is now determined by the following expressions:

2 Similarly, the temperature can be calculated analytically for elements with a circular cross-section. For simplicity, the expressions for circular cross-sections have not been included in this article, as they are similar to those for rectangular cross-sections

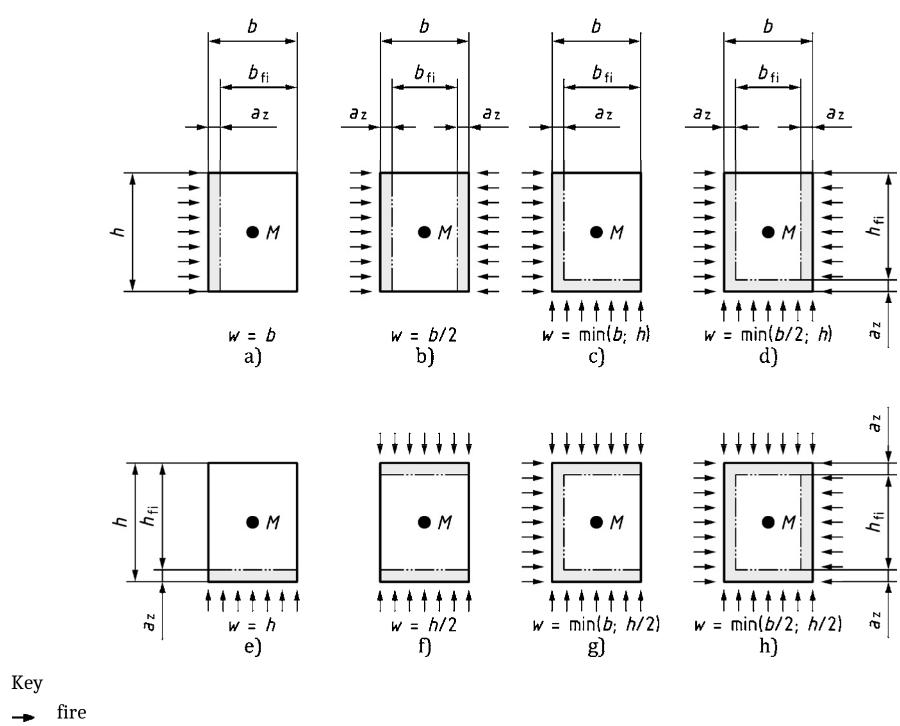


Figure 4. Determination of parameter w. Reproduction of Figure 7.5 [2].

$$a_z=\begin{cases} 0.011\sqrt{1+\dfrac{t-27}{27}\sqrt{\dfrac{w}{0.0125}}} & \text{for } 0.075 \leq w < 0.20 \\ 0.011\sqrt{1+4\,\dfrac{t-27}{27}} & \text{for } \geq 0.02 \end{cases} \tag{8}$$

which in [2] is used to determine a_z in a simplified way. Here, a_z depends uniquely on the time considered, t, and the w parameter[3]. In [1], w was obtained from an abacus, whereas now its determination has been simplified and is taken directly from a Figure, as appropriate case (Figure 4). It is important to note that in this expression, a_z does not depend on zone division. However, a_z can be determined more precisely by dividing the section into strips (or squares in the case of columns).

The expressions to determine a_z from the zones are similar to those that already existed, with the difference that now they are expressed in a more compact form and depend solely on the resistance of the concrete at each point. For the case of division into vertical zones, the next equation is used:

$$a_z = w\left(1-\frac{\left(1-\dfrac{0.02}{n}\right)}{n}\frac{\sum_{i=1}^{n} f_{cd,\theta}(\theta_i)}{f_{cd,\theta}(\theta_M)}\right) \tag{9}$$

where n is the number of zones into which the section is divided, $f_{cd,\theta}(\theta_i)$ is the concrete strength at temperature θ_i at the centroid of the zone i. $f_{cd,\theta}(\theta_M)$ is the concrete strength at point M, the centre of the section. This expression is actually not new, but brings together in a more compact form several expressions that were already present in [1].

3 w is a cross-sectional dimension used to obtain the reduced cross-section depending on the fire exposure and the cross-section geometry.

As can be seen, the advantage of using this expression compared to [1] is, except for the w parameter, that the rest of the values can be calculated directly and accurately, which allows, in addition to speeding up the calculation, to test different options in the search for an optimum solution. In addition, the parameter w is constant for each case analysed and is obtained in a simple way from Figure 7.5 of [2] (Figure 4).

Verification of the structural behaviour

Bending.

Once the temperatures and the thickness of the section area to be discounted have been determined, the last step is to calculate the resistant capacity of the section. A simplified assessment and a refined verification method are provided.

The expression for the calculation of the bending capacity, in the simplified form of [2] is:

$$M_{Rd,fi}=\frac{\gamma_s}{\gamma_{s,fi}}\,\frac{\sum_1^{n_{st}} f_{sy,\theta,i}}{n_{st}\,f_{yk}}\,M_{Ed}\,\frac{A_{s,prov}}{A_{s,req}} \tag{10}$$

With this expression[4], what is done is to correct the calculation moment in normal situation, with the relation between the resistance in case of fire against temperatures, the ratio between the steel area designed strictly (to building code specifications) and the real one, and the relation of the partial coefficients of the material. It must be considered that to be

4 In [1] there is an equation very similar to (10) (eq. (E.4)). The resisting moment is evaluated by correcting the bending moment by, among other factors, the ratio $(d–a)/d$, where a is a parameter that homogenizes the reinforcement, depending on temperatures and corner effects. As explained above, it is difficult to obtain the precise temperature in the bars, and corner effects are considered as a simple correction. In [2], this correction is made by calculating the steel strengths as a function of temperature, which can now be accurately determined.

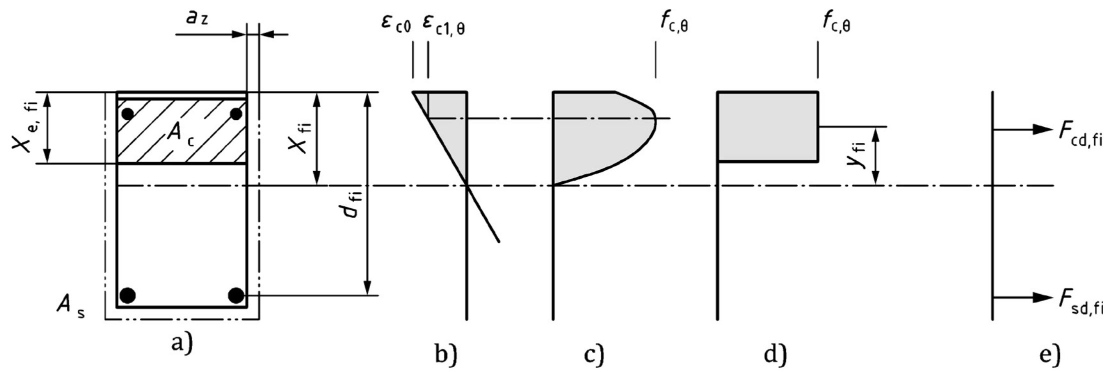


Figure 5. Stresses and strains in bending. Reproduction of Figure 7.7 [2].

able to evaluate the resistance capacity of a section by this method, a series of conditions must be fulfilled. The main one is that $A_{s,prov}/A_{s,req}$<1.3 to make sure that the compression zone is not decisive.

If the conditions are not met, or if a more accurate verification is desired, then the refined verification method must be used. This consists of evaluating the equilibrium of forces in the section, considering the loss of resistance capacity of the reinforcement, the rim zone to be discounted, and taking as the strength of the concrete that which is reached at the point as a function of the temperature ($f_{c,\theta}(\theta_M)$). The parameters to be considered are those shown in Figure 5. The maximum section strain and the depth of the compressed block are also given.

This method is basically the convergence between the 500 Isotherm method and zone method of [1]. The zone to be discarded is now given by a_z and not by the 500 °C isotherm. The residual strength value of the entire undamaged zone is $f_{c,\theta}(\theta_M)$, instead of $f_{cd,20}$.

Bending and axial loading

In the case of supports, there are also expressions for the calculation by the simplified and refined method. However, these are no longer as simple as in the case of simple bending. The simplified method would be equivalent to the refined method for the bending case, where the equilibrium of forces in the section has to be evaluated, considering the properties of the materials in case of fire, and the different components of the eccentricity (first order, geometric imperfections, thermal…). The refined method is basically the same as the one already present in [1]. It consists of determining the moment-curvature curve of the section and, from this, ultimate moment capacity ($M_{Rd,fi}$), as a combination of the ultimate first order moment ($M_{0,Rd,fi}$) and the nominal second order moment ($M_{2,fi}$). The main difference with [1] is that, as the temperatures of each point of the section can be calculated analytically, it is much easier to establish the moment-curvature diagram of the section at a given instant.

7
CONCLUSIONS

The following key changes of the new draft [2] can be highlighted:

- harmonized structure / table of contents [2] with other fire parts;
- amended and improved simplified design methods, especially the determination of the temperature through analytical expressions, makes it possible to simplify and automate the calculation. In addition, it allows the search for optimal solutions and more precise results to be obtained because new tables for columns and walls with more parameters are included;
- ensured consistency between tabulated design data, simplified and advanced design methods;
- properties of steel fibre reinforced concrete at high temperature;
- properties of recycled aggregate concrete at high temperature;
- specific rules for avoiding / controlling spalling.

Moreover, through the reduction of the number of alternative application rules, the clarification of the use and scope of tabulated data, the reduction of NDPs, and the reduction of the volume of text by about 25%, ease of use has been enhanced.

References[5]

[1] CEN, *EN 1992-1-2:2004 Eurocode 2: Design of concrete structures - Part 1-2: Structural fire design*. Brussels: CEN, 2004.

[2] CEN, **FprEN 1992-1-2:2023 Eurocode 2: Design of concrete structures - Part 1-2: Structural fire design*. Brussels: CEN, 2023.

[3] P. Pimienta, *Physical properties and behaviour of high-performance concrete at high temperature: State-of-the-art report of the RILEM technical committee 227-HPB*. Cham, Switzerland: Springer, 2019.

[4] CEN, *EN 1994-1-2:2005 Eurocode 4: Design of Composite Steel and Concrete Structures - Part 1-2: Structural Fire Design*. Brussels: CEN, 2005.

5 Documents marked with (*) are available through the National members at CEN TC250/SC2

[5] CEN, *Background document for prEN 1992-1-2:2022*. Brussels: CEN, 2022.
[6] FIB, *FIB Model Code for Concrete Structures*. Lausanne: Ernst & Sohn, 2010.
[7] DIN, *Fire behavior of building materials and building components - Part 4: Synopsis and application of classified building materials, components and special components*, DIN. Berlin, 2014.

APPENDIX

Extracted text of FprEN 1992-1-2:2023.

(6) For thermal actions in accordance with prEN 1991-1-2:2021, 5.3 (Physically based models), when considering the cooling phase, the strength of concrete heated to a maximum temperature $\theta_{c,max}$ and having cooled down to 20 °C may be taken according to Formula (5.8):

$$f_{c,\theta,20\,°C} = \varphi f_{ck} \tag{5.8}$$

where for:

— $f_{ck} < 70$ MPa

$$\varphi = f_{c,\theta max}/f_{ck} \quad \text{for } 20\,°C \leq \theta_{max} < 100\,°C \tag{5.8a}$$

$$\varphi = (-0{,}0005 \times \theta_{max} + 1{,}05)\,(f_{c,\theta max}/f_{ck}) \quad \text{for } 100\,°C \leq \theta_{max} < 300\,°C \tag{5.8b}$$

$$\varphi = 0{,}9\,(f_{c,\theta max}/f_{ck}) \quad \text{for } \theta_{max} \geq 300\,°C \tag{5.8c}$$

Extract 1: Concrete strength in the cooling phase. Text extract taken from article 5.2.3 (2) [2].

(1) The thermal conductivity λ_c of concrete may be taken as:

$$\lambda_c = 2 - 0{,}2451\,(\theta_c/100) + 0{,}0107\,(\theta_c/100)^2 \text{ W/(m K)} \quad \text{for } \theta_c \leq 140\,°C \tag{5.1a}$$

$$\lambda_c = -0{,}02604\,\theta_c + 5{,}324 \text{ W/(m K)} \quad \text{for } 140 < \theta_c < 160\,°C \tag{5.1b}$$

$$\lambda_c = 1{,}36 - 0{,}136\,(\theta_c/100) + 0{,}0057\,(\theta_c/100)^2 \text{ W/(m K)} \quad \text{for } 160\,°C \leq \theta_c \leq 1\,200\,°C \tag{5.1c}$$

Extract 2: Definition of conductivity λ_c function of temperature θ_c. Text extract taken from article 5.2.2 (1) [2].

(2) For performance requirements R15, verification for spalling may be omitted except for isolated members with webs thinner than 80 mm and $f_{ck} \geq 70$ MPa.

(3) A specific assessment of spalling should be undertaken (see (7), (8) or (9)), or polypropylene fibres should be specified for the concrete mix according to (10), under any one of the following conditions due to the expected high moisture content or specific behaviour:

— structures in a water saturated environment;

— insulating permanent formwork which prevents concrete from drying.

(4) When using tabulated design data (Clause 6), verification of spalling may be omitted for $f_{ck} < 70$ MPa, provided that the maximum content of silica fume is less than 6 % by weight of cement except for (3) above.

NOTE 2 Tabulated data have been developed based on fire tests or on calculations calibrated against full scale fire resistance tests, including tests where spalling occurred. Hence the effects of spalling are covered by tabulated data.

(5) When using simplified design methods or advanced design methods, verification of spalling may be omitted for $f_{ck} < 70$ MPa, provided that the maximum content of silica fume is less than 6 % by weight of cement except in the case of (3) and in the case of isolated members with three sides exposed, whose dimensions do not comply with Table 10.2. In these cases, a specific assessment of spalling should be undertaken (see (7), (8) or (9)), or polypropylene fibres should be specified for the concrete mix according to (10).

NOTE 3 When columns are highly loaded, it can result in higher susceptibility to spalling.

(6) For $f_{ck} \geq 70$ MPa or contents of silica fume above 6 % by weight of cement, a specific assessment of spalling should be undertaken (see (7), (8) or (9)), or polypropylene fibres should be specified for the concrete mix according to (10).

(7) The application of protective layers may be used to mitigate severe spalling (see 4.12).

(8) The effect on performance (R and/or EI) due to severe spalling may be taken into account by considering the loss of strength either at member or at structure level. This loss of strength may be assessed using a reduced effective cross-section, where the spalled layer of concrete is omitted when calculating the strength. The extent of the spalled layer of concrete may be based on experimental assessment according to (9).

(9) When assessment based on experimental evidence is required, it should be obtained from tests representative of the conditions of the structural member in terms of geometry, stress and moisture content.

(10) When polypropylene fibres are used to mitigate severe spalling, a minimum content k_{pp} of monofilament fibres with diameter less than or equal to 50 µm should be specified for the concrete mix. Alternative contents or diameters may be specified if experimental evidence according to (9) is provided.

NOTE 4 The value of k_{pp} is 2,0 kg/m^3, unless the National Annex gives a different value.

***Extract 3: Clauses referred in Table 6. Text extract taken from article 10** [2].*