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EN 1999-1-2 (2007) (English): Eurocode 9: Design of aluminium structures - Part 1-2: Structural fire design [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC]

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English Version

Eurocode 9 - Design of aluminium structures - Part 1-2: Structural fire design

Eurocode 9 - Calcul des structures en aluminium - Partie 1-2: Calcul du comportement au feu

Eurocode 9 - Bemessung und Konstruktion von Aluminiumtragwerken - Teil 1-2: Tragwerksbemessung für den Brandfall

This European Standard was approved by CEN on 18 September 2006.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN Management Centre or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the CEN Management Centre has the same status as the official versions.

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Foreword

This European Standard (EN 1999-1-2:2007) 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of an identical text or by endorsement, at the latest by August 2007, and conflicting national standard shall be withdrawn at the latest by March 2010.

This European Standard supersedes ENV 1999-1-2:1998

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, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

Background of the Eurocode programme

In 1975, the Commission of the European Community decided on an action programme in the field of construction, based on article 95 of the Treaty. The objective of the programme was the elimination of technical obstacles to trade and the harmonisation of technical specifications.

Within this action programme, the Commission took the initiative to establish a set of harmonised technical rules for the design of construction works which, in a first stage, would serve as an alternative to the national rules in force in the Member States and, ultimately, would replace them.

For fifteen years, the Commission, with the help of a Steering Committee with Representatives of Member States, conducted the development of the Eurocodes programme, which led to the first generation of European codes in the 1980s.

In 1989, the Commission and the Member States of the EU and EFTA decided, on the basis of an agreement[1] between the Commission and CEN, to transfer the preparation and the publication of the Eurocodes to the CEN through a series of Mandates, in order to provide them with a future status of European Standard (EN). This links de facto the Eurocodes with the provisions of all the Council's Directives and/or Commission's Decisions dealing with European standards (e.g. the Council Directive 89/106/EEC on construction products - CPD - and Council Directives 93/37/EEC, 92/50/EEC and 89/440/EEC on public works and services and equivalent EFTA Directives initiated in pursuit of setting up the internal market).

The Structural Eurocode programme comprises the following standards generally consisting of a number of Parts:

EN 1990	Eurocode 0:	Basis of Structural Design
EN 1991	Eurocode 1:	Actions on structures

[1] Agreement between the Commission of the European Communities and the European Committee for Standardisation (CEN) concerning the work on EUROCODES for the design of building and civil engineering works (BC/CEN/03/89).

EN 1992	Eurocode 2:	Design of concrete structures
EN 1993	Eurocode 3:	Design of steel structures
EN 1994	Eurocode 4:	Design of composite steel and concrete structures
EN 1995	Eurocode 5:	Design of timber structures
EN 1996	Eurocode 6:	Design of masonry structures
EN 1997	Eurocode 7:	Geotechnical design
EN 1998	Eurocode 8:	Design of structures for earthquake resistance
EN 1999	Eurocode 9:	Design of aluminium structures

Eurocode standards recognise the responsibility of regulatory authorities in each Member State and have safeguarded their right to determine values related to regulatory safety matters at national level where these continue to vary from State to State.

Status and field of application of Eurocodes

The Member States of the EU and EFTA recognise that Eurocodes serve as reference documents for the following purposes:

— as a means to prove compliance of building and civil engineering works with the essential requirements of Council Directive 89/106/EEC, particularly Essential Requirement No.1 – Mechanical resistance and stability, and Essential Requirement No 2 – Safety in case of fire

— as a basis for specifying contracts for the execution of construction works and related engineering services

— as a framework for drawing up harmonised technical specifications for construction products (En's and ETA's)

The Eurocodes, as far as they concern the construction works themselves, have a direct relationship with the Interpretative Documents[2] referred to in Article 12 of the CPD, although they are of a different nature from harmonised product standards[3]. Therefore, technical aspects arising from the Eurocodes work need to be adequately considered by CEN Technical Committees and/or EOTA Working Groups working on product standards with a view to achieving full compatibility of these technical specifications with the Eurocodes.

The Eurocode standards provide common structural design rules for everyday use for the design of whole structures and component products of both a traditional and an innovative nature. Unusual forms of construction or design conditions are not specifically covered and additional expert consideration will be required by the designer in such cases.

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[2] According to Art. 3.3 of the CPD, the essential requirements (ERs) shall be given concrete form in interpretative documents for the creation of the necessary links between the essential requirements and the mandates for harmonised ENs and ETAGs/ETAs.

[3] According to Art. 12 of the CPD the interpretative documents shall :

a) give concrete form to the essential requirements by harmonising the terminology and the technical bases and indicating classes or levels for each requirement where necessary ;
b) indicate methods of correlating these classes or levels of requirement with the technical specifications, e.g. methods of calculation and of proo technical rules for project design, etc. ;
c) serve as a reference for the establishment of harmonised standards and guidelines for European technical approvals.

The Eurocodes, *de facto*, play a similar role in the field of the ER 1 and a part of ER 2.

National standards implementing Eurocodes

The National Standards implementing Eurocodes will comprise the full text of the Eurocode (including any Annexes), as published by CEN, which may be preceded by a National title page and National foreword, and may be followed by a National Annex (informative).

The National Annex (informative) may only contain information on those parameters which are left open in the Eurocode for national choice, known as Nationally Determined Parameters, to be used for the design of buildings and civil engineering works to be constructed in the country concerned, i.e.:

— values for partial factors and/or classes where alternatives are given in the Eurocode;

— values to be used where a symbol only is given in the Eurocode;

— geographical and climatic data specific to the Member State, e.g. snow map;

— the procedure to be used where alternative procedures are given in the Eurocode;

— references to non-contradictory complementary information to assist the user to apply the Eurocode.

Links between Eurocodes and harmonised technical specifications (EN's and ETA's) for products

There is a need for consistency between the harmonised technical specifications for construction products and the technical rules for works[4]. Furthermore, all the information accompanying the CE Marking of the construction products which refer to Eurocodes shall clearly mention which Nationally Determined Parameters have been taken into account.

Additional information specific to EN 1999-1-2

EN 1999-1-2 describes the principles, requirements and rules for the structural design of buildings exposed to fire, including the following aspects.

Safety requirements

EN 1999-1-2 is intended for owners of construction works (e.g. for the formulation of their specific requirements), designers, contractors and relevant authorities.

The general objectives of fire protection are to limit risks with respect to the individual and society, neighbouring property, and where required, environment or directly exposed property, in the case of fire.

Construction Products Directive 89/106/EEC gives the following essential requirement for the limitation of fire risks:

"The construction works must be designed and build in such a way, that in the event of an outbreak of fire

— the load bearing resistance of the construction can be assumed for a specified period of time;

— the generation and spread of fire and smoke within the works are limited;

— the spread of fire to neighbouring construction works is limited;

[4] see Art.3.3 and Art.12 of the CPD, as well as clauses 4.2, 4.3.1, 4.3.2 and 5.2 of ID 1.

— the occupants can leave the works or can be rescued by other means;

— the safety of rescue teams is taken into consideration".

According to the Interpretative Document N° 2 "Safety in case of fire[5]" the essential requirement may be observed by following various possibilities for fire safety strategies prevailing in the Member States like conventional fire scenarios (nominal fires) or "natural" (parametric) fire scenarios, including passive and/or active fire protection measures.

The fire parts of Structural Eurocodes deal with specific aspects of passive fire protection in terms of designing structures and parts thereof for adequate load bearing resistance and for limiting fire spread as relevant.

Required functions and levels of performance can be specified either in terms of nominal (standard) fire resistance rating, generally given in national fire regulations or by referring to fire safety engineering for assessing passive and active measures.

Supplementary requirements concerning, for example

— the possible installation and maintenance of sprinkler systems;

— conditions on occupancy of building or fire compartment;

— the use of approved insulation and coating materials, including their maintenance.

are not given in this document, because they are subject to specification by the competent authority.

Numerical values for partial factors and other reliability elements are given as recommended values that provide an acceptable level of reliability. They have been selected assuming that an appropriate level of workmanship and of quality management applies.

Design procedures

A full analytical procedure for structural fire design would take into account the behaviour of the structural system at elevated temperatures, the potential heat exposure and the beneficial effects of active and passive fire protection systems, together with the uncertainties associated with these three features and the importance of the structure (consequences of failure).

At the present time it is possible to undertake a procedure for determining adequate performance which incorporates some, if not all, of these parameters and to demonstrate that the structure, or its components, will give adequate performance in a real building fire. However, where the procedure is based on a nominal (standard) fire the classification system, which call for specific periods of fire resistance, takes into account (though not explicitly), the features and uncertainties described above.

The design procedure for structural fire design is illustrated in Figure 0.1. The prescriptive approach and the performance-based approach are identified. The prescriptive approach uses nominal fires to generate thermal actions. The performance-based approach, using fire safety engineering, refers to thermal actions based on physical and chemical parameters.

NOTE Tabulated data, as shown in Figure 0.1, are not available for aluminium components.

For design according to this part, EN 1991-1-2 is required for the determination of thermal and mechanical actions to the structure.

5 see clause 2.2, 3.2(4) and 4.2.3.3

Design aids

It is expected, that design aids based on the calculation models given in EN 1999-1-2, will be prepared by interested external organizations.

The main text of EN 1999-1-2 together with normative Annexes includes most of the principal concepts and rules necessary for structural fire design of aluminium structures.

National Annex for EN 1999-1-2

This standard gives alternative procedures, values and recommendations for classes with notes indicating where national choices may have to be made. Therefore the National Standard implementing EN 1999-1-2 should have a National Annex containing the Eurocode all Nationally Determined Parameters to be used for the design of buildings and civil engineering works to be constructed in the relevant country.

National choice is allowed in EN 1999-1-2 through clauses:

2.3 (1)

2.3 (2)

2.4.2 (3)

4.2.2.1 (1)

4.2.2.3 (5)

4.2.2.4 (5)

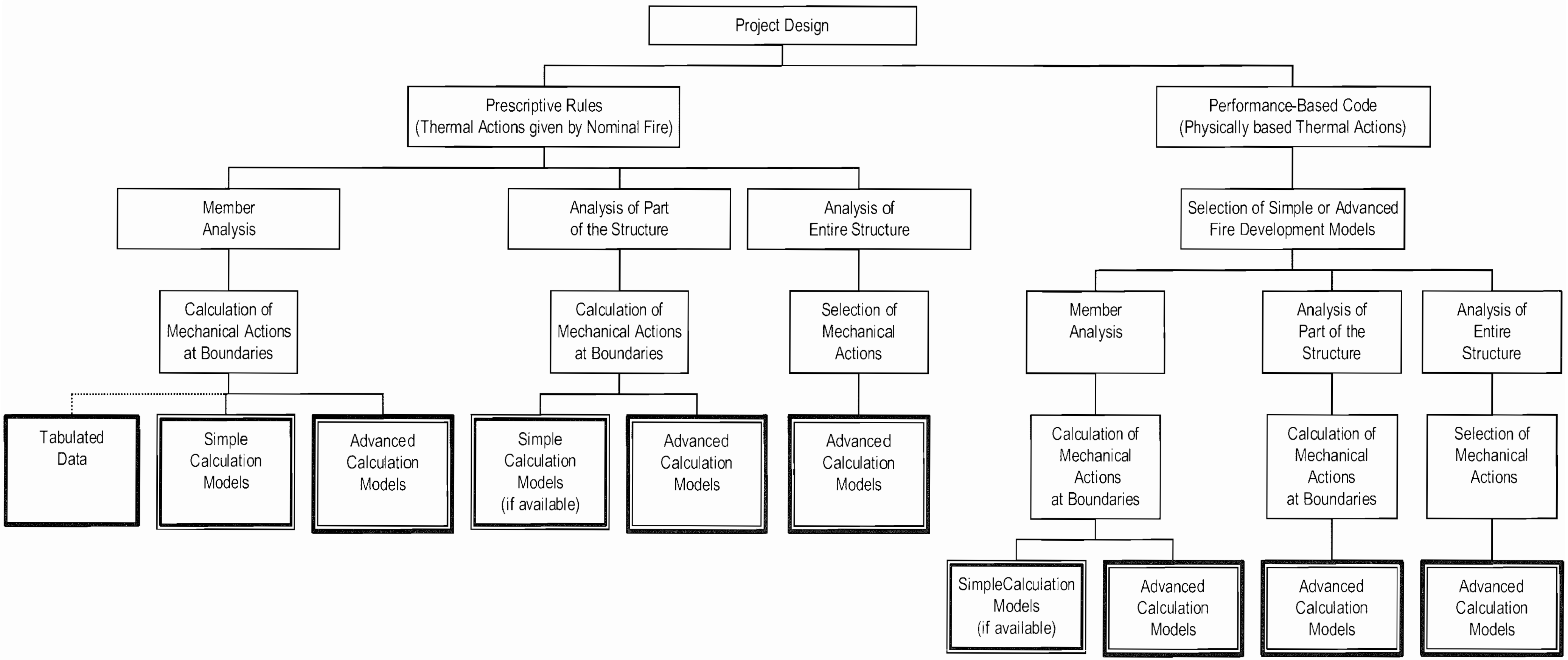


Figure 0.1 – A general illustration of the design procedure for structural fire design

1 General

1.1 Scope

1.1.1 Scope of EN 1999

(1)P EN 1999 applies to the design of buildings and civil engineering works in aluminium. It complies with the principles and requirements for the safety and serviceability of structures, the basis of their design and verification that are given in EN 1990 – Basis of structural design.

(2)P EN 1999 is only concerned with requirements for resistance, serviceability, durability and fire resistance of aluminium structures. Other requirements, e.g. concerning thermal or sound insulation, are not considered.

(3) EN 1999 is intended to be used in conjunction with:

— EN 1990 "Basis of structural design"

— EN 1991 "Actions on structures", all relevant parts

— European Standards for construction products relevant for aluminium structures

— EN 1998 "Design of structures for earthquake resistance", where aluminium structures are built in seismic regions

(4) EN 1999 is subdivided in five parts:

— EN 1999-1-1 Design of aluminium structures: General structural rules

— EN 1999-1-2 Design of aluminium structures: Structural fire design

— EN 1999-1-3 Design of aluminium structures: Structures susceptible to fatigue

— EN 1999-1-4 Design of aluminium structures: Cold formed structural sheeting

— EN 1999-1-5 Design of aluminium structures: Shell structures

1.1.2 Scope of EN 1999-1-2

(1) EN 1999-1-2 deals with the design of aluminium structures for the accidental situation of fire exposure and is intended to be used in conjunction with EN 1999-1-1 and EN 1991-1-2. EN1999-1-2 only identifies differences from, or supplements to, normal temperature design.

(2) EN 1999-1-2 deals only with passive methods of fire protection. Active methods are not covered.

(3) EN 1999-1-2 applies to aluminium structures that are required to fulfil load bearing function if exposed to fire, in terms of avoiding premature collapse of the structure.

NOTE This part does not include rules for separating elements.

(4) EN 1999-1-2 gives principles and application rules for design of structures for specified requirements in respect of the load bearing function and the levels of performance.

(5) EN 1999-1-2 applies to structures, or parts of structures, that are within the scope of EN 1999-1-1 and are designed accordingly.

(6) The aluminium alloy properties given in the Part 1-2 of EN 1999 apply to the following aluminium alloys:

EN AW-3004 – H34	EN AW-5083 – O and H12	EN AW-6063 – T5 and T6
EN AW-5005 – O and H34	EN AW-5454 – O and H34	EN AW-6082 – T4 and T6
EN AW-5052 – H34	EN AW-6061 – T6	

(7) The methods given in EN 1999-1-2 are applicable also to the other aluminium alloy/tempers of EN 1999-1-1 if reliable material properties at elevated temperatures are available or the simplified assumptions in 3.2.1 are applied.

1.2 Normative references

(1) This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only if incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies (including amendments).

EN 485-2 Aluminium and aluminium alloys. Sheet, strip and plate. Part 2: Mechanical properties

EN 755-2 Aluminium and aluminium alloys. Extruded rod/bar, tube and profiles. Part 2: Mechanical properties

EN 1990 Basis of structural design

EN 1991-1-2 Basis of design and actions on structures Part 1-2: Actions on structures exposed to fire

EN 1999-1-1 Design of aluminium structures: Part 1-1: General structural rules

AC1 EN 1090-3 AC1 Execution of steel structures and aluminium structures – Part 3: Technical requirements for aluminium structures

EN 13501-2 Fire classification of construction products and building elements. Part 2 Classification using data from fire resistance tests

AC1 *Text deleted* AC1

ENV 13381-2 Fire tests on elements of building construction. Part 2: Test method for determining the contribution to the fire resistance of structural members: By vertical protective membranes.

ENV 13381-4 Fire tests on elements of building construction. Part 4: Test method for determining the contribution to the fire resistance of structural members: By applied protection to steel structural elements.

AC1 CEN/TS 13381-1 Test methods for determining the contribution to the fire resistance of structural members – Part 1: Horizontal protective membranes AC1

1.3 Assumptions

(1) In addition to the general assumptions of EN 1990 the following assumption applies:
Any passive fire protection systems taken into account in the design will be adequately maintained.

1.4 Distinction between principles and application rules

(1) The rules given in EN 1990 1.4 apply.

1.5 Terms and definitions

(1) The rules in EN 1990 1.5 apply.

(2) The following terms are used in EN 1999-1-2 with the following meanings:

1.5.1 Special terms relating to design in general

1.5.1.1
part of structure
isolated part of an entire structure with appropriate support and boundary conditions

1.5.1.2
protected members
members for which measures are taken to reduce the temperature rise in the member due to fire

1.5.2 Terms relating to thermal actions

1.5.2.1
standard temperature-time curve
a nominal curve, defined in EN 13501-2 for representing a model of a fully developed fire in a compartment

1.5.2.2
temperature-time curves
gas temperature in the environment of member surfaces as a function of time. They may be:

— **nominal:** Conventional curves, adopted for classification or verification of fire resistance, e.g. the standard temperature-time curve, external fire curve, hydrocarbon fire curve;

— **parametric:** Determined on the basis of fire models and the specific physical parameters defining the conditions in the fire compartment

1.5.3 Terms relating to material and products

1.5.3.1
fire protection material
any material or combination of materials applied to a structural member for the purpose of increasing its fire resistance

1.5.4 Terms relating to heat transfer analysis

1.5.4.1
configuration factor
the configuration factor for radiative heat transfer from surface A to surface B is defined as the fraction of diffusely radiated energy leaving surface A that is incident on surface B

1.5.4.2
convective heat transfer coefficient
convective heat flux to the member related to the difference between the bulk temperature of gas bordering the relevant surface of the member and the temperature of that surface

1.5.4.3
emissivity
equal to absorptivity of a surface, i.e. the ratio between the radiative heat absorbed by a given surface, and that of a black body surface

1.5.4.4
net heat flux
energy per unit time and surface area definitely absorbed by members

1.5.4.5
resulting emissivity
the ratio between the actual radiative heat flux to the member and the net heat flux that would occur if the member and its radiative environment were considered as black bodies

1.5.4.6
section factor
for an aluminium member, the ratio between the exposed surface area and the volume of aluminium; for an enclosed member, the ratio between the internal surface area of the exposed encasement and the volume of aluminium

1.5.4.7
box value of section factor
ratio between the exposed surface area of a notional bounding box for the section to the volume of aluminium

1.5.5 Terms relating to mechanical behaviour analysis

1.5.5.1
critical temperature of a structural aluminium member
for a given load level, the temperature at which failure is expected to occur in a structural aluminium member for a uniform temperature distribution

1.5.5.2
effective 0,2 % proof strength
for a given temperature, the stress level at which the stress-strain relationship of aluminium gives a 0,2 % permanent strain

1.5.5.3
external member
structural member located outside the building that can be exposed to fire through openings in the building enclosure

1.6 Symbols

(1) For the purpose of EN 1999-1-2, the following symbols apply in addition to those given in EN 1999-1-1:

Latin upper case letters

A_m the exposed surface area of a member per unit length

A_p the area of the inner surface of the fire protection material per unit length of the member

E_{al} the modulus of elasticity of aluminium for normal temperature design

$E_{al,\theta}$ the modulus of elasticity for aluminium at elevated temperature, θ_{al}

V the volume of a member per unit length

Latin lower case letters

c_{al} the specific heat of aluminium

c_p the specific heat of the fire protection material

d_p the thickness of fire protection material

$f_{o,\theta}$ the effective 0,2 % proof strength at elevated temperature, θ_{al}

$\dot{h}_{net,d}$ the design value of the net heat flux per unit area

I_z is the radiative heat flux from the flame to beam face

k_θ the reduction factor of a strength property of aluminium at elevated temperature, θ_{al}

$k_{o,\theta}$ the strength reduction factor for the 0,2 proof strength at elevated temperature

$k_{o,\theta max}$ the strength reduction factor for the 0,2 proof strength at the maximum aluminium temperature

l the length at 20 °C

t the time in fire exposure

Greek upper case letters

Δt the time interval

Greek lower case letters

$\gamma_{M,fi}$ the partial safety factor for the relevant material property for the fire situation

η_{fi} the reduction factor for design load level in the fire situation

θ the temperature in °C

θ_{al} the aluminium temperature

ε_m the surface emissivity of the component

κ the adaptation factor

λ_{al} the thermal conductivity of aluminium

λ_p the thermal conductivity of the fire protection material

μ_0 the degree of utilisation at time $t = 0$

ρ_{al} the density of aluminium

ρ_p the density of the fire protection material

2 Basis of design

2.1 Requirements

2.1.1 Basic requirements

(1)P Where mechanical resistance in the case of fire is required, aluminium structures shall be designed and constructed in such a way that they maintain their load bearing function during the relevant fire exposure-criterion R.

(2)P Where compartmentation is required, the respective members shall be designed and constructed in such a way, that they maintain their separating function during the relevant fire exposure, i.e.:

— no integrity failure due to cracks, holes or other openings, which are large enough to cause fire penetration by hot gases or flames - criterion E;

— no insulation failure due to temperatures of the non-exposed surface exceeding ignition temperatures - criterion I.

(3) Criterion I may be assumed to be met where the average temperature rise during the standard fire exposure at the non-exposed surface does not exceed 140 °C and the maximum rise at any point on the non-exposed surface does not exceed 180 °C.

(4)P Members shall comply with criteria R, E, I as follows:

— separating only: E and I;

— load bearing only: R;

— separating and load bearing: R, E and I.

NOTE EN 1999-1-2 deals only with the R - criterion. The material properties given in this standard may be used when calculating temperatures for the I - criterion.

(5) Deformation criteria should be applied where the protection aims, or the design criteria for separating elements, require consideration of the deformation of the load bearing structure.

(6) Except from (5), consideration of the deformation of the load bearing structure is not necessary in the following cases, as relevant:

— the efficiency of the means of protection has been evaluated according to section 3.3.2;

— the separating components have to fulfil requirements according to a nominal fire exposure.

2.1.2 Nominal fire exposure

(1) For the standard fire exposure, members should comply with criteria R as follows:

— load bearing only: Mechanical resistance (criterion R).

(2) Criterion R is assumed to be satisfied where the load bearing function is maintained during the required time of fire exposure.

(3) With the hydrocarbon fire exposure curve the same criteria should apply, however the reference to this specific curve should be identified by the letters HC.

2.1.3 Parametric fire exposure

(1) The load-bearing function is ensured if collapse is prevented during the complete duration of the fire including the decay phase or during a required period of time.

2.2 Actions

(1) The thermal and mechanical actions should be taken from EN 1991-1-2.

(2) The values of $\dot{h}_{net,d}$ should be obtained from EN 1991-1-2 using:

$\varepsilon_m = 0{,}3$ for clean uncovered surfaces and

$\varepsilon_m = 0{,}7$ for painted and covered (e.g. sooted) surfaces,

2.3 Design values of material properties

(1) Design values of mechanical material properties $X_{fi,d}$ are defined as follows:

$$X_{fi,d} = k_\theta X_k / \gamma_{M,fi} \tag{2.1}$$

where

X_k is the characteristic value of a strength or deformation property (generally f_k or E_k) for normal temperature design according to EN 1999-1-1

$X_{k,\theta}$ is the value of a material property in fire design, generally dependent on the material temperature, see section 3

k_θ is the reduction factor for a strength or deformation property ($X_{k,\theta} / X_k$), dependent on the material temperature, see section 3

NOTE For mechanical properties of aluminium, the partial safety factor for the fire situation see National Annex. The use of $\gamma_{M,fi}$ = 1.0 is recommended.

(2) Design values of thermal material properties $X_{fi,d}$ are defined as follows:

— if an increase of the property is favourable for safety:

$$X_{fi,d} = X_{k,\theta} / \gamma_{M,fi} \tag{2.2a}$$

— if an increase of the property is unfavourable for safety:

$$X_{fi,d} = \gamma_{M,fi} X_{k,\theta} \tag{2.2b}$$

NOTE For thermal properties of aluminium, the partial safety factor for the fire situation see National Annex. The use of $\gamma_{M,fi}$ = 1,0 is recommended.

2.4 Verification methods

2.4.1 General

(1)P The model of the structural system adopted for design to EN1999-1-2 shall reflect the expected performance of the structure in fire.

NOTE Where rules given in EN1999-1-2 are valid only for the standard fire exposure, this is identified in the relevant clauses.

(2)P It shall be verified that, during the relevant duration of fire exposure t:

$$E_{fi,d} \leq R_{fi,d,t} \quad (2.3)$$

where

$E_{fi,d}$ is the design effect of actions for the fire situation, determined in accordance with EN 1991-1-2, including the effects of thermal expansions and deformations

$R_{fi,d,t}$ is the corresponding design resistance in the fire situation

(3) The structural analysis for the fire situation should be carried out according to EN 1990, 5.1.4 (2).

NOTE 1 For member analysis, see 2.4.2. For analysis of parts of the structure, see 2.4.3. For global structural analysis, see 2.4.4.

NOTE 2 For verifying standard fire resistance requirements, a member analysis is sufficient.

(4) As an alternative to design by calculation, fire design may be based on the results of fire tests, or on fire tests in combination with calculations.

2.4.2 Member analysis

(1) The effect of actions should be determined for time $t = 0$ using combination factors $\psi_{1,1}$ or $\psi_{2,1}$ according to EN 1991-1-2 clause 4.3.1.

(2) As a simplification to (1), the effect of actions $E_{fi,d}$ may be obtained from a structural analysis for normal temperature design as:

$$E_{fi,d} = \eta_{fi} E_d \quad (2.4)$$

where

E_d is the design value of the corresponding force or moment for normal temperature design, for a fundamental combination of actions (see EN 1990)

(3) The reduction factor η_{fi} for load combination (6.10) in EN 1990 should be taken as:

$$\eta_{fi} = \frac{G_k + \psi_{fi} Q_{k,1}}{\gamma_G G_k + \gamma_{Q,1} Q_{k,1}} \quad (2.5)$$

or for load combination (6.10a) and (6.10b) in EN 1990 as the smaller value given by the two following expressions:

$$\eta_{fi} = \frac{G_k + \psi_{fi} Q_{k,1}}{\gamma_G G_k + \gamma_{Q,1} Q_{k,1}} \quad (2.5a)$$

$$\eta_{fi} = \frac{G_k + \psi_{fi} Q_{k,1}}{\xi \gamma_G G_k + \gamma_{Q,1} Q_{k,1}} \quad (2.5b)$$

where

$Q_{k,1}$ is the principal variable load

G_k is the characteristic value of a permanent action

γ_G is the partial factor for permanent actions

$\gamma_{Q,1}$ is the partial factor for variable action 1

ψ_{fi} is the combination factor for frequent values, given either by $\psi_{1,1}$ or $\psi_{2,1}$

ξ is a reduction factor for unfavourable permanent actions G

NOTE 1 The values of γ_G, $\gamma_{Q,1}$, ψ_{fi} and ξ may be given in the National Annex. Recommended values are given in EN 1990. EN 1991-1-2 recommends using $\psi_{2,1}$ for ψ_{fi}.

NOTE 2 An example of the variation of the reduction factor η_{fi} versus the load ratio $Q_{k,1}/G_k$ for different values of the combination factor $\psi_{fi} = \psi_{1,1}$ according to expression (2.5), is shown in Figure 1 with the following assumptions: $\gamma_{GA} = 1,0$, $\gamma_G = 1,35$ and $\gamma_Q = 1,5$. Partial factors may be specified in the National Annexes of EN 1990, where recommended values are given. Equations (2.5a) and (2.5b) give slightly higher values.

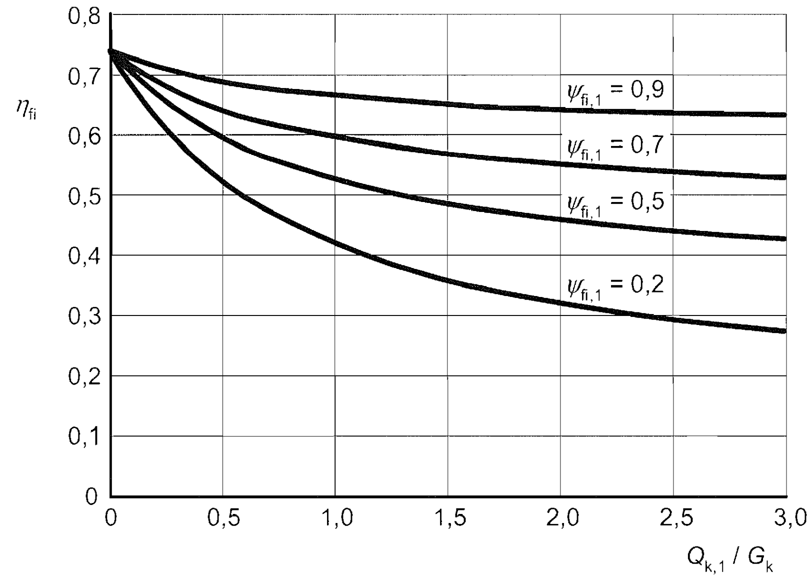


Figure 1 — Variation of the reduction factor η_{fi} with the load ratio $Q_{k,1}$ / G_k

NOTE 3 As a simplification the recommended value of η_{fi} = 0,65 may be used, except for imposed load according to load category E as given in EN 1991-1-1 (areas susceptible to accumulation of goods, including access areas) where the recommended value is 0,7.

(4) Only the effects of thermal deformations resulting from thermal gradients across the cross-section need to be considered. The effects of axial or in-plain thermal expansions may be neglected.

(5) The boundary conditions at supports and ends of member may be assumed to remain unchanged throughout the fire exposure.

(6) Simplified or advanced calculation methods given in clauses 4.2 and 4.3 respectively are suitable for verifying members under fire conditions.

2.4.3 Analysis of part of the structure

(1) 2.4.2 (1) applies.

(2) As an alternative to carrying out a structural analysis for the fire situation at time t = 0, the reactions at supports and internal forces and moments at boundaries of part of the structure may be obtained from a structural analysis for normal temperature as given in clause 2.4.2.

(3) The part of the structure to be analysed should be specified on the basis of the potential thermal expansions and deformations such, that their interaction with other parts of the structure can be approximated by time-independent support and boundary conditions during fire exposure.

(4) Within the part of the structure to be analysed, the relevant failure mode in fire exposure, the temperature-dependent material properties and member stiffness, effects of thermal deformations (indirect fire actions) should be taken into account

(5) The boundary conditions at supports and forces and moments at boundaries of part of the structure may be assumed to remain unchanged throughout the fire exposure.

2.4.4 Global structural analysis

(1) Where a global structural analysis for the fire situation is carried out, the relevant failure mode in fire exposure, the temperature-dependent material properties and member stiffness, effects of thermal deformations (indirect fire actions) should be taken into account.

3 Material

3.1 General

(1) Unless given as design values, the values of material properties given in this section should be treated as characteristic values.

(2) The mechanical properties of aluminium alloys at 20 °C should be taken as those given in EN 1999-1-1 for normal temperature design.

3.2 Mechanical properties of aluminium alloys

3.2.1 Strength and deformation properties

(1) For thermal exposure up to 2 hours, the 0,2 % proof strength at elevated temperature of the aluminum alloys listed in Table 1, follows from:

$$f_{o,\theta} = k_{o,\theta} \cdot f_o$$

where

$f_{o,\theta}$ is 0,2 proof strength at elevated temperature

f_o is 0,2 proof strength at room temperature according to EN 1999-1-1.

(2) For intermediate values of aluminium temperature, Figure 2a, 2b or linear interpolation may be used.

Table 1a — 0,2% proof strength ratios $k_{o,\theta}$ for aluminium alloys at elevated temperature for up to 2 hours thermal exposure period

Alloy	Temper	Aluminium alloy temperature °C							
		20	100	150	200	250	300	350	550
EN AW-3004	H34	1,00	1,00	0,98	0,57	0,31	0,19	0,13	0
EN AW-5005	O	1,00	1,00	1,00	1,00	0,82	0,58	0,39	0
EN AW-5005	H14[1)]	1,00	0,93	0,87	0,66	0,37	0,19	0,10	0
EN AW-5052	H34[2)]	1,00	1,00	0,92	0,52	0,29	0,20	0,12	0
EN AW-5083	O	1,00	1,00	0,98	0,90	0,75	0,40	0,22	0
EN AW-5083	H12[3)]	1,00	1,00	0,80	0,60	0,31	0,16	0,10	0
EN AW-5454	O	1,00	1,00	0,96	0,88	0,50	0,32	0,21	0
EN AW-5454	H34	1,00	1,00	0,85	0,58	0,34	0,24	0,15	0
EN AW-6061	T6	1,00	0,95	0,91	0,79	0,55	0,31	0,10	0
EN AW-6063	T5	1,00	0,92	0,87	0,76	0,49	0,29	0,14	0
EN AW-6063	T6[4)]	1,00	0,91	0,84	0,71	0,38	0,19	0,09	0
EN AW-6082	T4[5)]	1,00	1,00	0,84	0,77	0,77	0,34	0,19	0
EN AW-6082	T6	1,00	0,90	0,79	0,65	0,38	0,20	0,11	0

1) The values may be applied also for temper H24/H34/H12/H32
2) The values may be applied also for temper H12/H22/H32
3) The values may be applied also for temper H22/H32
4) The values may be applied also for EN AW-6060 T6 and T66
5) The values do not include an increase in strength due to aging effects. It is recommended to ignore such effects.

(3) The 0,2% proof strength of aluminium alloys at elevated temperature, not covered in Table 1a, but listed in Table 3.2a and 3.2b of EN 1999-1-1, should be documented by testing or the lower limit values of the 0,2% proof strength ratios given in Table 1b may be used.

Table 1b - Lower limits of the 0,2% proof strength ratios $k_{o,\theta}$ for aluminium alloys at elevated temperature for up to 2 hours thermal exposure period

	Aluminium alloy temperature °C							
	20	100	150	200	250	300	350	550
Lower limit values	1,00	0,90	0,75	0,50	0,23	0,11	0,06	0

Annex A gives strength reduction factors, $k_{o\theta}$, for some alloys and tempers not listed in EN 1999-1-1 Table 3.2a and 3.2b. The 0,2% proof strength of the material at room temperature f_o may be taken from EN 485-2 or EN 755-2

(4) The modulus of elasticity of all aluminium alloys after two hours thermal exposure to elevated temperature $E_{al,\theta}$ should be obtained from Table 2.

Table 2 — Modulus of elasticity of aluminium alloys at elevated temperature for a two hour thermal exposure period, $E_{al,\theta}$

Aluminium alloy temperature, θ (°C)	Modulus of elasticity, $E_{al,\theta}$ (N/mm²)
20	70 000
50	69 300
100	67 900
150	65 100
200	60 200
250	54 600
300	47 600
350	37 800
400	28 000
550	0

(5) The 0,2 proof strength ratios $k_{0,\theta}$ and the ratio $E_{al,\theta}/E_{al}$ for aluminium alloys at elevated temperature θ_{al}/°C are shown in Figure 2a and 2b for up to 2 hours thermal exposure period.

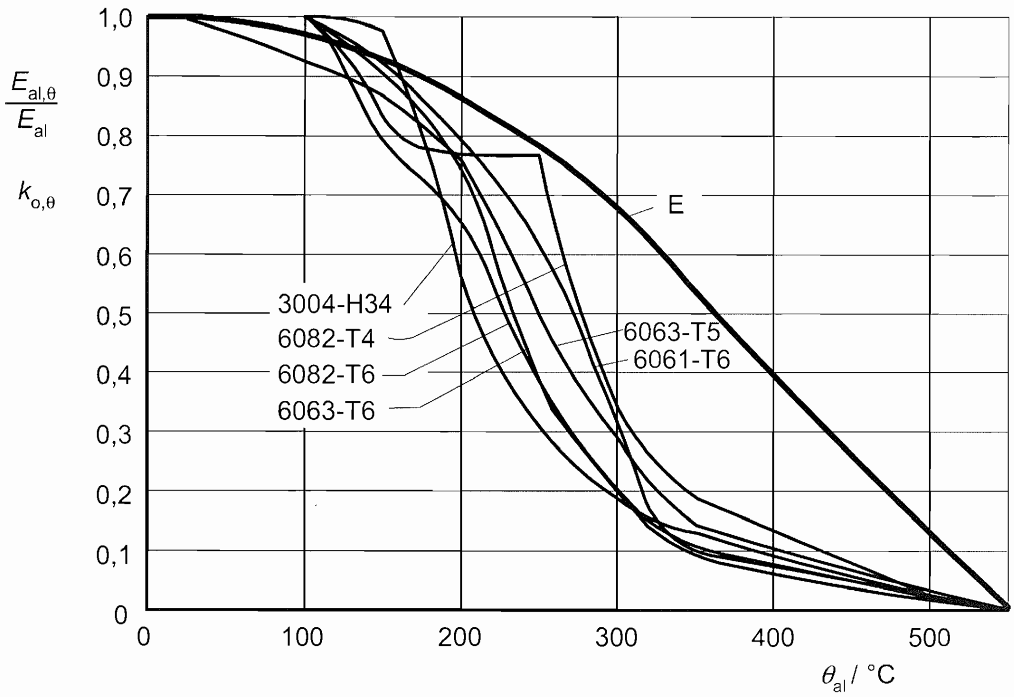


Figure 2a – 0,2% proof strength ratios $k_{o,\theta}$ and ratio E = $E_{al,\theta}/E_{al}$ for aluminium alloys at elevated temperature θ_{al} /°C for up to 2 hours thermal exposure period, EN-AW 3004 and 6xxx-alloys of Table 1a

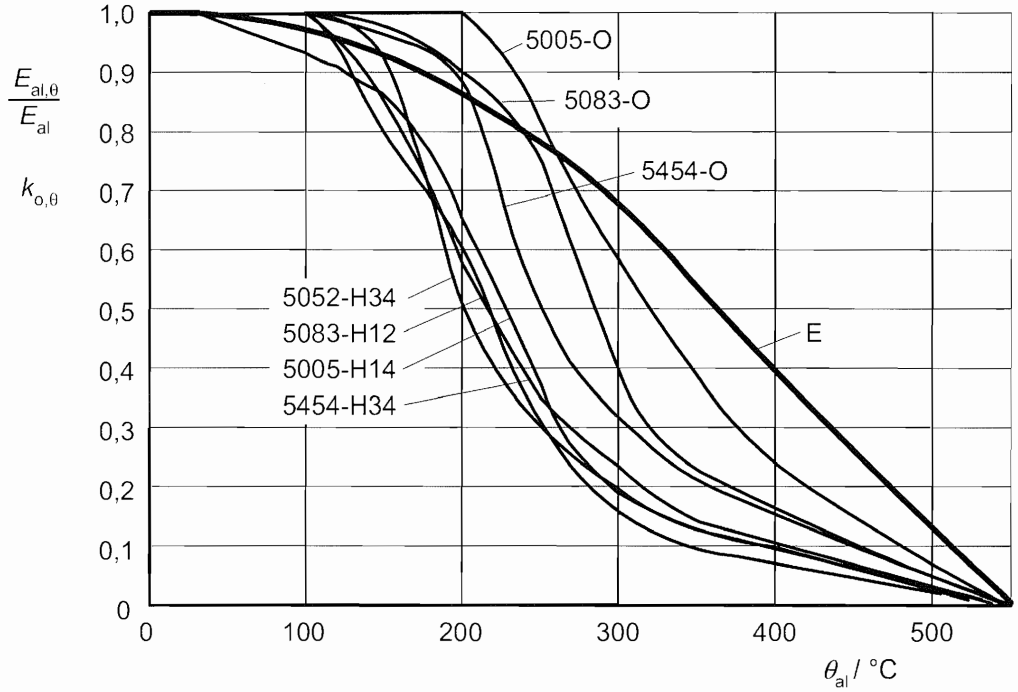


Figure 2b – 0,2% proof strength ratios $k_{o,\theta}$ and ratio E = $E_{al,\theta}/E_{al}$ for aluminium alloys at elevated temperature θ_{al} /°C for up to 2 hours thermal exposure period, 5xxx alloys of Table 1a

3.2.2 Unit mass

(1) The unit mass of aluminium ρ_{al} may be considered independent of aluminium temperature. The following value should be taken.

ρ_{al} = 2700 kg/m^3

3.3 Thermal properties

3.3.1 Aluminium alloys

3.3.1.1 Thermal elongation

(1) The relative thermal elongation (strain) of aluminium alloys, $\Delta l/l$, should be determined from the following:

for 0 °C < θ_{al} < 500 °C

$$\Delta l/l = 0{,}1 \cdot 10^{-7}\,\theta_{al}^2 + 22{,}5 \cdot 10^{-6}\,\theta_{al} - 4{,}5 \cdot 10^{-4}$$

where

l is the length at 20 °C

Δl is the temperature induced elongation

NOTE The variation in the relative thermal elongation with temperature is illustrated in Figure 3.

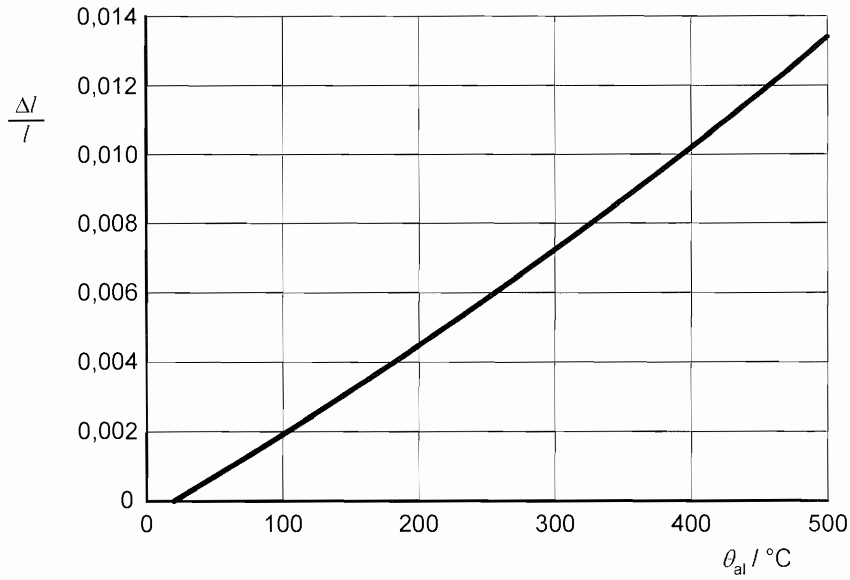


Figure 3 — Relative thermal elongation of aluminium alloys as a function of the temperature

3.3.1.2 Specific heat

(1) The specific heat of aluminium, c_{al}, should be determined from the following:

for 0 °C < θ_{al} < 500 °C

$$c_{al} = 0{,}41 \cdot \theta_{al} + 903 \quad \text{(J/kg °C)}$$

NOTE The variation in specific heat is illustrated in Figure 4.

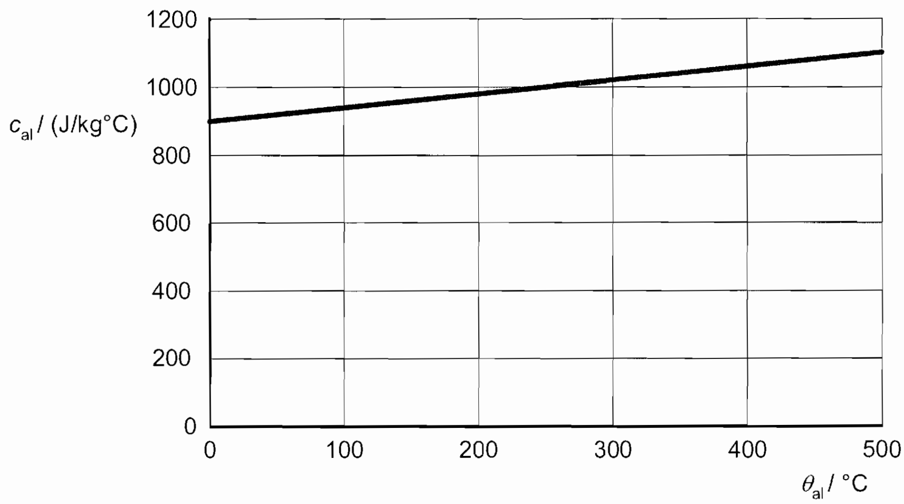


Figure 4 — Specific heat of aluminium alloys as a function of the temperature

3.3.1.3 Thermal conductivity

(1) The thermal conductivity of aluminium alloy, λ_{al}, for 0 °C < θ_{al} < 500 °C should be determined from the following:

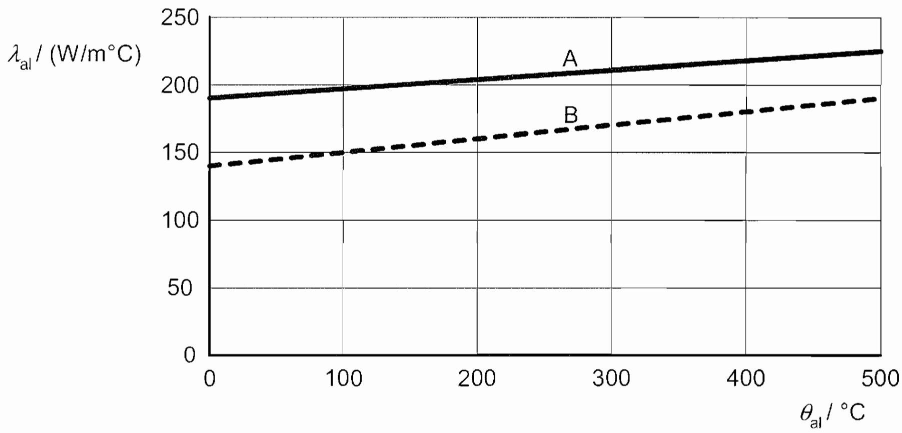
a) for alloys in 3xxx and 6xxx series:

$$\lambda_{al} = 0{,}07 \cdot \theta_{al} + 190 \ \ (\text{W/m°C})$$

b) for alloys in 5xxx and 7xxx series:

$$\lambda_{al} = 0{,}1 \cdot \theta_{al} + 140 \ \ (\text{W/m°C})$$

NOTE The variation of the thermal conductivity is illustrated in Figure 5.



A: 3xxx and 6xxx series, B: 5xxx and 7xxx series

Figure 5 — Thermal conductivity as a function of the temperature

3.3.2 Fire protection materials

(1) The properties and performance of fire protection materials used in design should be assessed as to verify that the fire protection remains coherent and cohesive to its support throughout the relevant fire exposure.

NOTE The verification of the properties of protection materials is generally performed by tests. Presently there are no European standard for testing of such materials in connection with aluminium structures. An illustration of such test applicable to fire protected steel structures is given in ENV 13381-4.

4 Structural fire design

4.1 General

(1) This section gives rules for aluminium structures that can be either:

— unprotected;

— insulated by fire protection material;

— protected by heat screens.

NOTE Examples of other protection methods are water filling or partial protection in walls and floors.

(2) Fire resistance should be determined by one or more of the following approaches:

— simple calculation models;

— advanced calculation models;

— testing.

(3) Simple calculation models are simplified design methods for individual members, which are based on conservative assumptions.

(4) Advanced calculation models are design methods in which engineering principles are applied in a realistic manner to specific applications.

4.2 Simple calculation models

4.2.1 General

(1)P The load-bearing function of an aluminium structure or structural member shall be assumed to be maintained after a time t in a given fire if:

$$E_{fi,d} \leq R_{fi,d,t} \qquad \text{(AC1) (4.1) (AC1)}$$

where

$E_{fi,d}$ is the design effect of actions for the fire design situation, determined in accordance with EN 1991-1-2, (the internal forces and moments $M_{fi,Ed}$, $N_{fi,Ed}$, $V_{fi,Ed}$ individually or in combination)

$R_{fi,d,t}$ is the design resistance of the aluminium structure or structural member, for the fire design situation, at time t, ($M_{fi,t,Rd}$, $M_{b,fi,t,Rd}$, $N_{fi,t,Rd}$, $N_{b,fi,t,Rd}$, $V_{fi,t,Rd}$ individually or in combination)

(2) $R_{fi,d,t}$ should be determined for the temperature distribution in the structural members at time t by modifying the design resistance for normal temperature design, determined from EN 1999-1-1, to take account of the mechanical properties of aluminium alloys at elevated temperature, see 3.2.1 and 3.2.2.

(3) The resistance of connections between members need not be checked provided that the thermal resistance $(d_p / \lambda_p)_c$ of the fire protection of the connection is not less than the minimum value of the thermal resistance $(d_p / \lambda_p)_M$ of the fire protection of any of the aluminium members joined by that connection.

(4) For welded connections the reduced strength in the heat affected zones shall be taken into account.

(5) It may be assumed that the clauses in 4.2.2.2, 4.2.2.3 and 4.2.2.4 are satisfied if at time t the aluminium temperature θ_{al} at all cross-sections is not more than 170 °C.

4.2.2 Resistance

4.2.2.1 Classification of cross-sections

(1) In a fire design situation, cross-sections may be classified as for normal temperature design according to 6.1.4 in EN 1999-1-1.

NOTE This rule is based on the same relative drop in the 0,2 % proof strength and modulus of elasticity. If the actual drop in modulus of elasticity is taken into account according to Figure 2, the classification of the section changes, and a larger capacity value of the section can be calculated. The National Annex may give provisions to take this into account.

4.2.2.2 Tension members

(1) The design resistance $N_{fi,t,Rd}$ of a tension member with a non uniform temperature distribution over the cross section at time t may be determined from:

$$N_{fi,t,Rd} = \sum A_i k_{o,\theta,i} f_o / \gamma_{M,fi} \tag{4.2}$$

where

A_i is an elemental area of the net cross-section with a temperature θ_i , including a deduction if required to allow for the effect of HAZ softening. The deduction is based on the reduced thickness of $\rho_{o,HAZ} \cdot t$

$k_{o,\theta,i}$ is the reduction factor for the effective 0,2 % proof strength at temperature θ_i. θ_i is the temperature in the elemental area A_i

(2) The design resistance $N_{fi,\theta,Rd}$ of a tension member with a uniform temperature θ_{al} should be determined from:

$$N_{fi,\theta,Rd} = k_{o,\theta}\, N_{Rd}\, (\gamma_{Mx} / \gamma_{M,fi})$$ [AC1) (4.3) (AC1]

where

N_{Rd} is the design resistance for normal temperature design according to EN 1999-1-1. N_{Rd} is either $N_{o,Rd}$ or $N_{u,Rd}$

γ_{Mx} is the material coefficient according to EN 1999-1-1. γ_{M1} is used in combination with $N_{o,Rd}$ and γ_{M2} is used in combination with $N_{u,Rd}$

The design resistance $N_{fi,\theta,Rd}$ is given by the combination of N_{Rd} and γ_{Mx} which gives the lowest capacity.

4.2.2.3 Beams

(1) The design moment resistance $M_{fi,t,Rd}$ of a cross-section in class 1 or 2 with a non uniform temperature distribution at time *t* may be determined from:

$$M_{fi,t,Rd} = \sum A_i\, z_i\, k_{o,\theta,i}\, f_o / \gamma_{M,fi} \tag{4.4}$$

where

z_i is the distance from the plastic neutral axis to the centroid of the elemental area A_i

(2) The design moment resistance $M_{fi,t,Rd}$ of a cross-section in class 3 or 4 with a non-uniform temperature distribution at time *t* may be determined from:

$$M_{fi,t,Rd} = k_{o,\theta max}\, M_{Rd}\, (\gamma_{Mx} / \gamma_{M,fi})$$ [AC1) (4.5) (AC1]

where

$k_{o,\theta max}$ is the 0,2% proof strength ratio for the aluminium alloys strength at temperature θ_{al} equal to the maximum temperature $\theta_{al,max}$ of the cross section reached at time *t*

M_{Rd} is the moment resistance of the cross-section for normal temperature design for class 3 or 4 according to EN 1999-1-1. M_{Rd} is either $M_{c,Rd}$ or $M_{u,Rd}$

γ_{Mx} is the material coefficient according to EN 1999-1-1. γ_{M1} is used in combination with $M_{c,Rd}$ and γ_{M2} is used in combination with $M_{u,Rd}$

The design resistance $M_{fi,t,Rd}$ is given by the combination of M_{Rd} and γ_{Mx} which gives the lowest capacity.

(3) The design $M_{fi,t,Rd}$ of a cross-section in class 1, 2, 3 or 4 with a uniform temperature distribution at time *t* may be determined from:

$$M_{fi,t,Rd} = k_{o,\theta}\, M_{Rd}\, (\gamma_{Mx}/\gamma_{M,fi})$$ [AC1) (4.6) (AC1]

where

M_{Rd} is the moment resistance of the cross-section for normal temperature design. M_{Rd} is either $M_{c,Rd}$ or $M_{u,Rd}$

γ_{Mx} is the material coefficient according to EN 1999-1-1. γ_{M1} is used in combination with $M_{c,Rd}$ and γ_{M2} is used in combination with $M_{u,Rd}$

The design resistance $M_{fi,t,Rd}$ is given by the combination of M_{Rd} and γ_{Mx} which gives the lowest capacity.

(4) For beams subjected to lateral-torsional buckling, the design buckling resistance moment $M_{b,fi,t,Rd}$ of a laterally unrestrained beam at time *t* may be determined using:

$$M_{b,fi,t,Rd} = k_{o,\theta,max}\, M_{b,Rd}\, (\gamma_{M1}/\gamma_{M,fi})$$ [AC1) (4.7) (AC1]

where

$M_{b,Rd}$ is the design buckling resistance moment for normal temperature design, according to EN 1999-1-1

(5) The design shear resistance $V_{fi,t,Rd}$ of a beam at time *t* may be determined from:

$$V_{fi,t,Rd} = k_{o,\theta}\, V_{Rd}\, (\gamma_{M1}/\gamma_{M,fi})$$ [AC1) (4.8) (AC1]

where

$k_{o,\theta}$ is the 0,2% proof stress ratio for the aluminium alloys strength at temperature θ_{al} ,where θ_{al} is the max temperature of that part of the cross section which carries the shear force

V_{Rd} is the shear resistance of the net cross-section for normal temperature design, according to EN 1999-1-1

NOTE The design resistances given with the formulae [AC1) (4.5), (4.7) and (4.8) (AC1] are based on the same relative drop in 0,2 % proof strength and modulus of elasticity at elevated temperatures. If the actual drop in the modulus of elasticity is taken into account larger capacity values can be obtained. The National Annex may give provisions to take this into account.

4.2.2.4 Columns

(1) The design buckling resistance $N_{b,fi,t,Rd}$ of a compression member at time *t* may be determined from:

$$N_{b,fi,t,Rd} = k_{o,\theta,max}\, N_{b,Rd}\, (\gamma_{M1}/1{,}2\ \gamma_{M,fi})$$ [AC1) (4.9) (AC1]

where

$N_{b,Rd}$ is the buckling resistance for normal temperature design according to EN 1999-1-1

1,2 is a reduction factor of the design resistance due to the temperature dependent creep of aluminium alloys

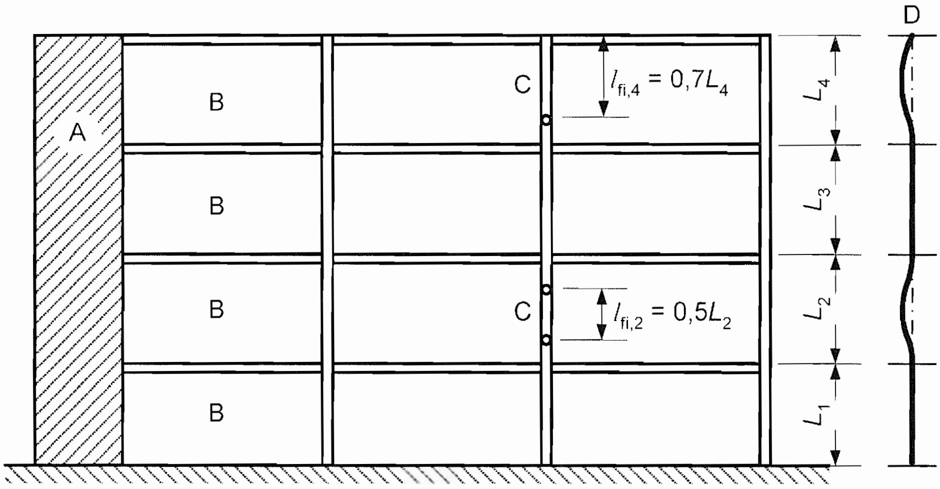
(2) For the determination of the relative slenderness the provisions of EN 1999-1-1 apply.

(3) For the determination of the buckling length l_{fi} of columns, the rules of EN 1999-1-1 apply, with the exception given hereafter.

(4) A column at the level under consideration, fully connected to the column above and below, if any, may be considered as effectively restrained, provided the resistance to fire of the building elements, which separate the levels under consideration, is at least equal to the fire resistance of the column.

(5) In the case of a braced frame in which each storey comprises a separate fire compartment with sufficient fire resistance, in an intermediate storey the buckling length l_{fi} of a column may be taken as $l_{fi} = 0{,}5L$ and in the top storey the buckling length may be taken as $l_{fi} = 0{,}7L$ where L is the system length in the relevant storey, see Figure 6.

NOTE The design resistance given with formula [AC1) (4.9) (AC1] is based on the same relative drop in the 0,2 % proof strength and modulus of elasticity. If the actual drop in modulus of elasticity is taken into account, a larger capacity value can be obtained. The National Annex may give provisions to take this into account.



A: Shear wall or other bracing system
B: Separate fire compartments in each storey
C: Column buckling length
D: Deformation mode in fire

Figure 6 — Examples of buckling lengths l_{fi} of columns in braced frames

(6) The design buckling resistance of a member subjected to combined bending and axial forces may be determined from EN 1999-1-1 using the combination rules for normal temperature design and using:

$N_{Ed} = N_{fi,Ed}$

$M_{y,Ed} = M_{y,fi,Ed}$

$M_{z,Ed} = M_{z,fi,Ed}$

as design loads.

The member resistance in fire is determined from 4.2.2.3 and 4.2.2.4 in this standard.

4.2.3 Aluminium temperature development

4.2.3.1 Unprotected internal aluminium members

(1) For an equivalent uniform temperature distribution in the cross-section, the increase of temperature $\Delta\theta_{al(t)}$ in an unprotected member during a time interval Δt should be determined from:

$$\Delta\theta_{al(t)} = k_{sh} \frac{1}{c_{al}\,\rho_{al}} \frac{A_m}{V} \dot{h}_{net} \Delta t \qquad \text{[AC1) (4.10) (AC1]}$$

where

k_{sh} is the correction factor for the shadow effect from 4.2.3.1 (2)

A_m/V is the section factor for unprotected aluminium members (m^{-1})

$\dot{h}_{net}$ is the design value of the net heat flux per unit area, see EN 1991-1-2

(2) For I-sections under nominal fire actions, the correction factor for the shadow effect may be determined from:

$$k_{sh} = 0{,}9 \frac{(A_m/V)_b}{A_m/V} \qquad \text{[AC1) (4.11) (AC1]}$$

where

$(A_m/V)_b$ is box value of the section factor

In all other cases, the value of k_{sh} should be taken as:

$$k_{sh} = \frac{(A_m/V)_b}{A_m/V} \leq 1{,}0 \qquad \text{[AC1) (4.12) (AC1]}$$

NOTE 1 For cross sections with a convex shape (e.g. rectangular or circular hollow sections) fully embedded in fire, the shadow effect has an insignificant influence and consequently the correction factor k_{sh} equals unity.

NOTE 2 Ignoring the shadow effect (i.e.: k_{sh} = 1,0) leads to conservative solutions.

(3) The value of $\dot{h}_{net,d}$ should be obtained from EN 1991-1-2 using ε_f = 1,0 and ε_m according to 2.2(2) where ε_f and ε_m are as defined in EN 1991-1-2.

(4) The value of Δt should not be taken as more than 5 seconds.

(5) In expression [AC1) (4.10) (AC1], the value of the section factor A_m/V should not be taken as less than 10 m^{-1}.

(6) For the calculation of the exposed surface area of the member, A_m, grooves with gap in the surface less than 20 mm should not be included in the exposed surface area. Grooves with gap in the surface > 20 mm, the area of the groove should be included in the area of the exposed area. See Figure. 7.

NOTE Some expressions for calculating design values of the section factor A_m/V for unprotected aluminium members are given in Table 3.

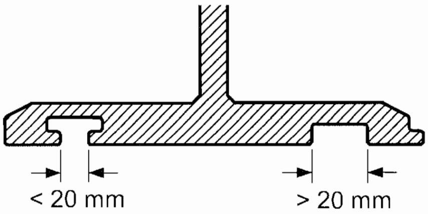
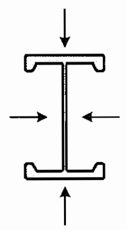
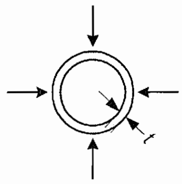
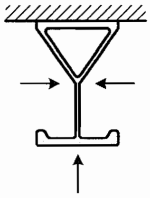
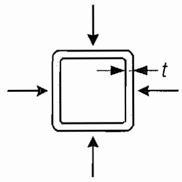
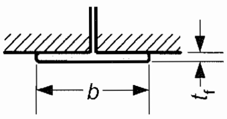
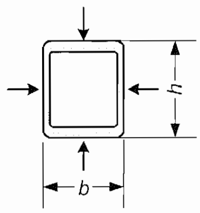
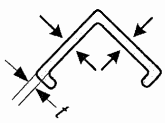
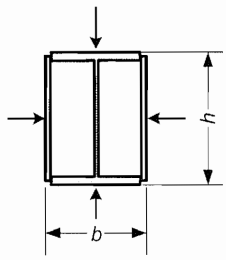
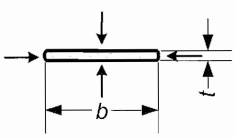
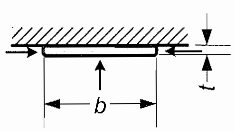


Figure 7 — Examples of grooves with gap in the surface < 20 mm, and grooves with gap in the surface > 20 mm

Table 3 — Section factor A_m/V for unprotected structural aluminium members when using the lumped mass method

Open section exposed to fire on all sides:  $\frac{A_m}{V} = \frac{\text{perimeter}}{\text{cross-section area}}$	Tube exposed to fire on all sides:  $\frac{A_m}{V} = \frac{1}{t}$
Open section exposed to fire on three sides:  $\frac{A_m}{V} = \frac{\text{surface exposed to fire}}{\text{cross-section area}}$	Hollow section (or welded box section of uniform thickness) exposed to fire on all sides:  If $t << b$: $\frac{A_m}{V} \approx \frac{1}{t}$
I section flange exposed to fire on three sides:  $\frac{A_m}{V} = \frac{b + 2t_f}{bt_f}$ If $t_f << b$: $\frac{A_m}{V} \approx \frac{1}{t_f}$	Box section exposed to fire on all sides:  $\frac{A_m}{V} = \frac{\text{[AC1⟩ } 2(b+h) \text{ ⟨AC1]}}{\text{cross-section area}}$
Angle (or any open section of uniform thickness) exposed to fire on all sides:  $\frac{A_m}{V} = \frac{2}{t}$	I section with box reinforcement exposed to fire on all sides:  $\frac{A_m}{V} = \frac{\text{[AC1⟩ } 2(b+h) \text{ ⟨AC1]}}{\text{cross-section area}}$
Flat bar exposed to fire on all sides:  $\frac{A_m}{V} = \frac{2b + 2t}{bt}$ If $t << b$: $\frac{A_m}{V} \approx \frac{2}{t}$	Flat bar exposed to fire on three sides:  $\frac{A_m}{V} = \frac{b + 2t}{bt}$ If $t << b$: $\frac{A_m}{V} \approx \frac{1}{t}$

4.2.3.2 Internal aluminium structures insulated by fire protection material

(1) For a uniform temperature distribution in a cross-section, the temperature increase $\Delta\theta_{al(t)}$ in an insulated member during a time interval Δt should be obtained from:

$$\Delta\theta_{al(t)} = \frac{\lambda_p / d_p}{c_{al}\,\rho_{al}} \frac{A_p}{V} \left[\frac{1}{1+\phi/3}\right] \left(\theta_{(t)} - \theta_{al(t)}\right) \Delta t - \left(e^{\phi/10} - 1\right) \Delta\theta_{(t)} \quad \text{(AC1) (4.13) (AC1)}$$

but $\Delta\theta_{al(t)} \geq 0$

in which:

$$\phi = \frac{c_p \rho_p}{c_{al} \rho_{al}} d_p \frac{A_p}{V} \quad \text{(AC1) (4.14) (AC1)}$$

where

A_p/V is the section factor for aluminium members insulated by fire protection material (m^{-1})

$\theta_{(t)}$ is the ambient gas temperature at time t (°C)

$\theta_{al(t)}$ is the aluminium temperature at time t (°C)

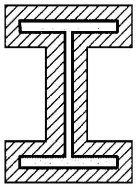
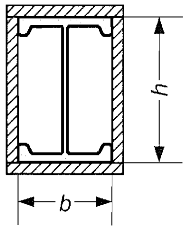
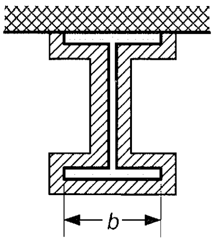
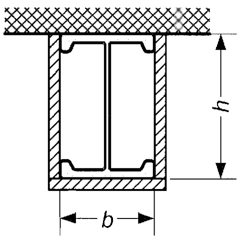
$\Delta\theta_{(t)}$ is the increase of the ambient temperature during the time interval Δt (°C)

(2) The value of Δt should not be taken as more than 30 seconds.

(3) Some design values of the section factor A_p/V for insulated aluminium members are given in Table 4.

(4) For most fire protection materials the calculation of the aluminium temperature increase $\Delta\theta_{al(t)}$ may be modified to allow for a time delay in the rise of the aluminium temperature when it reaches 100 °C.

Table 4 — Section factor A_p/V for structural aluminium members insulated by fire protection materials when using the lumped mass method

Sketch	Description	Section factor (A_p/V)
	Contour encasement of uniform thickness, exposed to fire on four sides.	$\dfrac{\text{aluminium perimeter}}{\text{aluminium cross - section area}}$
	Hollow encasement of uniform thickness, exposed to fire on four sides.	$\dfrac{2(b+h)}{\text{aluminium cross - section area}}$
	Contour encasement of uniform thickness, exposed to fire on three sides.	$\dfrac{\text{aluminium perimeter - } b}{\text{aluminium cross - section area}}$
	Hollow encasement of uniform thickness, exposed to fire on three sides.	$\dfrac{2h+b}{\text{aluminium cross - section area}}$

4.2.3.3 Internal aluminium structures in a void that is protected by heat screens

(1) The provisions given below apply to both of the following cases:

— aluminium members in a void which is bordered by a floor on top and by a horizontal heat screen below;

— aluminium members in a void which is bordered by vertical heat screens on both sides.

(2) For internal aluminium structures protected by heat screens, the calculation of the aluminium temperature increase $\Delta\theta_{al}$ should be based on the methods given in 4.2.3.1 or 4.2.3.2 as appropriate, taking the ambient gas temperature θ_t as equal to the gas temperature in the void.

(3) The properties and performance of the heat screens should be determined using a test procedure conforming with [AC1) CEN/TS 13381-1 (AC1] or ENV 13381-2 as appropriate.

(4) The temperature development in the void in which the aluminium members are situated should be determined from a standard fire test conforming to AC1 CEN/TS 13381-1 AC1 or ENV 13381-2 as appropriate, or calculated using an approved method.

(5) Values of the heat transfer coefficients for convection and radiation (α_c and α_r respectively) determined from tests conforming with AC1 CEN/TS 13381-1 AC1 or ENV 13381-2 as appropriate, may be used in the calculation of $\Delta\theta_{al}$ as an alternative to the values given in EN 1991-1-2.

4.2.3.4 External aluminium structures

(1) The temperature in external aluminium structures should be determined taking into account:

— the radiative heat flux from the fire compartment;

— the radiative heat flux and the convection heat flux from flames emanating from openings;

— the radiative and convective heat loss from the aluminium structure to the ambient atmosphere;

— the sizes and locations of the structural members.

(2) Heat screens may be provided on one, two or three sides of an external aluminium member in order to protect it from radiative heat transfer.

(3) Heat screens should be either:

— directly attached to that side of the aluminium member which they are intended to protect, or;

— large enough to fully screen this side from the expected radiative heat flux.

(4) Heat screens should be non-combustible and have a fire resistance of at least EI 30 according to EN ISO 13501-2.

NOTE Annex B gives information.

(5) The temperature in external aluminium structures protected by heat screens should be determined as specified in (1), assuming that there is no radiative heat transfer to those sides which are protected by heat screens.

(6) Calculations may be based on steady state conditions resulting from a stationary heat balance.

NOTE 1 Annex B gives recommended methods.

NOTE 2 Design using Annex B should be based on the model given in EN 1991-1-2 describing the compartment fire conditions and the flames emanating from openings, on which the calculation of the radiative and convective heat fluxes should be based.

4.3 Advanced calculation models

4.3.1 General

(1) Advanced calculation methods should be based on fundamental physical behaviour in such a way as to lead to a reliable approximation of the expected behaviour of the relevant structural component under fire conditions.

(2) Any potential failure modes not covered by the advanced calculation method (including local buckling and failure in shear) should be eliminated by appropriate means.

(3) Advanced calculation methods should include calculation models for the determination of:

— the development and distribution of the temperature within structural members (thermal response model);

— the mechanical behaviour of the structure or of any part of it (mechanical response model).

(4) Advanced calculation methods may be used in association with any heating curve, provided that the material properties are known for the relevant temperature range.

(5) Advanced calculation methods may be used with any type of cross-section.

4.3.2 Thermal response

(1) Advanced calculation methods for thermal response should be based on the acknowledged principles and assumptions of the theory of heat transfer.

(2) The thermal response model should consider:

— the relevant thermal actions specified in EN 1991-1-2;

— the variation of the thermal properties of the material with the temperature, see 3.3.

(3) The effects of non-uniform thermal exposure and of heat transfer to adjacent building components may be included where appropriate.

(4) The influence of any moisture content and of any migration of the moisture within the fire protection material may conservatively be neglected.

4.3.3 Mechanical response

(1) Advanced calculation methods for mechanical response should be based on the acknowledged principles and assumptions of the theory of structural mechanics, taking into account the changes of mechanical properties with temperature.

(2) The effects of thermally induced strains and stresses both due to temperature rise and due to temperature differentials, should be considered.

(3) The mechanical response of the model should also take account of:

— the combined effects of mechanical actions, geometrical imperfections and thermal actions;

— the temperature dependent mechanical properties of the material, see 3.2;

— geometrical non-linear effects;

— the effects of non-linear material properties, including the beneficial effects of loading and unloading on the structural stiffness.

(4) For metal temperature above 170 °C with a duration above 30 minutes the effects of transient thermal creep should be given explicit consideration.

(5) The deformations at ultimate limit state implied by the calculation method should be limited to ensure that compatibility is maintained between all parts of the structure.

(6) The design should take into account the ultimate limit state beyond which the calculated deformations of the structure would cause failure due to the loss of adequate support to one of the members.

(7) The analysis of members subjected to buckling can be performed using a sinusoidal initial imperfection with a maximum value at mid-height according to the maximum allowable deviations specified in EN 1090-3.

4.3.4 Validation of advanced calculation models

(1) A verification of the accuracy of the calculation models should be made on basis of relevant test results.

(2) Calculation results may refer to temperatures, deformations and fire resistance times.

(3) The critical parameters should be checked to ensure that the model complies with sound engineering principles, by means of a sensitivity analysis.

(4) Critical parameters may refer, for example to the buckling length, the size of the members, the load level.

Annex A
(informative)

Properties of aluminium alloys and/or tempers not listed in EN 1999-1-1

Table A.1 — 0,2% proof strength ratios $k_{o,\theta}$ for aluminium alloys at elevated temperature for a 2 hour exposure period

Alloy	Temper	Aluminium alloy temperature °C							
		20	100	150	200	250	300	350	550
EN AW-3003	O	1,00	1,00	0,90	0,79	0,64	0,46	0,38	0
EN AW-3003	H14	1,00	1,00	0,76	0,51	0,26	0,16	0,10	0
EN AW-3004	H38	1,00	1,00	0,88	0,46	0,25	0,16	0,10	0
EN AW-5005	H18	1,00	0,92	0,85	0,60	0,32	0,15	0,08	0
EN AW-5052	O	1,00	1,00	1,00	0,85	0,63	0,46	0,28	0
EN AW-5052	H38	1,00	0,98	0,80	0,44	0,24	0,16	0,10	0
EN AW-5154	O	1,00	1,00	0,96	0,92	0,70	0,50	0,30	0
EN AW-5154	H34	1,00	1,00	0,89	0,61	0,37	0,26	0,16	0
EN AW-5454	H32	1,00	1,00	0,92	0,78	0,36	0,23	0,14	0
EN AW-5086	O	1,00	1,00	0,96	0,91	0,70	0,46	0,30	0
EN AW-5086	H34	1,00	1,00	0,85	0,58	0,34	0,24	0,15	0
EN AW-6005	T5	1,00	0,93	0,81	0,66	0,42	0,23	0,11	0

As an approximation the values of $k_{o,\theta}$ for alloy EN AW-3003 may be used for alloy EN AW-3103.

Annex B
(informative)

Heat transfer to external structural aluminium members

B.1 General

B.1.1 Basis

(1) In this Annex B, the fire compartment is assumed to be confined to one storey only. All windows or other similar openings in the fire compartment are assumed to be rectangular.

(2) The determination of the temperature of the compartment fire, the dimensions and temperatures of the flames projecting from the openings, and the radiation and convection parameters should be performed according to Annex B of EN 1991-1-2.

(3) A distinction should be made between members not engulfed in flame and members engulfed in flame, depending on their locations relative to the openings in the walls of the fire compartment.

(4) A member that is not engulfed in flame should be assumed to receive radiative heat transfer from all the openings in that side of the fire compartment and from the flames projecting from all these openings.

(5) A member that is engulfed in flame should be assumed to receive convective heat transfer from the engulfing flame, plus radiative heat transfer from the engulfing flame and from the fire compartment opening from which it projects. The radiative heat transfer from other flames and from other openings may be neglected.

B.1.2 Conventions for dimensions

(1) The convention for geometrical data may be taken from Figure B.1.

B.1.3 Heat balance

(1) For a member not engulfed in flame, the average temperature of the aluminium member T_m [K] should be determined from the solution of the following heat balance:

$$\sigma T_m^4 + \alpha T_m = \Sigma I_z + \Sigma I_f + 293\alpha \qquad \text{(B.1)}$$

where

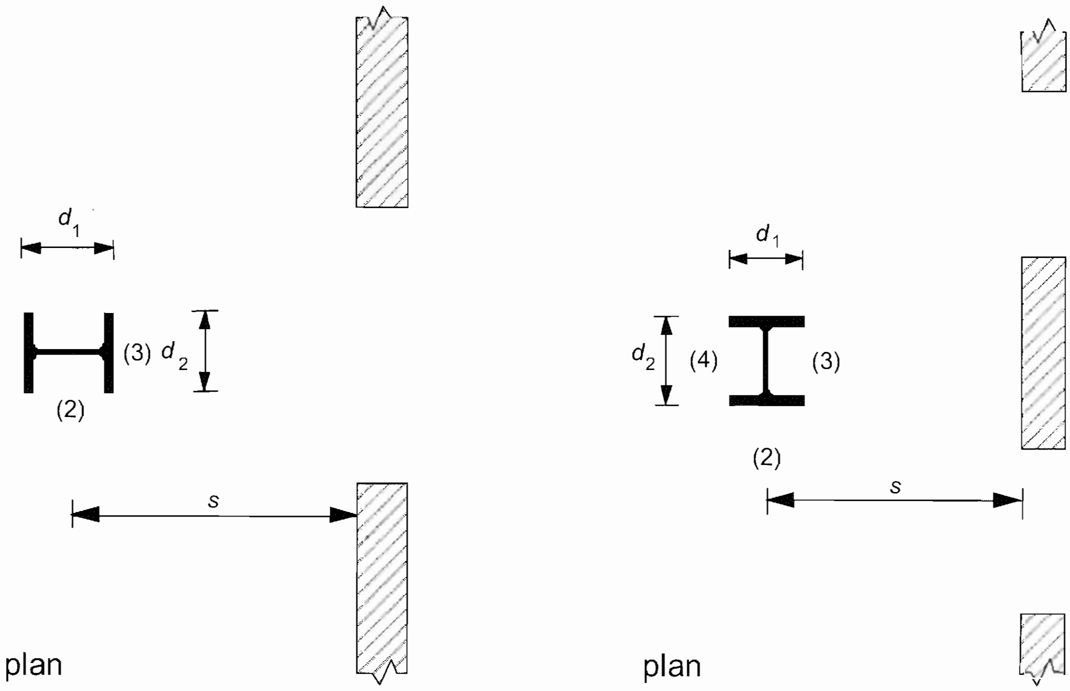
σ is the Stefan Boltzmann constant [$56,7 \times 10^{-12}$ kW/m^{2}K^4]

α is the convective heat transfer coefficient [kW/m^{2}K]

I_z is the radiative heat flux from a flame [kW/m^2]

I_f is the radiative heat flux from an opening [kW/m^2]

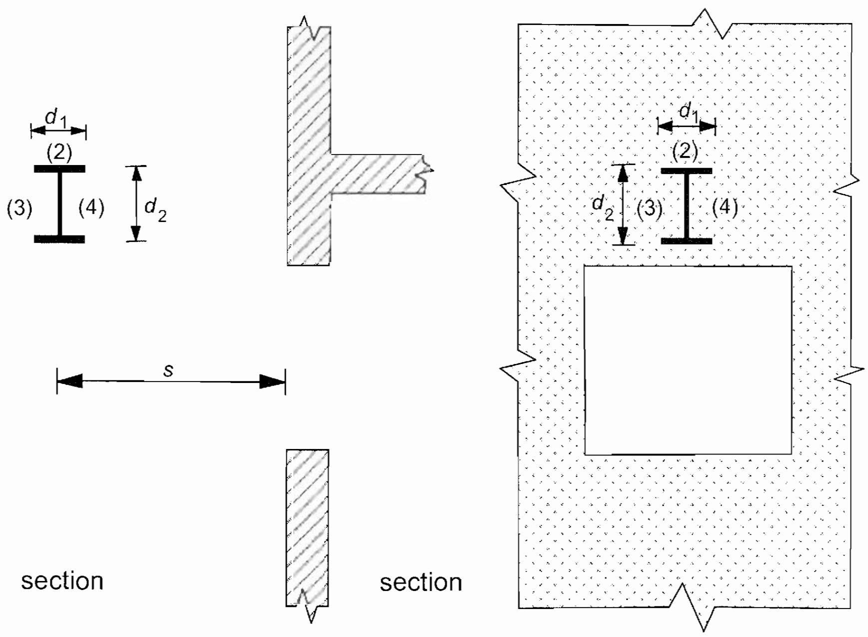
(2) The convective heat transfer coefficient α should be obtained from Annex B of EN 1991-1-2 for the 'no forced draught' or the 'forced draught' condition as appropriate, using an effective cross-sectional dimension $d = (d_1 + d_2)/2$.



1) Column opposite opening

2) Column between openings

a) Columns



1) Beam parallel to wall

2) Beam perpendicular to wall

b) Beams

Figure B.1 — Member dimensions and faces

(3) For a member engulfed in flame, the average temperature of the aluminium member T_m [°K] should be determined from the solution of the following heat balance:

$$\sigma T_m^4 + \alpha T_m = I_z + I_f + \alpha T_z \quad \text{(B.2)}$$

where

T_z is the flame temperature [K]

I_z Is the radiative heat flux from the flame [kW/m^2]

I_f Is the radiative heat flux from the corresponding opening [kW/m^2]

(4) The radiative heat flux I_z from flames should be determined according to the situation and type of member as follows:

— columns not engulfed in flame: see B.2;

— beams not engulfed in flame: see B.3;

— columns engulfed in flame: see B.4;

— beams fully or partially engulfed in flame: see B.5.

Other cases may be treated analogously, using appropriate adaptations of the treatments given in B.2 to B.5.

(5) The radiative heat flux I_f from an opening should be determined from:

$$I_f = \phi_f \varepsilon_f (1 - a_z) \sigma T_f^4 \quad \text{(B.3)}$$

where

ϕ_f is the overall configuration factor of the member for radiative heat transfer from that opening

ε_f is the emissivity of the opening

a_z is the absorptivity of the flames

T_f is the temperature of the fire [K] from Annex B of EN 1991-1-2

(6) The emissivity ε_f of an opening should be taken as unity, see Annex B of EN 1991-1-2.

(7) The absorptivity a_z of the flames should be determined from B.2 to B.5 as appropriate.

B.1.4 Overall configuration factors

(1) The overall configuration factor ϕ_f of a member for radiative heat transfer from an opening should be determined from:

$$\phi_f = \frac{(C_1\phi_{f,1} + C_2\phi_{f,2})d_1 + (C_3\phi_{f,3} + C_4\phi_{f,4})d_2}{(C_1 + C_2)d_1 + (C_3 + C_4)d_2} \quad \text{(B.4)}$$

where:

$\phi_{f,i}$ is the configuration factor of member face i for that opening, see Annex G of EN 1991-1-2

d_i is the cross-sectional dimension of member face i

C_i is the protection coefficient of member face i as follows:

— for a protected face: $C_i = 0$

— for an unprotected face: $C_i = 1$

(2) The configuration factor $\phi_{f,i}$ for a member face from which the opening is not visible should be taken as zero.

(3) The overall configuration factor ϕ_z of a member for radiative heat transfer from a flame should be determined from:

$$\phi_z = \frac{(C_1\phi_{z,1} + C_2\phi_{z,1})d_1 + (C_3\phi_{z,3} + C_4\phi_{z,4})d_2}{(C_1 + C_2)d_1 + (C_3 + C_4)d_2} \tag{B.5}$$

where

$\phi_{z,i}$ is the configuration factor of member face i for that flame, see Annex G of EN 1991-1-2

(4) The configuration factors $\phi_{z,i}$ of individual member faces for radiative heat transfer from flames may be based on equivalent rectangular flame dimensions. The dimensions and locations of equivalent rectangles representing the front and sides of a flame for this purpose should be determined as given in B.2 for columns and B.3 for beams. For all other purposes, the flame dimensions from Annex B of EN 1991-1-2 should be used.

(5) The configuration factor $\phi_{z,i}$ for a member face from which the flame is not visible should be taken as zero.

(6) A member face may be protected by a heat screen, see 4.2.3.4. A member face that is immediately adjacent to the compartment wall may also be treated as protected, provided that there are no openings in that part of the wall. All other member faces should be treated as unprotected.

B.2 Column not engulfed in flame

B.2.1 Radiative heat transfer

(1) A distinction should be made between a column located opposite an opening and a column located between openings.

NOTE Illustration is given in Figure B.2.

(2) If the column is opposite an opening the radiative heat flux I_z from the flame should be determined from:

$$I_z = \phi_z \varepsilon_z \sigma T_z^4 \tag{B.6}$$

where

ϕ_z is the overall configuration factor of the column for heat from the flame, see B.1.4

ε_z is the emissivity of the flame, see B.2.2

T_z is the flame temperature [K] from B.2.3

NOTE Illustrations are given in Figure B.3.

(3) If the column is between openings the total radiative heat flux I_z from the flames on each side should be determined from:

$$I_z = (\phi_{z,m}\, \varepsilon_{z,m} + \phi_{z,n}\, \varepsilon_{z,n})\, \sigma T_z^{\,4} \tag{B.7}$$

where

$\phi_{z,m}$ is the overall configuration factor of the column for heat from flames on side m, see B.1.4

$\phi_{z,n}$ is the overall configuration factor of the column for heat from flames on side n, see B.1.4

$\varepsilon_{z,m}$ is the total emissivity of the flames on side m, see B.2.2

$\varepsilon_{z,n}$ is the total emissivity of the flames on side n, see B.2.2

NOTE Illustrations are given in Figure B.4.

B.2.2 Flame emissivity

(1) If the column is opposite an opening, the flame emissivity ε_z should be determined from the expression for ε given in Annex B of EN 1991-1-2, using the flame thickness λ at the level of the top of the openings. Provided that there is no awning or balcony above the opening λ may be taken as follows:

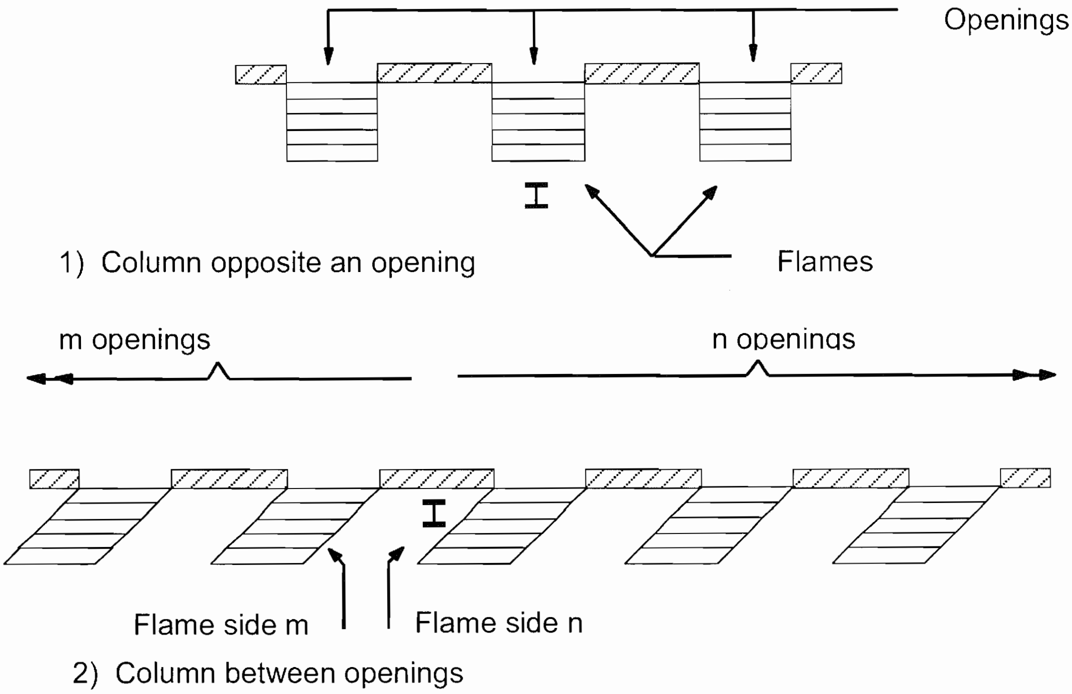
— for the 'no forced draught' condition:

$$\lambda = 2h/3 \tag{B.8a}$$

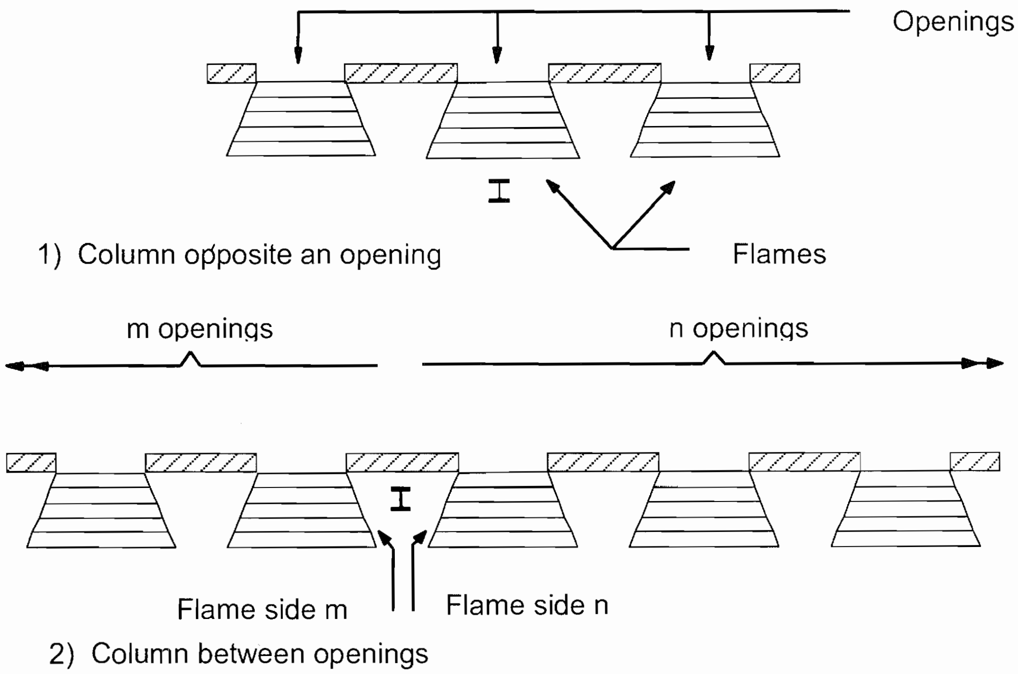
— for the 'forced draught' condition:

$$\lambda = x \text{ but } \lambda \leq hx/z \tag{B.8b}$$

where h, x and z are as given in Annex B of EN 1991-1-2.

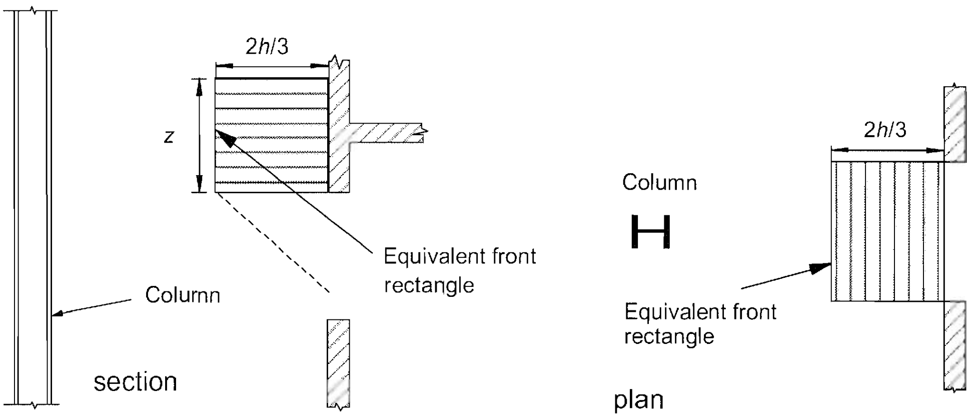


a) 'No forced draught' condition

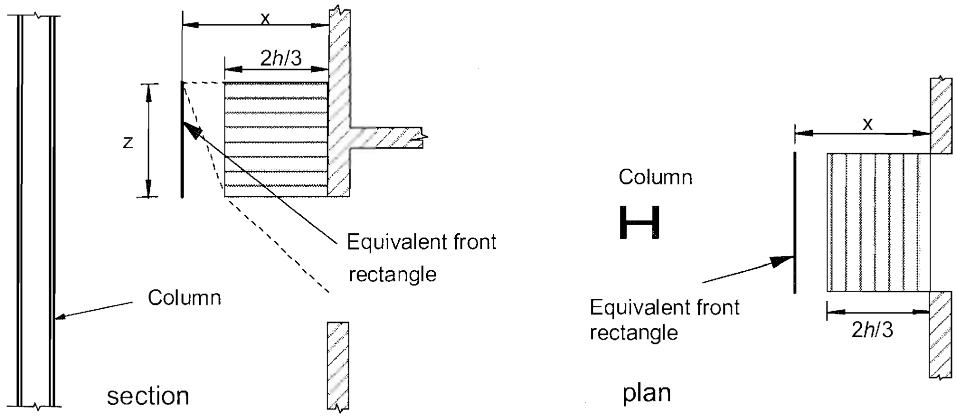


b) 'Forced draught' condition

Figure B.2 — Column positions

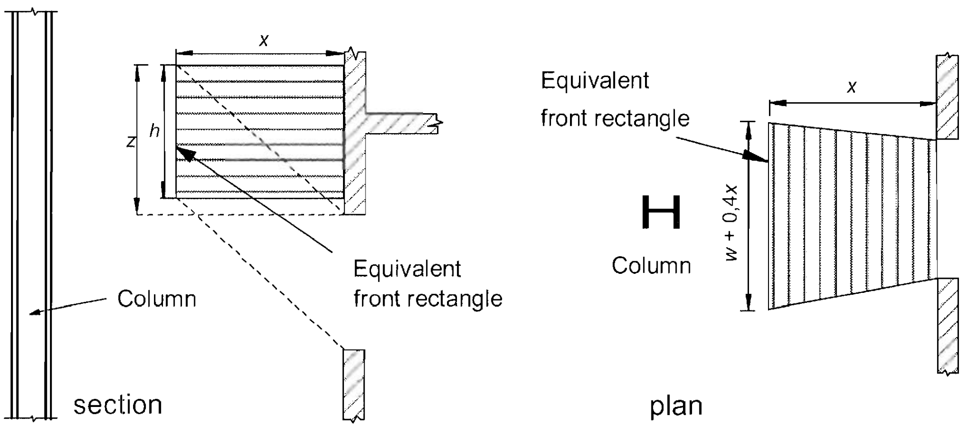


1) wall above and $h < 1{,}25w$



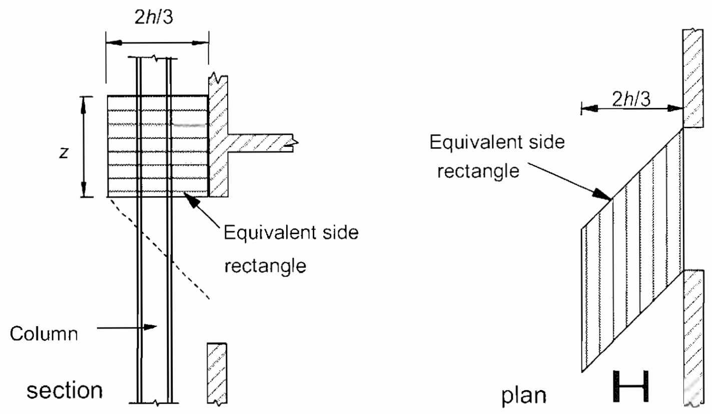
2) wall above and $h > 1{,}25w$ or no wall above

a) 'No forced draught'

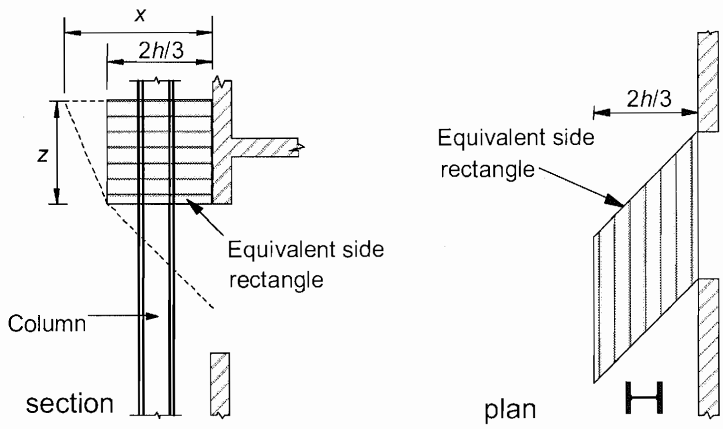


b) 'Forced draught'

Figure B.3 — Column opposite opening

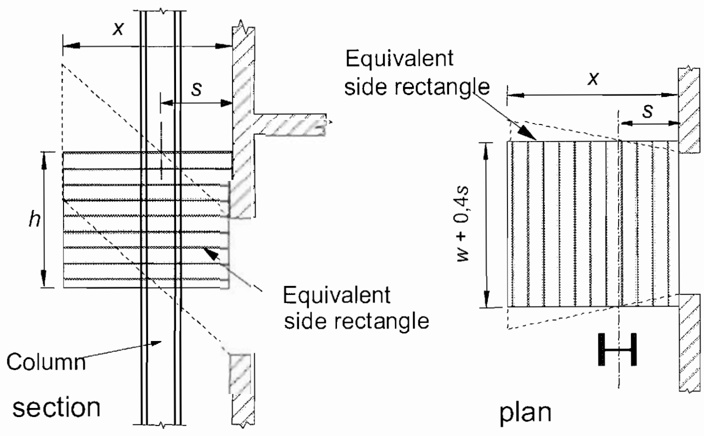


1) wall above and h < 1,25w



2) wall above and h > 1,25w or no wall above

a) 'No forced draught'



b) 'Forced draught'

Figure B.4 — Column between openings

(2) If the column is between two openings, the total emissivities $\varepsilon_{z,m}$ and $\varepsilon_{z,n}$ of the flames on sides m and n should be determined from the expression for ε given in Annex B of EN 1991-1-2 using a value for the total flame thickness λ as follows:

— for side m: $\lambda = \sum_{i=1}^{m} \lambda_i$ (B.9a)

— for side n: $\lambda = \sum_{i=1}^{n} \lambda_i$ (B.9b)

where

m is the number of openings on side m

n is the number of openings on side n

λ_i is the flame thickness for opening i

(3) The flame thickness λ_i should be taken as follows:

— for the 'no forced draught' condition: $\lambda_i = w_i$ (B.10a)

— for the 'forced draught' condition: $\lambda_i = w_i + 0{,}4s$ (B.10b)

where

w_i is the width of the opening i

s is the horizontal distance from the centreline of the column to the wall of the fire compartment, see Figure B.1

B.2.3 Flame temperature

(1) The flame temperature T_z should be taken as the temperature at the flame axis obtained from the expression for T_z given in Annex B of EN 1991-1-2, for the 'no forced draught' condition or the 'forced draught' condition as appropriate, at a distance l from the opening, measured along the flame axis, as follows:

— for the 'no forced draught' condition:

$l = h/2$ (B.11a)

— for the 'forced draught' condition:

— for a column opposite an opening:

$l = 0$ (B.11b)

— for a column between openings l is the distance along the flame axis to a point at a horizontal distance s from the wall of the fire compartment. Provided that there is no awning or balcony above the opening:

$l = sX/x$ (B.11c)

where X and x are as given in Annex B of EN 1991-1-2.

B.2.4 Flame absorptivity

(1) For the 'no forced draught' condition, the flame absorptivity a_z should be taken as zero.

(2) For the 'forced draught' condition, the flame absorptivity a_z should be taken as equal to the emissivity ε_z of the relevant flame, see B.2.2.

B.3 Beam not engulfed in flame

B.3.1 Radiative heat transfer

(1) Throughout B.3 it is assumed that the level of the bottom of the beam is not below the level of the top of the openings in the fire compartment.

(2) A distinction should be made between a beam that is parallel to the external wall of the fire compartment and a beam that is perpendicular to the external wall of the fire compartment, see Figure B.5.

(3) If the beam is parallel to the external wall of the fire compartment, the average temperature of the aluminium member T_m should be determined for a point in the length of the beam directly above the centre of the opening. For this case the radiative heat flux I_z from the flame should be determined from:

$$I_z = \phi_z \varepsilon_z \sigma T_z^4 \quad \text{(B.12)}$$

where

ϕ_z is the overall configuration factor for the flame directly opposite the beam, see B.1.4

ε_z is the flame emissivity, see B.3.2

T_z is the flame temperature from B.3.3 [K]

(4) If the beam is perpendicular to the external wall of the fire compartment, the average temperature in the beam should be determined at a series of points every 100 mm along the length of the beam. The average temperature of the aluminium member T_m should then be taken as the maximum of these values. For this case the radiative heat flux I_z from the flames should be determined from:

$$I_z = (\phi_{z,m} \varepsilon_{z,m} + \phi_{z,n} \varepsilon_{z,n}) \sigma T_z^4 \quad \text{(B.13)}$$

where:

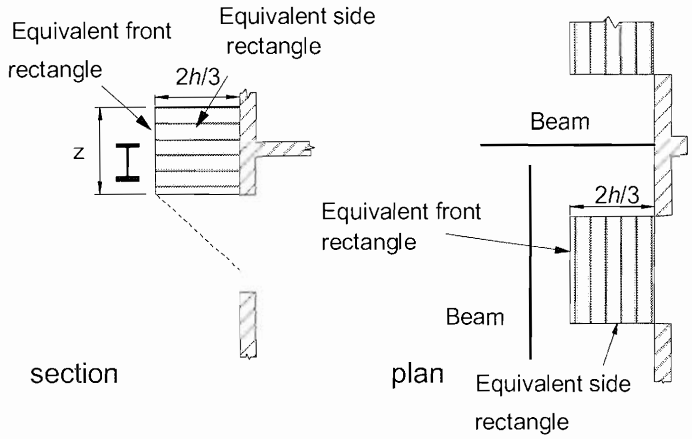
$\phi_{z,m}$ is the overall configuration factor of the beam for heat from flames on side m, see B.3.2

$\phi_{z,n}$ is the overall configuration factor of the beam for heat from flames on side n, see B.3.2

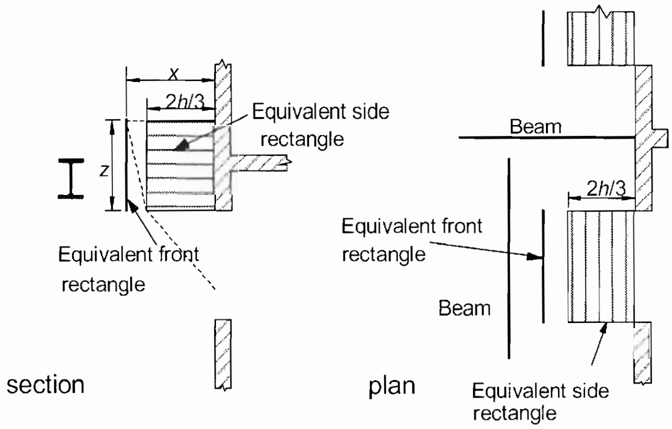
$\varepsilon_{z,m}$ is the total emissivity of the flames on side m, see B.3.3

$\varepsilon_{z,n}$ is the total emissivity of the flames on side n, see B.3.3

T_z is the flame temperature [K], see B.3.4

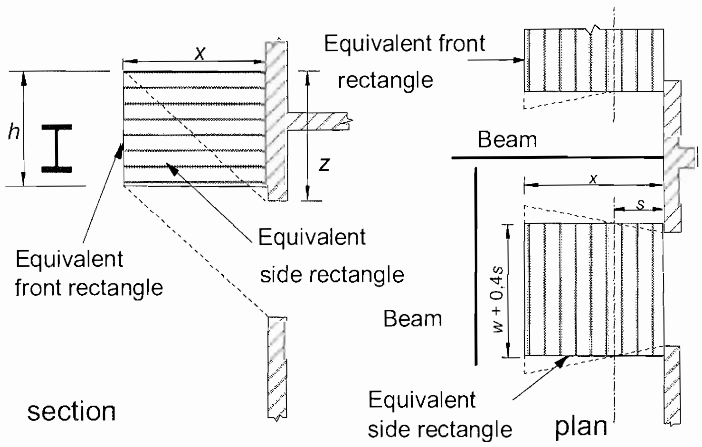


1) wall above and $h < 1{,}25w$



2) wall above and $h > 1{,}25w$ or no wall above

a) 'No forced draught'



b) 'Forced draught'

Figure B.5 — Beam not engulfed in flame

B.3.2 Flame emissivity

(1) If the beam is parallel to the external wall of the fire compartment, above an opening, the flame emissivity ε_z should be determined from the expression for ε given in Annex B of EN 1991-1-2, using a value for the flame thickness λ at the level of the top of the openings. Provided that there is no awning or balcony above the opening λ may be taken as follows:

c) for the 'no forced draught' condition:

$$\lambda = 2h/3 \tag{B.14a}$$

d) for the 'forced draught' condition:

$$\lambda = x \text{ but } \lambda \leq hx/z \tag{B.14b}$$

where h, x and z are as given in Annex B of EN 1991-1-2

(2) If the beam is perpendicular to the external wall of the fire compartment, between two openings, the total emissivities $\varepsilon_{z,m}$ and $\varepsilon_{z,n}$ of the flames on sides m and n should be determined from the expression for ε given in Annex B of EN 1991-1-2 using a value for the flame thickness λ as follows:

a) for side m: $$\lambda = \sum_{i=1}^{m} \lambda_i \tag{B.15a}$$

b) for side n: $$\lambda = \sum_{i=1}^{n} \lambda_i \tag{B.15b}$$

where

m is the number of openings on side m

n is the number of openings on side n

λ_i is the flame thickness for opening i

(3) The flame thickness λ_i should be taken as follows:

a) for the 'no forced draught' condition:

$$\lambda_i = w_i \tag{B.16a}$$

b) for the 'forced draught' condition:

$$\lambda_i = w_i + 0,4\,s \tag{B.16b}$$

where

w_i is the width of the opening i

s is the horizontal distance from the wall of the fire compartment to the point under consideration on the beam, see Figure B.5

B.3.3 Flame temperature

(1) The flame temperature T_z should be taken as the temperature at the flame axis obtained from the expression for T_z given in Annex B of EN 1991-1-2, for the 'no forced draught' or 'forced draught' condition as appropriate, at a distance l from the opening, measured along the flame axis, as follows:

a) for the 'no forced draught' condition:

$$l = h/2 \tag{B.17a}$$

b) for the 'forced draught' condition:

— for a beam parallel to the external wall of the fire compartment, above an opening:

$$l = 0 \tag{B.17b}$$

— for a beam perpendicular to the external wall of the fire compartment, between openings l is the distance along the flame axis to a point at a horizontal distance s from the wall of the fire compartment. Provided that there is no awning or balcony above the opening:

$$l = sX/x \tag{B.17c}$$

where X and x are as given in Annex B of EN 1991-1-2.

B.3.4 Flame absorptivity

(1) For the 'no forced draught' condition, the flame absorptivity a_z should be taken as zero.

(2) For the 'forced draught' condition, the flame absorptivity a_z should be taken as equal to the emissivity ε_z of the relevant flame, see B.3.2.

B.4 Column engulfed in flame

(1) The radiative heat flux I_z from the flames should be determined from:

$$I_z = \frac{(I_{z,1} + I_{z,2})d_1 + (I_{z,3} + I_{z,4})d_2}{2(d_1 + d_2)} \tag{B.18}$$

with:

$$I_{z,1} = C_1 \varepsilon_{z,1} \sigma T_z^4$$

$$I_{z,2} = C_2 \varepsilon_{z,2} \sigma T_z^4$$

$$I_{z,3} = C_3 \varepsilon_{z,3} \sigma T_o^4$$

$$I_{z,4} = C_4 \varepsilon_{z,4} \sigma T_z^4$$

where

$I_{z,i}$ is the radiative heat flux from the flame to column face i

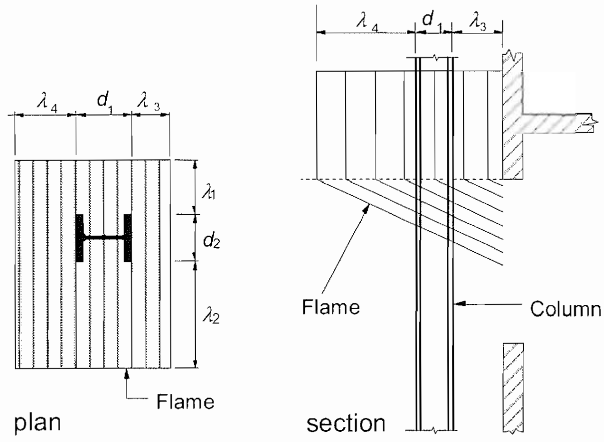
$\varepsilon_{z,i}$ is the emissivity of the flames with respect to face i of the column

i is the column face indicator (1), (2), (3) or (4)

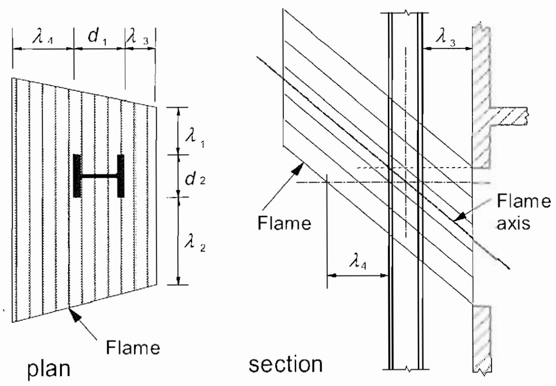
C_i is the protection coefficient of member face i, see B.1.4

T_z is the flame temperature [K]

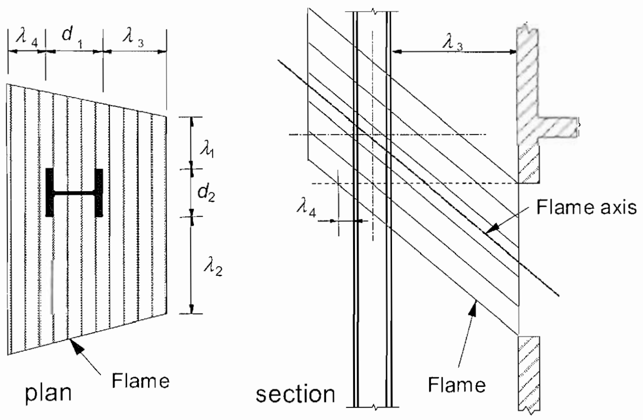
T_o is the flame temperature at the opening [K] from Annex B of EN 1991-1-2



a) 'No forced draught' condition



1) Flame axis intersects column axis below top of opening



2) Flame axis intersects column axis above top of opening

b) 'Forced draught' condition

Figure B.6 — Column engulfed in flame

(2) The emissivity of the flames $\varepsilon_{z,i}$ for each of the faces 1, 2, 3 and 4 of the column should be determined from the expression for ε given in Annex B of EN 1991-1-2, using a flame thickness λ equal to the dimension λ_i indicated in Figure B.6 corresponding to face *i* of the column.

(3) For the 'no forced draught' condition the values of λ_i at the level of the top of the opening should be used, see Figure B.6 (a).

(4) For the 'forced draught' condition, if the level of the intersection of the flame axis and the column centreline is below the level of the top of the opening, the values of λ_i at the level of the intersection should be used, see Figure B.6(b)(1). Otherwise the values of λ_i at the level of the top of the opening should be used, see Figure B.6b) (2), except that if $\lambda_4 < 0$ at this level, the values at the level where $\lambda_4 = 0$ should be used.

(5) The flame temperature T_z should be taken as the temperature at the flame axis obtained from the expression for T_z given in Annex B of EN 1991-1-2 for the 'no forced draught' or 'forced draught' condition as appropriate, at a distance l from the opening, measured along the flame axis, as follows:

a) for the 'no forced draught' condition:

$$l = h/2 \qquad \text{(B.19a)}$$

b) for the 'forced draught' condition, l is the distance along the flame axis to the level where λ_i is measured. Provided that there is no balcony or awning above the opening:

$$l = (\lambda_3 + 0{,}5 d_1) X/x \text{ but } l \leq 0{,}5 hX/z \qquad \text{(B.19b)}$$

where h, X, x and z are as given in Annex B of EN 1991-1-2

(6) The absorptivity a_z of the flames should be determined from:

$$a_z = \frac{\varepsilon_{z,1} + \varepsilon_{z,2} + \varepsilon_{z,3}}{3} \qquad \text{(B.20)}$$

where $\varepsilon_{z,1}$, $\varepsilon_{z,2}$ and $\varepsilon_{z,3}$ are the emissivities of the flame for column faces 1, 2, and 3

B.5 Beam fully or partially engulfed in flame

B.5.1 Radiative heat transfer

B.5.1.1 General

(1) Throughout B.5 it is assumed that the level of the bottom of the beam is not below the level of the top of the adjacent openings in the fire compartment.

(2) A distinction should be made between a beam that is parallel to the external wall of the fire compartment and a beam that is perpendicular to the external wall of the fire compartment, see Figure B.7.

(3) If the beam is parallel to the external wall of the fire compartment, its average temperature T_m should be determined for a point in the length of the beam directly above the centre of the opening.

(4) If the beam is perpendicular to the external wall of the fire compartment, the value of the average temperature should be determined at a series of points every 100 mm along the length of the beam. The maximum of these values should then be adopted as the average temperature of the aluminium member T_m.

(5) The radiative heat flux I_z from the flame should be determined from:

$$I_z = \frac{(I_{z,1} + I_{z,2})d_1 + (I_{z,3} + I_{z,4})\,d_2}{2(d_1 + d_2)} \quad \text{(B.21)}$$

where

$I_{z,i}$ is the radiative heat flux from the flame to beam face i

i is the beam face indicator (1), (2), (3) or (4)

B.5.1.2 'No forced draught' condition

(1) For the 'no forced draught' condition, a distinction should be made between those cases where the top of the flame is above the level of the top of the beam and those where it is below this level.

(2) If the top of the flame is above the level of the top of the beam the following equations should be applied:

$$I_{z,1} = C_1 \varepsilon_{z,1} \sigma T_o^4 \quad \text{(B.22a)}$$

$$I_{z,2} = C_2 \varepsilon_{z,2} \sigma T_{z,2}^4 \quad \text{(B.22b)}$$

$$I_{z,3} = C_3 \varepsilon_{z,3} \sigma(T_{z,1}^4 + T_{z,2}^4)/2 \quad \text{(B.22c)}$$

$$I_{z,4} = C_4 \varepsilon_{z,4} \sigma(T_{z,1}^4 + T_{z,2}^4)/2 \quad \text{(B.22d)}$$

where:

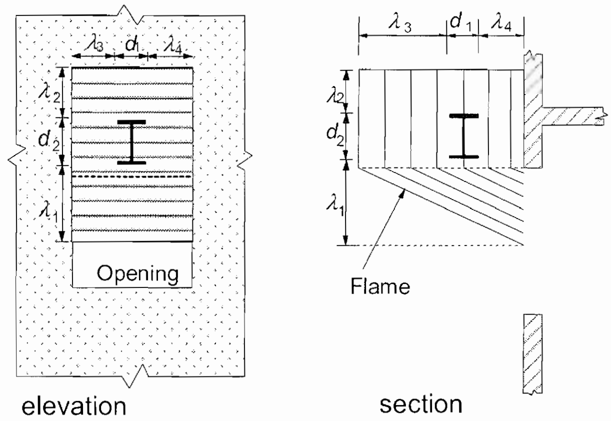
$\varepsilon_{z,i}$ is the emissivity of the flame with respect to face i of the beam, see B.5.2

T_o is the temperature at the opening [K] from Annex B of EN 1991-1-2

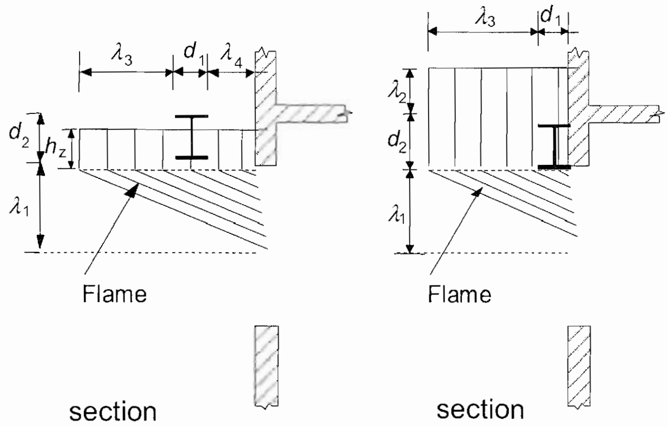
$T_{z,1}$ is the flame temperature [K] from Annex B of EN 1991-1-2, level with the bottom of the beam

$T_{z,2}$ is the flame temperature [K] from Annex B of EN 1991-1-2, level with the top of the beam

(3) In the case of a beam parallel to the external wall of the fire compartment C_4 may be taken as zero if the beam is immediately adjacent to the wall, see Figure B.7.

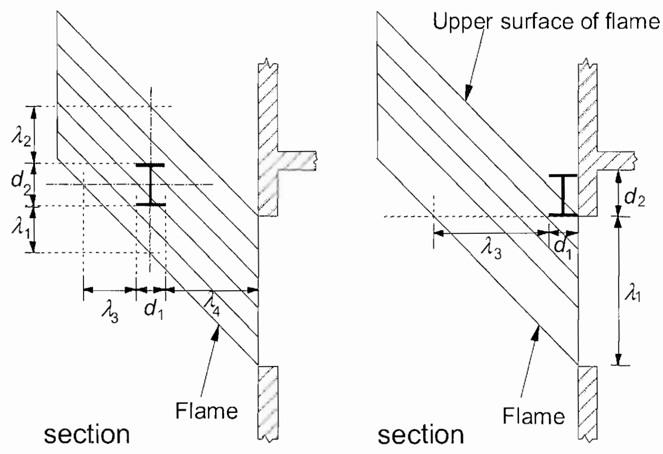


1) Beam perpendicular to wall 2) Beam parallel to wall



3) Top of flame below top of beam 4) Beam immediately adjacent to wall

a) 'No forced draught' condition



1) Beam not adjacent to wall 2) Beam immediately adjacent to wall

b) 'Forced draught' condition

Figure B.7 — Beam engulfed in flame

(4) If the top of the flame is below the level of the top of the beam the following equations should be applied:

$$I_{z,1} = C_1 \varepsilon_{z,1} \sigma T_o^4 \quad \text{(B.23a)}$$

$$I_{z,2} = 0 \quad \text{(B.23b)}$$

$$I_{z,3} = (h_z / d_2) C_3 \varepsilon_{z,3} \sigma (T_{z,1}^4 + T_x^4)/2 \quad \text{(B.23c)}$$

$$I_{z,4} = (h_z / d_2) C_4 \varepsilon_{z,4} \sigma (T_{z,1}^4 + T_x^4)/2 \quad \text{(B.23d)}$$

where

T_x is the flame temperature at the flame tip [813 K]

h_z is the height of the top of the flame above the bottom of the beam

B.5.1.3 'Forced draught' condition

(1) For the 'forced draught' condition, in the case of beams parallel to the external wall of the fire compartment a distinction should be made between those immediately adjacent to the wall and those not immediately adjacent to it.

NOTE Illustrations are given in Figure B.7.

(2) For a beam parallel to the wall, but not immediately adjacent to it, or for a beam perpendicular to the wall the following equations should be applied:

$$I_{z,1} = C_1 \varepsilon_{z,1} \sigma T_o^4 \quad \text{(B.24a)}$$

$$I_{z,2} = C_2 \varepsilon_{z,2} \sigma T_{z,2}^4 \quad \text{(B.24b)}$$

$$I_{z,3} = C_3 \varepsilon_{z,3} \sigma (T_{z,1}^4 + T_{z,2}^4)/2 \quad \text{(B.24c)}$$

$$I_{z,4} = C_4 \varepsilon_{z,4} \sigma (T_{z,1}^4 + T_{z,2}^4)/2 \quad \text{(B.24d)}$$

(3) If the beam is parallel to the wall and immediately adjacent to it, only the bottom face should be taken as engulfed in flame but one side and the top should be taken as exposed to radiative heat transfer from the upper surface of the flame, see Figure B.7(b)(2). Thus:

$$I_{z,1} = C_1 \varepsilon_{z,1} \sigma T_o^4 \quad \text{(B.25a)}$$

$$I_{z,2} = \phi_{z,2} C_2 \varepsilon_{z,2} \sigma T_{z,2}^4 \quad \text{(B.25b)}$$

$$I_{z,3} = \phi_{z,3} C_3 \varepsilon_{z,3} \sigma (T_{z,1}^4 + T_{z,2}^4)/2 \quad \text{(B.25c)}$$

$$I_{z,4} = 0 \quad \text{(B.25d)}$$

where $\phi_{z,i}$ is the configuration factor relative to the upper surface of the flame, for face i of the beam, from Annex G of [AC1) EN1991-1-2 (AC1].

B.5.2 Flame emissivity

(1) The emissivity of the flame $\varepsilon_{z,i}$ for each of the faces 1, 2, 3 and 4 of the beam should be determined from the expression for ε given in Annex B of EN 1991-1-2, using a flame thickness λ equal to the dimension λ_i indicated in Figure B.7 corresponding to face *i* of the beam.

B.5.3 Flame absorptivity

(1) The absorptivity of the flame a_z should be determined from:

$$a_z = 1 - e^{0,3h} \qquad \text{(B.26)}$$

Bibliography

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