Fire Design of Steel Structures
2nd Edition

Eurocode 1: Actions on Structures
Part 1-2: Actions on structures exposed to fire
Eurocode 3: Design of Steel Structures
Part 1-2: Structural fire design

Jean-Marc Franssen
Paulo Vila Real

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FIRE DESIGN OF STEEL STRUCTURES

2ND EDITION

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FIRE DESIGN OF STEEL STRUCTURES

2ND EDITION

Eurocode 1: Actions on structures
Part 1-2 – General actions – Actions on structures exposed to fire
Eurocode 3: Design of steel structures
Part 1-2 – General rules – Structural fire design

Jean-Marc Franssen
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Design of Steel Structures

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FOREWORD

Designing for fire is an important and essential requirement in the design process of buildings and civil engineering structures. Within Europe the fire resistance requirements for buildings are specified in the national Building Regulations. All buildings must meet certain functional requirements and these are usually linked to the purpose and height of the building. For the purpose of this publication, the most important requirement is for the building to retain its stability for a reasonable period. This requirement has traditionally been linked to the required time of survival in the standard fire test. The most common method of designing a steel structure for the fire condition is to design the building for the ambient temperature loading condition and then to cover the steel members with proprietary fire protection materials to ensure that a specific temperature is not exceeded. Although this remains the simplest approach for the majority of regular steel framed buildings, one of the drawbacks with this approach is that it is often incorrectly assumed that there is a one to one correspondence between the survival time in the standard fire test and the survival time in a real fire. This is not the case and real fire can be more or less severe than the standard fire test depending on the characteristics of the fire enclosure.

The fire parts of the Eurocodes set out a new way of approaching structural fire design. To those more familiar with the very simple prescriptive approach to the design of structures for fire, the new philosophy may appear unduly complex. However, the fire design methodology in the Eurocodes affords the designer much greater flexibility in his approach to the subject. The options available range from a simple consideration of isolated member behaviour subject to a standard fire to a consideration of the physical parameters influencing fire development coupled with an analysis of the entire building.

The Eurocode process can be simplified into three components consisting of the characterisation of the fire model, a consideration of the temperature distribution within the structure and an assessment of the structural response to the fire. Information on thermal actions for temperature analysis is given in EN 1991-1-2 and the method used to calculate the temperature rise of structural steelwork (either protected or unprotected) is found in EN 1993-1-2. The design procedures to establish structural resistance are set out in EN 1993 but the actions (or loads) to be used for the assessment are taken from the relevant parts of EN 1991.

This publication follows this sequence of steps. Chapter 2 explains how to calculate the mechanical actions (loads) in the fire situation based on the information given in EN 1990 and EN 1991. Chapter 3 presents the models that may be used to represent the thermal actions. Chapter 4 describes the procedures that may be used to calculate the temperature of the steelwork from the temperature of the compartment and Chapter 5 shows how the information given in EN 1993-1-2 may be used to determine the load bearing capacity of the steel structures. The methods used to evaluate the fire resistance of bolted and welded connections are described in Chapter 7. In all of these chapters the information given in the Eurocodes is presented in a practical and usable manner. Each chapter also contains a set of easy to follow worked examples.

Chapter 8 describes a computer program called ‘Elefir-EN’ which is based on the simple calculation model given in the Eurocode and allows designers to quickly and accurately calculate the performance of steel components in the fire situation. Chapter 9 looks at the issues that a designer may be faced with when assessing the fire resistance of a complete building. This is done via a case study and addresses most of the concepts presented in the earlier chapters. Finally the annexes give basic information on the thermal and mechanical properties for both carbon steel and stainless steel.

The concepts and fire engineering procedures given in the Eurocodes may seem complex to those more familiar with the prescriptive approach. This publication sets out the design process in a logical manner giving practical and helpful advice and easy to follow worked examples that will allow designers to exploit the benefits of this new approach to fire design.

David Moore
BCSA Director of Engineering

PREFACE TO THE 2ND EDITION

The first edition of *Fire Design of Steel Structures* was published by ECCS as paperback in 2010. Since 2012, this publication is also available in electronic format as an e-book. Nevertheless, the interest for this publication was so high that it appeared rapidly that the paper copies would be sold out within a short time and a second edition would have to be printed.

The authors took the opportunity of this second edition to review their own manuscript. The standards that are described and commented in this book, namely EN 1991-1-2 and 1993-1-2, are still in application in the same versions as those that prevailed at the time of writing the first edition. It was nevertheless considered that an added value would be given by, first, rephrasing some sentences or sections that had generated questions by some readers but, above all, adding some new material for the benefit of completeness.

The new material namely comprises:

- A section dealing with the thermal response of steel members under several separate simultaneous localised fires, including one worked example with multiple fire scenarios in a car park (Chapter 4);
- An important section on classification of cross sections. The case of combined bending and axial force, including one worked example comparing different methodologies to obtain the position of the neutral axis, has been added (Chapter 5);
- A worked example of a beam-column with Class 4 cross section (Chapter 5);
- A new section with comparisons between the simple and the advanced calculation models in Chapter 6 (shadow factor – including one example, buckling curves and adaptation factors κ_1 and κ_2);
- New references have been included.

Jean-Marc Franssen
Paulo Vila Real
June 2015

PREFACE 1ST EDITION

When a fire breaks out in a building, except in very few cases, the structure has to perform in a satisfactory manner in order to meet various objectives such as, e.g., to limit the extension of the fire, to ensure evacuation of the occupant or to allow safe operations by the fire brigade. Steel structures are no exception to this requirement.

Eurocode 3 proposes design methods that allow verifying whether the stability and resistance of a steel structure is ensured. A specific Part 1-2 of Eurocode 3 is dedicated to the calculation of structures subjected to fire. Indeed, the fact that the stress-strain relationship becomes highly non-linear at elevated temperatures, plus the fact that heating leads to thermal expansion with possible restraint forces, make the rules derived for ambient temperature inaccurate in the fire situation.

After a long evolution and maturation, the Eurocodes have received the status of European standards. The fire part of Eurocode 3 is EN 1993-1-2. This makes the application of these rules mandatory in member states of the European Community. In many other parts of the world, these standards are considered as valuable pieces of information and their application may be rendered mandatory, either by law or by contractual imposition.

Nevertheless, standards are not written with pedagogic objectives. Yet, for a designer who has not been involved in the research projects that are at the base of the document, some questions may arise when the rules have to be applied to practical cases.

The objective of this book is to explain the rules, to give some information about the fundamental physics that is at the base of these rules and to show by examples how they have to be applied in practice. It is expected that a designer who reads this book will reduce the probability of doing a non appropriate application of the rules and, on the contrary, will be in a better position to make a design in a situation that has not been explicitly foreseen in the code.

A design in the fire situation is based on load combinations that are different from those considered at room temperatures. Actions on structures from fire exposure are classified as accidental actions and the load combinations for the fire situation are given in the Eurocode, EN 1990. The thermal environment created by the fire must also be defined in order to calculate the temperature elevation in the steel sections and different models are given in part 1.2 of Eurocode 1 for representing the fire. In order to encompass in one single document all aspects that are relevant to the fire design of steel structures, this book deals with the fire part of Eurocode 1 as well as that of Eurocode 3.

The requirements, i.e., for example, the duration of stability or resistance that has to be ensured to the structure, is not treated in the Eurocodes. This aspect is indeed very often imposed by the legal environment, especially when using a prescriptive approach, or has to be treated separately by, for example, a risk analysis based on evacuation time. In line with the Eurocodes, this book does not deal with the requirement.

A computer program, Elefir-EN, which has been developed for the fire design of structural members in accordance with the simple calculation models given in the Eurocodes, is supplied with this book. The software is an essential tool for structural engineers in the design office, enabling quick and accurate calculations to be produced, reducing design time and the probability of errors in the application of the equations. It can also be used by academics and students.

The program has been carefully checked for reliability and do not contain any known errors, but the authors and the publisher assume no responsibility for any damage resulting from the use of this program. No warranty of any type is given or implied concerning the correctness or accuracy of any results obtained from the program. It is the responsibility of the program user to independently verify any analysis results. Please contact the authors if any errors are discovered. The program is licensed to the purchasers of this book who are strongly encouraged to register in its web site so that any updated version can be delivered.

Jean-Marc Franssen
Paulo Vila Real
March 2010

NOTATIONS

Latin lower case letters

b	material parameter in the walls, width of a steel section, width of a plate
c	specific heat, width of a plate in an open steel section
c_a	specific heat of steel
c_p	specific heat of protection material
d	diameter of a circular hollow section
d_{eq}	characteristic size of a structural member
d_f	flame thickness
d_p	thickness of a fire protection material
f	factor for the effect of non-uniform bending moment distribution on lateral torsional buckling
f_b	stress due to bending moment
f_c	stress due to axial force
$f_{0.2p,\theta}$	0.2% proof strength
$f_{p,\theta}$	limit of proportionality of steel at temperature θ
f_u	ultimate strength at 20 ºC
$f_{u,\theta}$	ultimate strength of steel at temperature θ
f_y	yield strength at 20 ºC
$f_{y,\theta}$	effective yield strength of steel at temperature θ
h	height of an opening, height of a radiating surface, height of a steel section, height of a component being considered above the bottom of the beam
$\dot{h}$	impinging heat flux
$\dot{h}_{net}$	heat flux at the surface of a steel element
h_{eq}	averaged height of the vertical openings
h_w	depth of the web
i	radius of gyration of a cross section
k	multiplication factor in the parametric fire model

$k_{2\%,\theta}$	correction factor for the determination of the yield strength of stainless steel at elevated temperature
$k_{b,\theta}$	reduction factor for bolts
$k_{p0.2\theta}$	reduction factor for the 0.2% proof strength
$k_{E,\theta}$	reduction factor for the Young's modulus
$k_{E,\theta,com}$	reduction factor for the Young’s modulus at the maximum steel temperature in the compression flange
$k_{p,\theta}$	reduction factor for the limit of proportionality
k_{sh}	correction factor for the shadow effect
$k_{u,\theta}$	reduction factor for tensile strength of stainless steel at elevated temperature
k_w	effective length factor referring to end warping
$k_{w,\theta}$	reduction factor for welds
$k_{y,\theta}$	reduction factor for the effective yield strength
$k_{y,\theta,com}$	reduction factor for the yield strength of steel at the maximum temperature in the compression flange
$k_{y,\theta,web}$	reduction factor for the yield strength at the web temperature θ_{web}
k_z	effective length factor referring to end rotation on plan
k_θ	reduction factor for a strength or deformation property
k_σ	plate buckling factor
l	length of a member
l_{fi}	buckling length in fire situation
p	moisture content of a protection material
q_c	heat flux by convection
q_{cr}	combine heat flux by convection and radiation
q_{Ed}	design value of a distributed load in the normal situation
$q_{f,d}$	design value of the fire load density related to the floor area
$q_{fi,Ed}$	design value of a distributed load in the fire situation
q_r	heat flux by radiation
$q_{t,d}$	design value of the fire load density related to the total area of enclosure
r	horizontal distance from the fire plume, distance between an emitting an a receiving surface, root fillet
t	time, thickness of the walls in a hollow section, plate thickness in general
t^*	expanded time in the parametric fire model
t_f	flange thickness

$t_{fi,d}$	design value of the fire resistance
$t_{fi,req}$	required fire resistance time
t_{lim}	limit time in the parametric fire model
$t_{\max}$	duration of the heating phase in the parametric fire model
t_v	length of the horizontal plateau in a heating curve
t_w	thickness of the web
w	width of a radiating surface
w_t	sum of the window widths
x	cartesian coordinate
y	parameter in a localised fire model, cartesian coordinate
z	vertical elevation in a fire plume
z'	vertical position of the virtual heat source
z_g	level of the application of the load
z_i	distance from the plastic neutral axis to the centroid of an elemental area
z_0	vertical position of the virtual origin of the fire source

Latin upper case letters

A	area of a wall, cross section area of a steel member, surface area of a member exposed to the heat flux
A_c	gross cross sectional area of a plate
$A_{c,eff}$	effective area of the compression zone of a plate
A_d	indirect fire actions
A_m	surface area of a member exposed to the heat flux
A_m/V	section factor of unprotected sections
A_p/V	section factor of protected sections
$[A_m/V]_b$	box value of the section factor
A_f	floor area
A_{fire}	area of a fire source
A_p	appropriate area of fire protection material per unit length of a member
A_t	total area of an enclosure, including the openings
A_v	area of a vertical opening, shear area
C	matrix of capacity, compression force
C'	compression force
D	the diameter of a fire, depth of a beam

D/W	ratio for the external members
E	Young’s modulus of steel
$E_{a,\theta}$	Young’s modulus of steel at temperature θ
E_d	effects of actions in the normal situation
$E_{fi,d}$	design effect of actions for the fire situation
$E_{fi,d,t}$	design effect of actions for the fire situation at time t
EI_z	flexural stiffness of a section
EI_w	warping stiffness of a section
F	thermal load vector
$F_{b,Rd}$	design bearing resistance of bolts at normal temperature
$F_{b,t,Rd}$	design bearing resistance of bolts in the fire situation
$F_{t,Rd}$	design tension resistance of bolts at normal temperature
$F_{ten,t,Rd}$	design tension resistance of bolts in the fire situation
$F_{v,Rd}$	design shear resistance of a bolt per shear plane in the normal situation
$F_{v,t,Rd}$	fire design resistance of a bolt loaded in shear
$F_{w,Rd}$	design weld resistance per unit length at normal temperature
$F_{w,t,Rd}$	design weld resistance per unit length in the fire situation
G	shear modulus
G_k	characteristic value of a permanent action
GI_t	torsional stiffness of a section
H	altitude above mean sea level, vertical distance from the fire source to the ceiling
I	second moment of area
I_f	radiative heat flux from an opening
I_t	torsion constant
I_w	warping constant
I_z	second moment of area about the minor axis, radiative heat flux from a flame
K	matrix of conductivity
L	column length, unrestrained length of the beam
L_f	vertical length of a flame
L_h	horizontal flame length
L_L	vertical extension of a flame above the top of the window
L_X	distance from the window
M	bending moment
$M_{b,fi,t,Rd}$	design lateral-torsional buckling resistance moment at time t

M_{cr}	elastic critical moment for lateral-torsional buckling
M_{el}	elastic moment
M_{Ed}	design value of a bending moment in the normal situation
$M_{fi,Ed}$	design value of a bending moment in the fire situation
$M_{fi,t,Rd}$	design value of bending moment resistance in the fire situation
$M_{fi,\theta,Rd}$	design moment resistance of a cross section with a uniform temperature θ_a
$M_{N,fi,Rd}$	design plastic moment resistance reduced due to the axial force
M_{pl}	plastic moment
M_Q	maximum moment due to lateral load only
M_{Rd}	design resistance for bending for normal temperature design
$M_{y,V,fi,Rd}$	design plastic resistance moment in fire situation, allowing for the shear force effect
N	axial force
$N_{b,fi,Ed}$	design value of the compression force in fire situation
$N_{b,fi,t,Rd}$	design buckling resistance at time t of a compression member
$N_{b,fi,\theta,Rd}$	design resistance of a compression member, with a uniform steel temperature θ_a
$N_{fi,Ed}$	design value of axial force in the fire situation
$N_{fi,t,Rd}$	design value of axial resistance force in the fire situation
$N_{fi,\theta,Rd}$	design resistance of a tension member with a uniform temperature θ_a
N_{Rd}	design resistance of the cross section for normal temperature
O	opening factor of an opening
P	perimeter of a section exposed to the fire, prestressing load
Q	rate of heat release of a fire
$\dot{Q}$	internal heat source
Q_c	convective part of the rate of heat release
Q_D^*	non-dimensional rate of heat release, related to D
Q_H^*	non-dimensional rate of heat release, related to H
Q_k	characteristic value of a variable action
$Q_{k,1}$	characteristic value of the leading variable action
R	fire resistance criterion for load bearing capacity
$R_{fi,d,t}$	design value of the resistance in the fire situation at time t
RHR_f	maximum rate of heat release per square meter
T	tension force
T_f	temperature in the fire compartment

T_W	flame temperature at the window
T_Z	temperature of the flame along the axis, flame temperature
V	volume of the member per unit length
$V_{fi,Ed}$	design value of a shear force in fire situation
$V_{fi,t,Rd}$	design shear resistance at time t
$V_{pl,Rd}$	design plastic shear resistance of a gross cross section for normal temperature design
V_{Rd}	design shear resistance of a gross cross section for normal temperature design
$W_{el,y}$	elastic section modulus
$W_{pl,y}$	plastic section modulus
W_2	size of the fire compartment perpendicular to wall 1
$X_{d,fi}$	design values of mechanical material properties in fire situation
X_k	characteristic value of a strength or deformation property

Greek lower case letters

α	parameter for time integration, convective heat transfer coefficient, imperfection factor for buckling curves or for lateral torsional buckling
α_c	coefficient of convection
α_{cr}	combined convection and radiation coefficient
α_f	absorptivity of a flame
α_r	coefficient of heat transfer by radiation
$\beta_{M,y}$	equivalent uniform moment factor about the y-y axis
$\beta_{M,z}$	equivalent uniform moment factor about the z-z axis
$\beta_{M,LT}$	equivalent uniform moment factor for lateral torsional buckling
γ_G	partial safety factor for the permanent action
$\gamma_{M,fi}$	partial safety factor for the relevant material property, for the fire situation
γ_{M0}	partial safety factor for the resistance of cross sections
$\gamma_{Q,1}$	partial safety factor for the leading variable action
ε	emissivity, parameter for section classification
ε_f	emissivity of a fire, emissivity of a flame
ε_m	surface emissivity of a member
$\varepsilon_{p,\theta}$	strain at the proportional limit at elevated temperature
$\varepsilon_{y,\theta}$	yield strain at elevated temperature

$\varepsilon_{t,\theta}$	limiting strain for yield strength at elevated temperature
$\varepsilon_{u,\theta}$	ultimate strain at elevated temperature
η_{fi}	reduction factor for the loads in the fire situation
θ	temperature
$\theta_{a,com}$	maximum temperature in the compression flange
$\theta_{a,cr}$	critical temperature of steel
$\theta_{a,\max}$	maximum steel temperature in a section
$\theta_{cr,d}$	design value of the critical temperature
θ_d	design value of steel temperature
θ_g	gas temperature
θ_h	temperature at height h of the steel beam
θ_m	surface temperature of a steel member
$\theta_{\max}$	gas temperature at the end of the heating phase
θ_r	radiation temperature of the fire environment
$\theta_{(z)}$	temperature in a fire plume
θ_{web}	average temperature of a web
θ_0	bottom flange temperature of a steel beam remote from the connection
θ_∞	surrounding ambient temperature
k_1	adaptation factor for non-uniform temperature across the cross section
k_2	adaptation factor for non-uniform temperature along the beam
λ	thermal conductivity, member slenderness
λ_f	effective thermal conductivity of a fire protection material
λ_1	eulerian slenderness
λ_a	thermal conductivity of steel
λ_p	thermal conductivity of protection material
$\bar{\lambda}$	non-dimensional slenderness at room temperature
$\bar{\lambda}_{LT}$	non-dimensional slenderness for lateral torsional buckling
$\bar{\lambda}_p$	normalised plate slenderness
$\bar{\lambda}_\theta$	non-dimensional slenderness for the temperature θ_a
μ_0	degree of utilization
ν	Poisson’s ratio
ρ	specific density, reduction factor for plate buckling
ρ_a	specific density of steel
σ	Stephan Boltzmann constant, equal to 5.67×10^{-8} W/m²K^4

σ_c	compression stress
σ_{cr}	elastic critical buckling stress
σ_t	tension stress
τ_F	free burning duration time
χ_{fi}	reduction factor for flexural buckling in the fire design situation
$\chi_{LT,fi}$	reduction factor for lateral-torsional buckling in the fire design situation
ψ	ratio between tension and compression stress, ratio between bending moments at both ends of a member
ψ_1	coefficient for the frequent value of an action
ψ_2	coefficient for the quasi-permanent value of an action
ψ_{fi}	coefficient for the variable loads in the fire situation, equal to $\psi_1 \, or \, \psi_2$

Greek upper case letters

Γ	expansion coefficient in the parametric fire model
D	prefix for increment
ϕ	amount of heat stored in the protection
ϕ_f	overall configuration factor of a member from an opening
ϕ_{pl}	rotation needed to form a fully plastic stress distribution
Φ	geometrical configuration factor

Chapter 1

INTRODUCTION

1.1. RELATIONS BETWEEN DIFFERENT EUROCODES

The structural Eurocodes are a set of reference documents recognised by the Member States of the European Community and of the European Free Trade Association as a suitable means for demonstrating the compliance of building structures with the essential requirements listed in the Council Directive 89/106/CEE on construction products, in particular essential requirement No. 1, mechanical resistance and stability, and essential requirement No. 2, safety in case of fire.

EN 1990 forms the basic document of all Eurocodes because it gives the basis of design, i.e., the principles and the requirements for safety, serviceability and durability of structures. It is thus the first document to read when the fire resistance of a structure has to be evaluated.

The Eurocode philosophy is based on the concept of limit states, either ultimate limit states or serviceability limit states. The occurrence of limit states is verified according to a semi-probabilistic approach. This means that deterministic verifications are being carried out on the base of design values of applied loads and material strength. The design values are obtained from characteristic values, corresponding to 5% or 95% probability of occurrence, multiplied or divided by partial safety factors. The partial safety factors have been calibrated by the code writers to ensure that the probability of occurrence of the limit states is lower than a defined accepted probability, but the real probability of occurrence in a particular design is not known to the designer.

The fire resistance of a structure can be assessed using the Eurocodes provided the structure has been designed according to the rules given in the

Eurocodes for the ambient temperature situation. The design at room temperature is based on EN 1991, where the actions on structures are defined independently of the material of the structure. The mechanical behaviour of steel structures in buildings at room temperature is assessed on the basis of EN 1993-1-1.

In the fire situation, the combinations of actions are different from those at room temperature. EN 1991-1-2 gives the combinations for mechanical actions that have to be applied to the structure in the fire situation, as well as the fire actions, i.e., the thermal environment created by the fire. This Eurocode is independent of the material of the structure. Characteristic values of the loads are required to determine the mechanical load combinations applied to the structure; the characteristic values are given in EN 1991-1-1, 1991-1-3 and 1991-1-4.

For steel structures, EN 1993-1-2 gives the rules for calculating the temperature development in the structure together with the rules for calculating the mechanical behaviour of the structure at elevated temperatures.

For composite steel-concrete structures, EN 1994-1-1 should be used for assessing the mechanical behaviour at ambient temperature and EN 1994-1-2 should be used to determine the behaviour, thermal and mechanical, in the fire situation.

Fig. 1.1 shows the relationships between the different Eurocodes in a schematic way.

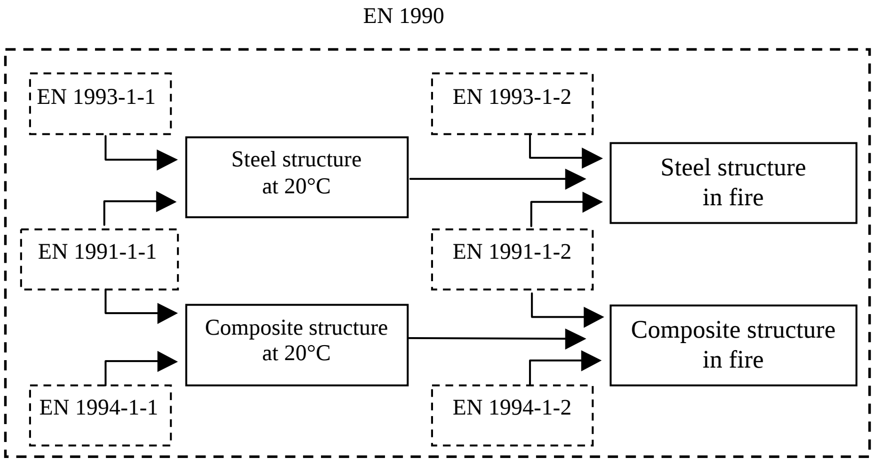

Figure 1.1 – Relationships between different Eurocodes