Design of Fire-resistant Concrete Structures

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Kristian Dahl Hertz

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About the author

Kristian Dahl Hertz MSc, PhD is a professor in the design of building structures at the Department of Civil Engineering at the Technical University of Denmark (DTU). He has also a background in firefighting as a lieutenant of the reserve in civil defence and as a part-time consulting engineer for M. Folmer Andersen Ltd. Here, he designed building structures for the Ministry of Foreign Affairs of Saudi Arabia, the Royal Theatre in Copenhagen, the National Bank of Iraq, the Parliament of Greenland, factories and domestic buildings.

Kristian began teaching in structural fire safety design at DTU in 1978 and, for 16 years, was a regular visiting professor at London City University. After completing his PhD (*Properties of Fire Exposed Concrete*) in 1980, he became a part-time associate professor and started developing methods for the design of fire-resistant concrete structures, which is the subject of this book.

In 1999 he completed a Master's degree in Fire Safety at DTU. Throughout the 1990s he also served as a head of department and merged 14 small DTU departments into the Department of Civil Engineering. At the same time, he was active in code writing and implemented some of the methods for designing concrete structures for fire exposure in the Danish and European codes.

In 2009, Kristian invented super-light structures and pearl-chain technology. These light and fire-resistant concrete structures are now applied in a number of countries.

Notation

A	area of openings of a compartment
A_i	area of opening i
A_c	area of concrete cross-section
A_s	area of steel cross-section
A_{tot}	total enclosing surface area of a compartment
a	thermal diffusivity
a	parameter proportional to ε_c
a_c	damaged zone of a cross-section
a_o	a for ε_o instead of ε_c
a_u	ultimate value of a
B	coefficient of total deflection
B_f	width of flange of T-shaped cross-section
b	thermal inertia
b_o	b for $a = a_o$
C	thickness of cross-section
C	thickness of cover
C	arbitrary constant
C_{eff}	effective width ($= \eta^{4/3} C$)
C'	half period of a fire heat pulse
C_i	constant of number i
c	reduced thickness of cross-section
c_c	cover thickness
c_p	heat capacity
D'	thermal amplitude
D_s	diameter of reinforcing steel
d	depth of insulation on a cross-section
d_c	depth of force of compression zone
d_g	distance to centre of gravity from compressed edge
d_N	depth of normal force N
d_P	depth of prestressing force P
d_{P+N}	depth of the resultant of P and N
d_s	depth of steel reinforcement
$d_{s,\text{ave}}$	average of d_s
d'_s	depth of steel opposite the steel at d_s
dr	increment of radial coordinate
E	modulus of elasticity (E-modulus)
E'	constant temperature of a fire
E_c	E-modulus of concrete
E_0	initial tangent modulus
E_{c0}	initial tangent modulus of concrete
E_{c020}	E_{c0} at 20°C
E_{c20}	E_c at 20°C
E_{cM}	E-modulus of concrete at the midpoint

E_P	tangent modulus of a prestressed steel
E_s	E-modulus of steel
E_{s20}	E_s at 20°C
EA_c	axial stiffness of concrete section
EA_s	axial stiffness of steel section
EI_c	flexural stiffness of concrete section
EI_s	flexural stiffness of steel section
e	eccentricity
e_{load}	eccentricity of applied load
e_{th}	thermal eccentricity including transience
e_{tr}	additional eccentricity from transient thermal expansion
F	force
F_c	force of a concrete cross-section
F_{cE}	Euler force of a concrete column
F_{cr}	critical force
F_{crc}	F_{cr} of a plain concrete column
F_{cu}	ultimate force of a concrete cross-section
F_E	Euler force (column strength with elastic working curve)
F_{load}	force load
F_R	Rankine force (column strength with curved working curve)
F_s	force of a steel cross-section
F_{sE}	Euler force of a steel column
F_{su}	ultimate force of a steel cross-section
F_u	ultimate force of a cross-section
F_w	force in web of a T-shaped cross-section
f	strength
f_{cc}	compressive strength of concrete
$f_{cc,ave}$	average of f_{cc}
f_{cc20}	concrete compressive strength at 20°C
f_{cM}	compressive strength of concrete at midpoint
f_{ct}	tensile strength of concrete
f_{ct20}	f_{ct} at 20°C
f_s	tensile strength of idealised steel
f_{s20}	f_s at 20°C
f_{su}	ultimate tensile stress of steel
$f_{sy,0}$	so-called 'effective yield strength'
f_u	ultimate stress
f_{ac}	concrete compressive strength at an angle α to a reinforcing bar
$f_{0.2}$	0.2% proof stress
H	height of cross-section
h	reduced height of cross-section

h_{ave}	average height of openings
h_i	height of opening i
I	moment of inertia
I_c	moment of inertia of a reduced concrete cross-section
I_{c20}	I_c at 20°C
I_s	I of a steel cross-section
k	minimum reduction factor (minimum of $\zeta(T)$)
k	parameter defined as N/F_{cu}
k	parameter in simplified expression for temperature in a cross-section
k_{fict}	fictive factor
k_{tr}	transient factor
L	length
l	length of beam or column
M	moment load
M_c	moment of concrete section
M_f	moment corresponding to flange of a T-shaped cross-section
M_o	midspan moment
M_s	moment of steel section
M_u	ultimate moment
M_{u+}	positive moment capacity
M_{u-}	negative moment capacity
M_w	moment corresponding to web of a T-shaped cross-section
M_1	constant moment
m	total moment load
m_w	iterated moment
N	normal load
O	opening factor
P	prestressing force
Q	total fire load in a compartment
q	fire load per unit enclosing surface area of compartment
R	radius
r	radial coordinate
T	temperature in °C
T_c	temperature of concrete at edge of reduced cross-section
T_{cM}	temperature at the centre line or midpoint of concrete section
T_d	design temperature
T_h	hot zone temperature
T_M	temperature at centre line or midpoint

T_s	steel temperature
$T_{s,ave}$	average T_s
T_1-T_{10}	temperatures at wood crib row 1–10 from bottom in long compartment
T_1-T_{64}	parameters describing a damage curve $\zeta(T)$ for a material
t	time
t_d	time of end of heating
u	midspan deflection of a column
V	shear force
V_c	shear force with respect to concrete in compression
V_{ct}	shear force with respect to concrete in tension
V_s	shear force with respect to the steel links
v_{TR}	speed of temperature increase in a cylinder
W	width of one-sided exposed cross-section or width of half of a two-sided exposed cross-section
W_f	thickness of flange
W_i	width of side i
W_w	width of half web
w_i	width of opening i
x	depth of the neutral axis
x, y, z	coordinates
y	depth of compression zone
α	angle
Γ	factor for fully developed fire depending on b and O
δ	deflection
δ_u	ultimate deflection
ε	strain
ε_o	concrete strain at minimum compressed edge
ε_c	concrete strain at maximum compressed edge
ε_{creep}	creep strain of concrete
ε_{cu}	ultimate concrete strain at stress f_{cc}
ε_{cup}	ultimate plastic strain of concrete ($>\varepsilon_{cu}$)
ε_{cu20}	ε_{cu} at 20°C
ε_{load}	instantaneous stress-related concrete strain
ε_p	steel strain at prestress
ε_s	steel strain
ε_{smin}	minimum ε_s to obtain stress f_s
ε_{sy}	yield strain of steel
ε_{th}	thermal strain
$\varepsilon_{th,ave}$	average ε_{th}
ε_{tr}	transient strain

η	stress-distribution factor
η_f	stress-distribution factor of flange
η_w	stress-distribution factor of web
θ	inclination of compression stresses
κ	curvature
κ_{creep}	κ caused by creep
κ_{load}	κ caused by $\varepsilon_{\text{load}}$
κ_{th}	thermal curvature
κ_{tr}	κ caused by ε_{tr}
λ	conductivity
ν	Poisson's ratio or shear effectiveness factor
ν_{20}	Poisson's ratio at 20°C
ζ	strength reduction
ζ_c	reduction of f_{cc} due to heating
$\zeta_{cc\text{COLD}}$	reduction of f_{cc} in a COLD condition
$\zeta_{cc\text{HOT}}$	reduction of f_{cc} in a HOT condition
ζ_{cM}	ζ_c at centre line of a cross-section
ζ_{cMf}	ζ_c at top of a flange of a T-shaped cross-section
ζ_{cMw}	ζ_c at centre line of a web of a T-shaped cross-section
$\zeta_{c\text{rapid}}$	reduction in f_{cc} due to rapid heating
ζ_{ct}	reduction of f_{ct} due to heating
ζ_s	reduction of f_s
$\zeta_{s,\text{ave}}$	average ζ_s
$\zeta_{s0.2}$	reduction of yield strength or 0.2% strength
$\zeta_{s2.0}$	reduction of 2.0% ultimate strength
ζ_{scw}	yield strength reduction for cold-worked steel
ζ_{scwC}	yield strength reduction for cold-worked steel after cooling
$\zeta_{scw0.2}$	0.2% strength reduction for cold-worked steel
$\zeta_{scw2.0}$	ultimate strength reduction for cold-worked steel
$\zeta_{scw2.0C}$	ultimate strength reduction for cold-worked steel after cooling
ζ_{sp}	yield strength reduction for prestressing wire
ζ_{spC}	yield strength reduction for prestressing wire after cooling
$\zeta_{sp2.0}$	ultimate strength reduction for prestressing wire
$\zeta_{sp2.0C}$	ultimate strength reduction for prestressing wire after cooling
ζ_{sq}	yield strength reduction of quenched and self-tempered steel
ζ_{sqC}	yield strength reduction of quenched and self-tempered steel after cooling

ζ_{sq2-0}	ultimate strength reduction of quenched and self-tempered steel
ζ_{sq2-0C}	ultimate strength reduction of quenched and self-tempered steel after cooling
ρ	density
σ	stress
σ_c	concrete stress at maximum compressed edge
σ_{cT}	transverse compressive stress
σ_o	concrete stress at minimum compressed edge
σ_p	prestress of steel
σ_s	stress of steel
σ_v	vertical stress
τ	shear stress
τ_{bond}	bond stress
τ_{fp}	bond strength of smooth wire related to cylinder strength
τ_{fz}	bond strength of embossed wire related to cylinder strength
τ_p	bond strength of prestressing wire with smooth strands
τ_z	bond strength of prestressing wire with embossed strands
v	effectiveness factor for shear

Indices

ave	average
B	bottom of slab
C	cold condition (after a fire)
COLD	cold condition
c	concrete
cc	concrete compression
cE	concrete Euler
cM	concrete at midpoint
cr	critical
cT	concrete transverse
ct	concrete tension
cu	concrete ultimate
cw	cold-worked
E	Euler
eff	effective
f	flange
fict	fictive
HOT	hot condition (during a fire)
<i>i</i>	number
M	midpoint of cross-section

P	prestressing
pq	quenched and tempered prestressing steel
q	quenched and self-tempered slack reinforcement
R	Rankine
s	steel
sE	steel Euler
su	steel ultimate
sy	steel yield
T	top of slab
th	thermal
tr	transient
u	ultimate
v	vertical
w	web
0	initial
0·2	0·2% proof (stress)
20	at 20°C
+	positive
—	negative

Introduction

Dear reader, difficult matters do not exist – only bad explanations.

Many consider the nature of fire-exposed concrete structures hard to understand. The aim of this book is to present this subject so that you understand all aspects fully and will be able to design fire-resistant concrete structures efficiently. The book introduces chemical and physical properties in Chapter 1 on materials and Chapter 2 on fire exposure. Based on this, methods for describing the impact of fire on structures are derived in Chapter 3 and logical design methods are presented in Chapter 4. Chapter 5 provides calculation examples and shows how to apply the design methods in context. Finally, a design guide is presented in Chapter 6 – this is where practical engineers can find the methods needed when designing a fire-resistant concrete structure.

So that you can easily find the background for a certain formula and find a calculation example demonstrating its use, the sections in Chapter 4 (which presents the derivation and explanation of design methods), Chapter 5 (containing calculation examples) and Chapter 6 (the design guide) are numbered as equivalents. For example, Section 4.1.4 T-shaped and ribbed beams in Chapter 4 explains the design methods and derives the formulas for T-shaped beams. The similarly numbered Section 5.1.4 in Chapter 5 provides a calculation example for a T-shaped beam and Section 6.1.4 in Chapter 6 presents the formulas and methods needed for the design.

The author used to say to his students that when you know where you are, and know where you come from, you can better see where you are going. History contributes to understanding of present developments. Therefore, as far as possible, this book refers to the first findings on the subjects dealt with.

When the author graduated in the 1970s, engineers designed concrete structures for the ultimate limit state and for service load by well-documented design methods. However, when they documented fulfilment of fire safety requirements, they only had rules of thumb and random experience as a basis for the assessments.

Since fire safety considerations are decisive for the design of roughly a third of all structures for concrete buildings and

tunnels, the author decided to contribute to research on the subject in order to establish a rational basis for engineering design. He completed a PhD on the properties of fire-exposed concrete structures in 1980 (Hertz, 1980a, 1980b, 1980c).

The PhD project concerned the properties of concrete at elevated temperatures and a new method for heating concrete rapidly without thermal gradients by means of microwave power. It also presented data for the anchorage capacity of reinforcement and a new test method for measuring it, and it presented about 500 references on the subject of fire-exposed concrete structures.

The external examiner for the author's PhD was Professor Ove Pettersson. He was head of a fire research group at Lund University, Sweden, that had carried out comprehensive work on the fire safety of steel structures (Magnusson *et al.*, 1974; Pettersson *et al.*, 1976) and some work on reinforcement for concrete structures (Anderberg, 1978, 1988). However, the Swedish government changed priorities from structural fire research to rescue-related research and this meant that the group was not able to continue the work.

In the following years, the author therefore conducted a series of projects at the Technical University of Denmark, establishing design methods for fire-exposed concrete structures and publishing the results in nine reports for the international group CIB W14, including the publication first introducing the reduced cross-section method (Hertz, 1985).

The author further developed the design methods and documented the results of a number of research projects, students' theses and experience from application of the methods in practice as a consulting engineer. He reported some of the data and methods in journal papers and, of course, in teaching. As a member of the project team writing the fire part of EN 1992-1-2: Eurocode 2 (CEN, 2002), he introduced some of the design methods in that code.

This book presents design methods and data for fire-resistant concrete structures as a whole in order to facilitate their application in practice and provide engineers with sufficient background knowledge to understand them.

The book's aim is thus as follows: you should be able to design any structure made of any concrete to resist load at any time of any fire exposure.

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