ECCS N° 89

Fire Resistance of Steel Structures

(On the basis of ENV 1993 part 1-2 "Design of steel structures - Structural fire design") Sept. 1995

1. Introduction

The required fire resistance of steel structures - in terms of fire resistance classes R30/R60/R90 etc. - is given by national regulations. These requirements should consider the number of floors, the use of the building, the fire load, the number of people and the favourable effect of active measures, such as sprinklers, automatic fire detection, and type and proximity of the fire brigade.

The assessment of the fire resistance of structural elements is based either on standard fire tests in furnaces or on calculation. This Technical Note describes calculation methods for unprotected and protected internal steelwork based on the European prestandard ENV 1993-1-2 [1], [2].

2. Principles of Calculation

2.1 Steel temperature

The increase in steel temperature is given by the following factors:

a) The section factor (A_m/V): i.e. the relation between the surface area exposed to the heat flux and the volume of the member per unit length. Calculation methods and values of (A_m/V) for common sections are given in Section 5.

b) The thermal properties of a fire protection material: i.e. thermal conductivity λ_p, its specific heat c_p and its thickness d_p. Thermal properties for various protection materials are given in Section 4. At present no European Norm is available to determine λ_p. Therefore product specifications must be obtained in each country from approved testing laboratories, or other expert institutes on condition that they are based on officially approved tests (Section 10).

c) For fire protection material containing water, the evaporation of the water causes a delay of the temperature increase of the steel when the temperature of the steel reaches 100°C (Example A1).

2.2 Mechanical properties of steel at elevated temperatures

Steel properties change with temperature (Fig. 1). For a member at a uniform temperature, called critical temperature Θ_{cr}, the load bearing capacity becomes equal to the effect of the applied loads. Failure will then occur.
The critical temperature is determined by the level of the applied load (action), expressed as the degree of utilisation in fire, given by

$$\mu_0 = E_{fi,d} / R_{fi,d,0}$$

$E_{fi,d}$: the design effect of actions in fire

$R_{fi,d,0}$: the design resistance in fire, for time t = 0 (i.e. room temperature, $\gamma_M = \gamma_{M,fi} = 1.0$, support conditions for the fire situation: 0.5 L for intermediate, 0.7 L for top storey columns)

2.3 Temperature distribution

An adaptation factor κ is introduced to take account of a non-uniform temperature distribution over the height and alongside the steel section. The value of the adaptation factor κ should be taken as follows:

– beams:
  · exposed on all four sides: κ = 1.0
  · exposed on three sides, with a composite or concrete slab on side four: κ = 0.7
– statically indeterminate beams at support:
  · exposed on all four sides: κ = 0.85
  · exposed on three sides, with a composite or concrete slab on side four: κ = 0.6

Stability problems (to account for lower strain level) κ = 1.2

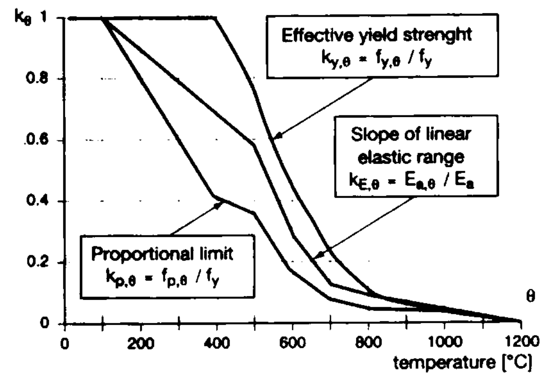


Fig. 1: Reduction factors for steel strength and stiffness at elevated temperatures

2.4 General assumptions

The calculation of the fire resistance is based on the following assumptions:

- the temperature increase follows the standard fire curve (ISO 834)
- uniform heating of the steel member. A non-uniform heat distribution is considered by the factor κ (Section 2.3)
- steel grades according to EN 10 025 (S 235, S 275, S 355) and EN 10113 (S 420, S 460)
- for member analysis, the effects of thermal expansion of the member may be neglected
- steel sections of classes 1, 2 or 3 (with A_m/V > 10 m^{-1}). For sections of class 4 see example C.
- Temperature increase curves calculated for $\gamma_{n,r} = \gamma_{n,c} = 1.0$ according to ENV 1991-2-2. (If the National Application Document gives other values, see Section 10)
- Temperature increase curves for insulated steel calculated with $\phi = 0$ (Modification factors for other values see Section 4).

3. Calculation Procedure

- Calculate the degree of utilisation μ_0 (Section 2.2). For a preliminary design μ_0 may be taken as 0.6. This is normally a conservative assumption.
- The non-dimensional slenderness of a column is a function of the temperature Θ and has to be adapted for the calculation of μ_0:

$$\bar{\lambda}_{fi,\Theta,max} = \bar{\lambda}_{fi,0} \cdot \sqrt{k_{y,\Theta,max} / k_{E,\Theta,max}}$$

with Θ_{max} the steel temperature at failure

$$\mu_0 = E_{fi,d} / R_{fi,d,0}$$

$R_{fi,d,0}$ is calculated using $\bar{\lambda}_{fi,\Theta,max}$ as given above, the yield strength f_y at room temperature and buckling curve c.

The values of $\sqrt{k_{y,\Theta,max} / k_{E,\Theta,max}}$ are given in Table 1a.
The calculation procedure for columns is illustrated in Example D. Table 1b gives directly the critical temperatures for intermediate columns and Table 1c for top storey columns.
For a preliminary design $\bar{\lambda}_{fi,\Theta,max} = 1.2 \cdot \bar{\lambda}_{fi,0}$ may be assumed.
- Determine the section factor. A_m/V for unprotected steel members and A_p/V for steel members insulated by fire protection material (Section 5). The thermal section factor $[(A_p/V)\cdot(\lambda_p/d_p)]$ can be derived according to Section 4 and 7.1 Example A1.
- The fire resistance time t_f is assessed by making use of the nomogram (see Section 6 and Examples in Section 7).
- A series of adaptation factors κ are considered by special curves on the left side of the nomogram.

- For a preliminary design the increase of the fire resistance time caused by the effects of moisture in the protection material may be added ($t_r = t_t + t_v$), if data is taken from Table 2. Evaporation time $t_v = (p \cdot \rho_p \cdot d_p^2) / (5 \cdot \lambda_p)$ [min]. No increase is allowed if the moisture is already considered implicitly in the national λ_p-values of the table in Section 10.

Tab. 1a Slenderness modification factor $\sqrt{k_{y,\Theta,max} / k_{E,\Theta,max}}$ at elevated temperatures

steel temp. Θ_a [°C]	300	400	500	600	700	800	900
$\sqrt{k_{y,\Theta,max} / k_{E,\Theta,max}}$	1.12	1.20	1.14	1.23	1.33	1.11	0.94

Tab. 1b Critical steel temperature of internal columns, for $\ell_{cr,fi,0} = 0.5$ L, $\kappa = 1.2$

$\mu_{0,c}$	$\bar{\lambda}_{0,c}$									
	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00
0.30	642	648	658	671	686	701	717	732	744	754
0.35	618	625	635	648	664	679	691	699	710	718
0.40	597	605	615	629	645	660	673	682	688	693
0.45	579	586	597	611	628	644	657	666	673	677
0.50	561	569	580	595	613	629	642	652	659	663
0.55	545	553	565	580	598	615	629	639	646	651
0.60	529	538	550	567	585	603	617	627	635	640

Tab. 1c Critical steel temperature of top storey columns, for $\ell_{cr,fi,0} = 0.7$ L, $\kappa = 1.2$

$\mu_{0,c}$	$\lambda_{0,c}$									
	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00
0.30	638	640	643	648	652	656	658	660	661	662
0.35	614	617	621	626	631	635	638	640	642	642
0.40	594	596	601	606	613	617	621	623	624	625
0.45	575	578	583	589	596	601	605	608	609	610
0.50	557	561	566	573	581	586	591	593	595	597
0.55	540	544	550	558	566	573	577	580	582	584
0.60	524	528	535	544	553	560	565	568	570	572

$\mu_{0,c}$ = design load in fire / design buckling resistance for: $\Theta = 20°$, $\ell_{fi} = 1.0$ L, buckling curve c, $\gamma_{M,fi} = 1.0$

$\bar{\lambda}_{0,c}$ = non dimensional slenderness of column for $\ell_{fi} = 1.0$ L

4. Properties of Fire Protection Material

Table 2: General properties for preliminary design*. The following material properties may be used to calculate the modified section factor: $\frac{A_p}{V} \cdot \frac{\lambda_p}{d_p} \cdot \frac{1}{1 + \phi / 2}$; $\phi = \frac{c_p \cdot d_p \cdot \rho_p \cdot A_p}{c_a \cdot \rho_a \cdot V}$

As simplification ϕ may be taken equal to 0 (this leads to conservative results). The delay t_v caused by the moisture content of the protection material may be considered according to Example A1. The protection material must be fixed in such a way that it will keep its protective function during the required fire resistance time.

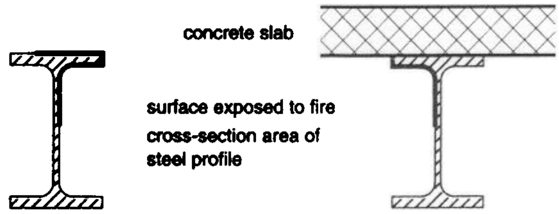
Material	unit mass ρ_p [kg / m³]	mosture content p [%]	thermal conductivity λ_p [W / (m·k)]	specific heat c_p [J/(kg·K)]
Sprays				
- mineral fibre	300	1	0.12	1200
- vermiculite cement	350	15	0.12	1200
- perlite	350	15	0.12	1200
High-density sprays				
- vermiculite (or perlite) and cement	550	15	0.12	1100
- vermiculite (or perlite) and gypsum	650	15	0.12	1100
Boards				
- vermiculite (or perlite) and cement	800	15	0.20	1200
- fibre-silicate or fibre-calcium-silicate	600	3	0.15	1200
- fibre-cement	800	5	0.15	1200
- gypsum board	800	20	0.20	1700
Compressed fibre boards				
- fibre silicate, mineral-wool, stone-wool	150	2	0.20	1200
Concrete	2300	4	1.60	1000
Light weight concrete	1600	5	0.80	840
Concrete bricks	2200	8	1.00	1200
Bricks with holes	1000	-	0.40	1200
Solid bricks	2000	-	1.20	1200

* Properties obtained by national fire tests of trade products are given in Section 10 on the last page of this technical note

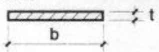
5. Section factors

5.1 Unprotected steel members

Section factor: $\frac{A_m}{V} = \frac{\text{exposed surface area per unit length}}{\text{volume of the member per unit length}}$

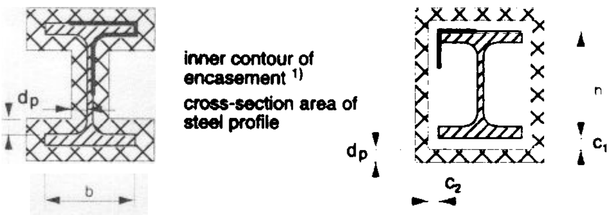


Examples:

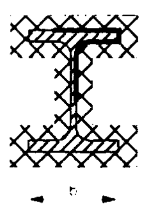
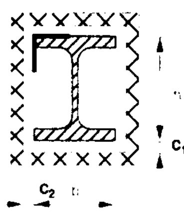
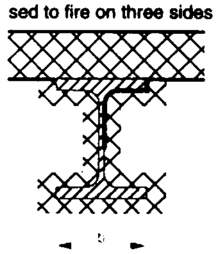
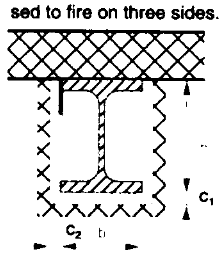
Description	A_m / V
flat bar 	exposed to fire on all sides: ≈ $^2/_t$ exposed to fire on one sides: ≈ $^1/_t$
Open section with uniform thickness 	exposed to fire on all sides: ≈ $^2/_t$
Hollow section with uniform thickness 	exposed to fire from outside: ≈ $^1/_t$
Solid section 	exposed to fire on all sides: = $^4/_d$

5.2 Steel members insulated by fire protection material

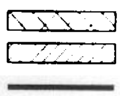
Section factor $\frac{A_p}{V} = \frac{\text{inner contour of encasement}}{\text{steel cross-section area}}$



Examples:

Description		A_p / V
Contour encasement of uniform thickness. 	Hollow encasement [1] of uniform thickness. 	Contour encasement: $\frac{\text{steel perimeter}}{\text{steel cross-section area}}$ Hollow encasement: $\frac{2\,(b + h)}{\text{steel cross-section area}}$ [1]
Contour encasement of uniform thickness, exposed to fire on three sides 	Hollow encasement [1] of uniform thickness, exposed to fire on three sides. 	Contour encasement: $\frac{\text{steel perimeter - b}}{\text{steel cross-section area}}$ Hollow encasement: $\frac{(2h + b)}{\text{steel cross-section area}}$ [1]

1) The clearance dimensions c_1 and c_2 should not normally exceed h/4



Legend:
insulation (with thickness d_p)
steel cross section
inner contour A_p

contour A_p

inner contour A_p

inner contour A_p

5.3 Section factors A_m/V (resp. A_p/V) in $[m^{-1}]$ for hot rolled profiles

UNP				
80	283	227	242	186
100	275	222	238	185
120	255	205	222	173
140	239	196	210	166
160	227	187	200	160
180	218	178	193	153
200	205	170	182	147
220	192	160	170	139
240	183	153	163	133
260	172	144	154	126
280	167	140	149	122
300	161	136	144	119
320	129	110	116	97
350	135	116	122	103
380	138	119	125	107
400	129	111	117	99
UAP				
80	308	234	266	192
100	290	224	253	187
130	267	211	236	180
150	239	189	211	160
175	226	181	201	155
200	213	172	190	148
220	205	165	183	143
250	188	153	168	134
(270)	180	146	161	127
300	167	137	150	119

IPE				
80	430	329	370	269
100	389	301	335	247
120	359	278	310	230
140	335	259	290	215
160	309	240	268	200
180	292	226	254	188
200	269	210	234	175
220	253	197	221	164
240	235	184	204	153
270	226	176	197	147
300	215	167	187	139
330	199	156	174	131
360	185	145	162	122
400	174	137	152	116
450	163	129	143	110
500	150	120	132	103
550	140	113	124	97
600	129	105	115	91
750 · 137	143	116	128	101
147	134	109	120	95
173	114	93	102	81
196	102	83	91	72

IPEA				
140	408	313	354	259
160	382	295	331	244
180	354	270	308	227
200	325	253	282	210
220	298	231	259	192
240	276	214	240	178
270	265	205	222	170
300	249	192	208	160
330	228	178	199	149
360	211	165	182	138
400	200	158	175	133
450	187	149	165	126
500	172	138	152	118
550	161	129	143	111
600	147	119	131	103

INP				
80	401	321	345	266
100	349	283	301	235
120	309	250	268	209
140	274	225	238	189
160	252	205	219	172
180	229	187	200	158
200	211	173	184	146
220	195	160	171	135
240	183	150	160	127
260	169	139	148	118
280	158	130	138	111
300	149	123	131	104
320	140	115	123	99
340	132	109	116	94
360	124	103	109	88
380	118	98	104	85
400	112	94	99	80
450	100	84	89	72
500	90	76	80	65
550	84	70	75	61
600	75	64	67	55

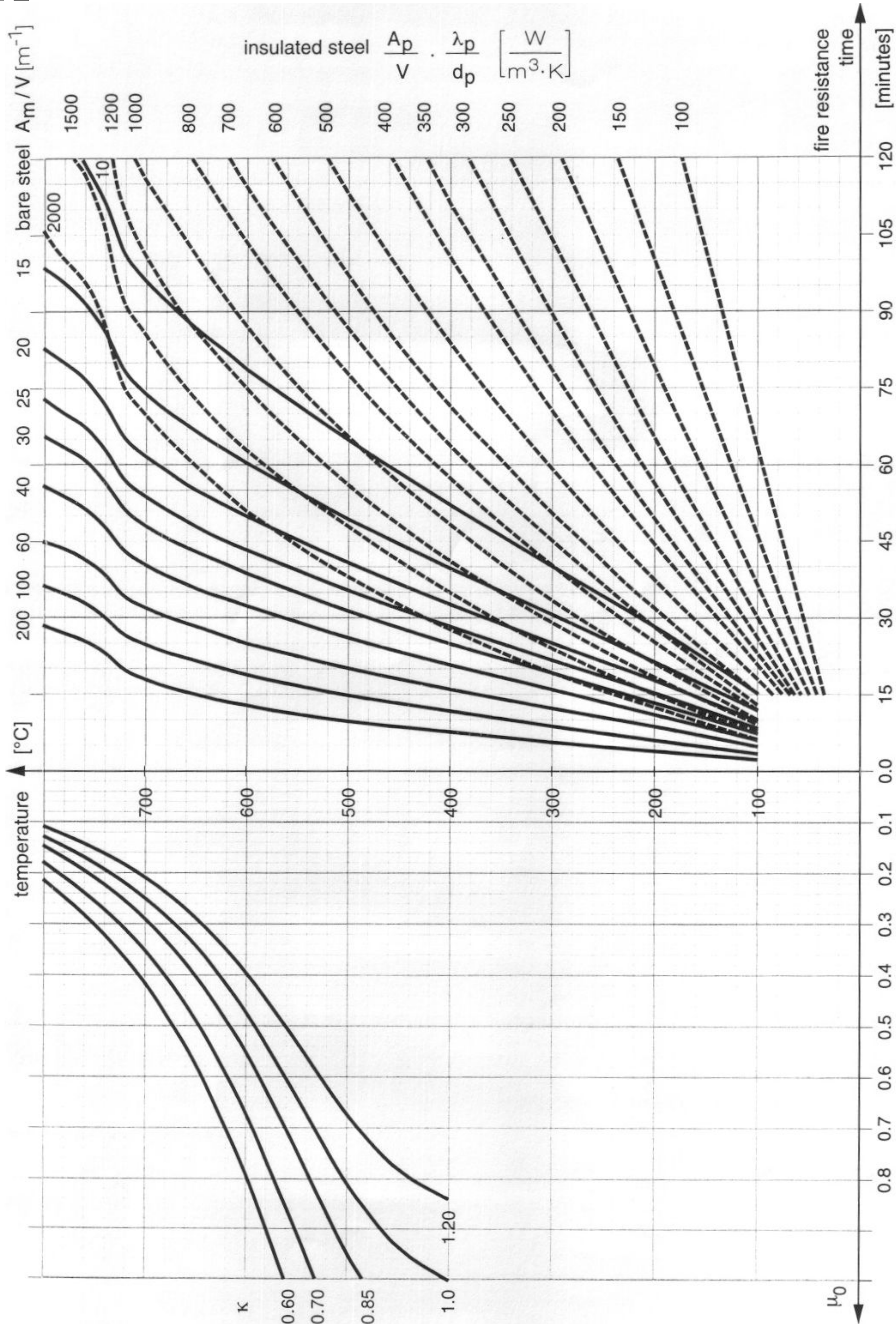
HEA				
100	265	184	217	137
120	267	185	220	137
140	252	173	208	129
160	230	160	189	119
180	225	155	185	115
200	211	145	174	107
220	196	133	161	99
240	178	122	147	91
260	170	117	140	87
280	164	113	135	84
300	152	104	126	78
320	141	98	117	74
340	134	94	111	71
360	128	91	107	70
400	120	86	101	67
450	112	83	96	66
500	106	80	91	64
550	104	79	90	65
600	102	78	88	65
650	99	77	87	65
700	96	76	84	64
800	94	76	83	65
900	90	74	81	64
1000	89	74	80	65
HEAA				
100	354	244	290	180
120	360	246	295	182
140	341	232	280	172
160	296	202	244	150
180	278	190	229	140
200	256	174	210	129
220	242	165	199	122
240	225	153	185	114
260	213	146	176	108
280	204	139	168	103
300	191	131	158	97
320	183	127	152	95
340	176	123	146	93
360	170	119	142	91
400	160	115	135	89
450	156	114	132	90
500	151	112	129	90
550	142	107	122	87
600	138	106	120	87
650	134	104	117	87
700	129	101	113	85
800	121	97	108	84
900	113	92	101	80
1000	108	90	97	79

HEB				
100	218	153	179	115
120	201	141	166	105
140	187	130	154	97
160	169	117	139	88
180	157	110	130	82
200	147	102	121	76
220	139	96	115	72
240	130	90	107	67
260	126	87	104	65
280	123	85	102	63
300	116	80	95	60
320	109	76	91	58
340	105	74	88	57
360	102	73	85	56
400	97	70	82	55
450	91	68	77	55
500	88	67	76	54
550	87	66	75	55
600	85	66	74	55
650	84	66	74	55
700	82	65	72	55
800	81	65	72	56
900	78	64	70	56
1000	77	65	70	57
HEM				
100	116	85	96	65
120	111	80	92	61
140	103	75	85	57
160	99	71	82	54
180	96	68	79	51
200	91	64	75	49
220	88	62	73	47
240	73	51	60	39
260	71	50	59	38
280	70	49	58	37
300	60	42	50	32
320	59	42	50	32
340	60	43	50	33
360	60	44	50	34
400	61	45	52	35
450	62	46	53	37
500	63	48	54	39
550	64	49	55	40
600	65	50	56	42
HHD				
260 · 54	213	146	176	108
68	170	117	140	87
93	126	87	104	65
114	104	72	86	54
142	85	60	71	46
172	71	50	59	38
225	56	40	47	31
299	44	32	37	25
320 · 74	183	127	152	95
98	141	98	117	74
127	109	76	91	58
158	89	63	74	48
198	73	51	60	39
245	59	42	50	32
300	50	36	42	28
368	42	31	35	24
451	35	26	30	20
360 · 134	125	85	104	63
147	114	78	95	58
162	104	71	86	53
179	95	65	79	49
196	88	60	73	45
400 · 187	94	64	78	47
216	83	56	68	42
237	76	51	62	38
262	69	47	57	35
287	63	43	52	32
314	58	40	48	30
347	53	37	44	28
382	49	34	40	25
421	45	31	37	23
463	41	29	34	22
509	38	27	31	20
551	35	25	29	19
592	33	23	28	18
634	31	22	26	17
677	30	21	25	16
744	27	20	23	15
818	25	18	21	14
900	23	17	19	13
990	22	16	18	12
1086	20	15	17	11

UB				
838 · 292 · 226	100	80	90	70
838 · 292 · 194	115	90	100	80
838 · 292 · 176	125	100	110	90
762 · 267 · 197	100	85	90	70
762 · 267 · 173	115	95	105	80
762 · 267 · 147	135	110	120	95
762 · 267 · 134	150	120	135	105
686 · 254 · 170	110	90	100	75
686 · 254 · 152	120	95	110	85
686 · 254 · 140	130	105	120	90
686 · 254 · 125	150	115	130	100
610 · 305 · 238	80	65	70	50
610 · 305 · 179	105	80	95	70
610 · 305 · 149	125	95	110	80
610 · 229 · 140	120	95	105	80
610 · 229 · 125	135	105	120	90
610 · 229 · 113	145	115	130	100
610 · 229 · 101	160	130	145	110
533 · 210 · 122	125	95	110	85
533 · 210 · 109	135	110	120	95
533 · 210 · 101	145	115	130	100
533 · 210 · 92	160	125	145	110
533 · 210 · 82	180	140	160	120
457 · 191 · 98	135	105	120	90
457 · 191 · 89	145	115	130	100
457 · 191 · 82	160	125	140	105
457 · 191 · 74	175	135	155	115
457 · 191 · 67	195	150	170	130
457 · 152 · 82	145	120	130	105
457 · 152 · 74	160	130	145	115
457 · 152 · 67	175	145	160	125
457 · 152 · 60	195	160	175	140
457 · 152 · 52	225	180	200	160
406 · 178 · 74	160	125	140	105
406 · 178 · 67	175	140	155	115
406 · 178 · 60	195	155	175	130
406 · 178 · 54	220	170	190	145
406 · 140 · 46	230	185	210	160
406 · 140 · 39	270	215	245	190
356 · 171 · 67	165	125	145	105
356 · 171 · 57	190	145	170	120
356 · 171 · 51	215	160	185	135
356 · 171 · 45	240	180	210	150
356 · 127 · 39	240	195	215	165
356 · 127 · 33	280	225	250	195
305 · 165 · 54	185	140	160	115
305 · 165 · 46	215	160	185	135
305 · 165 · 40	245	185	210	150
305 · 127 · 48	180	145	160	120
305 · 127 · 42	205	160	180	140
305 · 127 · 37	230	180	205	155
305 · 102 · 33	245	200	220	175
305 · 102 · 28	280	230	255	200
305 · 102 · 25	320	255	285	225
254 · 146 · 43	200	150	175	120
254 · 146 · 37	230	170	200	140
254 · 146 · 31	270	200	235	165
254 · 102 · 28	255	200	225	175
254 · 102 · 25	285	225	250	190

UC				
305 · 305 · 283	55	40	45	30
305 · 305 · 240	65	45	55	35
305 · 305 · 198	75	50	65	40
305 · 305 · 158	95	65	75	50
305 · 305 · 137	105	70	90	55
305 · 305 · 118	120	85	100	60
305 · 305 · 97	145	100	120	75
254 · 254 · 167	75	50	65	40
254 · 254 · 132	95	65	80	50
254 · 254 · 107	115	75	95	60
254 · 254 · 89	135	90	110	70
254 · 254 · 73	160	110	135	80
203 · 203 · 86	115	80	95	60
203 · 203 · 71	135	95	115	70
203 · 203 · 60	160	110	135	80
203 · 203 · 52	185	125	150	95
203 · 203 · 46	205	140	170	105
152 · 152 · 37	190	135	165	100
152 · 152 · 30	240	160	200	120
152 · 152 · 23	310	210	255	155

6. Nomogram



70
80
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150
120
140
155
175
200
225
120
140
165
175
190
30
35
40
50
55
60
75
40
50
60
70
80
60
70
80
95
105
100
120
155

7. Worked Examples

7.1 Example A

Input: degree of utilisation, thickness of fire protection and section factor.
To determine: fire resistance time.

Example A1 Column HEA 300, encased with fibre-calcium-silicate board (d_p = 25 mm, λ_p = 0.15 W/(m·K), p = 3 %, from Table 2).
μ_0 = 0.6. Obtained after iteration (see Example E and Section 3).
A_p/V = 104 m^{-1}, taken from Section 5.
The thermal section factor (for ϕ simplified to 0.0) is calculated as:

$$\frac{A_p}{V} \cdot \frac{\lambda_p}{d_p} = 104 \cdot \frac{0.15}{0.025} = 624\,W/(m^3 \cdot K)$$

The fire resistance time t_t can be dervied from the nomogram with μ_0 = 0.6 and κ = 1.2, as t_t = 101 minutes.
Taking into account ϕ:

$$\phi = \frac{1200 \cdot 0.025 \cdot 600}{600 \cdot 7850} \cdot 104 = 0.397$$

the modified thermal section factor is calculated as

$$\frac{A_p}{V} \cdot \frac{\lambda_p}{d_p} \cdot \frac{1}{1+\phi/2} = 521\,W/(m^3 \cdot K)$$

The fire resistance time t_t can be found from the nomogram with μ_0 = 0.6 and κ = 1.2, as 117 minutes (a substantial increase compared to the simplified assumption ϕ = 0).
The increase in fire resistance due to the moisture content of the protection can be calculated as follows:

$$t_v = \frac{p \cdot \rho_p \cdot d_p^2}{5 \cdot \lambda_p} = \frac{3 \cdot 600 \cdot 0.025^2}{5 \cdot 0.15} = 1 \text{ minute}$$

NB: If the influence of moisture has already been included in the λ_p-values, t_v cannot be considered again.
The protected column fulfils the R90 requirement.

Example A2 Same conditions as Example A1, but a lower degree of utilisation (μ_0 = 0.4). From the nomogram the fire resistance time is extrapolated to be t_t = 121 minutes (for ϕ simplified to 0). t_t = 140 minutes for actual value of ϕ = 0.397.

7.2 Example B

Input: degree of utilisation and required fire resistance time.
To determine: required section factor and/or fire protection (type and thickness d_p of the fire protection material).

Beam IPE 300, required fire resistance R90

1. **Degree of utilisation** μ_0: Design bending moment (from static analysis, no lateral torsional buckling of the beam because it is stabilised by a concrete slab, steel grade S 235)

$M_{fi,d}$ = 67.5 kNm

$M_{fi,0,Rd}$ = 148 kNm (for $\gamma_{M,fi}$ = 1.0)

$\mu_0 = M_{fi,d} / M_{fi,0,Rd}$ = 0.456

The critical temperature is Θ_{cr} = 654 °C, derived from the nomogram for μ_0 = 0.459 and κ = 0.7.

2. **Encasement:** Beam with a concrete or composite slab on side four, i.e. section factor A_p/V = 139 m^{-1}
For a critical temperature of 654 °C, it is found from the nomogram that the thermal section factor should be smaller than 1150 W/(m^3·K) to reach R90.
For A_p/V = 139 m^{-1}, the light and dry encasement (for simplification ϕ taken as 0 on safe side) must fulfil the following condition:

$$\frac{d_p}{\lambda_p} \geq \frac{A_p/V}{1150} = \frac{139}{1150} = 0.121\,\frac{m^2 \cdot K}{W}$$

The required thickness d_p of a fibre cement board encasement (Table 2) with a thermal conductivity of λ_p = 0.15 W/(m·K) is:
$d_p \geq \lambda_p \cdot 0.121 = 0.15 \cdot 0.121 = 0.018$m = 18mm.

7.3 Example C

Input: section factor, critical temperature Θ_{cr}, fire resistance time.
To determine: Insulation thickness.

Note: A limitation of the steel temperature can be directly considered using the nomogram, e.g. for class 4 sections, Θ_{cr} = 350°C, or for strengthening of concrete with epoxy bonded flat steel reinforcement, $\Theta_{cr} \approx$ 90 °C.
Beam with class 4 section, A_p/V = 200, fire resistance R60, Θ_{cr} = 350 °C (see ENV 1993-1-2 4.2.4).
Minimal thickness of protection by fibre-silicate boards:
According to the nomogram the thermal section factor
$(A_p / V) \cdot (\lambda_p / d_p)$ must be less then 610W/(m^3·K).
With A_p / V = 200 m^{-1} the encasement must fulfil the following condition:

$$\frac{d_p}{\lambda_p} \geq \frac{A_p/V}{610} = \frac{200}{610} = 0.33\,\frac{m^2 \cdot K}{W}$$

The required thickness d_p of fibre-silicate boards (Table 2) with the thermal conductivity λ_p = 0.15 W/(m·K) results in $d_p \geq \lambda_p \cdot 0.33 = 0.15 \cdot 0.33 = 0.049$ m = 49 mm.

7.4 Example D

Input: section factor, column length, action in fire.
To determine: fire resistance time.

Solid intermediate column 250 mm diameter, L = 4.0 m, steel grade S 235, compression force in fire $N_{fi,d}$ = 3000kN;
section factor: A_m / V = 4 / d = 16m^{-1}, A = 49'100mm^2
Assessment using Table 1b:
Non-dimensional-slenderness:

$\bar{\lambda}_{0,c} = \ell_{fi} / (i \cdot \pi \cdot \sqrt{E_a / f_y}) = 4000 / (62.5 \cdot \pi \cdot \sqrt{210 / 0.235}) = 0.68$

Buckling resistance for 20 °C, $\gamma_{M,fi}$ = 1.0, buckling curve c:
Buckling factor χ = 0.7370; Design buckling resistance:
$N_{Rd} = \chi \cdot f_y \cdot A = 0.7370 \cdot 0.235 \cdot 49'100 = 8504$ kN
$\mu_{0,c}$ = 3000 / 8504 = 0.35 (as defined after table 1c)
Critical temperature from Table 1b (linear interpolation): Θ_{cr} = 640°C.
From the nomogram the fire resistance time for the section factor of 16 m^{-1} is found to be 63 minutes.

7.5 Example E

Input: section factor, column length, action in fire.
To determine: fire resistance time.

Solid column 250 mm diameter, L = 2.0 m, support conditions in fire ℓ_{fi} = 1.0 L, steel grade S 235, action in fire $N_{fi,d}$ = 3000 kN
Assessment using an iterative procedure:
The non-dimensional-slenderness is temperature dependant therefore the following iterative procedure must be used if the support conditions are not covered by Tables 1b (ℓ_{fi} = 0.5 L) or 1c (ℓ_{fi} = 0.7 L) (see Example D).

1. Step: normal temperature $\sqrt{k_{y,\Theta,max} / k_{E,\Theta,max}}$ = 1.0:
Non-dimensional-slenderness for 20 °C; support conditions for fire ℓ_{fi} = 1.0 L:

$\bar{\lambda}_{fi,0} = \ell_{fi} / (i \cdot \pi \cdot \sqrt{E_a / f_y}) = 2000 / (62.5 \cdot \pi \cdot \sqrt{210 / 0.235}) = 0.34$

Buckling resistance for $\gamma_{M,fi}$ = 1.0, buckling curve c: Buckling factor χ = 0.929; Buckling resistance:
$N_{Rd} = \chi \cdot f_y \cdot A = 0.9286 \cdot 0.235 \cdot 49100 = 10715$ kN
μ_0 = 3000 / 10715 = 0.28
Critical temperature from the nomogram with μ_0 = 0.28 and κ = 1.2: Θ_{cr} = 647°C.

2. Step: Θ_{cr} = 647°C = Θ_{max} —> $\sqrt{k_{y,\Theta,max} / k_{E,\Theta,max}}$ = 1.28
(interpolation from Tab. 1a) $\bar{\lambda}_{fi,\Theta,max}$ = 1.28 · 0.34 = 0.44
Buckling resistance for $\gamma_{M,fi}$ = 1.0, buckling curve c: Buckling factor χ = 0.876; Buckling resistance:
$N_{Rd} = \chi \cdot f_y \cdot A = 0.876 \cdot 0.235 \cdot 49100 = 10108$ kN
μ_0 = 3000 / 10108 kN = 0.30
Critical temperature from the nomogram with μ_0 = 0.30 and κ = 1.2: Θ_{cr} = 640°C. The iteration process can be stopped. Fire resistance time for the nomogram for Θ_{cr} = 640°C and a section factor A_m/V of 16 m^{-1} is found to be 63 minutes.

8. Symbols and Units

8.1 Symbols

Symbol	Meaning	Unit
A	the cross-section area	[m^2]
A_m	the surface area of a member per unit length	[m]
A_p	the area of the inner surface of the fire protection material per unit length of the member	[m]
V	the volume of a member per unit length	[m^2]
E_a	the modulus of elasticity of steel for normal temperature design 20°C ($E_a = 210 \cdot 10^3$ N/mm²)	[N/mm²]
$E_{a,\Theta}$	the slope of the linear elastic range for steel at elevated temperature Θ	[N/mm²]
c_p	the specific heat of fire protection material	[J/(kg·K)]
c_a	the specific heat of steel, $c_a \approx 600$ J/(kg·K)	[J/(kg·K)]
d_p	the thickness of fire protection material	[m]
f_y	the yield strength of steel at room temperature	[N/mm²]
$f_{y,\Theta}$	the effective yield strength of steel at elevated temperature Θ	[N/mm²]
i	the radius of gyration	[m]
$k_{y,\Theta}$	the relative value for the effective yield strength, $k_{y,\Theta} = f_{y,\Theta}/f_y$	
$k_{E,\Theta}$	the relative value for the slope of the linear elastic range, $k_{E,\Theta} = E_{a,\Theta}/E_a$	
L	system length	[m]
l_{fi}	the buckling length in fire	[m]
p	the moisture content of fire protection material	[%]
t	the thickness of steel	[m]
t_r	the total fire resistance time	[min]
t_t	the fire resistance time neglecting the influence of the moisture content	[min]
t_v	the increase of fire resistance time due to the moisture content of the fire protection material	[min]
$\gamma_{M,fi}$	the partial material safety factor in fire design	
Θ	the temperature	[°C]
Θ_{cr}	the critical steel temperature	[°C]
κ	adaption factor	
$\bar{\lambda}_{fi,0}$	the non dimensional slenderness for end conditions in fire and room temperature	
$\bar{\lambda}_{fi,\Theta,max}$	the non dimensional slenderness for end conditions in fire and steel temperature at failure	
λ_p	the thermal conductivity of the fire protection material	[W/(m·K)]
μ_0	the degree of utilisation: $\mu_0 = E_{fi,d}/R_{fi,d,0}$	[-]
ϕ	$[(c_p \cdot \rho_p \cdot d_p)/(c_a \cdot \rho_a)] \cdot A_p/V$, (see section 4)	
ρ_a	the density of steel ($\rho_a = 7850$ kg/m³)	[kg/m³]
ρ_p	the density of fire protection material	[kg/m³]

8.2 Units

SI-units are generally used.

Temperatures in Celsius [°C] are marked with Θ. For conversion temperature the following relation holds: 0 °C = 273 K, and the conversion factor between °C and K is 1.

Between Joule [J], Watt [W] and the former unit calorie [cal] the following relation holds: 1 W = 1 J/sec, 1 cal = 4.18 J.

9. References

[1] ENV 1993-1-2 ("General rules, Structural fire design"), CEN, Brussels 1995

[2] ECCS Technical Note 92, Explanatory Document to ECCS No 89,Fire resistance of steel structures, Brussels 1996

10. Rules given in the National Application Document and Properties of Proprietary Fire Protection Material According to National Test Results

Information on additional rules and changes of boxed values given in the National Application Document (NAD) and the thermal properties derived from recognised national fire tests can be ordered from the following organisations:

Austria
Österreichischer Stahlbauverband
Larochegasse 28
A-1130 Wien

Belgium
CRIF - Section Construction métallique
Université de Liège
Institut du Génie Civil
Quai Banning 6
[illegible]0 Liège

Croatia
Hrvatska Zajednica za Metalne Konstrukcije
Janka Rakuse 1
CRO-41000 Zagreb

Czech Republic
Czech Steelwork Fabricators Association - CSFA
Komerçni 5a
CZ-710 00 Ostrava

Denmark
Dansk Stalinstitut
Overgade 21-2
DK-5000 Odense C

Finland
Federation of Finnish Metal, Engineering and Electrotechnical Industries
P.O. Box 10
Etelaranta 10
FI-00130 Helsinki

France
CTICM
Domaine de Saint-Paul BP 64
F-78470 Saint-Rémy-lès-Chevreuse

Germany
Deutscher Stahlbau-Verbund DSTV
Ebertplatz 1
D-50668 Köln

Greece
Federation of Greek Industries
Xenofontosstreet 5
GR-105 57 Athens

Italy
Associazione fra i Costruttori in Acciaio Italiani
Viale Abruzzi 66
I-20131 Milano

Luxemburg
Profil ARBED Recherches
66 rue de Luxembourg / BP 141
L-4221 Esch/Alzette

Netherlands
TNO-Bouw, Centrum voor Brandveiligheid
Postbus 49
NL-2600 AA Delft

Norway
Den Norske Stalgruppen
Postboks 7072-Homansbyen
N-0306 Oslo 3

Spain
Empresa Nacional Siderurgica S.A. (Ensidesa)
Direccion de Asistencia a Proyectos
Paseo de la Castellana 91,la planta
ES-28046 Madrid

Sweden
The Swedish Institute of Steel Construction
Box 27751
S-11592 Stockholm

Switzerland
Schweizerische Zentralstelle für Stahlbau
Seefeldstrasse 25
CH-8034 Zürich

Turkey
Tucsa - Turkish Constructional Steelwork Association
Bahariye, Sair Latifi Sokak 29
TR-81310 Kadikoy - Istanbul

United Kingdom
The Steel Construction Institute
Silwood Park
UK-Ascot Berks SL5 7QN

BCSA
4 Whitehall Court
UK-London SW1A 2ES

Portugal
Instituto da Construçao - POLO IST
Departamento de Engenharia Civil
Instituto Superior Tecnico
Av. Rovisco Pais
PT - 1096 Lisboa codex

Slovenia
Institut za Metalne Konstrukcije
Mencingerjeva 7
Lubljana
Republika Slovenija