A Rational Approach to Fire Engineering Design of Steel Buildings

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At present there is a clear trend in many countries toward developing building regulations containing more functionally based requirements and performance criteria. However, concerning the fire engineering design of buildings, the regulations in most countries are still based upon strongly stereotyped requirements. For a load bearing structure the regulations normally require a certain time of fire resistance according to a standard fire test. It is, however, a well known fact that the conditions during a real fire can differ to a very great extent from these during a standard fire test. The fire resistance time is therefore of rather limited interest if we want to know the behavior and load bearing capacity of a structure during a real fire. Wanting to know this, we must use more differentiated or rational design methods, not based upon stereotyped standard rules, but on physical realities.

In 1967 the National Board of Urban Planning, which is the central authority for planning and building in Sweden, took an essential step towards more functionally based regulations in the field of fire engineering design. The Board's standard specifications for that year for the first time clearly pointed out the possibility of carrying through a more differentiated fire engineering design as an alternative to the stereotyped design. A problem in this connection, however, has been the complicated calculations, the lack of data, and the lack of manuals to facilitate the practical design work.

A manual giving a rational fire engineering design method with design diagrams applicable to steel structures has recently been published in Sweden.[1] The manual, which has been approved in general by the Swedish Building Authority, was developed in close collaboration between Lund Institute of Technology and the Swedish Institute of Steel Construction. It makes available for practical design purposes the results of recent work in the field of fire engineering research. The design method presented in the manual is based upon physical realities and enables us to design a steel structure in such a way that it will fulfill its function during a real fire.

In a differentiated fire engineering design method, consideration is given in an accurate way to several factors which are neglected in a stereotyped design based upon a standard fire resistance time. It is therefore not surprising that the rational design method can very often significantly reduce the cost of obtaining the necessary fire protection.

PRINCIPLES OF A RATIONAL FIRE ENGINEERING DESIGN METHOD

The rational fire engineering design method presented is based on four main steps:[2]

1. Determination of the Fire Load—The first step is to determine the fire load. Statistical investigations of the fire load in different kinds of buildings have been carried out in Sweden.[3,4,5,6] The results of these investigations have been put together in the manual.

2. Determination of the Gas Temperature in the Fire Compartment—The second step is to determine the gas temperature-time curve in the fire room or compartment. Such gas temperature-time curves have been computed through energy balance equations for a number of typical and representative fire compartments.[7] These curves have been presented in the manual as a function of the fire load and the ventilation conditions of the compartment. Consideration is also taken of the thermal properties of the surrounding structures of the compartment. The computed gas temperature-time curves have been verified through comparison with results from full scale tests to form a relevent basis for the practical design.[7,8]

3. Determination of the Maximum Steel Temperature—The third step is to determine the temperature of the steel structure. The steel temperature can be computed with energy balance equations on the basis of the gas tempeature-time curves. The results of such calculations have been put together in design tables, from which the maximum steel temperature for a specific fire condition easily can be determined. There are such tables for exposed as well as for protected steel structures.

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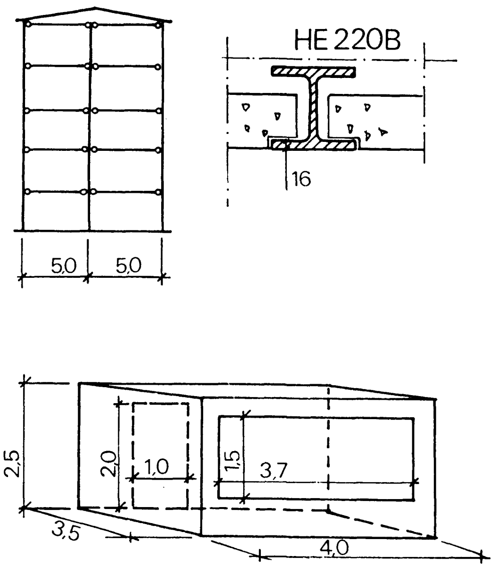


Fig. 1. Five story hotel building

Table 1. Loading Values to be Applied in a Differentiated Structural Fire Engineering Design

Type of Fire Compartment	Permanent Loading Part (kp·m^{-2})	Movable Loading Part (kp·m^{-2})
(a) Complete evacuation of occupants not certainly anticipated		
Dwellings, hotels, and hospitals	35	70
Offices and schools	35	100
Stores and assembly rooms (excluding rooms with compact disposed loading)	35	250
(b) Complete evacuation of occupants certainly anticipated		
Dwellings, hotels, and hospitals	35	35
Offices and schools	35	55
Stores and assembly rooms (excluding rooms with compact disposed loading)	35	70

Note: It is to be proved that the load-bearing structure or structural member does not collapse during the complete process of fire development for the most unfavorable combination of

1. the dead load,
2. the snow load, multiplied by the load factor 1.2, and
3. the live load, multiplied by the load factor 1.4.

The dead load is determined conventionally. For the snow load, values are to be applied for the permanent and movable parts corresponding to 80 percent of the values according to current specifications. For the live load, the tabular values are applied.

4. Determination of the Critical Load—The last step of this rational fire design method is to determine the load bearing capacity or the critical load of the steel structure in case of fire. The load bearing capacity can be calculated on the basis of the strength and deformation characteristics of the steel at elevated temperatures. The results from such calculations[9,10] have been presented in design diagrams from which the critical load can be easily and directly determined for beams as well as columns as a function of the maximum steel temperature. By comparing the actual load with the critical load, it can be judged whether or not the structure will fulfill its function during a real fire. If better protection against fire is required, a determination of the maximum steel temperature and the critical load for the new value of insulation can be rapidly carried through with the aid of the design tables and diagrams.

THE MANUAL

In order to facilitate practical engineering design work, the manual[1] has been divided into four parts: a main section, a design section, examples, and a section describing an alternative design method. In the main section, the backgrounds and principles of the differentiated design method are given. The theories and equations used are thoroughly described. In the design section, all diagrams and tables necessary for practical design work are put together. The example section contains ten different examples, with solutions thoroughly describing the design procedure and the way to use the design tables and diagrams. The alternative design method is based upon the concept equivalent time of fire duration[11] and gives some rules and diagrams for translating the results from standard fire tests of steel structures to real fire conditions.

With the design method and the tables and diagrams presented in the manual, the necessary fire insulation can very often be reduced, leading to reduced costs of fire protection. In some cases it is even possible to prove that a steel structure, or part of it, can be left exposed without any risk of collapse, even under rather severe fire conditions.

An idea of the use of the manual in practical engineering design work is given by the following example.

APPLICATION TO A HOTEL BUILDING

The floor slabs in a 5-story hotel building are supported by steel beams, as shown in Fig. 1. The distance between the beams is 4.0 m and the span is 5.0 m.* The beams are simply supported and the dead load of the floor slabs is 700 kp/m^2. The beam section modulus is W = 736 cm^3 and the yield point at room temperature is 2600 kp/cm^2. The surrounding structure of the fire compartment consists of concrete floors, a front wall of double sheet steel panels with mineral wool insulation and inside walls of double plasterboard panels. In case of fire a complete evacuation of occupants can not be anticipated with certainty.

The question to be answered is: Do the lower flanges of the beams have to be insulated against fire or not?

* *Ed. Note: The metric units in this example are those used in the fire engineering manual (Ref. 1); they do not conform to the SI (International System), which will shortly become the metric standard in Sweden as well as in the U. S. The Nomenclature section at the end of the paper provides data for conversion to equivalent SI and English system units.*

Static Load Which a Beam Must Bear during Fire—

Dead load:	700 kp/m^2
Live load and load factor according to Table 1:	147 kp/m^2
	847 kp/m^2

The uniformly distributed load that the beam must bear thus is 3400 kp/m.

Fire Load and Opening Factor of the Fire Compartment— The fire load for hotels is 19.5 $Mcal/m^2$ total surrounding area of the fire compartment, according to Table 2. This value includes only the mobile fire load. The contribution in fire load from floor and wall covering, etc., is roughly calculated to 2.5 $Mcal/m^2$ total surrounding area of the fire compartment. Total fire load is thus 22 $Mcal/m^2$.

Total surrounding area of the compartment is

$$A_t = (2 \times 3.5 \times 4) + (2.5 \times 4) + (2 \times 2.5 \times 3.5) = 65.5 \text{ m}^2$$

Window area $A = 1.5 \times 3.7 = 5.6 \text{ m}^2$

Window height $h = 1.5$ m

Thus, the opening factor which defines the ventilation conditions is $A\sqrt{h}/A_t = 0.105 \text{ m}^{1/2}$.

Table 2. Design Value of Fire Load q for Different Kind of Buildings Based on Recent Swedish Investigations

Type of Fire Compartment	Total $Mcal/m^2$ Surrounding Area of the Fire Compartment
1) Dwellings[a]	
1a) Two rooms and a kitchen	40.0
1b) Three rooms and a kitchen	35.5
2) Offices[b]	
2a) Technical offices	34.5
2b) Administrative offices	31.5
2c) All offices investigated	33.0
3) Schools[b]	
3a) Schools—junior level	23.5
3b) Schools—middle level	28.0
3c) Schools—senior level	17.0
3d) All schools investigated	23.0
4) Hospitals	35.0
5) Hotels[b]	19.5

Notes:
a. Floor covering excluded.
b. Only movable fire load components included.

Table 3. Coefficient k_f for Transforming the Fire Load and Opening Factor with Respect to the Thermal Properties of the Surrounding Structures of the Compartment

Type of Compartment	Surrounding Structures	Opening Factor 0.02	0.04	0.06	0.08	0.10	0.12
A	Thermal properties corresponding to an average of concrete, brick, lightweight concrete	1	1	1	1	1	1
B	Concrete	0.85	0.85	0.85	0.85	0.85	0.85
C	Lightweight concrete	3.0	3.0	3.0	3.0	3.0	2.5
D	50% concrete 50% lightweight concrete	1.35	1.35	1.35	1.50	1.55	1.65
E	50% lightweight concrete 33% concrete	1.65	1.50	1.35	1.50	1.75	2.00
F[a]	80% steel sheet 20% concrete	1.00–0.50	1.00–0.50	0.80–0.50	0.70–0.50	0.70–0.50	0.70–0.50
G	80% plasterboard—air space—plasterboard 20% concrete	1.50	1.45	1.35	1.25	1.15	1.05
H	Steel sheet—mineral wool—steel sheet	3.0	3.0	3.0	3.0	3.0	2.5

[a] The lowest value of k_f applies to a fire load density $q = 120$ $Mcal/m^2$ the highest value to a fire load density $q = 15$ $Mcal/m^2$. For intermediate fire load densities, linear interpolation gives sufficient accuracy.

Table 4. Portion of Table Giving max. Steel Temperature of Fire Exposed Uninsulated Steel Structures[a] for Varying Fire Conditions (Ref. 1)

q (Mcal/m²)	$\frac{A\sqrt{h}}{A_t}$ (m$^{1/2}$)	$\frac{F_s}{V_s}$ (m^{-1})	ϑ_{max} (°C) ϵ_r 0.3	ϵ_r 0.5	ϵ_r 0.7
25	0.01	25	455	490	500
		50	510	525	530
		75	525	530	535
		100	530	535	535
		125	530	535	540
		150	535	540	540
		300	535	540	540
		400	540	540	540
	0.02	50	555	600	625
		75	610	640	650
		100	640	650	655
		125	650	655	660
	0.04	50	570	645	700
		75	650	720	760
	0.06	25	355	420	510
		50	525	600	700
		75	640	690	780
	0.08	50	480	590	655
		75	590	700	770
		100	660	775	—
	0.12	25	240	280	385
		50	400	460	590
		75	500	580	700
		100	590	655	800
		125	650	720	—

[a]Tables for insulated steel structures can also be found in Ref. 1.

Transforming the Fire Load and Opening Factor with Respect to the Thermal Properties of the Surrounding Structures of the Compartment—Consideration is given to the thermal properties of the surrounding structure of a fire compartment through a coefficient k_f, by which the fire load and opening factor are transformed to new values based on a fire compartment with standardized thermal properties of the surrounding structure. These new values give the same gas temperature as the real fire load and opening factor would have given in the real fire compartment. This technique of transforming values between fire compartments of different thermal properties has the great advantage that the design diagrams and tables can be limited to only one type of fire compartment.

In Table 3 the coefficient k_f can be found for different types of fire compartments. In our example the surrounding structures consist of concrete, plasterboard, and mineral wool insulated sheet steel in the proportions 49%, 44%, and 7%. The compartment thus is a combination of compartment types B, G, and H (see Table 3.) By interpolation

$$k_f = 0.07(k_f)_H + 0.55(k_f)_G + 0.38(k_f)_B = 1.14$$

The new value of fire load q will then be $1.14 \times 22 = 25$ Mcal/m^2.

The new opening factor is $1.14 \times 0.105 = 0.12$ m$^{1/2}$.

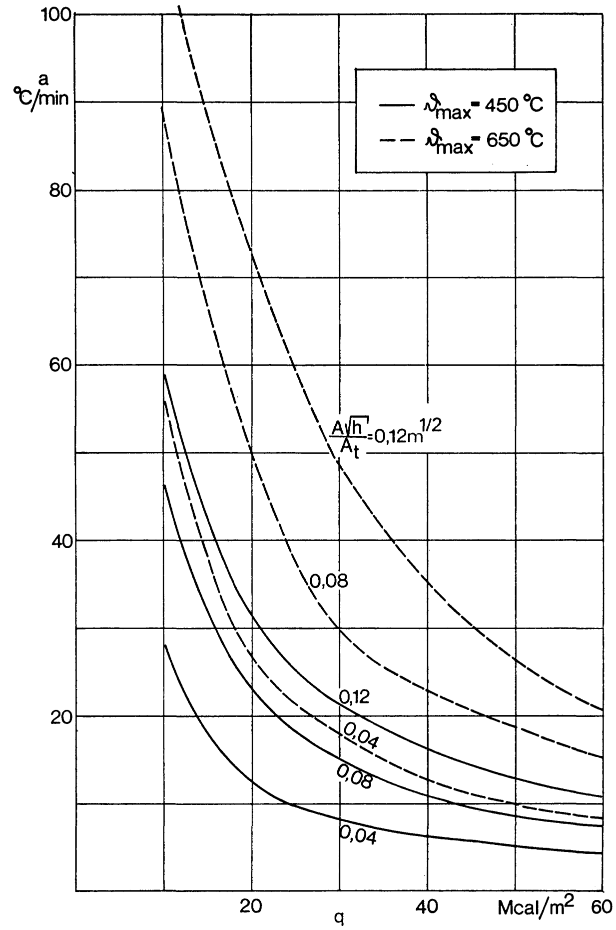


Fig. 2. Average rate of heating a for a fire exposed steel beam as a function of the fire load q, the opening factor $A\sqrt{h}/A_t$, and the maximum steel temperature ϑ_{max}

Maximum Steel Temperature—To determine the maximum steel temperature, it is necessary to know, in addition to the fire load q and the opening factor $A\sqrt{h}/A_t$, the ratio of the fire exposed surface area to the volume of the steel structure, F_s/V_s, and the resultant emissivity, ϵ_r. According to the manual, the ratio F_s/V_s in this case can be approximated as $1/t$, where t is the flange thickness of the beam, or 62.5 m^{-1}.

Moreover it can be found that a value of the resultant emissivity of $\epsilon_r = 0.5$ is valid for floor beams.

With the input data $q = 25$, $A\sqrt{h}/A_t = 0.12$, $F_s/V_s = 62.5$, and $\epsilon_r = 0.5$, the following values can be found from Table 4:

F_s/V_s	ϑ_{max}
50	460
62.5	520*
75	580

The maximum steel temperature during a real fire thus is determined to $\vartheta_{max} = 520$°C.

* *Interpolated value.*

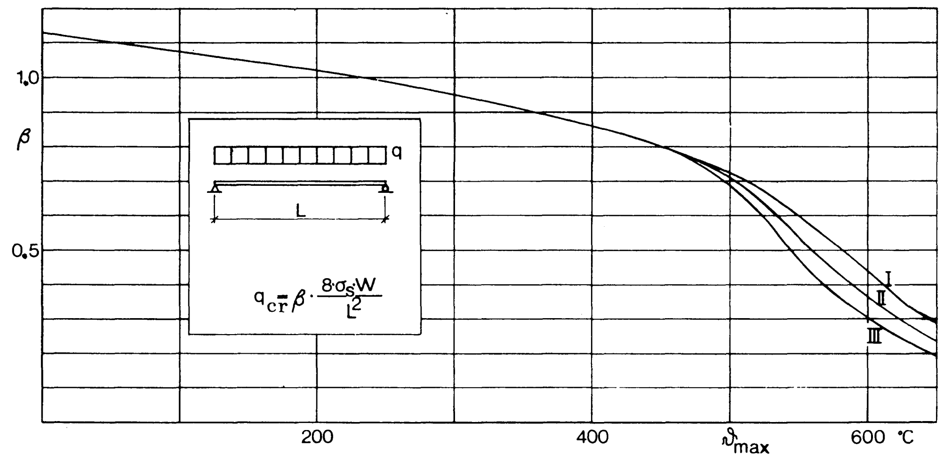


Fig. 3. Diagram for determination of the critical load q_{cr} for a simply supported steel beam with uniformly distributed load. The three curves correspond to different heating rates, a (I = 100°C/min., II = 20°C/min., III = 4°C/min.)

Critical Load—As a consequence of the creep effect, the critical load of the beam at the temperature 520°C is to some extent dependent on the heating rate. From Fig. 2, the heating rate can be roughly estimated. Through interpolation it is found that the values q = 25 Mcal/m^2, $A\sqrt{h}/A_t$ = 0.12 m$^{1/2}$, and ϑ_{max} = 520°C approximately give a heating rate of a = 40°C/min.

For a simply supported beam with a uniformly distributed load, the critical load can be determined from Fig. 3 as a function of the maximum steel temperature and the heating rate. From Fig. 3, with ϑ_{max} = 520°C and the heating rate 40°C/min., we find β = 0.68. The static load at which the beam can be supposed to collapse during the fire is

$$q_{cr} = \beta \frac{\sigma_s W}{L^2}$$

where

σ_s = yield point at room temperature
W = elastic modulus of section

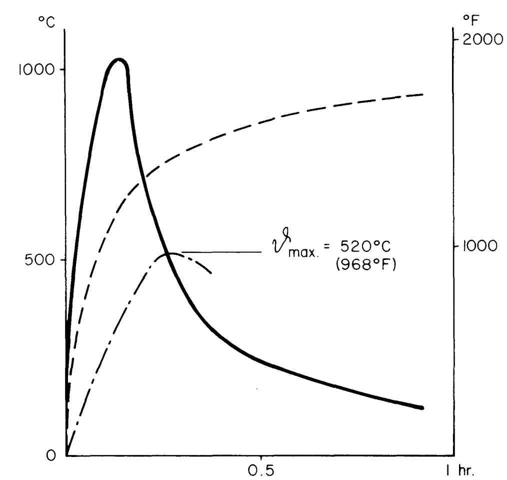
$$q_{cr} = 0.68 \left(\frac{8 \times 2600 \times 736}{500^2}\right) = 4200 \text{ kp/m}$$

The load which the beam must be able to bear during the fire, calculated previously, q = 3400 kp/m. This load is less than the critical load; consequently, the beam will fulfill its function during the fire without the lower flange being protected against fire.

CONCLUDING REMARKS

The fire engineering design method presented in the manual is based upon the physical realities of real fires, rather than stereotyped rules connected to a standard fire curve. For instance, the gas temperature-time curves used in the design procedure correspond to the real fire load, to the real ventilation condition, and to the real thermal properties of the surrounding structure of the fire compartments. In Fig. 4 the gas temperature-time curve used in the example above is compared with the ISO-standard fire curve. Figure 4 also shows the steel temperature-time curve for the lower flange when subjected to the gas temperature of the real fire. The maximum steel temperature of 520°C in the lower flange can, as has been demonstrated in the example, be directly determined from the tables in the manual.

The temperature of 520°C is not critical for the steel beam in the example. Its loadbearing capacity at 520°C is greater than the static load which must be considered during the fire. It can be added that for this particular structure the real loadbearing capacity will be still higher than shown by the calculation, because the temperature in the upper flange will be much less than 520°C.



LEGEND:

—— Gas temperature used in the example. (The curve corresponds to a fire load of q = 25 Mcal/m^2 and an opening factor $A\sqrt{h}/A_t$ = 0.12 m$^{1/2}$ in a fire compartment with standard thermal properties of the surrounding structures).

– – – ISO - standard fire curve.

—·— Steel temperature in the lower flange.

Fig. 4. Temperature-time curves

To sum up, it should be emphasized that in a rational fire engineering design, consideration can be given to several important factors which can not be considered in a more stereotyped design. The cost of providing the necessary fire protection of a steel structure can be significantly reduced by this design method. With the aid of the manual, the practical design work for normal cases can be carried out easily.

NOMENCLATURE

a	=	heating rate, °C/min (1°C/min = 9/5 °F/min)
A	=	opening area of the fire compartment, m^2 (1 m^2 = 10.76 sq ft)
A_t	=	total internal surface area of the fire compartment, m^2 (1 m^2 = 10.76 sq ft)
F_s/V_s	=	ratio of area per unit length exposed to fire to enclosed steel volume per unit length, m^{-1} (1 m = 3.28 ft)
h	=	height of fire compartment openings, m (1 m = 3.28 ft)
k_f	=	conversion factor
L	=	span of beam, cm (1 cm = 0.394 in.)
q	=	fire load, Mcal/m^2 total internal surface area (1 Mcal/m^2 = 4190 kJ/m^2 = 369 Btu/sq ft)
q_{cr}	=	critical static load, kp/cm (1 kp/cm = 9.81 N/cm = 5.60 lbs/in.)
W	=	elastic modulus of section, cm^3 (1 cm^3 = 0.061 $in.^3$)
β	=	coefficient for determination of critical load
ϵ_r	=	resultant emissivity
ϑ_{max}	=	maximum steel temperature, °C (°C × 9/5 + 32 = °F)
σ_s	=	yield stress of the steel, kp/cm^2 (1 kp/cm^2 = 98.1 kPa = 14.22 psi)

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