Fire Engineering Design of Structures Based on Design Guides

by

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1. ABSTRACT

Performance-based design of structures exposed to fire has been possible for many years, due to extensive research on mechanical and thermal properties of concrete and steel, and on the behaviour of steel and concrete structures in fire since 1970 /1, 2/. Analytical design methods /3-5/ and databases on material properties have been employed in fire-dedicated computer programs developed for steel, concrete, aluminium and wooden structures /7-9/.

A performance-based design means most often more engineering work. This is, however, not the case if a design guide is available. The design guide facilitates the design considerably by giving advice on which concrete or insulated steel structure can be used to fulfil the load-bearing and/or separating function. The information in a design guide is provided in such a way that an optimal solution can be found and competitive products can be compared and considered.

Rather than repeating the fire design process for each product of standard pre-cast concrete elements and fire protection of steel members, general design guides may be developed. The assessment of general design guides, covering the bulk of all practical applications, is the most rational approach to performance-based fire engineering.

Fire engineering design based on design guides, provide a very competitive alternative or complement to expensive full scale fire testing and will cover a much wider range of applications compared to fire tests.

Several examples of beneficial design guides for building components and insulation barriers are presented in this paper. The contents was put forward with emphasis placed on illustrating advantageous effects of each design guide. The design guide may be expressed in tables and/or in design charts for optimal use of the data assessed.

2. INTRODUCTION

During the past few years there has been a rapidly growing interest in performance-based methods applied to fire safety engineering. Several national building codes (Sweden, Norway, New Zealand, Australia, UK etc.) have already been revised to follow this new approach, thus pointing the way to future developments in fire safety engineering. The performance-based concept provides a flexibility when selecting technical solutions to fire safety problems, but requires new tools (e.g. design guides) and methods as well as skills, competence and experience of the engineers working in this field.

Structures and members are generally divided into fire classes or designed to fulfil parametric fires (real fires based on fire load and ventilation characteristics) with respect to their load-carrying (R) and separating (EI) function. The separating performance comprises sub-requirements of integrity (E) and insulation (I). Consequently there is a need for appropriate means of determining the capabilities of any given structure, sub-assembly or building component with respect to its load-bearing and separating function under fire exposure. The fulfilment of a requirement may be verified by calculation, full scale testing or a combination of the two.

The analytical approach typically comprises thermal and subsequent structural analyses for determination of the load-bearing capacity. By incorporating the thermal and mechanical properties of the studied materials as function of elevated temperatures, the members may be evaluated with respect to their performance when exposed to fire. The load-carrying function in the fire situation is maintained by ensuring that the design load does not exceed the load-carrying capacity.

3. THE DESIGN GUIDE CONCEPT

In order to take advantage of the possibilities provided in the performance-based codes, and in order to extend its applicability for the benefit of manufacturers, a concept called design guides has been introduced. In generic terms the design guide provides optimised solutions for standard applications of all sorts of passive fire protection materials and pre-fabricated concrete or sandwich components.

This may be accomplished by employing fire-dedicated key engineering software tools for heat transfer and structural load-bearing capacity calculations respectively. Based on systematic computerised predictions, product specific design guides may be assessed for any pre-determined scope.

The scope of the design guide is determined in close collaboration with the client to suit its best needs and to cover the areas carrying the bulk of its sales. The overall governing criteria for the design guide normally comprise verification of load-bearing and separating function for a given fire scenario.

The design guide may be expressed in tables and/or in design charts for optimised use of the data assessed. Typically the design guide may comprise information on:

- minimum member thickness required as function of the fire duration
- load-bearing capacity as function of the fire duration for various members and structures
- minimum member dimensions as function of fire duration
- minimum concrete cover and/or number of reinforcing strands in concrete slabs
- required thermal barrier thickness for protection of metal members and structures at various fire durations

4. NEED AND BENEFIT OF DESIGN GUIDES

The building market is dominated by standard pre-cast and pre-fabricated building components, manufactured in large numbers, e.g. different types of concrete columns, beams and slabs, brick walls, steel beams embedded in concrete and other composite and sandwich members etc. For such building members, the load-bearing capacity and separating function in fire can be calculated once and for all and presented in a design guide where it´s readily accessible. This means that standard calculations do not have to be repeated over and over again.

Fire-exposed metal structures normally need passive fire protection (PFP), e.g. mineral wool, gypsum boards, wooden based boards, intumescent paint, epoxy materials, vermiculite-concrete based materials etc. The cost of PFP is substantial. Hence huge savings can be made by optimising the use of the material. The optimisation of the material application is also a competitive advantage for the manufacturer who can provide protection solutions to equivalent standard with less insulation material.

Historically manufacturers have been obliged to resort to expensive full scale furnace testing, when demonstrating the capability of their product. The design guide approach, however, offers the possibility of combining furnace testing and computer simulations, thus allowing for improvements in terms of:

- reduced testing costs
- extended applicability

All relevant design guidelines will be assembled in one package. This is very useful in the material procurement stage and for cost estimations in a project. The design guide furthermore speeds up the design process by providing the relevant data at the fingertips of its user, and hence the time spent on determining the right members (with or without thermal insulation) in the fire engineering process can be reduced substantially. Additionally quality assurance issues are promoted as a consistent safety level may be attained through out the building. The design guide will considerably promote the selection of optimal solutions with respect to cost and performance, while complying with stated requirements.

If the thermal properties of the material are not known they can be assessed by computer simulation of tailor-made fire tests. By applying computer methods the design approach and the thickness of insulation for metal members can be optimised for different member materials, geometries and different types of fire exposure.

5. WHAT FIRE SCENARIO SHALL BE DESIGNED FOR?

The design fire exposure is maybe the most decisive parameter in the entire fire design process, as it affects subsequent analyses throughout. It is also very hard to predict. Therefore a number of models and standard time heat regimes have been assessed to match the variety of possible fire scenarios that may occur within an analysed fire compartment.

When comprehensive information about the geometry of the fire compartment and the combustibles contained in it is available, a more accurate prediction of the design fire scenario may be undertaken, and consequently the design will be adapted to the current project.

The predominant fire exposure for compartments used in the past in fire design of buildings is the standard fire exposure in accordance with ISO 834 /6/. Models of natural fires or parametric fires, based on the heat load and ventilation characteristics of the fire compartment, may also be used. If the fire involves hydrocarbon (HC) material rather than cellulosic goods the temperature increase will be more rapid and the maximum temperature will be dependent on the heat load level expressed in MW/m^2 as indicated below.

5.1 Standard Fire

The cellulosic ISO 834 standard fire /6/ is characterised by a time temperature development in accordance with equation 1.

$$T_t = 345 \cdot \log(480t + 1) + T_0 \qquad \text{eq. (1)}$$

where, t =time in hours
T_t =gas temperature at t minutes (°C)
T_0=initial temperature (°C).

5.2 Parametric Fires

The governing parameters in the natural fire model are heat load density (MJ/m^2) and opening factor ($m^{0.5}$) for a fire compartment. Based on these input, the time temperature regime of a parametric (natural) fire can be determined. The natural fire comprises three phases, viz. ignition phase, flame phase and cooling phase. The natural fire model is limited to a maximum floor area of 500 m^2 and is not applicable in larger compartments.

The heat load is calculated from information of the combustion energy of the material in the fire compartment. Opening factors depend on the relation between openings, i.e. doors, windows, smoke evacuation etc., and the total inner area of the compartment, inclusive of openings.

5.3 Hydrocarbon Fires

The gas temperature-time relation of a hydrocarbon fire is defined by equation 2 below. The magnitude of the maximum temperature of the radiation source (T_1) is crucial for the time temperature development.

$$T(t) = T_1\left(1 - 0.325\,e^{-0.167t} - 0.204\,e^{-1.417t} - 0.471\,e^{-15.833t}\right) \qquad \text{eq. (2)}$$

where, T(t) = temperature of radiation source as function of time [°C]
T_1 = maximum temperature of radiation source [°C]
t = time [minutes]

The maximum temperature of the radiation source for various heat loads are calculated in accordance to Stephan-Bolzmanns law assuming blackbody radiation, i.e. no loss of radiation and an emissivity factor of 1.0.

5.4 Gas Temperature Development

The gas temperature development with time, for the fire scenarios discussed in the previous sections, are presented in Fig 1 below for illustration of their respective differences.

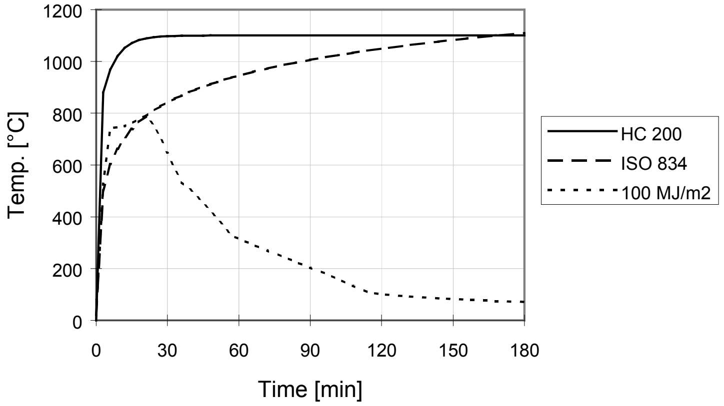


Fig 1

Illustration of differences in time heat regimes for HC 200, ISO 834 and parametric fire (heat load = 100 MJ/m^2, opening factor = 0.04 m$^{1/2}$)

6. TRADITIONAL AND PERFORMANCE-BASED FIRE SAFETY ENGINEERING

Current fire protection engineering practice is largely based on the application of prescriptive requirements whereby the engineer designs in accordance with pre-determined requirements based on generic occupancies or classes of fire risk.

Traditional fire design is based on a standard fire in conformity with ISO 834. This time heat regime is normally much more severe than a natural (real) fire, derived from fire load density and ventilation characteristics of the fire compartment. The standard fire is characterised by a continuous temperature increase while the natural fire has both a heating phase and a subsequent cooling phase as illustrated in Fig 1.

The fire resistance requirement in the prescriptive code is expressed by target fire resistance ratings for members subjected to ISO 834 fire exposure. This means that a structural member should be designed in such a way that it does not collapse within 30, 60, 90 or maybe 120 minutes. No classes in-between are available. Hence if a test specimen collapses after 59 minutes it will be categorised in the R30 fire class, irrespective of the loading level.

Suppose the load level in the previously mentioned test equalled 100 % of the design load at normal temperature design. By using a more adequate loading level, preferably in the range of 50-70 %, the time to structural failure can be prolonged. Accordingly many structural members fire-tested in the old-fashioned way could be classified in a higher fire class, if only the load-utilisation was considered.

In the performance-based design the structure is not allowed to collapse during the complete process of fire including the cooling phase. This makes the design more complicated because the critical time, with respect to minimum load-bearing capacity or separating ability, occurs at some time during cooling, and therefore must be found. This occasion must often be assessed by repeated computer calculations, The extra effort, however, usually pays off because the natural fire is normally less severe than the prescribed fire duration of the standard fire.

7. FIRE ENGINEERING DESIGN BASED ON DESIGN GUIDES

7.1 Fire Design Process

The fire design process for separating structures only comprise thermal analysis whilst for load-bearing structures both a thermal and a subsequent structural analysis is required.

The overall fire design process can be separated into the activities illustrated in Fig 2. The flow chart below emphasises that the load-bearing capacity is very much depending on the assessed design fire scenario.

Thermal input data are; heat transfer coefficients at boundaries, thermal conductivity and thermal capacitivity of the materials. The thermal analysis comprises a determination of the temperature field versus time in the components under design.

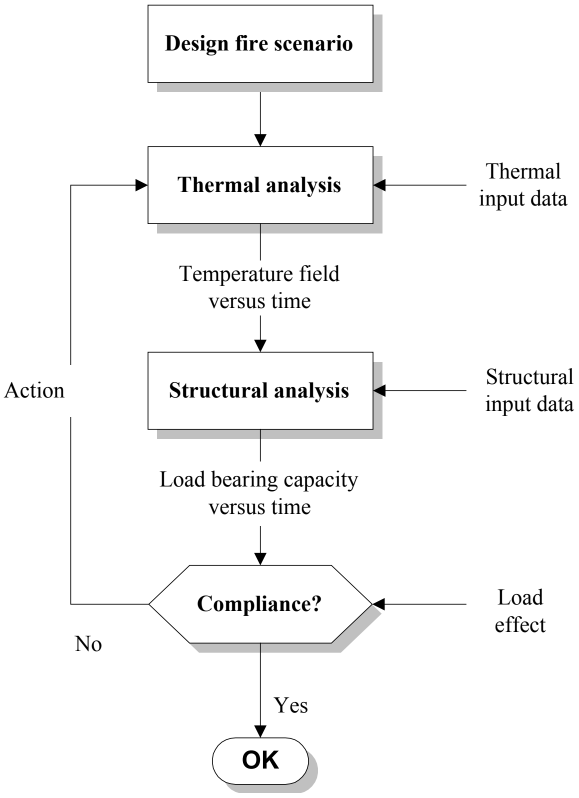


Fig 2 Fire design process.

Due to the thermal exposure a temperature gradient inevitably will develop in members subjected to fire. Temperature gradients are accounted for when a computerised design approach is adopted, but not in simplified calculations for slab and beam members, which shall provide safe side conservative results.

Based on the results obtained in the thermal analysis and on the structural input data the reduced load-bearing capacity can be calculated in the structural analyses. Structural input data encompass mechanical properties (strength, modulus of elasticity and stress strain relation) as function of temperature and structural boundary conditions. If the calculated load-bearing capacity does not exceed the load effect actions must be taken.

Simplified design for metal beam members is based on a critical temperature, which in turn is a function of the tensile strength. Based on the tensile strength the load-bearing capacity is assessed. The simplified design of concrete slabs and concrete beams is similarly based on a critical temperature of the steel reinforcement. The load-bearing capacity assessment is based on the tensile strength and the actual cross-section. Examples from design guides for simplified design of concrete slabs and beams as well as steel members will be illustrated.

The load-carrying capacity in the fire situation can be calculated either by a global structural analysis or by a simplified member calculation. The global structural analysis shall be based on verified and acknowledged theory and comprehensive non-linear computer programs. Practical tools used to develop the design guides, exemplified in this paper, are Super-

Tempcalc /7/ for thermal analysis and Fire Design /8/ for load-bearing capacity assessment. Comprehensive steel structures are analysed by Global Collapse Analysis /9/.

7. 2 Design Guide for Simplified Design of Concrete Slabs and Beams

There is a relationship between the load utilisation and the maximum steel temperature for slabs as well as for beams. Based on the critical temperature of the steel reinforcement and the thermal profile of the structure, design diagrams for concrete slabs and beams can be developed.

If the design fire and the load utilisation degree is given, the minimum concrete cover (axis distance) of slabs and rectangular concrete beams can easily be assessed for normal reinforcement and for prestressing wires. In Fig 3 the minimum axis distance of slabs as function of the steel temperature can be determined for varying fire loads at opening factor 0.04 $m^{0.5}$. This is only an example and similar diagrams exist for other opening factors and fire loads and for different fire classes.

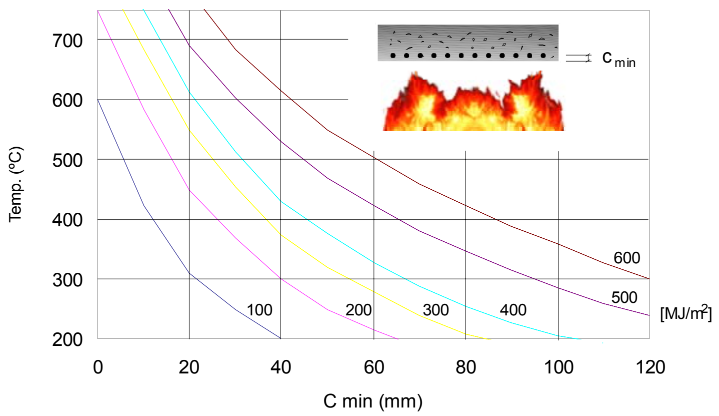


Fig 3

Minimum axis distance (c) as function of steel temperature for a reinforced concrete slab (thicknesses $\geq$120 mm) exposed to real fires with varying heat load for the opening factor = 0.04 $m^{1/2}$.

A similar simplified design diagram for a rectangular concrete beam is shown as an example in Fig 4 giving the minimum axis distance (c) for varying heat loads and reinforcement steel temperatures at the opening factor 0.04 $m^{0.5}$.

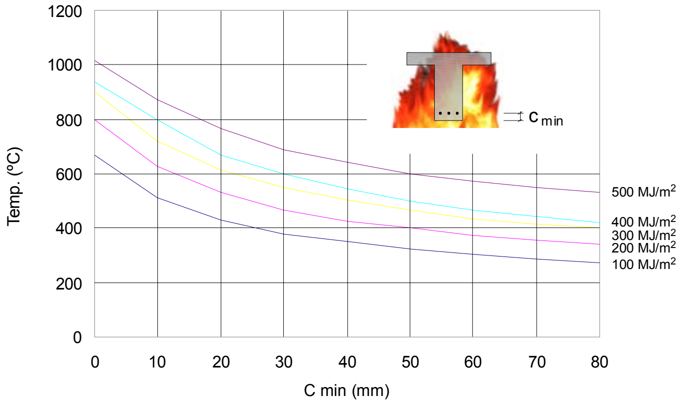


Fig 4

Minimum axis distance (c) as function of steel temperature for reinforced concrete beam exposed to real fires with varying heat load at the opening factor= 0.04 $m^{1/2}$.

7.3 Design Guide for Prestressed Hollow Slabs and T-beams

Design guides for precast concrete products applicable to the standard fire (ISO 834) and parametric fires have been developed. The load-bearing capacity, expressed as the bending moment capacity, has been assessed for the standard fire with durations of 30-120 minutes and for parametric fires. The parametric fires were characterised by different ventilation factors (opening factor 0.01-0.08 m ^{½}) and fire load densities 100-200 MJ/m^2.

As an example of the results in the design guide the minimum relative bending moment capacity is illustrated in Fig 5 for a precast hollow slab refered to as HD 120/32 (width = 1200 mm, height =320 mm) with a reinforcing steel area of 8 cm^2 and 11 cm^2 respectively. The guidelines apply to parametric fires with varying opening factors 0.02-0.08 m^{½} and varying fire loads 100-200 MJ/m^2.

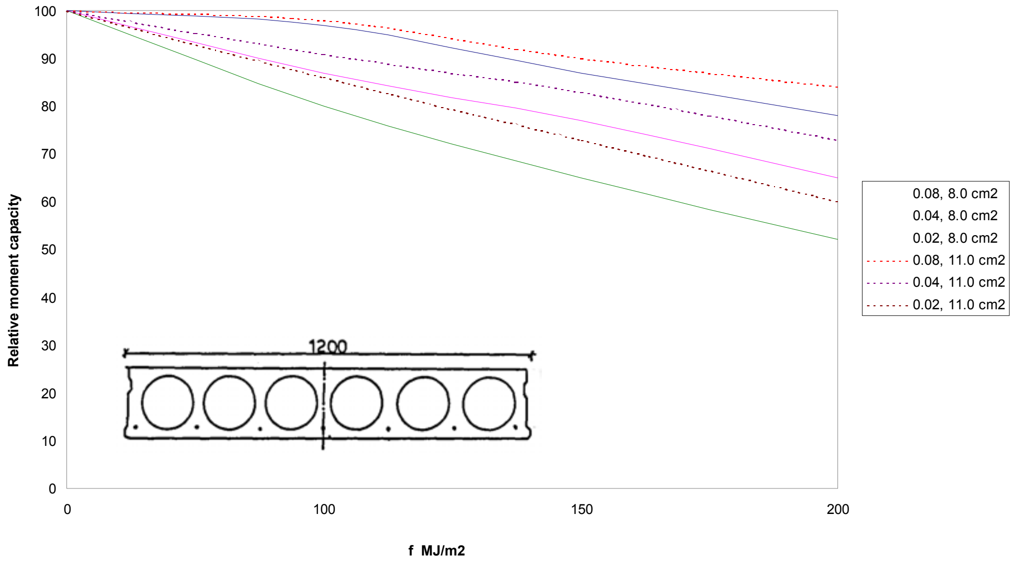


Fig 5 Relative moment capacity (kNm) for hollow slab (HD-F 120/32) as function of fire load density MJ/m^2 and opening factor 0.02-0.08 m^{½}. The initial moment capacity was 393 and 500 kNm for 8 and 11 cm^2 steel area respectively.

The same type of fire design diagram is shown in Fig 6 for the slab TTf 240-10/60.

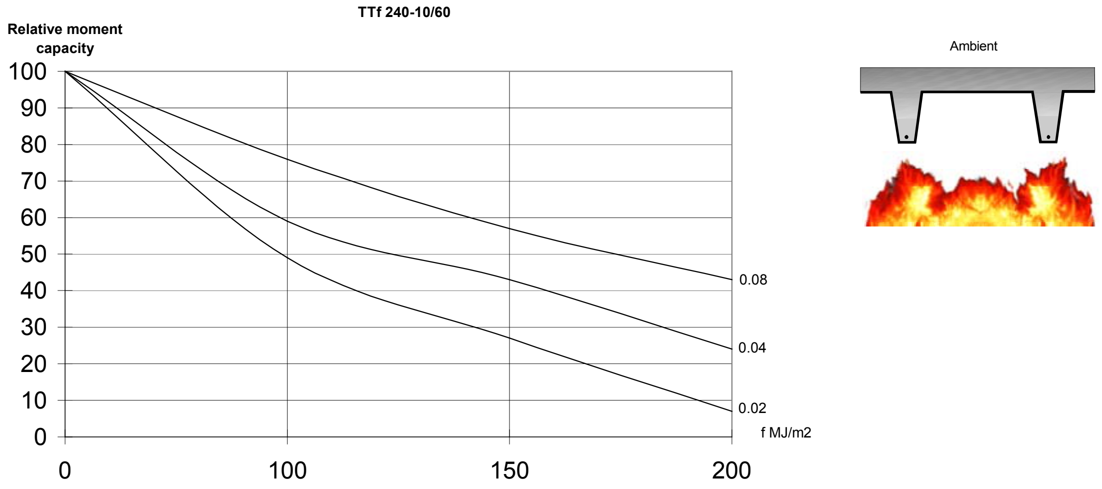


Fig 6 Relative moment capacity for a T-beam TTf 240-10/60 as function of fire load density MJ/m^2 and opening factor 0.02-0.08 m$^{1/2}$. The initial moment capacity was 650 and 553 kNm with and without an extra concrete cover of 60 mm respectively.

7.4 Design Guide for Precast Hollow Slabs

Fire design diagrams has been constructed for different precast hollow slabs with varying concrete cover and number of wires at fire classes R60, R90 and R120 and for parametric fires.

As an example from a design guide, a fire design diagram is illustrated in Fig 7 for a precast hollow concrete slab. The diagram shows the load-bearing capacity for different numbers of prestressing wires and at varying concrete covers as function of fire classes.

Presuming the load effect on an HD-F 120/19 hollow slab is 65kNm and R90 is required. What slab does fulfil this requirement? Fig 7 shows that a choice of either 7 wires with a concrete cover of 35 mm or 4 wires with a concrete cover of 45 mm is satisfactory.

The information in a design guide is provided in such a way that an optimal solution can be found and competitive products can be compared and considered.

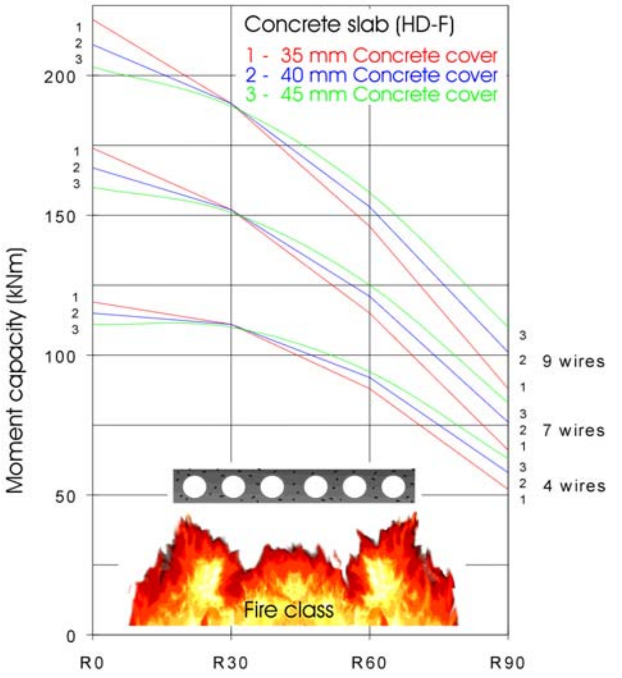


Fig 7
Bending moment capacity of hollow slab HD-F 120/19 as function of fire class with varying no:s of wires and at different concrete covers.

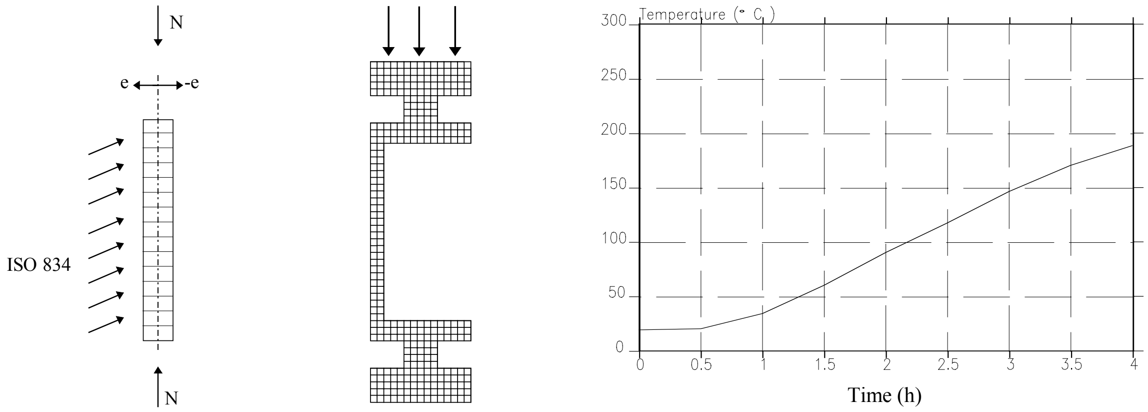
7.5 Design Guide for Concrete Walls

A general fire design guide for 3 different concrete block walls (thicknesses 100, 150 and 200 mm including voids) at heights 2.5 and 3.5 m has been developed. The design fire scenario was in accordance with ISO 834, with one- and two-sided exposure. The maximum distributed load per unit length was assessed for different eccentricities as function of time (fire duration).

The procedure for calculation of load-bearing capacity follows the Swedish requirements stated in ”Masonry 90” /10/ using the thermal and mechanical properties of concrete.

In Fig 8a the one-sided fire exposure is illustrated. Fig 8b shows the block geometry and finite element mesh for calculation of the temperature field as function of time. The fire exposed side is identified with arrows.

The separating requirement states a maximum increase in temperature of 140 °C on the back side. This temperature development is illustrated in Fig 8c for a concrete block of 150 mm. The separating criterion is fulfilled (160 °C) for approximately 3.5 hours.



a) b) c)

Fig 8 Concrete block wall of 150 mm wall thickness.

a) Fire exposure on one side.
b) Finite element mesh and block geometry.
c) Back face temperature increase with time.

An example of a load-bearing capacity diagram from the design guide is shown in Fig 9.

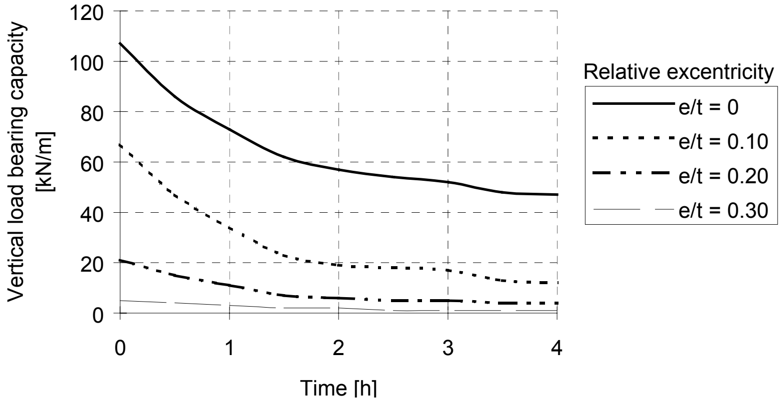


Fig 9

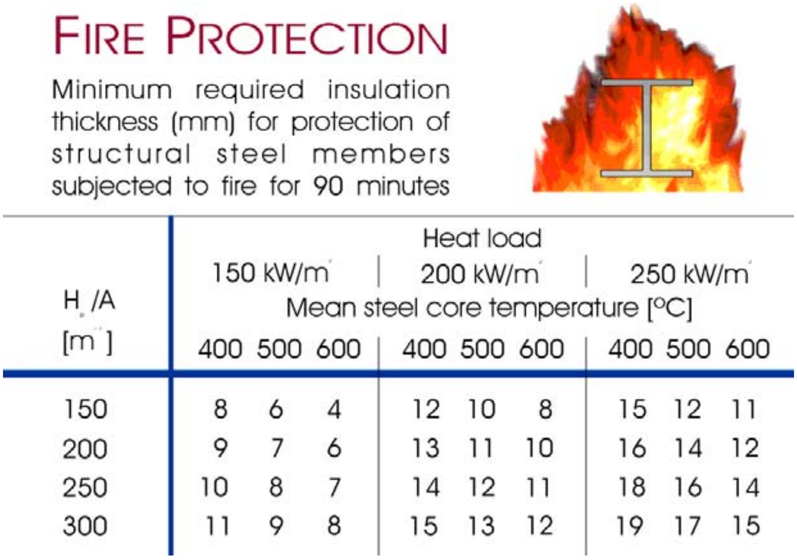
Maximum vertical load per unit length (kN/m) for one-sided fire exposure (ISO 834) of a concrete block wall, as function of fire duration for different relative eccentricities, e/t.

e: eccentricity
t: wall thickness, 150 mm
wall height: 3.5 m

7.7 Design Guides for Epoxy Insulation Materials

Passive fire protection manufacturers often find it useful to posses a tool which facilitates the assessment of relevant design application thicknesses. Hence several epoxy material manufacturers have chosen to develop design guides.

Intumescing materials provide fire protection by generating an insulating foam barrier around the object to be protected. The heat consuming intumescing process results in a carbonaceous char that is several times thicker than the original coat. The complex chemical reactions, when subjected to fire, inevitably result in complicated thermal properties. In the design guide, optimised insulation thicknesses for various fire scenarios, maximum steel core temperatures and for different structural elements may be assessed. In Table 1 an example of optimisation is presented.



FIRE PROTECTION

Minimum required insulation thickness (mm) for protection of structural steel members subjected to fire for 90 minutes

H_p/A [m^{-1}]	Heat load 150 kW/m^2			200 kW/m^2			250 kW/m^2		
	Mean steel core temperature [°C] 400	500	600	400	500	600	400	500	600
150	8	6	4	12	10	8	15	12	11
200	9	7	6	13	11	10	16	14	12
250	10	8	7	14	12	11	18	16	14
300	11	9	8	15	13	12	19	17	15

Table 1

Minimum insulation thickness for protection of structural steel members.

8. CONCLUSIONS

Design in accordance with prescriptive regulations result in a conservative and very expensive overdesign in many cases, but sometimes also in an unsafe structure at risk of structural collapse. Solutions based on prescriptive design is characterised by an uneven safety level.

Performance-based design is characterised by optimisation based on realistic design fire scenarios and load effects, thus reflecting the predicted structural performance under fire and providing a fire-safe structure. Verification of structural stability in fire may be conducted member by member or for the structure as a whole system.

By conducting a more diversified analysis of fire-related problems, expensive and sometimes inadequate solutions can be avoided. Comprehensive conservative assumptions as concerns the fire scenario generate costs that can be avoided by undertaking a closer study of the opening factor and the amount of combustibles contained in the compartment and consequently achieving a more accurate description of the potential fire development.

Based on the experiences from using parametric fires as basis for fire design compared with prescribed target fire resistance requirement R30, R60, R90 etc., it is possible to estimate the average decrease in fire severity to about 50 %. This influence on precast concrete members means considerable savings and less overdesign, as indicated by the examples.

Fire engineering design based on design guides is very fast and gives an optimised design of members and sub-assemblies with the option of comparing various alternatives in a cost-benefit analysis. Furthermore the engineering work required in the design process is reduced to a minimum by undertaking the structural fire design of concrete and steel elements once and for all.

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