STRUCTURAL FIRE DESIGN
FOR COMPOSITE SLABS AND BEAMS

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ABSTRACT

Performance-based design of structures exposed to fire has been more and more used during the last 20 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 /1-5 /. Still very few national building codes do today allow a performance-based design following engineering principles. However this development of functional approach in Europe influenced the start of creating the first general prestandard of Eurocodes (ENV) in 1989. After about 8 years of experience in using the ENV-standard improvements have been implemented and the final standard (EN) is ready to be used in all European countries in 2003.

Analytical design methods /9-13/ and databases on material properties have been employed in fire-dedicated computer programs developed for steel, concrete, aluminium and wooden structures /6,7/. The software presented in this paper is today very powerful instruments in the fire safety design procedure. Computer calculations 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 and costs are reduced considerably. Especially the calculation of the behaviour and load-bearing capacity of composite concrete slabs exposed to fire have shown that the correlation between fire tests and computer simulations is very good and reliable. Computer simulations of fire tests can replace full-scale fire tests of composite slabs /14, 16, 17 /.

An application of the new Eurocode 4 for fire safety design by calculation is made for a composite slab. The beneficial effect of continuity of the composite slab is also illustrated. The aim of this paper is to give confidence and to encourage the use of calculation approach for especially composite steel and concrete structures.

KEYWORDS

Fire engineering design, performance-based design, functional approach, prescriptive rules, analytical tools, computer simulations, thermal and structural analysis and composite concrete structures.

BACKGROUND

The knowledge in fire safety has during the last 20 years been growing considerably. Fire safety design methods and analytical tools have been developed to facilitate the engineering approach in practise. During this development the need to transform the prescriptive and restrictive building codes into performance based codes with functional and flexible requirements has increased heavily. 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. This interest of functional approach has also led to the development of a European prestandard (ENV) called Eurocodes and is soon transformed into a final standard (EN) to be used in all Europe in about 2003. Also within offshore design in Europe performance-based fire safety regulations has been introduced. The performance-based concept provides 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.

PRESCRIPTIVE VERSUS PERFORMANCE-BASED FIRE REGULATIONS

Prescriptive building codes are very rigid and restrictive and do not allow engineering thinking. The safety level is also very much varying, in many cases it is very conservative and uneconomical but sometimes also unsafe. The prescriptive approach may not meet the expectations of either building owners or code officials, especially for more complex buildings or processes or where the potential exists for extremely high property or life losses. Examples of such occupancies include high ceiling or large volume spaces that house unusual processes or power generating facilities, in which a very small fire could threaten continuity of operations and result in a large loss.

Performance-based design for fire protection opens the door for the practical engineer to use his knowledge and the tools developed in the fire engineering field. The modern building code requirement on fire resistance of a structural element can be fulfilled in different ways either by fire testing in furnaces (prescribed regulations) or by calculation but also by a combination of these two. Furnace testing has been the predominant procedure in design for many years due to the prescribed rules in the codes. However during the last 10 years a gradual change into performance-based regulations with functional requirements and engineering principles based on calculation has taken place. Testing for fire safety by computer is more and more common today.

The application of fire safety engineering based on performance-based building codes have already led to new ideas how to improve the fire safety and how to consider fire risks and consequences. The creativity of the engineer has grown considerably and new solutions found. The flexibility in performance-oriented codes makes it possible to choose alternatives for fire safety measures. A new engineering thinking has started and people does not ask what are the requirements but how is the fire safety met in my project.

The analytical approach typically comprises thermal and subsequent structural analyses for determination of the load-bearing capacity.

EUROCODES-PERFORMANCE-BASED STRUCTURAL FIRE ENGINEERING DESIGN

The Commission of the European Community (CEC) took the initiative in 1989 to establish a set of harmonised technical rules for the design of construction works which, in the first stage, would serve as an alternative to the national rules in force in the Member States and ultimately, would replace them. The structural Eurocode programme comprises the following standards generally consisting of a number of Parts:

EN1990	Eurocode:	Basis of structural design
EN1991	Eurocode 1	Basis of design and actions on structures
		Part 2.2: Actions on structures exposed to fire

Eurocode 2-6 and 9 are referred to in Part 1:2 General rules - Structural fire design

EN1992	Eurocode 2	Design of conrete structures
EN1993	Eurocode 3	Design of steel structures
EN1994	Eurocode 4	Design of composite steel and concrete structures
EN1995	Eurocode 5	Design of timber structures
EN1996	Eurocode 6	Design of masonry structures
EN1997	Eurocode 7	Geotechnical design of structures
EN1998	Eurocode 8	Design of structures for earthquake design
EN1999	Eurocode 9	Design of aluminium alloy structures

These parts concerning fire were accepted within CEN as ENV:s (prestandard). The final stage EN (European standard) is planned to be ready about 2003. During this intermediary period, European member states can use the ENV drafts together with a National Application Document (NAD).

The Eurocodes standards provide common structural design rules for everyday use for the design of whole structures and component products of both a traditional and an innovative nature and it is stated that the structural model adopted for design shall reflect the expected performance of the structure in fire exposure.

In the standard six essential requirements have to be fulfilled and one of them is ”Safety in case of fire” and the Directive states: The construction works must be designed and built in such a way that in the event of fire:

- The load-bearing capacity of the construction can be assumed for a specific period of time
- The generation and spread of fire and smoke are limited
- The spread of fire to neighbouring construction works is limited
- Occupants can leave the building or rescued by other means
- The safety of rescue teams is taken into consideration

In the Eurocodes the load-bearing function is defined by R, separating function by E (radiation) and I (insulation). When both load-bearing and separating function shall be fulfilled R, E and I are simultaneously required.

R30 or R60 - load-bearing criteria for 30 or 60 min in standard fire exposure
E30 or E60 - integrity criteria (no fire penetration) for 30 or 60 min in standard fire exposure
I30 or 60 - thermal insulation criteria (temperatures on the nonexposed surface does not exceed ignition temperatures for 30 or 60 min standard fire exposure

In the Eurocodes three levels of fire design can be used viz. (1) tabulated data, (2) simplified member calculation or by (3) global structural analysis.

The Eurocodes give on level 2 and 3 the user the possibility to choose the prescriptive approach using nominal fires to generate thermal actions or the performance-based using “real” fires. The thermal actions are defined in “Eurocode 1, Part 2.2 Actions on structures”. Examples of these are shown in

Fig 1 for the nominal fires, ISO 834 /15/ and the hydrocarbon fire and for natural fire models representing parametric (real) fires derived from fire load density (100 MJ/m^2 of enclosed area) and ventilation characteristics (opening factor =0.04 m$^{1/2}$) for the fire compartment. The nominal (standard) fires are characterised by a heating phase while the natural fires have both a heating phase and a subsequent cooling phase.

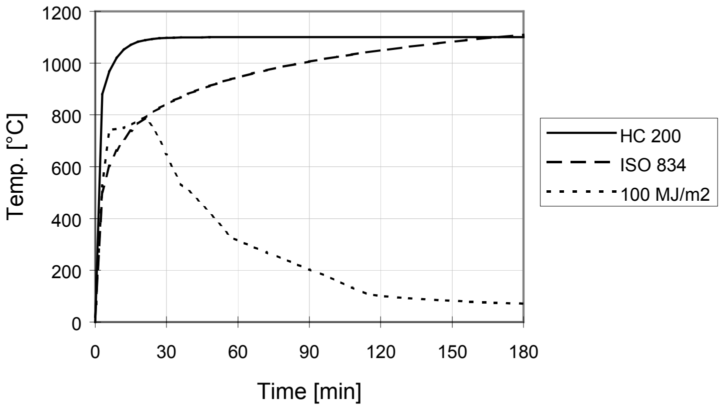


Fig 1

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$^{1/2}$)

In Annex E of Eurocode 1 the fire load densities (of floor area) of different occupancies are presnted and illustrated in in Table 1. The transformation of floor area to enclosed area must first be done and is presented below. If the floor area is chosen to be 20 or 50 m^2 the room size can be lxbxh=5x4x2.5 or 10x5x2.5 and the enclosing area is 85 m^2 and 175 m^2 respectively. The corresponding values are given in column 4 and 5 of the table.

Fire load densities $q_{f,k}$	(MJ/m^2 floor area)	(MJ/m^2 floor area)	(MJ/m^2 enclosing area)	
Occupancy	Average	80 % fractile	80 % fractile	
Floor area	-	-	20 m^2	50 m^2
Dwelling	780	948	225	270
Hospital (room)	230	280	66	80
Hotel (room)	310	377	89	108
Library	1500	1824		
Office	420	511	120	146
Classroom of a school	285	347	82	99
Shopping centre	600	730		
Theatre (cinema)	300	365		104
Transport (public space)	100	122		35

Table 1 Fire load densities in accordance with Eurocode 1, Annex E

Traditional fire design is based on a standard fire in conformity with ISO 834, which normally is much more severe than a real fire. In many occupancies as shown in Table 1 the fire load density is less than 150 MJ/m^2 (enclosed area) and this is less severe compared with 1 hour ISO 834 standard fire. For hospital, hotel rooms and classrooms of schools it is less than 100 MJ/m^2 i.e .a fire duration of about 21 min!

ANALYTICAL TOOLS

The modern Era of calculations means that computer programs are frequently used to solve engineering design problems. Fire engineering design is no exception.

When designing structures for fire the first step is to calculate the temperature field within the member for the design fire and then the load-bearing capacity, based on temperatures assessed. This is possible by using the simplified (limit state) design or the more sophisticated global analysis design in accordance with the Eurocodes. The three programs developed by Fire Safety Design (FSD) are Super-Tempcalc / /, Fire Design and Global Collapse Analysis respectively, which will be described below.

Super-Tempcalc

Super-Tempcalc is a fire-dedicated two-dimensional finite element program developed by FSD for use on personal computers. The software is widely used in the field of passive fire protection, and as part of structural analysis, in buildings and on offshore-platforms. It is accepted for structural fire design in a number of countries and by organisations and for North Sea applications.

The program solves the two-dimensional, non-linear, transient, heat transfer differential equation incorporating thermal properties, which vary with temperature. The program allows the use of rectangular or triangular finite elements, in cylindrical or rectangular co-ordinates. Heat transferred by convection and radiation at the boundaries can be modelled as a function of time. Structures comprising several materials can be analysed and the heat absorbed by any existing voids in the structure is also taken into consideration. The program can also simulate boards falling off at specified times as well as spalling of concrete. When the geometry is changed the program automatically updates the FE-mesh, which is a unique feature. Also cable penetration can be modelled.

A comprehensive materials properties database is integrated with the main program. A pre-processor creates the finite element division automatically and retrieves the relevant information from the database for efficient use in the calculation and to minimise the work for the user.

Super-Tempcalc has been validated against more than 1000 tests since 1985 worldwide. The program has also been used to develop approved design temperature diagrams for the *Swedish Association for Concrete Building Components* and for a manual on "Fire Engineering Design of Concrete Structures" and in Eurocode 2. FSD has also used the programme to produce Design Guides for manufacturers of insulation materials to make their material more competitive on the market.

The computer program Super-Tempcalc has been used frequently abroad and it has been installed at a great number of consultancies and fire research bodies around the world.

Fire Design

Fire Design is integrated with Super-Tempcalc and is using its output and chosen mechanical properties from the database, Fire Design predicts the ultimate load-bearing capacity during the whole fire process for beams and columns in steel, aluminium, concrete and steel and concrete composite members. If the load effect is greater than the load-bearing capacity a redesign is necessary.

Global Collapse Analysis

Global Collapse Analysis (GCA) is a nonlinear two-dimensional finite element program integrated with Super-Tempcalc for use on personal computers to predict the mechanical behaviour of a steel structure where a part of it or the whole is exposed to fire. The software performs a progressive collapse analysis, which is based on the theory of plasticity and the prediction of the formation of plastic hinges in the structure analysed, leading to local and possible global collapse. The development of stresses, deflections, node deformations, restraint forces and moments can easily be obtained.

GCA has a large potential to be used preferably on offshore platforms but also on high rise buildings in steel. The safety margin to progressive collapse, the investigation of possible redundant members to reduce passive fire protection and the collapse steel core temperature can be assessed by the program. Assessment of structural fire safety margin against collapse by identifying critical parts of the structures for analysis of the most severe fire scenarios is also an important application. GCA can be used for verification of the overall PFP-optimisation on a high rise building or an offshore platform.

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.

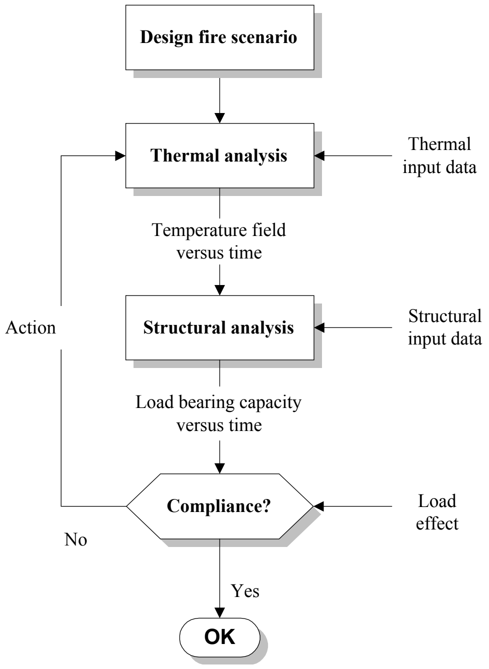


Fig 2 Fire design process

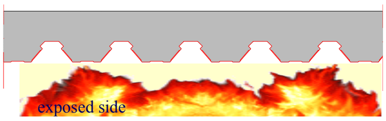
Due to the thermal exposure a temperature gradient inevitably will develop in members subjected to fire. Temperature gradients are accounted for when a computerised design approach is adopted, but not in simplified calculations for slab and beam members, which shall provide safe side conservative results.

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.

The simplified design of concrete and steel composite slabs and beams is 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.

STRUCTURAL DESIGN OF COMPOSITE BEAMS AND SLABS

An extensive research both experimentally and theoretically on the behaviour and load-bearing capacity of concrete and steel composite slabs and beams has provided such a good knowledge that almost all design today can be carried out by computer simulations. An example of such a member is the “New Combideck 900 Slab (NC 900 Slab)” illustrated in Fig 4. The structural fire design comprising a thermal and structural analysis of this composite slab and the advantage of continuity will be illustrated below.



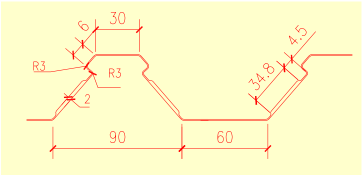
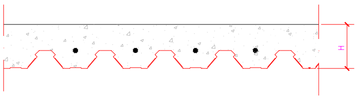


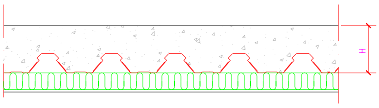
Fig 3 a) Fire exposed New Combideck 900 slab b) geometry of the profile

Structural fire protection methods for composite slabs

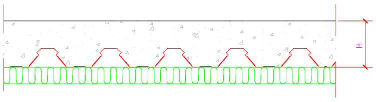
If the unprotected composite slab as presented in Fig 3 does not fulfil the fire resistance requirements there are five major options to increase the fire resistance as illustrated in Fig 4. The extra reinforcement shown in a) can be rebars or post-tensioned cables which increase the fire resistance considerably. Negative reinforcement is preferably used for continous slabs and is very efficient and cost-effective for high fire resistance requirements.



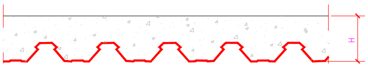
a) Extra fire reinforcement



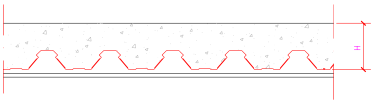
d) Rockwool and gypsum board



b) Rockwool



e) Intumescent paint



c) Gypsum board

Fig 4 Fire protection methods of NC 900 slab

A board of rockwool insulation (b) appropriately fixed to the steel sheet is very effective. A protection with a 13 mm gypsum board will increase the fire resistance of about 15 min but a combination of rockwool and a gypsum board (d) is very effective but a more expensive solution. Intumescent paint (e) is the fifth option and is used when you want to see the steel sheet surface.

FE-description of the the NC 900 Slab

The FE-mesh of the unprotected NC 900 Slab 45 is illustrated in Fig 5. Extra reinforcement is positioned 45 mm from the bottom surface and positioned in node 45.

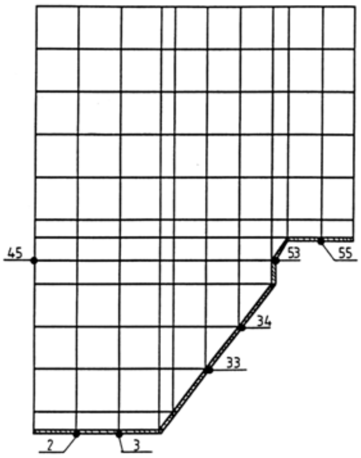
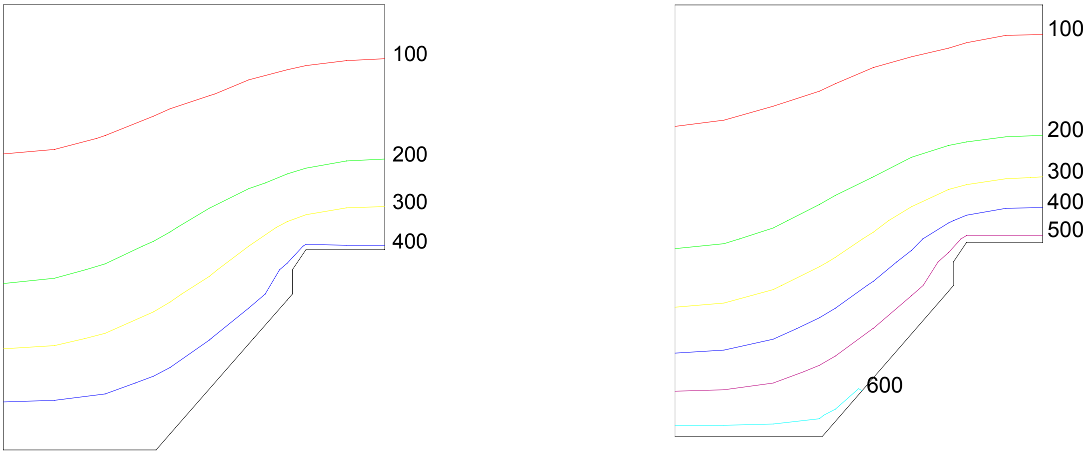


Fig 5 FE-mesh of NC 900 Slab

Thermal Analysis

Following the fire design process given in Eurocode 1 and 3 of composite concrete structures the design scenarios shall be chosen. Parametric fires with the fire load f = 100-250 MJ/m^2 and the opening factor $A\sqrt{h}/A_{tot} = 0.04m^{1/2}$ are analysed for two situations viz. unprotected steel sheet of the composite slab and protected by 1 gypsum board of 13 mm and at 5 different heights of the slab. In Fig 6a the temperature profile and the critical time (time for minimum load-bearing capacity) for the fire load of 150 MJ/m^2 and opening factor of 0.04 $m^{1/2}$ for the unprotected slab is shown. The corresponding illustration is given in Fig 6b for the protected slab at the fire load 250 MJ/m^2. The heating phase is 0.5 and 1.25 h but the minimum load-bearing capacity is attained during cooling after 0.7 and 1.0 h respectively. The temperature of the unexposed surface is far below the separating requirement of temperature increase of 140 °C.



a) Unprotected steel sheet
Opening factor 0.04 $m^{1/2}$
Fire load density 150 MJ/m^2
Heating phase = 0.55 h, Critical time $t_{cr} = 0.7$ *h*

b) Protected steel sheet, 1 gypsumboard 13 mm
Opening factor 0.04 $m^{1/2}$
Fire load density 250 MJ/m^2
Heating phase = 1.25 h, Critical time $t_{cr} = 1.00$ *h*

Fig 6 Temperature isotherms for NC 900 slab exposed to parametric fires

The temperature as function of time for the steel sheet and the extra rebars is shown in Fig 7. The temperature is decreased by about 100 °C for both the steel sheet and the rebar due to the influence of the gypsum board.

Structural Analysis

The next step in the design procedure is to use the temperature field calculated by Super-Tempcalc and the mechanical properties as input in the Fire Design program for calculating the load-bearing capacity. For all the varying parameters like fire loads, varying heights with and without gypsum board protection the relative load–bearing capacity is shown in Fig 8. The load-bearing capacity for the unprotected slab decreases to 43 % at the fire load 250 MJ/m^2 and the positive effect of the gypsum board is about 20% increase.

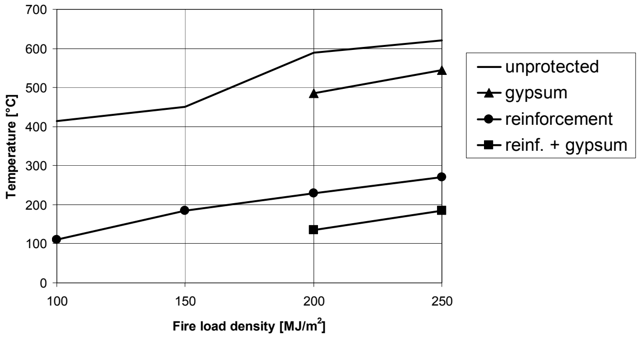


Fig 7 Temperature of steel sheet and extra reinforcement as function of fire load density with and without gypsum board protection on steel surface.

Fig 8 Relative load-bearing capacity as function of fire load with and without gypsum board protection

Principal influence of continuity

Continuous composite slabs have a considerable improved fire resistance by using negative reinforcement of rebars or post-tensioned wires. The load-bearing capacity can be fulfilled even if no capacity is left in the span due to moment redistribution from the span to the supports. The negative reinforcement over supports is very well protected form the fire and is much less influenced on its strength. This means that unprotected slab can be used also for longer fire durations

CONCLUSIONS

The good knowledge about fire behaviour of composite slabs makes it possible to simulate fire tests in computer as well as performing a reliable structural fire design. The application of the functional requirements in the Eurocodes to composite slabs and beams has shown that the introduction of parametric (real) fires is much more advantageous than ISO 834 fire. Design fires in accordance to Eurocode 1 in most normal building are represented by a fire load less than 200 MJ/m^2 and a fire duration of 0.65 h. The continuity of composite slabs with a negative reinforcement is very efficient and the bending moment capacity in the span can be reduced to a fraction and the slab will still carry the load due to redistribution of moments from the span to the supports.

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