European Experiences in Fire Design of Structural Steel

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Abstract

Performance-based building codes and offshore regulations permit fire safety engineering calculation methods to be used. This paper is describing the analytical tools developed by Fire Safety Design (Super-Tempcalc, Fire Design, Global Collapse Analysis), their capabilities and use on the European market since 1985. It is also illustrated what types of structures that must be handled by calculation rather than by using the traditional standards and the benefits by using functional approaches. The implications of structural design for both standard fire and natural fires are discussed. Temperature analysis followed by structural analysis, limit state design, are illustrated for some various cases in buildings and on offshore platforms. Experience in savings on insulation costs are described for buildings as well as for offshore platforms.

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 flexibel requirements has increased heavily. Therefore some countries in Europe like England, Wales and Sweden have already developed performance-based codes and many more countries are in the developing process to do so. Also within offshore design in Europe performance-based fire safety regulations has been introduced. 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. /2/

This paper describes the experiences in Europe on fire design of steel structures when using functional approaches and engineering principles.

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Traditional standard design and performance-based design

Traditional fire design is based on a standard fire in conformity with ISO 834, which normally is much more severe than a natural (real) fire derived from fire load density and ventilation characteristics for the fire compartment. The standard fire is characterized by a heating phase while the natural fire has both a heating phase and a subsequent cooling phase as illustrated in Fig 1.

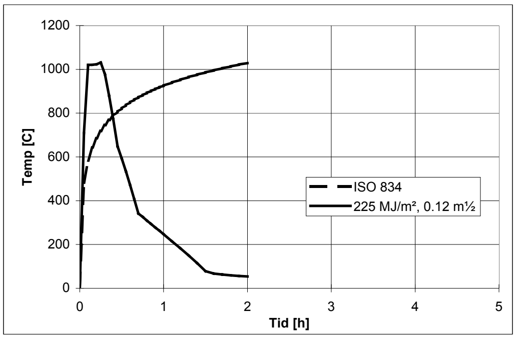

Fig 1 Standard fire, ISO 834 and natural fire $A\sqrt{h}/A_t$*= 012* $m^{1/2}$*,* f_d*= 225 MJ/m²*
where A= enclosing area, h= average height of openings, A_t*= area of openings,* $A\sqrt{h}/A_t$ *= opening factor and* f_d*= fire load density*

The fire resistance requirements in the prescriptive code means that a structural member should be designed in such a way that it does not collapse within 30, 60, 90 or maybe 120 min. In the performace-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 during cooling, when the minimum load-bearing capacity or separating ability is reached, must be found. This occasion must often be assessed by repeated computer calculations, but it is worthwhile because the design (natural) fire is normally less severe than the prescribed fire duration of the standard fire.

In the traditional code the design is based on the assumption that the steel temperature is uniform all over the cross-section and methods like the conventional form factor method is normally used. (The form factor F/A is defined as the perimeter of the section exposed to fire and A the cross-sectional area.) This simplification is very often not valid, e.g. when partial exposure is regarded. Thus a more functionally based design must be carried out.

In many cases the fire exposure is not uniform around a structural member and therefore a steep temperature gradient will arise and consequently no critical temperature exist. This means that the answer cannot easily be found and accordingly the structural consequence must be analysed.

Analytical tools

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

When designing steel 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 making use of the limit state design or the more sophisticated collapse analysis design. The three programs developed by FSD are Super-Tempcalc /1/, 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 by a number of countries and 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. A materials properties database is integrated with the main program. Also integrated into the program are pre- and post-processors which allow fast and user-friendly input/output procedures. The pre-processor creates the finite element division automatically and retrieves the relevant information from the database for use in the calculation

Super-Tempcalc has been validated against a large number of tests since 1985 both in Sweden and abroad. More than 1000 fire tests on concrete and steel structures (insulated with Rockwool, Gullfiber, gypsum boards, intumescent paint, Fiberfrax, Chartek III and IV, Thermolag 440, Pittchar XP, Mandolite 550 etc) have been simulated successfully.

The program has also been used to develop design temperature diagrams for the *Swedish Association for Concrete Building Components* and for a manual on "Fire Engineering Design of Concrete Structures" which are officially approved by authorities in Sweden.

FSD has also used the programme to produce Design Guides for manufacturers of insulation materials to make their material more competitive on the market. A Design Guide (DG) gives guidance on how to optimise the use of the PFP (passive fire protection)-material in most applications and at various fire exposures. The DG concept has been approved by *Lloyds* in England.

Calculations based on Super-Tempcalc were accepted by the *Norwegian Petroleum Directorate* for use on the Saga Petroleum, Snorre Platform, by *Lloyds* on the Marathon Oil, East Brae Platform and on the Newfoundland Offshore Contractors, Hibernia Platform and by De Norske Veritas (DNV) for use on the Shell, Troll Phase 1 Platform.

The computer program Super-Tempcalc has been used frequently abroad and it has been installed at 11 companies and fire research bodies around the world.

Fire Design

Based on the temperature profile from Super-Tempcalc and mechanical properties from the database, Fire Design (two-dimensional finite element program) predicts the ultimate load-bearing capacity during the whole fire process for steel, aluminium and concrete members. The result is compared with the load effect.
Structural fire protection analysis based on Super-Tempcalc and Fire Design were accepted by Lloyds for use on the Newfoundland Offshore Contractors, Hibernia Platform.

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. An extension to 3 dimensions is in progress. The development of stresses, deflections, node deformations, restraint forces and moments are all illustrated on the screen during the whole process of fire.

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 an offshore platform.

<u>Performance-based design</u>

Performance fire design requires normally engineering approaches by using computer technics. This will be elucidated on four different cases as follows:

Library in Malmö, Sweden

The most important step in a fire engineering design is the estimation of fire severity. A striking example of this is a new library in Malmö (total height of 15 m) where the authorities claimed that the design fire scenario effect should be 20 MW. A simulation of the situation was performed at a fire laboratory on identical steel shelves filled with books. The tests showed that the fire effect was very low only 0.5 MW but the value of 1 MW was used in the design. This more realistic fire scenario was applied in design of the smoke evacuation system and for steel structures and no insulation was therefore needed for many steel members like beams at the roof, steel columns 3 m above the floor level and supports for the shelves.

Aker Brygge, Oslo, Norway

A large complex with office buildings, residential houses 7-9 stories is mainly built up by a steel framework. The design fire in the building was a fully developed fire based on the fire load 200-300 MJ/m^2. The fire protection of all steel beams and columns inside and outside the building was optimized by calculation. The fire exposure on outdoor columns varying with the distance from openings in the facade was much less than those inside the building and that was accounted for. Most steel members were built in and therefore only partly fire-exposed which rendered a thermal gradient which was calculated.

Limit state design was performed on all steel members and some of them were changed to larger profiles to reduce the amount of insulation when it was found to be more cost effective. The amount of intumescent paint, mineralwool insulation and number of gypsum boards were decreased considerably compared with standard design. Some beams inside the building had only the bottom flange exposed to fire and was designed with minimum painting or sometimes without any painting on the bottom flange depending on the steel thickness of the bottom flange and the load utilization degree.

All columns were filled with concrete and painted with a minimum thickness of intumescent paint. Without any concrete filling, painting was not sufficient to avoid collapse. The effect on a concrete filled column as concerns steel temperature is shown in Fig 2 for unprotected and for protected (minimum amount of intumescent paint) outer surface. The maximum steel temperature occurs after 1.2 and 1.7 hours during cooling and is decreased from 800 to 480 °C when unprotected and protected respectively. The exposure was a natural fire as shown in Fig 2. This temperature was acceptable from an load-bearing viewpoint but with concrete filling and no protection the temperature was much too high (900 °C).

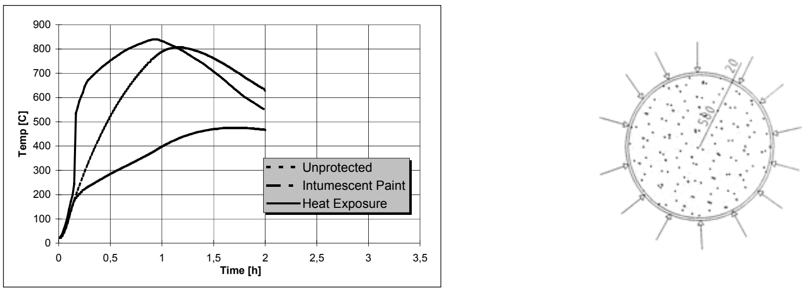

Fig 2 Steel temperature as function of time for fire-exposed (natural fire), concrete filled steel column with and without protection (intumescent paint)

Hat profiles embedded in concrete

In Europe it is very common to use hat profiles as the main load-bearing system in buildings. Their structural behaviour during fire is very adventegous because only the bottom flange can be exposed to fire. A systematic study has been conducted for most types of hat profiles and a guidance of how to optimise the protection with intumescent paint is developed for the standard fire. (The same study could be performed for various natural fires.). The isotherms after 1 and 1.5 hours standard fire exposure as well as the load-bearing capacity as function of time for unprotected and protected bottom flange is illustrated in Fig 3. The protection renders an increase in relative load-bearing capccity of about 40-55 % after 1 and 1.5 hours. Depending on the load-utilization degree sometimes no protection is needed.

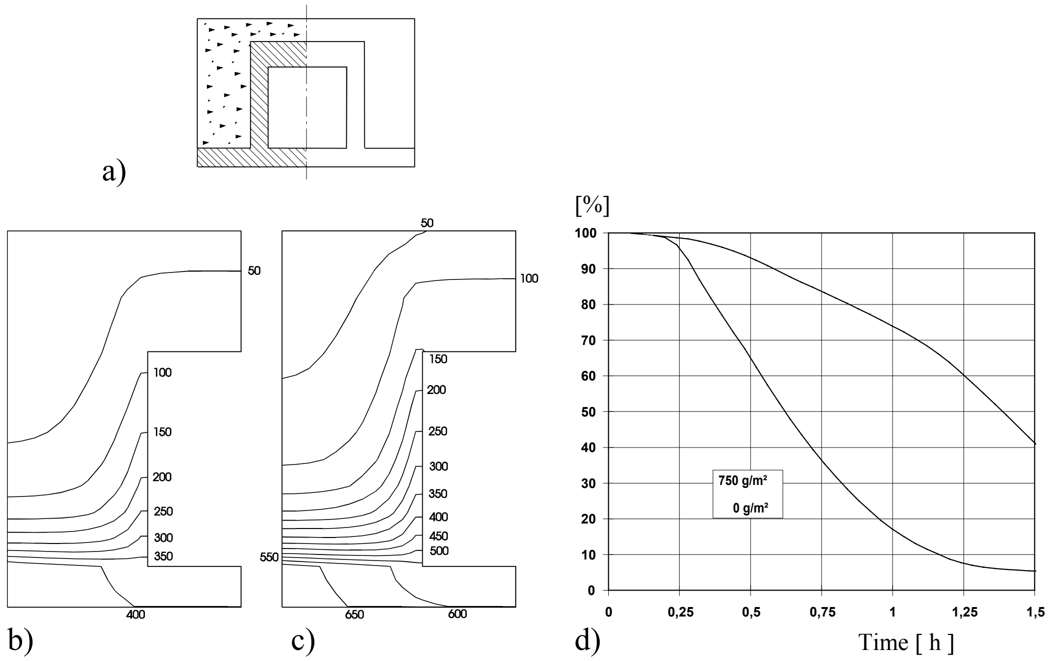

Fig 3 Fire exposed bottom flange of a hat profile embedded in concrete
- *a) Geometrical shape of hat profile embedded in concrete*
- *b) Temperature profiles after 1 for protected flange (750 g/m^2)*
- *c) Temperature profiles after 1.5 hours for protected flange (750 g/m^2*
- *d) Relative load-bearing capacity for the cross-section as function of time for unprotected flange and protected flange (750 g/m^2, intumescent paint)*

Main deck of the Hibernia Platform

The thermal and structural behaviour is briefly presented for an uninsulated underdeck girder in case of fire during 2 hours on a platform main deck (Fig 4).

The temperature profile of the I-beam after 1 hour pool fire exposure (150 kW/m^2) is illustrated in Fig 4 b and the temperature at a position of about 350 mm from the top flange is only 100 °C, but the top flange temperature is more than 1000 °C. The temperature does stabilize after 1 hour exposure, which can be observed from Fig 4 c illustrating the relative load-bearing capacity of 50 % stabilized after 1 hour. The cooling effect on unexposed surfaces makes the thermal gradient constant after 1 hour. The minimum relative moment capacity of 50% means that a load utilisation degree of about 67 % ($0.7 \cdot 0.67 \approx 0.50$ where 0.7 is the general partial factor at fire) can be accepted for this girder. It is very positive that the temperature and consequently the load-bearing capacity stabilize after 1 hour.

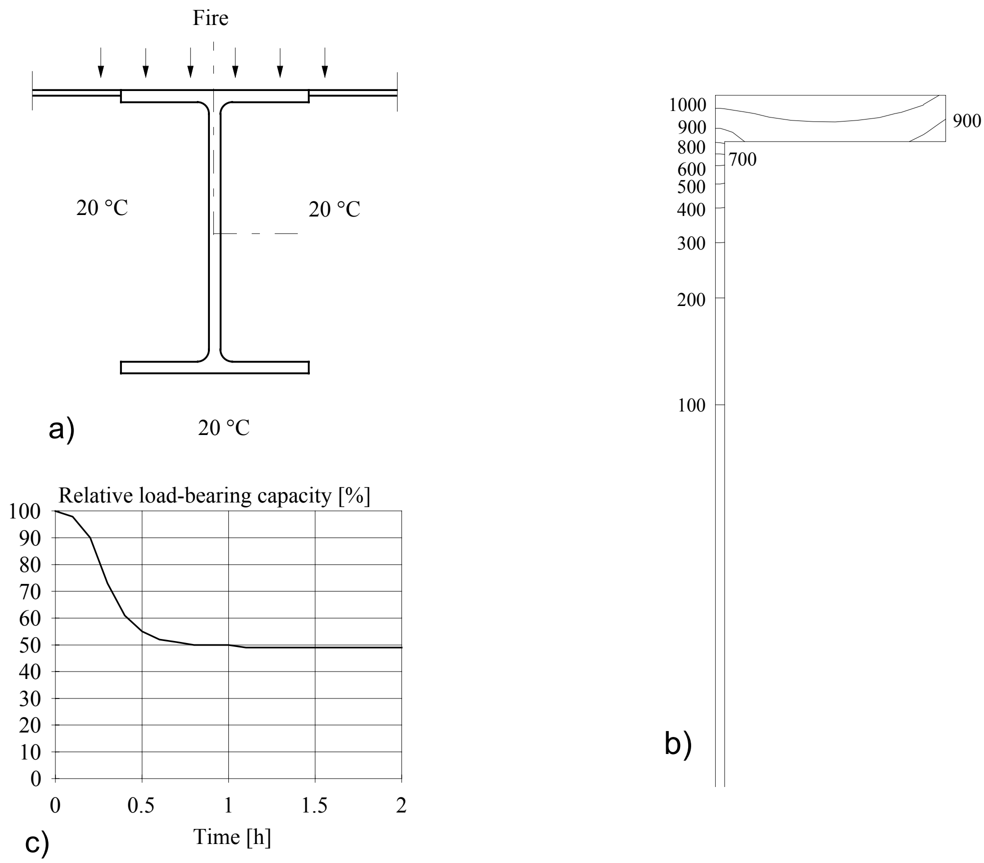

Fig 4 Relative load-bearing capacity for underdeck girder exposed to heat only on the top flange and unexposed on other surfaces

a) I 1500 x 500 x 20 x 50 exposed to the heat load 150 kW/m^2 for 2 hours

b) Isotherms [°C] of the I-beam after 1 h fire exposure.

c) Relative moment capacity as function of time.

Experience in savings on offshore platforms

Considerable savings in the amount of insulation used, compared with estimates derived from manufacturer's recommended tables, can be achieved by employing computer analysis (Super-Tempcalc, Fire Design). Experience has been obtained on the following 9 platform case studies /3, 4/:

1. Heidrun EPS, 1987-88, Norway
2. Snorre TLP, 1989-90, Norway
3. East Brae, 1990-91, UK
4. AGIP, Tiffany, 1991, UK
5. Troll Phase 1, 1992-93, Norway
6. Troll Phase 2, 1993-94, Norway
7. Hibernia, 1992-94, Canada
8. Ekofisk Development, 1995, Norway
9. Brittania, 1995, UK
10. Njord, 1996, Norway

In well-bay area on Snorre Platform 70 tons of insulation (2 millions USD) were saved and on the Hibernia Platform 350 tons (10 millions USD).
Less insulation means reduction in platform weight and further reduced costs.

By computations generally, 30 % less insulation material is required on normal steel members and in heat transfer zones, the coat back distance insulation is reduced to less than 50 % compared with existing rules of thumb methods.

Further reduction of weight of the offshore platform to be achieved while maintaining structural safety margins. proves that the safety margin against collapse still is acceptable The result of these computations with GCA is estimated to provide savings 5-10% on an offshore platform and to satisfy authorities and insurance companies.

Benefit from performance-based design in buildings

Cost effective solutions based on performance design are neccessary for the clients to reduce the building costs. The code authority in Sweden no longer checks the calculations but the consultant and the builder has the whole responsibility for the design solutions of the building. The needs for the structural engineer to be able to design steel structures for fire conditions are consequently very urgent.

By using natural fires as design fire instead of the standard fire the fire severity is often reduced by 50%. This means that the majority of buildings which are classified in accordance with the code have a very conservative design. Performance-based optimization of PFP on steel results in saving of about 30-40 % compared with the traditional design.

Analysis of the potential for reduction of insulation on a steel structure (especially high rise buildings) due to redistribution of forces and the redundant members indentified in the collapse analysis (GCA) will be of great interest when userfriendly software are employed.

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