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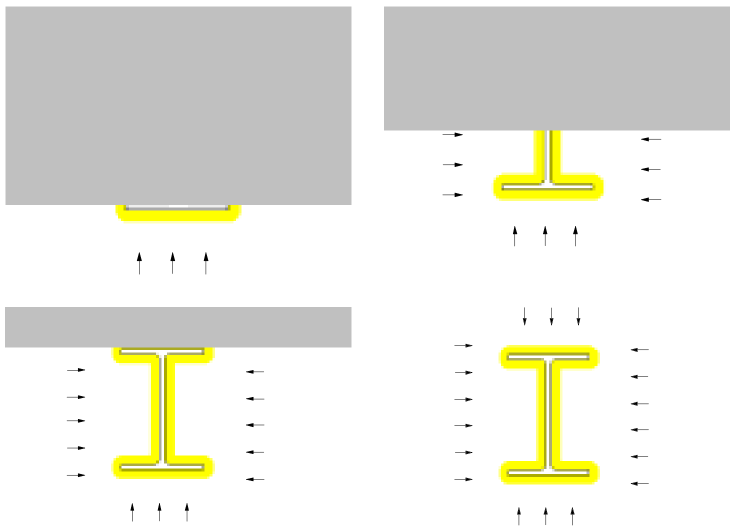
Report 5004

Loadbearing Capacity of Fire Exposed Steel Beams Partially Embedded in Concrete

- a Theoretical Analysis



Kristian Lavesson

Lund, December 1996

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- a Theoretical Analysis

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Abstract: A theoretical analysis using computer simulations of the loadbearing capacity of ISO 834 standard fire exposed HEA, HEB, IPE and HSQ steel beams partially embedded in concrete and protected with Hensotherm intumescent paint.

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APPENDIX A: Fire test of fire protection insulation system for structural steel members, intumescent paint.

Summary

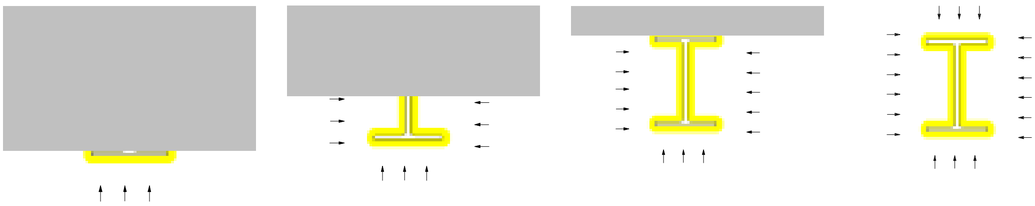
This report was made in 1996 as a Master of Science Thesis by Kristian Lavesson. It was made possible by the cooperation between Fire Safety Design AB and the Department of Fire Safety Engineering at Lund Institute of Technology at Lund University.

The development of computers has made it easier and quicker to calculate the fire resistance of a structure, but finding a good design can still be a rather lengthy process. The objective of this report is to perform the calculations once and for all and present them in a way that makes it quick and easy to compare different beam sizes, beam types and amounts of embeddment in concrete in order to find an optimal design with a minimum of effort.

The calculated fire resistance in terms of plastic bending moment capacity reduction in fire exposed passively protected steel beams partially embedded in concrete was calculated for different application thicknesses of fire protection paint.

Four different geometrical configurations were considered in the study. The geometries are shown in the figure below and comprise:

a) Steel beam embedded in concrete. Only the sides and bottom of the lower flange are exposed to fire, the rest of the beam is protected by the concrete.
b) Steel beam semi embedded in concrete. The top half of the beam is inside the concrete while the rest of the beam is exposed to fire.
c) Steel beam with concrete on top. Concrete is placed on top of the beam, hence nearly the whole cross-section is fire exposed.
d) Steel beam with 4-sided fire exposure.



Case a) Case b) Case c) Case d)

Figure 0.1 The cases studied in this report.

The steel beams studied were of the types HEA, HEB and HEM. Case a) also included a brief study of HSQ-beams and case d) a study of IPE-beams.

There is a number of different fire protection materials on the market, but this report has only studied Hensotherm 4 KS. It is a water based swelling paint that turns into a thick foam when exposed to fire.

The calculations were made with TCD /15/, a program package which was developed by Fire Safety Design AB in Lund, Sweden. The TCD package comprises, among other things, SUPER-TEMPCALC for calculation of temperature field gradients and Fire Design for calculation of load bearing capacity of fire exposed members.

For obvious reasons the fire resistance is improved with extended concrete embeddment, thus indicating a significant fire resistance of case a whilst a considerably lower ditto for case d.

The relative moment capacity is often found to be approximately proportional to A/F.

The calculated results were summarized in the design tables in chapter 11.

Acknowledgements

This is it folks, I've finally done it. This is the final project for my Master of Science degree in Civil Engineering, and I would like to take this page to thank the people who have helped me in so many different ways.

First I would like to mention professor Sven Erik Magnusson at the Department of Fire Safety Engineering at Lund Institute of Technology at Lund University who has had the responsibility of being examinator for the project. Thanks also to his colleague senior lecturer Björn Karlsson for interesting discussions about a suitable subject for the project.

Next up is PhD Yngve Anderberg, Managing Director at Fire Safety Design AB (FSD), who has been instructor and MSc Jens Oredsson who has had the role of deputy instructor. Additional staff members of FSD have also been involved in the project, for example MSc Richard Nilsson and MSc Sebastian Jeansson who have been helpful with installation and problem solving regarding the computer programs used during the project.

Special thanks to Anette Cederlöv for helping me with Excel, Word and Power Point.

Thanks also to the steel wholesale dealers Tibnor and Bröderna Edstrand for supplying catalogues and other useful information.

I now wish you happy reading and hope that my work will turn out to be useful.

Kristian Lavesson
Malmö, Sweden
December 1996

1 Introduction

1.1 Background

In the beginning of the science of fire safety there were slide-rules and mechanical calculators. The comprehensive amount of work required for detailed calculations resulted in design guide lines that were simple and rational to use. The simple models were based on assumptions which made the results quite conservative. This resulted in buildings which in most cases cost more to build than would have been necessary if the calculations had been more detailed.

The development of computers has resulted in new and more accurate models which consequently require more calculations to be undertaken. Each new generation of computers has resulted in new possibilities to take more variables into account and thereby reduce the assumptions even further. One disadvantage about the new computer models is that they need so detailed information that they take quite a bit of time to use, especially if an optimization procedure needs to be undertaken. This means that finding a good solution to a design problem can be a rather lengthy process.

Another thing that has been developed relatively recently is fire protection paint, for example Hensotherm. New materials need new knowledge in order to be used efficiently, and this report will hopefully supply part of that knowledge.

1.2 Objective

The objective of this report is to perform the calculations once and for all and present them in a way that makes it quick and easy to compare different beam sizes, beam types and amounts of embeddment in concrete in order to find an optimal design with a minimum of effort.

1.3 Assumptions and Limitations

Although the computers have developed enormously, they still have limitations in memory and processor capacity that have to be taken into account. The assumptions and limitations used throughout this report are presented in more detail in some of the following chapters, but here is a summary of the most important ones.

Assumptions:

- The cross-section is divided into about 700 rectangular elements, each comprising four nodes. The element temperature is calculated as the average of the four nodal temperatures. Future versions of the computer programs will allow for a larger number of elements and thereby be more accurate. It seems that the error created by this assumption varies from very small up to one or a couple of percent.
- The materials behave according to the material data that have been found by simulating empirical tests.

Limitations:

- The results are only valid for the calculated beam types and surrounding conditions if nothing else is specified.
- Instability phenomenons such as tipping and buckling have not taken into account in this report. Only the bending moment capacity of each given cross-section has been studied.
- The results are applicable only to ISO 834 standard fire.

1.4 Structure of Report

The first five chapters of this report is an explanation of how this report has been made followed by a description of the materials studied and the computer programs used.

Chapter 6 contains a practical validation where an actual fire test has been simulated to verify the accuracy of the simulation methods used in this report.

This report is structured to be quick and easy to use as reference material when looking for a good design. When designing it is usually known which degree of embeddment in concrete that will be used. Chapters 7 through 10 therefore partially overlap so that it is possible to read only the chapter relevant to the design at hand.

Chapter 11 summarizes the calculated results in design tables.

2 Methodology

In figure 2.1 the adopted methodology is displayed. Section 2.1 through 2.5 on the next page comment on the vital steps in the calculation procedure.

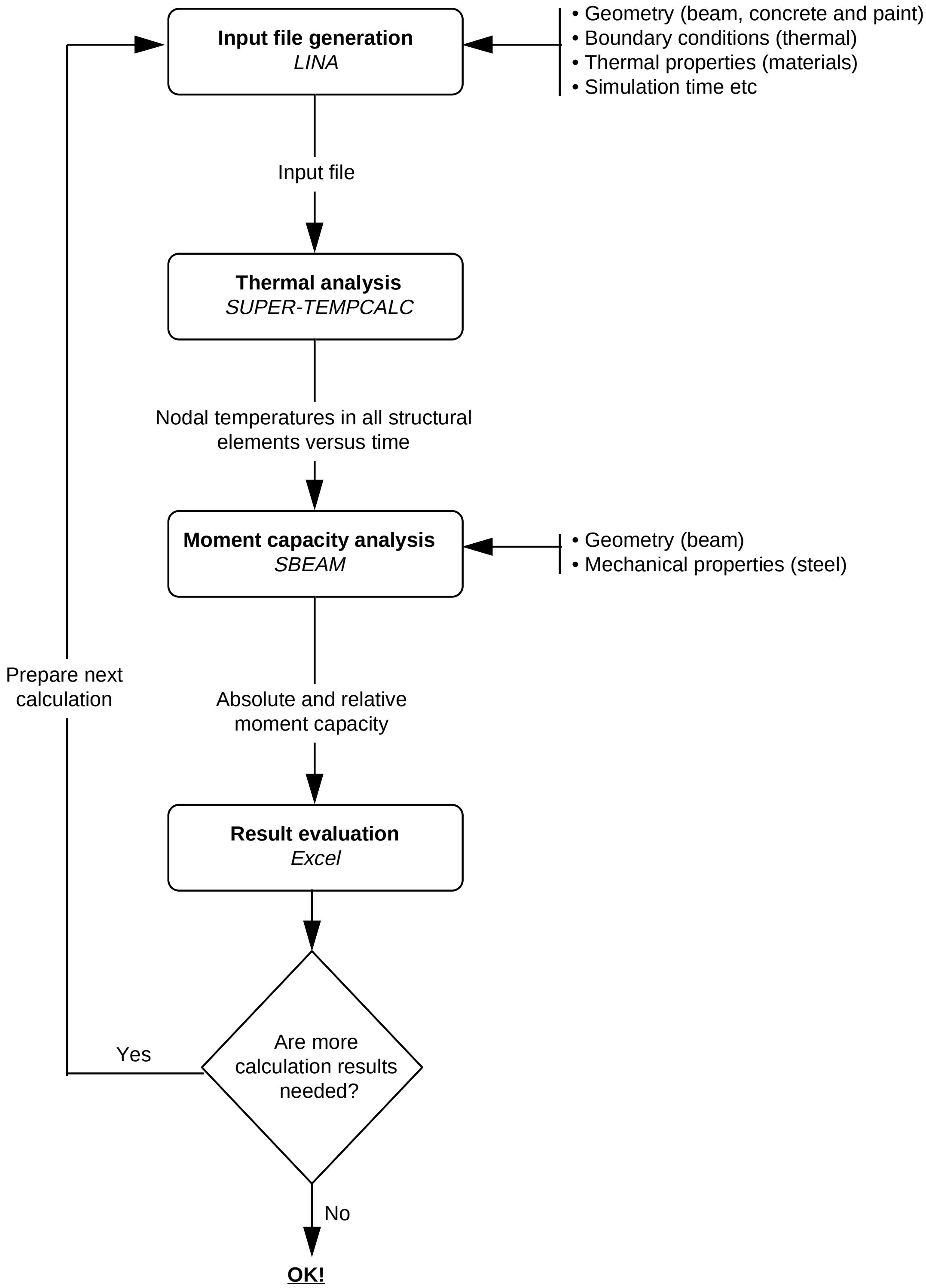


Figure 2.1 Method for calculation of moment capacity /18/.

2.1 Preparation

The suitable beams, surrounding conditions and parameter combinations were selected with the help of earlier work and steel catalogues /11-13/. Material data derived from earlier experiments were put into a database called LISA. The relative strength of steel as a function of temperature, according to Eurocode 3, was put into another part of the LISA database.

2.2 Input

The input process was conducted in five steps.

1. The beam and, when applicable, concrete were drawn on scale by hand so that the coordinates of the corners could be determined and a first approximation of the elements could be made.
2. The coordinates, elements and materials were put into a preprocessor called LINA.
3. The elements were adjusted so that there were as many as possible of them, usually around 700.
4. Simulation time, intervals and a couple of other variables were specified.
5. LINA created an input file using the input information and the material data in LISA.

2.3 Temperature Calculation

SUPER-TEMPCALC reads the input file created by LINA and calculates the temperature in every node at the specified intervals during the specified simulation time and creates an output file.

2.4 Moment Capacity Calculation

The next step was to use SBEAM which is a part of the FIRE DESIGN program. SBEAM takes information from LISA and SUPER-TEMPCALC’s output file and uses the Finite Element Method (FEM) to calculate the moment capacity of the cross-section at the intervals specified earlier. The result, in terms of an absolute bending moment capacity as well as a percentage of the initial ditto, were stored in an output file.

2.5 Evaluation

The results were plotted and evaluated using Excel /16/.

3. Scope of work

The scope of work was defined by the following six main parameters:

1. Geometry
2. Fire exposure
3. Fire protection
4. Steel beams
5. Concrete
6. Duration

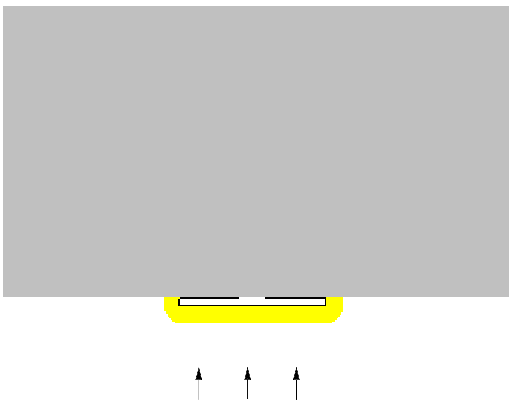
In section 3.7 the calculation matrix for the studied parameters is presented.

3.1 Geometries

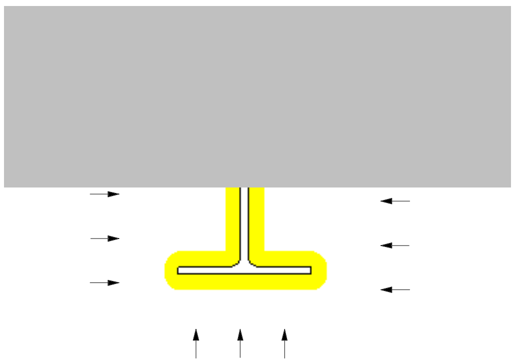
Four different geometrical configurations were considered in the study. The geometries are shown in the figure below and are:

a) Steel beam embedded in concrete. Only the sides and bottom of the lower flange are exposed to fire, the rest of the beam is protected by the concrete.
b) Steel beam semi embedded in concrete. The top half of the beam is inside the concrete while the rest of the beam is exposed to fire.
c) Steel beam with concrete on top. Concrete is placed on top of the beam, hence nearly the whole cross-section is fire exposed.
d) Steel beam with 4-sided fire exposure.

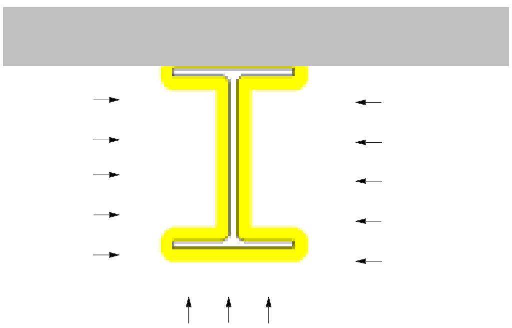
For more details about the geometries see chapters 7 through 10.



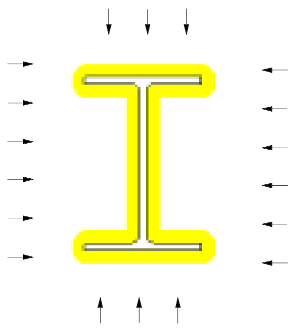
a) Steel beam embedded in concrete



b) Steel beam semi embedded in concrete



c) Steel beam with concrete on top



d) Steel beam with 4-sided fire exposure

Figure 3.1 The four studied geometrical configurations.

3.2 Fire Exposure - ISO 834

The temperature-time development used as boundary condition on fire exposed surfaces was in all cases ISO 834, more known as the Standard Fire. The definition of the fire is:

$$T_t = 345 \times \log(480t + 1) + T_0 \qquad t > 0 \qquad \text{(Equation 3.1)}$$

where

t	=	time in hours
T_t	=	gas temperature in °C at time t
T_0	=	temperature in °C at time 0.

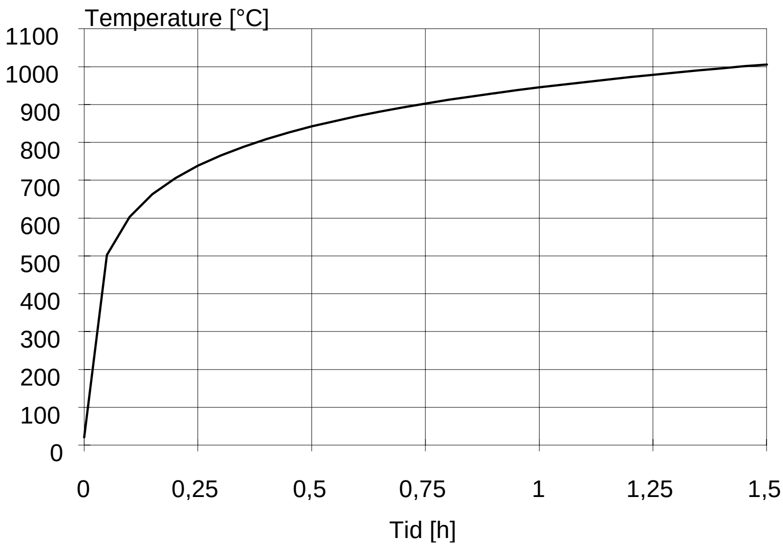


Figure 3.2 Temperature as function of time according to ISO 834.

3.3 Fire Protection - Intumescent Paint

There is a number of different fire protection materials on the market, but this report has only studied Hensotherm 4 KS. It is a water based swelling paint that turns into a thick foam when exposed to fire. The minimum amount of paint used in practice is 400 grams of paint per protected square meter, and the reason for that is that it is difficult to get an efficient foam with smaller amounts. The maximum paint thickness that is practicable is 3000 g/m^2, and that is because the foam gets too heavy to stick to the surface when more paint is used.

Within the scope of the present study the application thicknesses 0, 500, 750, 1000, 2000 and 3000 g/m^2 were considered. Hensotherm paint is manufactured by a company called Hensotherm AB which is located in Trelleborg, Sweden.

3.4 Steel Beams

3.4.1 Steel Beams Embedded in Concrete

In case a) of figure 3.1 the following beams were studied:
- HEA, HEB and HEM in dimensions 100, 140, 200, 240, 300, 400, 500 and 600
- Eight different HSQ-beams with varying height, width and lower flange thicknesses.

The reason for this selection was that:
- It is not realistic to use dimensions higher than 600 in this case.
- It seemed like there would be a big difference in the behaviour of the different low beams, hence the dimensions 140 and 240 were included.
- HSQ is a kind of beam that is made especially to be embedded in concrete, and it is therefore only studied in this case.

3.4.2 Steel Beams Semi Embedded in Concrete

In case b) of figure 3.1 the following beams were studied:
- HEA, HEB and HEM in dimensions 100, 200, 300, 400, 500 and 600

The reason for this selection was that:
- It is not realistic to use dimensions higher than 600 in this case.
- The difference between the low beams were not as dramatic as they seemed, so the dimensions 140 and 240 were not studied in this and the following cases.

3.4.3 Steel Beams with Concrete on Top

In case c) of figure 3.1 the following beams were studied:
- HEA, HEB and HEM in dimensions 100, 200, 300, 400, 600 and 800.

The reason for this selection was that:
- When the beam is not embedded in concrete it is sometimes preferable to use as large dimensions as 800.
- The calculation results were approximately linear for large beams, hence the dimension 500 was not worthwhile to study.

3.4.4 Steel Beams with 4-sided Fire Exposure

In case d) of figure 3.1 the following beams were studied:
- HEA, HEB and HEM in dimensions 100, 200, 300, 400, 600 and 800.
- IPE in dimensions 100, 200, 300, 400, and 600.

The reason for this selection was that:
- When the beam is not embedded in concrete it is sometimes preferable to use as large dimensions as 800.
- The calculation results were approximately linear for large beams, hence the dimension 500 was not worthwhile to study.
- IPE has such narrow flanges that it is practically useful only in this case.
- IPE is not available in higher dimensions than 600.

3.5 Concrete

Since the only function of the concrete in the calculations was to slow down the heating of the steel it was not necessary to choose a particular kind of concrete. Accordingly the concrete was not considered to contribute to the structural load bearing capacity.

3.6 Duration

The calculations were run with a total simulation time of 90 minutes, thus allowing for continuos comparisons throughout the scenario.

3.7 Calculations Matrix

The studied parameters result in the calculations matrix shown below. A total of 396 calculations have been undertaken.

	Case a) Paint amount [kg/m2]					Case b) Paint amount [kg/m2]					Case c) Paint amount [kg/m2]					Case d) Paint amount [kg/m2]				
Beam	0,0	0,5	0,75	1,0	2,0	0,0	0,5	1,0	2,0	3,0	0,0	0,5	1,0	2,0	3,0	0,0	0,5	1,0	2,0	3,0
HEA 100	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEA 140	X	X	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HEA 200	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEA 240	X	X	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HEA 300	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEA 400	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEA 500	X	X	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
HEA 600	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEA 800	-	-	-	-	-	-	-	-	-	-	X	X	X	X	X	X	X	X	X	X
HEB 100	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEB 140	X	X	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HEB 200	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEB 240	X	X	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HEB 300	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEB 400	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEB 500	X	X	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
HEB 600	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEB 800	-	-	-	-	-	-	-	-	-	-	X	X	X	X	X	X	X	X	X	X
HEM 100	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEM 140	X	X	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HEM 200	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEM 240	X	X	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HEM 300	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEM 400	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEM 500	X	X	-	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
HEM 600	X	X	-	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HEM 800	-	-	-	-	-	-	-	-	-	-	X	X	X	X	X	X	X	X	X	X
HSQ	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IPE 100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	X	X	X
IPE 200	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	X	X	X
IPE 300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	X	X	X
IPE 400	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	X	X	X
IPE 600	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	X	X	X

Figure 3.3 Calculations matrix.

4 Properties of Materials

Relevant properties of materials for the analysis comprise thermal and mechanical properties respectively. Since load bearing capacity only is studied for steel in this report it is only for steel that mechanical properties are relevant.

The thermal properties are divided into capacitivity and conductivity. Thermal capacitivity is the amount of energy required to heat a certain volume a certain number of degrees and is often measured in $kJ/(m^3K)$. Thermal conductivity is a measurement of how easy a material lets heat pass through it and is usually measured in $W/(m^2K)$.

4.1 Steel

4.1.1 Thermal Properties

As can be seen in Figure 4.1 below steel does not go through any radical changes in terms of thermal properties when exposed to fire.

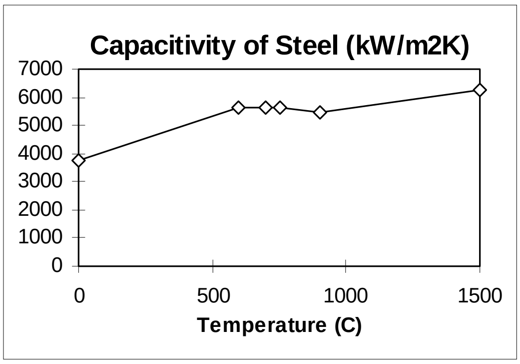


Figure 4.1 a) Thermal capacitivity of steel.

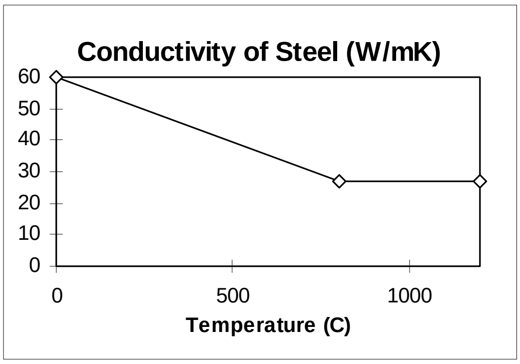


Figure 4.1 b) Thermal conductivity of steel.

4.1.2 Mechanical Properties

For the studied beams instability phenomenons are not relevant and the modulus of elasticity will therefore not be discussed here.

The calculations are for the limit state, hence full plasticizing of the cross-section is assumed and thereby full use of yield stress.

$$f_{yd} = \frac{f_{yk}}{\gamma_m \gamma_n}$$ (Equation 4.1 /8/)

where

f_{yd} is the design yield stress of the steel.
f_{yk} is the characteristic yield stress of the steel.
γ_m depends on material properties, especially deviations in cross-sectional measurements.
γ_m = 1,0 for HEA, HEB, HEM, IPE and U-beams and welded beams and plates.
γ_n depends on the safety class.

When designing for accidental loads with the risk of structural collapse $\gamma_m = \gamma_n$ = 1,0.

In this report f_{yd} is chosen to be 265 MPa since that is the value of steel type S275 with a maximum material thickness of 40 mm. Most of the hot rolled beams available in Sweden are made from steel type S275.

The relative strength of steel as a function of temperature according to Eurocode 3 /3/ is shown in Figure 4.2 below. The figure is valid when the critical strain of the steel is 2%.

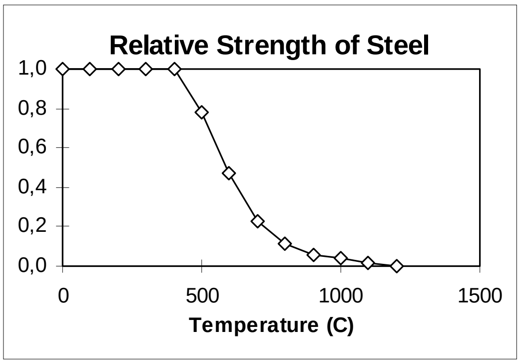


Figure 4.2 Relative strength of steel.

4.2 Hensotherm - Thermal Properties

The capacitivity of Hensotherm is approximately 1 kJ/(m^3K). This means that it is practically negligible compared to steel which is about 5000 times as high.

As can be seen in the plot below, Hensotherm's conductivity temperature curve is very complex. Generally sophisticated computer tools need to be incorporated in order to account for its extreme performance in fire. At room temperature Hensotherm is a thin coat of paint, but around 100°C it starts turning into an isolating foam. At around 230°C the transformation is complete, and then it has good protection abilities until the product is terminated by means of sublimation at around 900°C.

To complicate things even further the conductivity is different depending on the shape of the object upon which the paint is applied. Hensotherm has lower conductivity, and thereby better fire protecting qualities, on objects that have a high F/A. The resulting modeling problem is solved by using three different conductivity-curves depending on the F/A factor of the object. The three curves can be seen in Figure 4.3 below and their areas of use are as follows:

- 4KS1 when F/A < 110 m^{-1}
- 4KS2 when 110 < F/A < 250 m^{-1}
- 4KS3 when 250 < F/A

In reality the conductivity is a continuos function of F/A instead of just being able to take on three sets of values. To compensate for this the results for the beams with F/A values close to the limits between two curves have been interpolated between one result run with each curve. In case a) and b) no such interpolations were needed thanks to the fact that all beams had such low F/A-values that 4KS1 could be used for all beam sizes.

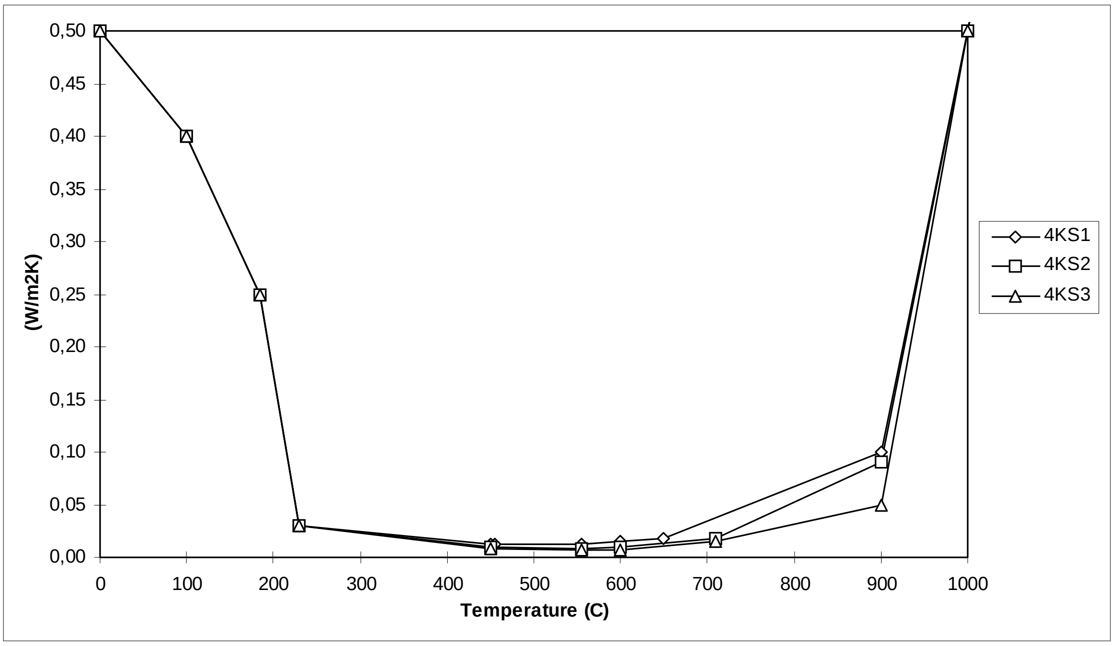


Figure 4.3 Thermal conductivity of Hensotherm.

4.3 Concrete - Thermal Properties

The thermal properties of concrete can be seen in Figure 4.4 below. The peak in capacitivity around 100°C is caused by the large amount of heat required to evaporize the water that exists inside the small pores of the concrete.

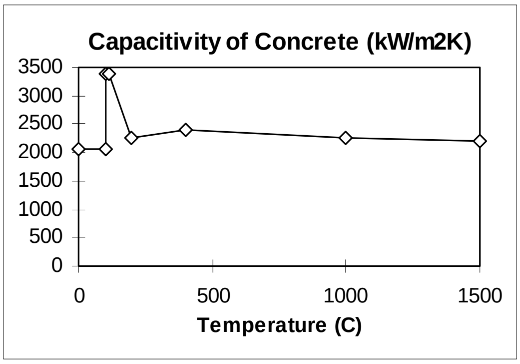


Figure 4.4 a) Capacitivity of concrete.

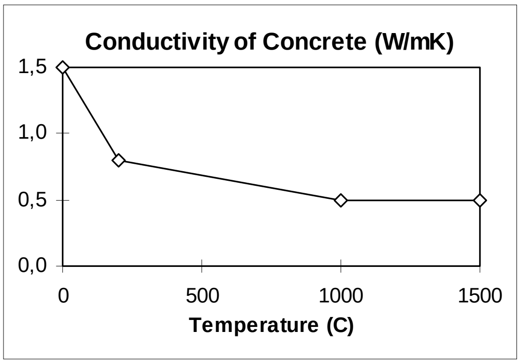


Figure 4.4 b) Conductivity of concrete.

5 TCD

5.1 About TCD

TCD /15/ is a program package which was developed by Fire Safety Design AB in Lund, Sweden. The TCD package comprises, among other things, SUPER-TEMPCALC for calculation of temperature field gradients and Fire Design for calculation of load bearing capacity of fire exposed members. SUPER-TEMPCALC originates from a program called TEMPCALC which was first introduced in 1985. This is not an attempt to describe all the features of TCD, it is just a brief description of the parts that have been used during this project. For more information about TCD please refer to the TCD manual /9/ or the staff of FSD.

5.2 Input Procedure

5.2.1 General Data

In this project many cross-sections of fire exposed steel beams have been studied. TCD contains a data base called LISA, i.e. parameters that were used many times could be put into the computer once and for all. Some examples:

- Material data. In each input procedure the materials could be selected from a menu. The data consists of conductivity, capacitivity and information about whether or not the properties are reversible.
- Structures. If something turned out to be wrong a structure could be retrieved from the data base and modified. Time could also be saved by using an old structure as a mould when creating a new cross-section similar to the old one.
- Fire exposures. The data base contains different exposures, but in this project ISO 834 was chosen once and then used for all applications.

Some information was put into the input procedure once and then used without changes throughout the whole project, for example:

- Start time: 0,000 h — The temperature build up of the fire starts as the simulation time exceeds 0,000 h.
- Stop time: 1,500 h — Duration of simulation.
- Step: 0,002 h — The simulation was done in steps of 7,2 seconds. This is also known as the time increment of the calculation.
- Prints to output file: 60 — The temperatures of all nodes were put into the output file every simulated 1,5 minutes.
- Start temperature: 20 °C — Initial temperature of the structure.

5.2.2 Each Simulation

The input procedure in TCD is handled by a preprocessor called LINA. Defining a cross-section is usually done in the following steps:

1. The cross-section is drawn on scale on a piece of paper. This is not necessary but usually saves more time than it takes. The purpose is to find out the coordinates of the corners of the materials and get an estimate of how big the elements should be in the different parts of the cross-section.
2. The next step is to put the coordinates into LINA and define the boundary conditions, for example fire or ambient room temperature. If the cross-section is symmetrical, which is usually the case, then time can be saved by only looking at half or a quarter of it. The axis of symmetry is input as an adiabatic line because no heat moves across to the other half of the cross-section since the symmetrical halves are identical.
3. The grid is created by specifying the lines that create the grid. An example of a grid can be seen in Figure 5.1 below. The best accuracy is achieved if the line are put close to each other where temperature changes quickly and further apart where changes are slow. This results in a grid with elements that are tiny near the surface and slightly larger deep inside the structure. Present versions of TCD can handle around 700 elements in a cross section, but a new version with higher capacity is being developed.
4. The program needs to know which material is where and that information is input either as a series of dots inside the elements or as areas containing each material.
5. When all this is done it is time to check that everything is correct and that is done by looking at the cross-section with the draw function. It is possible to zoom in and out to check that everything is where it is supposed to be.
6. The cross-section is then saved into the structure register so that it can be used again later, for example as a mould for similar beams.
7. It is advisable to check that the materials are selected in the way intended.
8. The last thing done with LINA is to save the data as a file called lina.dat and to generate a file called input.dat. The lina.dat file allows the information to be retrieved the next time LINA is used, and input.dat is the file that SUPER-TEMPCALC needs to run the temperature simulation.

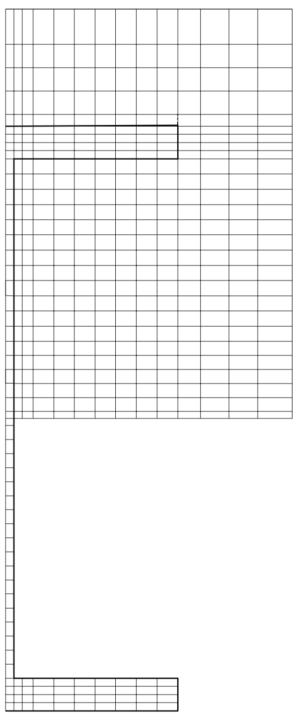


Figure 5.1 Grid of HEB 500 semi embedded in concrete.

5.3 SUPER-TEMPCALC

5.3.1 Introduction

SUPER-TEMPCALC is a fire-adapted two-dimensional finite element program developed by FSD for use on personal and mainframe computers. It is a further development of *TEMPCALC*, originally developed in 1985, and is included in the TCD /15/ program package.

The program 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 North Sea applications by a number of countries and organizations.

The program solves the two-dimensional, non-linear, transient, heat transfer differential equation (Equation 5.1) incorporating thermal properties which vary with temperature.

$$\frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + Q = \rho c \frac{\partial T}{\partial t} \qquad \text{(Equation 5.1)}$$

where

T	= temperature [°C]
k_x, k_y	= thermal conductivity [W/m°C]
c	= specific thermal capacity [J/kg °C]
ρ	= density [kg/m^3]
Q	= internal heat generation [W/m^3]

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 modeled as a function of time. Structures comprising several materials can be analyzed and the heat absorbed by any existing void in the structure is also taken into account.

5.3.2 Fire Exposed Boundary

The heat is transferred from the fire gases to the exposed structure through radiation and convection (see Equation 5.2). At high temperatures the radiation dominates. The radiation is expressed by the resulting emissivity factor which takes into account the emissivity of the fire source, ε_r, and the absorptivity of the heated surface, α. The convection is calculated from the temperature difference between the structure and ambient gases, depending on the gas velocity (second term of Equation 5.2). Emissivity and convection factors used, are shown in Figure 5.2. These are in accordance with recommendations issued by ISO.

Emissivity/convection	ε_r	h_C [W/m^{2}K]
Exposed surface	0.6	25

Figure 5.2 Resulting emissivity and convection factor for exposed surfaces.

$$q_n = h_c(T_g - T_b) + \varepsilon_r \sigma (T_g^4 - T_b^4) \qquad \text{(Equation 5.2)}$$

where

- q_r = radiative heat emitted [kW/m^2]
- s = Stefan-Boltzmann constant [5.67x10^{-8} W/m^2 K^4]
- T_g = absolute temperature of radiation source [°K]
- T_b = boundary temperature [°K]
- ε_r = resulting emissivity factor of the radiation source and the heated surface
- q_n = heat flow at the boundary [W/m^2]
- h_c = convection heat transfer coefficient [W/m^2°C]

5.3.3 Adiabatic Boundary

A boundary where no heat is said to pass (q_n=0) is often referred to as an adiabatic boundary. These are for example symmetry lines. Structures with extreme extension in two of the three directions are often considered to have a one dimensional heat flow and consequently adiabatic boundaries will be adopted in the calculation. A steel plate is an example of such a structure.

5.3.4 Enclosed Air Boundary

Total engulfment of hollow versus open section profiles, differ as concerns the conditions for the steel surface/ambient interface. Open sections have one type of boundary conditions, which is the exposure on outer surfaces. Hollow profiles, such as for example HSQ, feature an additional boundary condition which is the in void enclosed air. The amount of air enclosed in these cavities provides an additional heat absorbing potential which is favourable for the minimization of the steel core temperature.

The heat transfer between inner surfaces facing the enclosed air is generated by the fundamental laws of physics, requiring a complete heat exchange between the enclosed air and the steel surfaces. In this instance the heat is transferred in terms of radiation only.

The parameters of emissivity and convection were under these circumstances given values (ISO recommendation) in accordance with Figure 5.3 below.

Emissivity/convection	e	h_c [W/m^{2}K]
Cavity	0.6	15

Figure 5.3 Emissivity and convection factor for enclosed air boundary.

Once again incorporating Equation 5.2, accounting for the above values of emissivity and convection factors and substituting the steel temperature for the temperature of the radiation source and the temperature of the enclosed air for the boundary temperature, the heat exchange is readily calculated.

5.3.5 Results

SUPER-TEMPCALC creates a result file called output.res that contains the temperatures in all the nodes at the intervals determined, in this project every 1,5 minutes. The temperature in the nodes can be studied with other programs in the TCD package or converted to a format that can be read by Excel /16/.

5.4 FIRE DESIGN

Due to thermal gradients in the fire exposed beam cross-sections, the moment capacity inevitably will decrease. This decrease, or reduction, as well as the absolute magnitude of the moment, is readily calculated with the program SBEAM. It is a part of the FIRE DESIGN program that is included in the TCD /15/ package. SBEAM determines the moment capacity by combining Equations 5.3 and 5.4.

$$M_{red} = \sum_{i=1}^{n} f_i(T) A_i d_i \qquad \text{(Equation 5.3)}$$

$$\longrightarrow \sum_{i=1}^{n} f_i(T) A_i = 0 \qquad \text{(Equation 5.4)}$$

where

A_i: cross-sectional area for element i
$f_i(T)$: yield strength magnitude in element i considering the element temperature
d_i: lever arm for element i
M_{red}: reduced moment capacity

Cross-sectional nodal temperatures are provided from the output file of SUPER-TEMPCALC. The cross-sectional geometry is retrieved from the SUPER-TEMPCALC input file called input.dat. Actual values of the decrease percentage of steel strength as a function of the temperature is specified, along with the nominal yield strength at room temperature, in the file sbeam.dat. The results can be plotted with functions in FIRE DESIGN, but in this project the sbeam.dat files have instead been converted to Excel for further evaluation. FIRE DESIGN was developed by FSD.

6 Practical Validation

6.1 Introduction

Since TCD has been used for so many years it was not relevant to do an extensive validation of the computer program package. One thing that felt relevant, however, was to check how accurate the results are when Hensotherm is involved. A simulation was made of a test done by the Swedish National Testing and Research Institute in 1994. The test is described in the report *Fire test of fire protection insulation system for structural steel members, intumescent paint* which is included in this report as Appendix A.

6.2 The Test

The test was conducted with a 2000 mm long HEA 140 steel beam coated with 1490 µm (3000 g/m^2) of Hensotherm 4KS. The steel temperature was measured with eight thermocouples placed as shown in the picture below. The beam was exposed to ISO 834 standard fire during 68 minutes and 30 seconds. For more details about the setup of the test please refer to Appendix A.

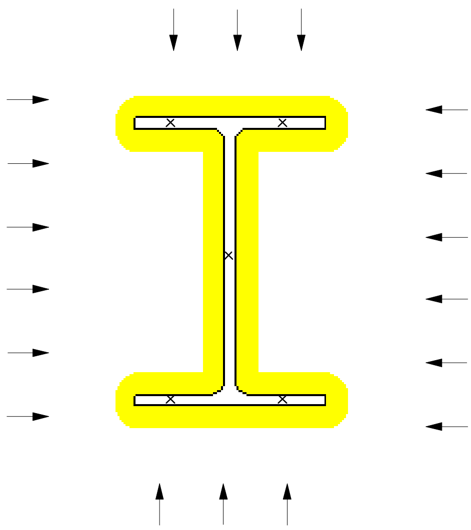


Figure 6.1 The setup of the SP-test with placing of thermocouples marked with X.

6.3 The Simulation

The simulation was made with the TCD program package in the same way the rest of the simulations in this report was made. Since the structure has two-axial symmetry and calculation of the moment capacity was not an objective in the practical validation it was only necessary to use one fourth of the cross-section and adiabatic lines to show the symmetry. The two nodes corresponding to the locations of the thermocouples in the test turned out to be node 57 in the flange and node 157 in the center of the beam.

6.4 The Result

The result can be seen in the figure below. The simulation temperatures are close to and slightly higher than the temperatures in the test. The simulation result is thereby slightly conservative and very relevant.

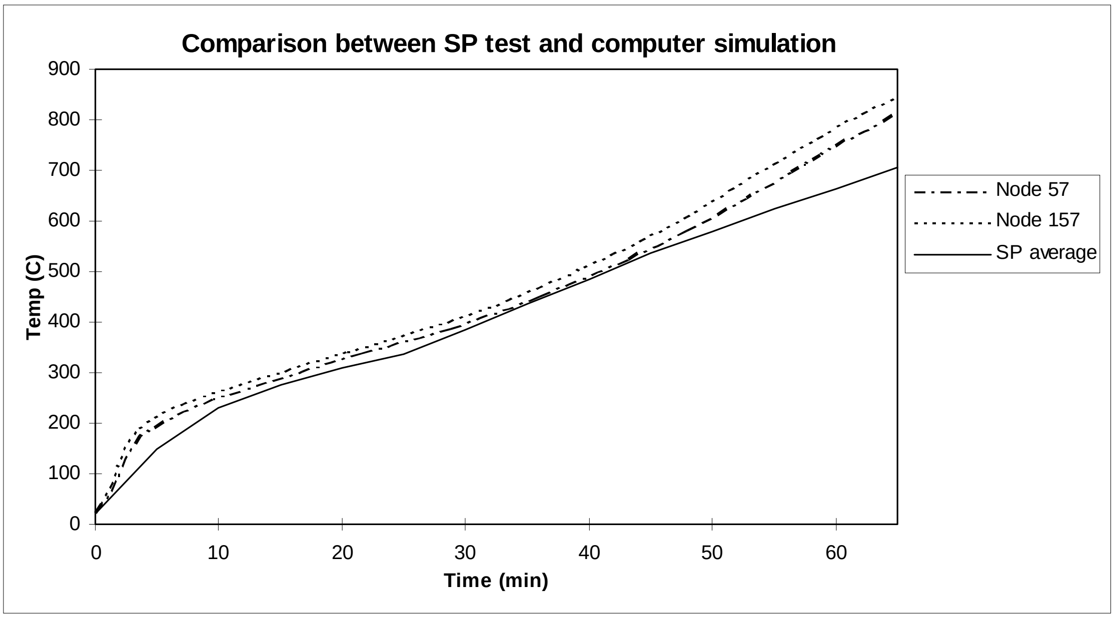


Figure 6.2 Comparison between SP test and computer simulation.

7 Steel Beams Embedded in Concrete

7.1 Introduction

7.1.1 The Setup

The steel beam is placed so that all parts of the beam are in contact with the concrete except the sides and the bottom of the lower flange. This allows the beam to expand without cracking the concrete when it is heated.

Since the cross-section is symmetrical the simulation was done with the left half replaced with an adiabatic line so that no heat passed to or from the left side. The dashdotted line in Figure 7.1 indicates the symmetry.

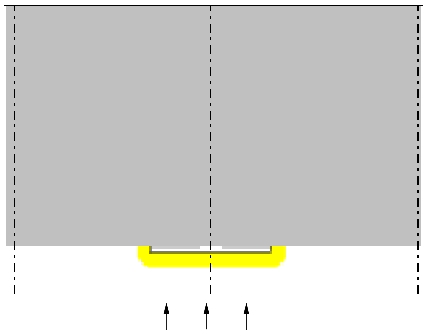


Figure 7.1 Steel beam embedded in concrete.

To the right side of the beam an adiabatic line was placed 100 mm from the steel since the heatflow is quite one-dimensional that far away from the beam. A simulation was made with the symmetry line 200 mm from the beam instead to verify that the results were not affected by the location of the adiabatic boundary, and no such errors were found.

An adiabatic line was put 100 mm above the beam. The reason for this was that:
- 100 mm is a normal amount of concrete to use in this type of system of joists.
- An adiabatic layer lets through less heat than any material, and the results are thereby conservative no matter what type of flooring is placed on top of the concrete.
- A simulation was made with 200 mm of concrete on top of the beam, and the results were exactly the same. The reason is mainly that the temperatures that deep inside the concrete are still virtually unchanged after 90 minutes of fire exposure.

7.1.2 Relevancy

The calculated results are conservative when:
- Nothing or anything is placed on top of the concrete.
- The beam is embedded in a material with higher capacitivity and lower conductivity than concrete.

The results are not or might not be conservative when:
- Less than 100 mm of concrete is used on top of the beam.
- The beam is embedded in a material with lower capacitivity and/or higher conductivity than concrete.
- The concrete does not cover the top of the lower flange and the whole web. For such cases conservative results are achieved by using the simulation case in chapter 8, steel beam semi embedded in concrete.

Practical problems can arise especially when beams lower than 200 mm are used. The reason is that it is difficult to find suitable placing of the reinforcing bars in the concrete that allows for sufficient anchoring distance.

7.1.3 F/A Versus A/F

One variable that normally is employed when fire resistances of steel beams are calculated is the F/A-factor. F is the circumference of the part of the steel that is exposed to the fire and A is the area of the whole cross-section of the steel beam. A/F is the inverse of F/A and they can both be seen in Figure 7.2 below.

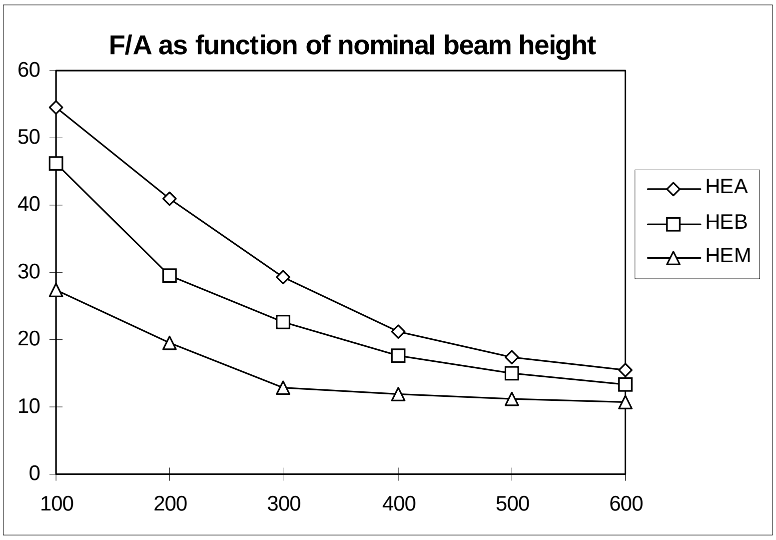


Figure 7.2a F/A as function of nominal beam height (m^{-1}).

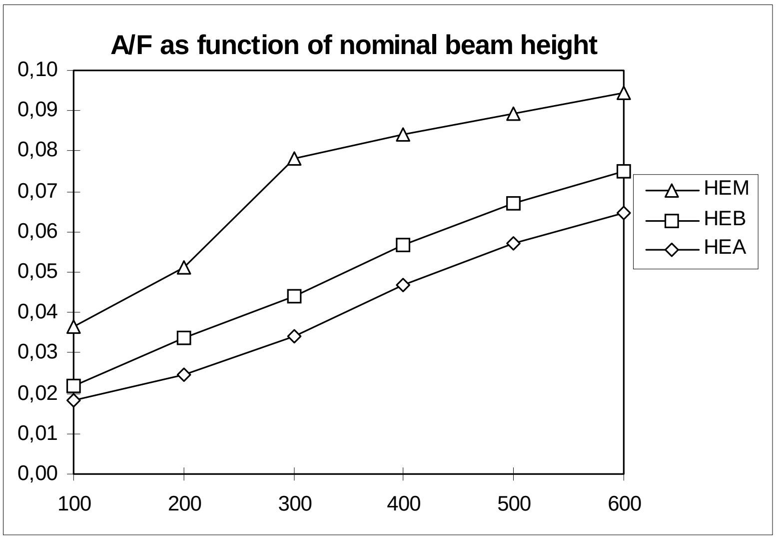


Figure 7.2b A/F as function of nominal beam height (m).

7.2 Results

7.2.1 General Comments

Embedding a steel beam in concrete is an efficient way to achieve good fire resistance with little or no fire protection paint. Another advantage is that it creates a set of joists that is thinner than when the concrete is placed on top of the beam. One problem is that it takes a bit of extra time to build because the reinforcing bars are trickier to place in the joists. In some of the calculations the relative moment capacity is approximately proportional to A/F.

7.2.2 Structural Performance During Fire Exposure

The effect of the fire exposure can basically be divided into the three stages that are shown in Figure 7.3 below:

1. The lower flange of the beam is heated until it reaches 400 °C.
2. The lower flange gradually loses its strength as it is heated to around 1000 °C where its strength is almost completely lost.
3. The heat is slowly spread into the concrete and that causes the web to gradually loose its strength.

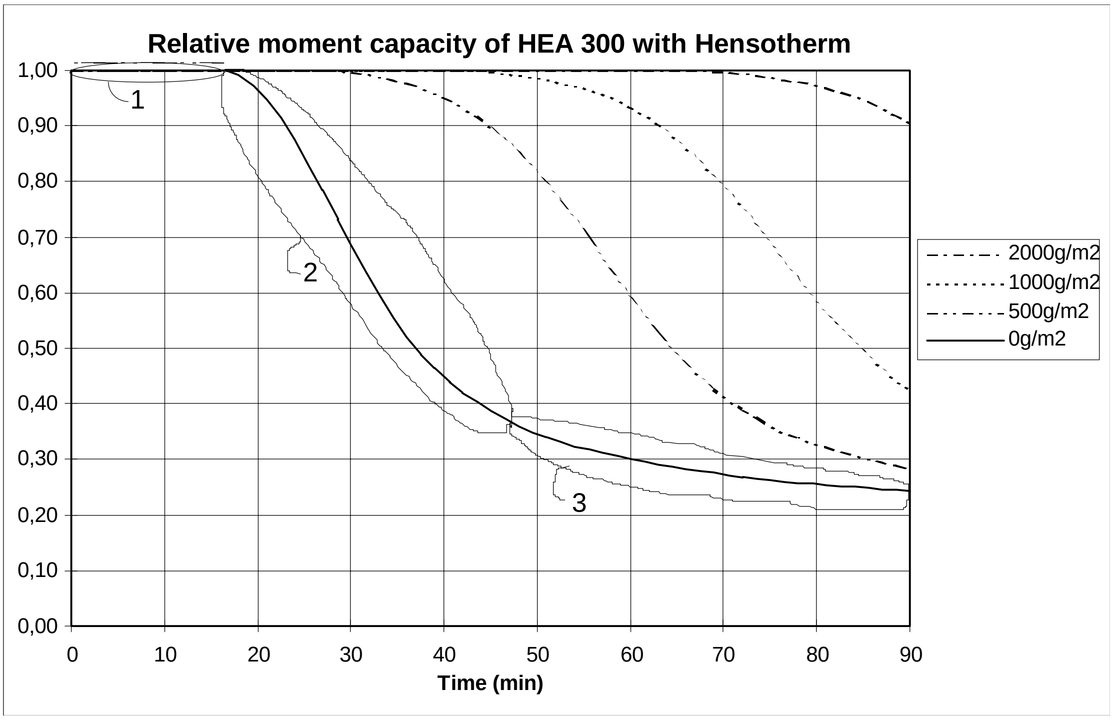


Figure 7.3 Relative moment capacity of HEA 300 with Hensotherm.

As can be seen in the figure above the use of Hensotherm does not prevent the beam from losing its moment capacity, but it slows down the process significantly. To include the figures for all the calculated beams would have made this report about twice as thick, so that was not realistic to do. Instead the figures have been analyzed and the following observations made:

- Stage 1 takes longer time when more Hensotherm is used.
- Stage 1 takes longer time when beams with lower F/A-factors are used.
- Stage 2 takes approximately the same amount of time independently of the other variables.
- Stage 3 basically has higher relative moment capacity for higher beams.

7.2.3 HEA-beams

The results of the calculations for HEA after 30, 60 and 90 minutes can be seen on the next page.

When designing for 30 minutes of fire it is in many cases possible to manage without any insulating paint, especially when using large beams. Using more than 500 g/m^2 of paint is not necessary.

After 60 minutes unprotected beams are in or approaching stage 3, i.e. they are getting too weak to be useful. In most cases it is appropriate to use 500 g/m^2 of Hensotherm.

After 90 minutes paint application should in most cases be at least 1000 g/m^2.

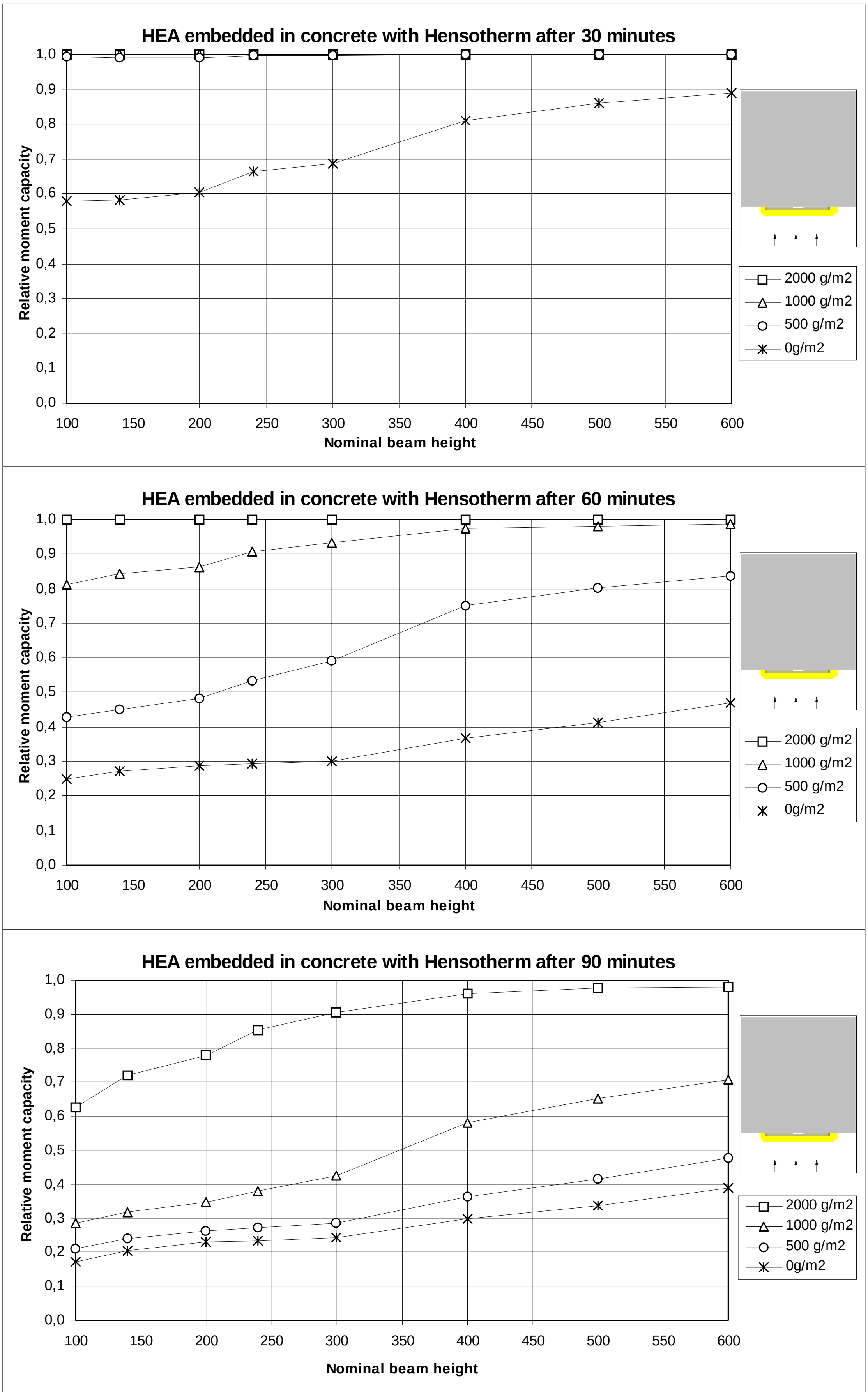


Figure 7.4 Relative moment capacity of HEA-beams embedded in concrete.

7.2.4 HEB-beams

The results of the calculations for HEB after 30, 60 and 90 minutes can be seen on the next page. HEB-beams provide a better fire resistance than HEA-beams thanks to lower F/A-values.

When designing for 30 minutes of fire it is in most cases possible to manage without paint, especially when using large beams. Using more than 500 g/m^2 of paint is unnecessary.

After 60 minutes unprotected beams are in or approaching stage 3, so they are getting too weak to be useful. In most cases it is appropriate to use 500 g/m^2 of Hensotherm.

After 90 minutes suitable paint application thicknesses range from 500 to 1500 g/m^2.

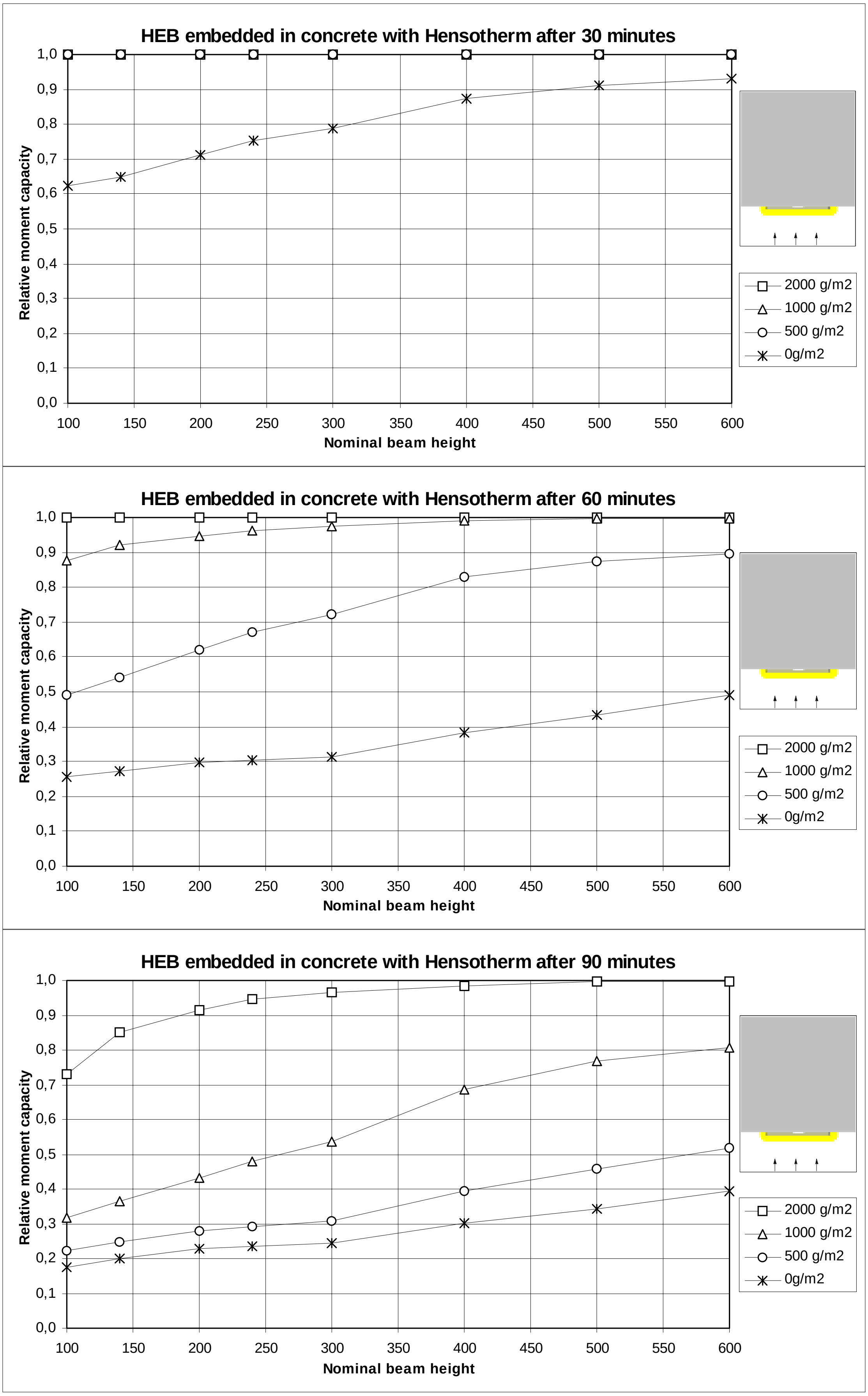


Figure 7.5 Relative moment capacity of HEB-beams embedded in concrete.

7.2.5 HEM-beams

The results of the calculations for HEM after 30, 60 and 90 minutes can be seen on the next page. HEM-beams provide a better fire resistance than HEA and HEB thanks to lower F/A-values.

When designing for 30 minutes of fire it is in all cases possible to manage without paint, even when using small beams.

After 60 minutes unprotected beams are in or approaching stage 3, i.e. they are getting too weak to be useful. In all cases 500 g/m^2 of Hensotherm is sufficient.

After 90 minutes suitable paint application thicknesses range from 500 to approximately 1200 g/m^2.

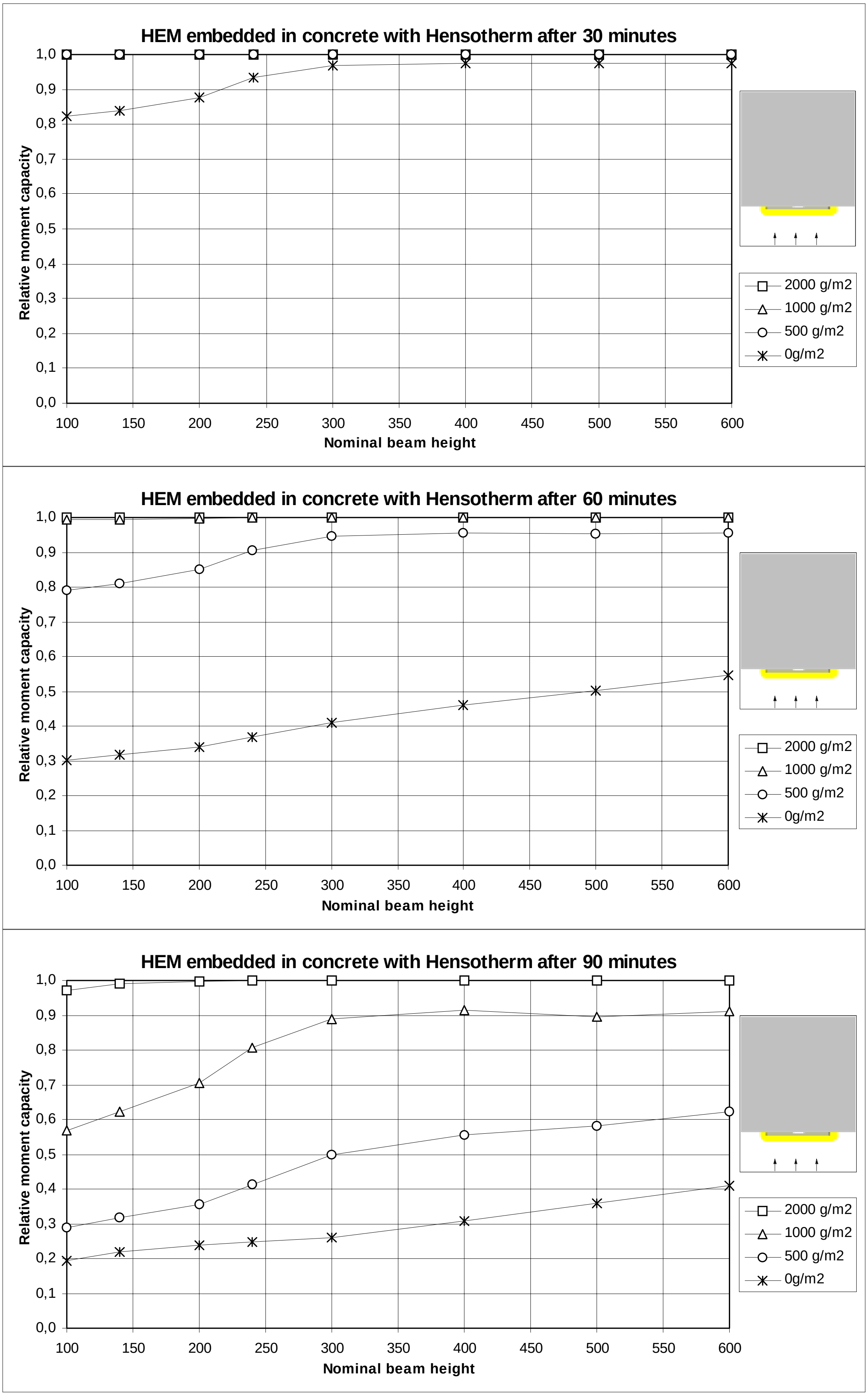


Figure 7.6 Relative moment capacity of HEM-beams embedded in concrete.

7.2.6 HSQ-beams

HSQ is unlike the other beams in this report not manufactured by hot-rolling. It is instead welded together according to the specifications provided by the customer as can be seen below in Figure 7.7. Since so many variables can assume so many different values it is difficult to provide general design guide lines. This is not an attempt to make a complete evaluation of the fire resistance of HSQ-beams, it is meant more as basic information for people that want so study HSQ more thoroughly.

Figure 7.7 HSQ-beam.

Some tendencies were found. In order to have a high relative moment capacity when exposed to fire the beam should:

- Be as high as possible.
- Have a thick lower flange.
- Be as narrow as possible.

The following measurements were used for the simulations:

- d = 5 mm
- t1 = 25 mm
- H = 200 or 380 mm
- t2 = 25 or 40 mm
- b2 = 350 or 550 mm
- b1 = b2 - 200 mm

The following amounts of paint were required to achieve the specified relative moment capacity (α) after 60 minutes of fire.

			Amount of paint (g/m2)	
H (mm)	t2 (mm)	α (%)	b2=350mm	b2=550mm
200	25	70	400	400
200	25	56	400	400
200	25	42	400	400
200	40	70	400	400
200	40	56	0	400
200	40	42	0	0
380	25	70	400	400
380	25	56	400	400
380	25	42	0	400
380	40	70	400	400
380	40	56	0	0
380	40	42	0	0

Figure 7.8 Paint amounts after 60 minutes according to computer simulation.

This correlates quite well with the design guide lines in a Hensotherm brochure /14/ that for 60 minutes are as follows.

		Amount of paint (g/m2)	
t2 (mm)	α (%)	b2=350mm	b2=550mm
10	70	1000	1250
10	56	750	1000
10	42	500	750
20	70	500	750
20	56	400	500
20	42	400	500
30	70	400	500
30	56	400	400
30	42	400	400

Figure 7.9 Paint amounts after 60 minutes according to design guide lines /14/.

The following amounts of paint were required to achieve the specified relative moment capacity (α) after 90 minutes of fire.

			Amount of paint (g/m2)	
H (mm)	t2 (mm)	α (%)	b2=350mm	b2=550mm
200	25	70	1000	1000
200	25	56	750	1000
200	25	42	500	750
200	40	70	400	750
200	40	56	400	500
200	40	42	400	400
380	25	70	750	1000
380	25	56	750	1000
380	25	42	400	750
380	40	70	400	500
380	40	56	400	400
380	40	42	0	400

Figure 7.10 Paint amounts after 90 minutes according to computer simulation.

This correlates quite well with the design guide lines in a Hensotherm brochure /14/ that for 90 minutes are as follows.

t2 (mm)	α (%)	Amount of paint (g/m2) b2=350mm	b2=550mm
10	70	-	-
10	56	-	-
10	42	1250	-
20	70	1250	-
20	56	1000	1250
20	42	750	1000
30	70	1000	1250
30	56	750	1000
30	42	500	750

Figure 7.11 Paint amounts after 90 minutes according to design guide lines /14/.

8 Steel Beams Semi Embedded in Concrete

8.1 Introduction

8.1.1 The Setup

The steel beam is placed so that the top half of the beam is embedded in the concrete.

Since the cross-section is symmetrical the simulation was done with the left half replaced with an adiabatic line so that no heat passed to or from the left side. The dashdotted line in Figure 8.1 indicates the symmetry.

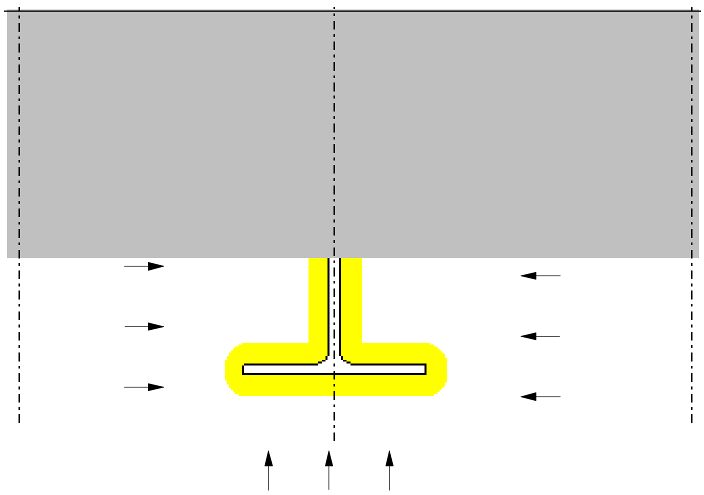


Figure 8.1 Steel beam semi embedded in concrete.

To the right side of the beam an adiabatic line was placed 100 mm from the steel since the heatflow is quite one-dimensional that far away from the beam. A simulation was made with the symmetry line 200 mm from the beam instead to verify that the results were not affected by the location of the adiabatic boundary, and no such errors were found.

An adiabatic line was put 100 mm above the beam. The reason for this was that:
- 100 mm is a normal amount of concrete to use in this type of system of joists.
- An adiabatic layer lets through less heat than any material, and the results are thereby conservative no matter what type of flooring is placed on top of the concrete.

8.1.2 Relevancy

The calculated results are conservative when:
- Nothing or anything is placed on top of the concrete.
- The beam is semi embedded in a material with higher capacitivity and lower conductivity than concrete.
- More than half the beam is inside the concrete.

The results are not or might not be conservative when:
- Less than 100 mm of concrete is used on top of the beam.
- The beam is semi embedded in a material with lower capacitivity and/or higher conductivity than concrete.
- Less than half the beam is inside the concrete.

Practical problems can arise especially when beams lower than 200 mm are used. The reason is that it is difficult to find suitable placing of the reinforcing bars in the concrete that allows for sufficient anchoring distance.

8.1.3 F/A Versus A/F

One variable that normally is employed when fire resistances of steel beams are calculated is F/A. F is the circumference of the part of the steel that is exposed to the fire and A is the area of the whole cross-section of the steel beam. A/F is the inverse of F/A and they can both be seen in Figure 8.2 below.

One surprising fact that can be seen in the diagram below is that HEM-beams have their highest A/F value for beam heights around 300 mm. The reason for this is that the higher beams have approximately the same flange width, flange thickness and web thickness. It is only the height of the web that is increased to get the largest beams, and the A/F values can thereby have a maximum value for HEM-beams with heights around 300 mm.

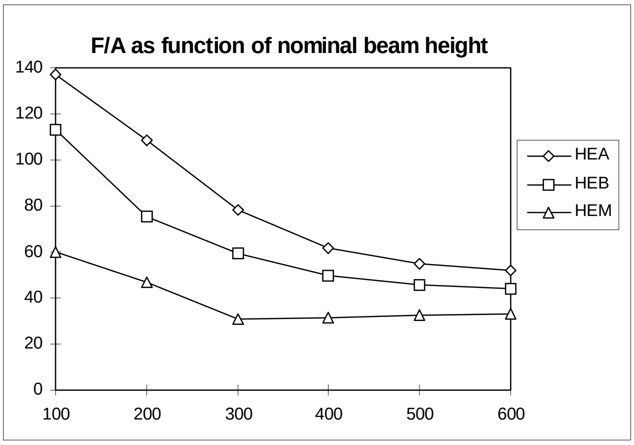


Figure 8.2a F/A as function of nominal beam height (m^{-1}).

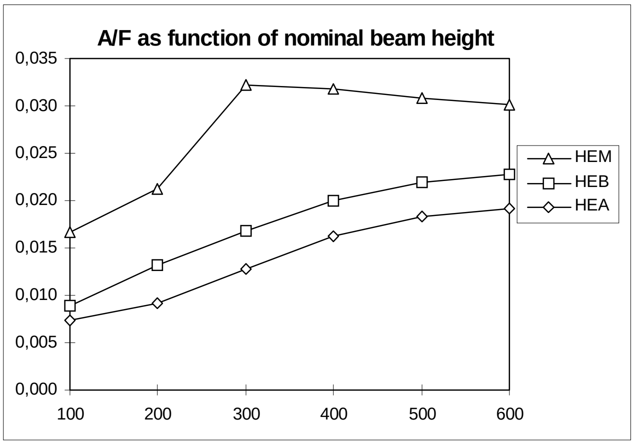


Figure 8.2b A/F as function of nominal beam height (m).

8.2 Results

8.2.1 General Comments

It is only in very rare cases that a semi embedded beam can be recommended. The reasons for this is mainly that:

- This design has much lower fire resistance than a fully embedded beam but takes roughly the same amount of time to build.
- A semi embedded beam has about the same fire resistance as a beam with concrete on top but takes much longer time to build.

In many of the calculations the relative moment capacity is approximately proportional to the A/F-factor.

8.2.2 Structural Performance During Fire Exposure

The effect of the fire exposure can basically be divided into the three stages that are shown in Figure 8.3 below:

1. The lower half of the beam is heated until it reaches 400 °C.
2. The lower half gradually loses its strength as it is heated to around 1000 °C where its strength is almost completely lost.
3. The heat is slowly spread into the concrete and that causes the upper half of the beam to gradually loose its strength.

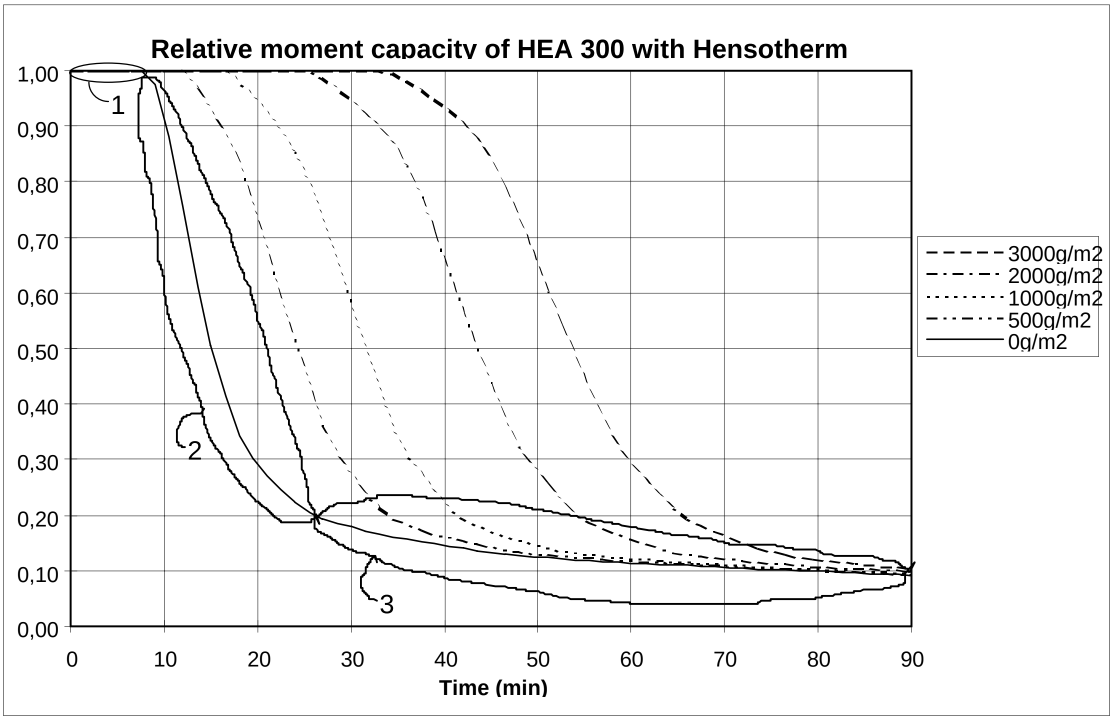


Figure 8.3 Relative moment capacity of HEA 300 with Hensotherm.

As can be seen in the Figure 8.3 on the previous page the use of Hensotherm does not prevent the beam from losing its moment capacity, but it slows down the process significantly. To include the figures for all the calculated beams would have made this report about twice as thick, so that was not realistic to do. Instead the figures have been analyzed and the following observations made:

- Stage 1 takes more time when more Hensotherm is used.
- Stage 1 takes more time when beams with lower F/A-factors are used.
- Stage 2 takes approximately the same amount of time independently of the other variables, but takes slightly more time for beams with low F/A.
- Stage 3 basically has higher relative moment capacity for beams with low F/A.

8.2.3 HEA-beams

The results of the calculations for HEA after 30, 60 and 90 minutes can be seen on the next page.

When designing for 30 minutes of fire it is for large beams suitable to use between 500 and 1000 g/m^2 of Hensotherm. Smaller beams may require up to approximately 1500 g/m^2.

After 60 minutes only large beams with 3000 g/m^2 and very large beams with 2000 g/m^2 of paint have enough moment capacity left to be useful.

After 90 minutes it is not possible to have more than 20% of the moment capacity left.

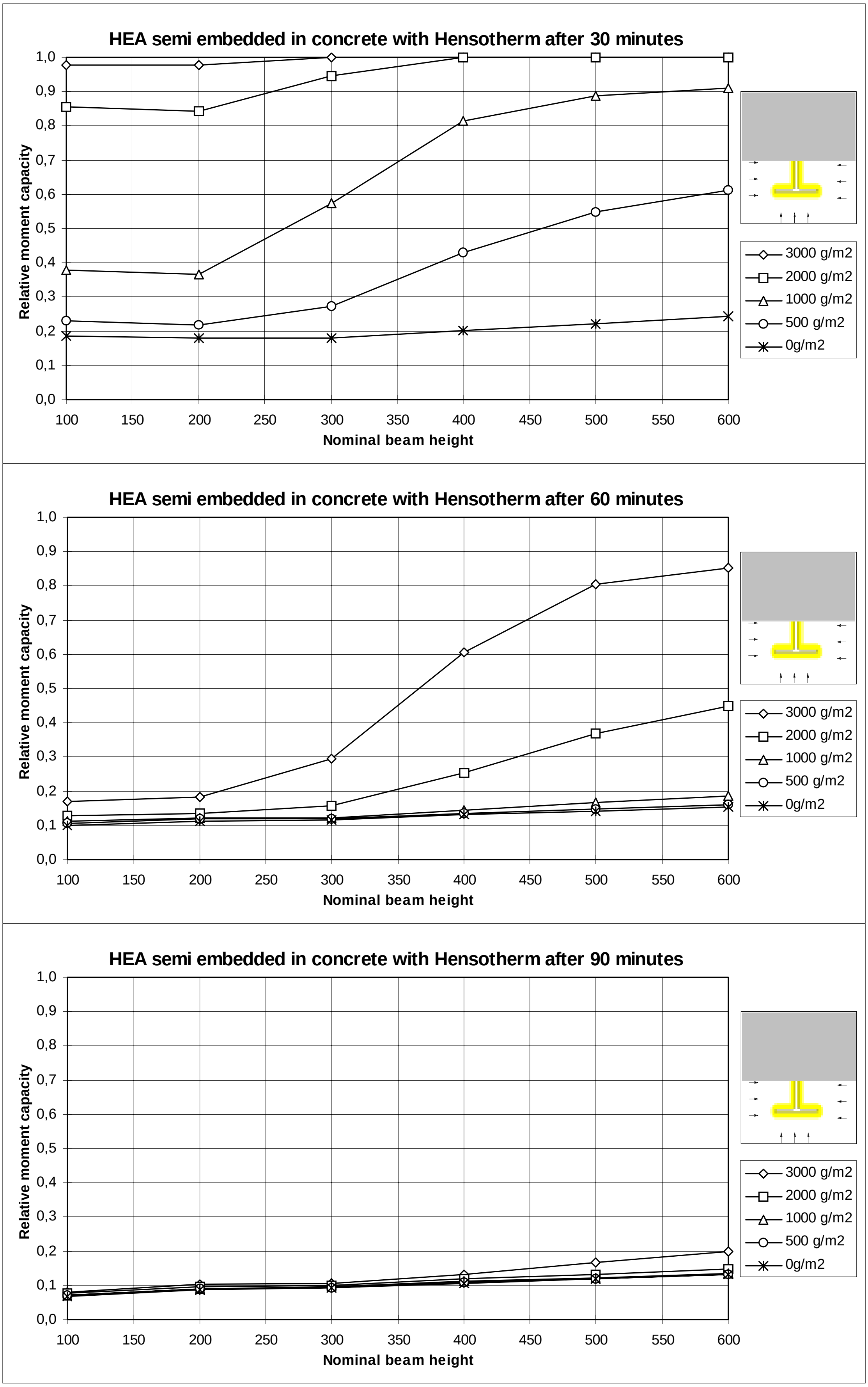


Figure 8.4 Relative moment capacity of HEA-beams semi embedded in concrete.

8.2.4 HEB-beams

The results of the calculations for HEB after 30, 60 and 90 minutes can be seen on the next page. HEB-beams provide a better fire resistance than HEA-beams thanks to lower F/A-values.

When designing for 30 minutes of fire it is in most cases suitable to use 500 or for small profiles 1000 g/m^2 of Hensotherm. Using more than 1000 g/m^2 of paint is unnecessary.

After 60 minutes only beams with 3000 g/m^2 and large beams with 2000 g/m^2 of paint have enough moment capacity left to be useful.

After 90 minutes it is not possible to have more than 30% of the moment capacity left.

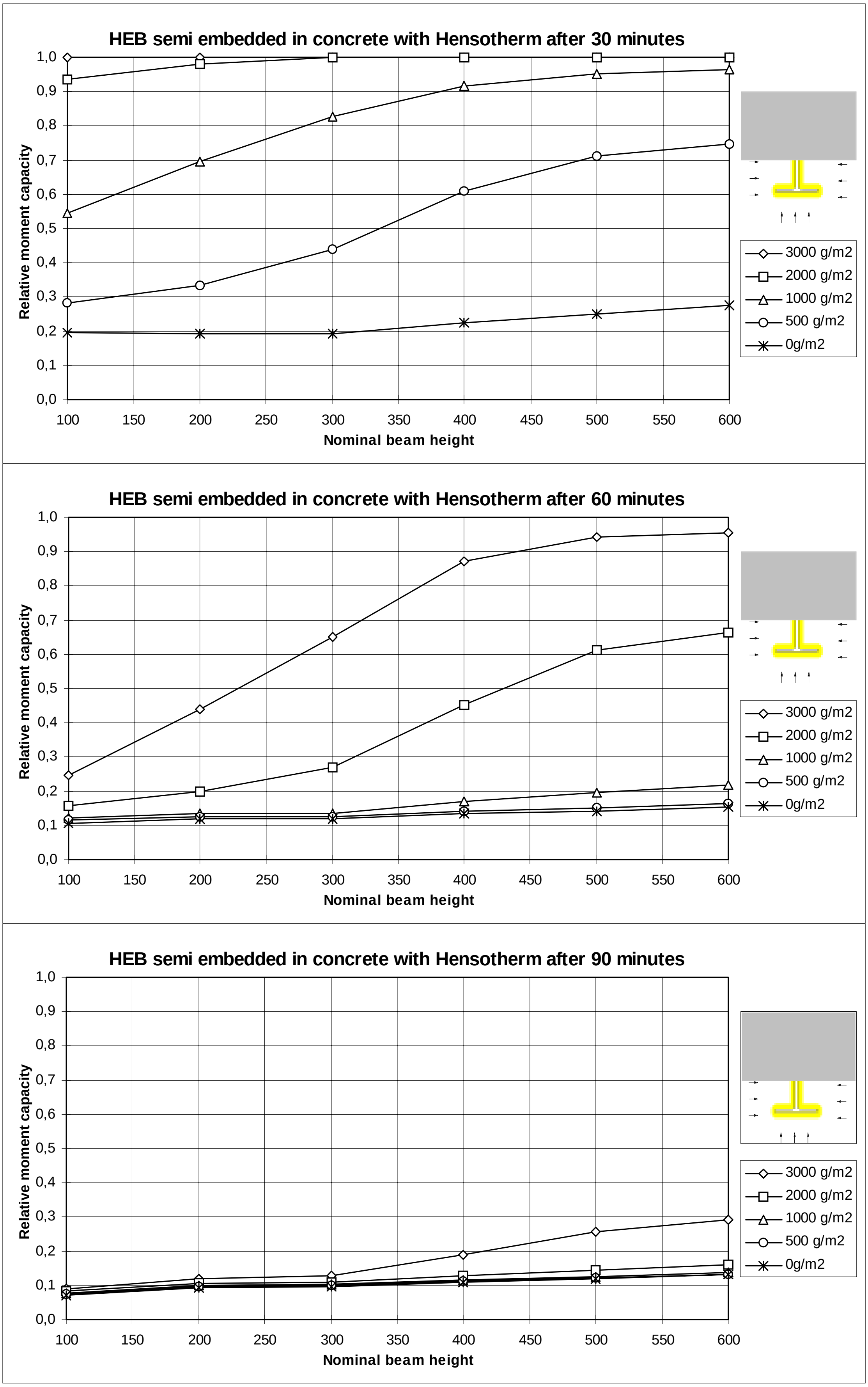


Figure 8.5 Relative moment capacity of HEB-beams semi embedded in concrete.

8.2.5 HEM-beams

The results of the calculations for HEM after 30, 60 and 90 minutes can be seen on the next page. HEM-beams provide a better fire resistance than HEA and HEB thanks to lower F/A-values.

HEM-beams have a minimum F/A-ratio for HEM 300. This phenomenon reflects on the charts of Figure 8.6 which indicate a maximum relative bending moment capacity for this specific beam size.

Unprotected steel beams show a rather constant relative bending moment capacity independant of the beam height. The moment capacity varies from approximately 35% to 10% for 30, 60 and 90 minutes respectively.

When designing for 30 minutes of fire it is sufficient to use 500 g/m^2 of Hensotherm, which is close to the minimum application thickness of the product.

After 60 minutes paint amounts between 1000 and 3000 g/m^2 can be appropriate.

After 90 minutes a satisfactory design requires quite large beams with 3000 g/m^2 of paint.

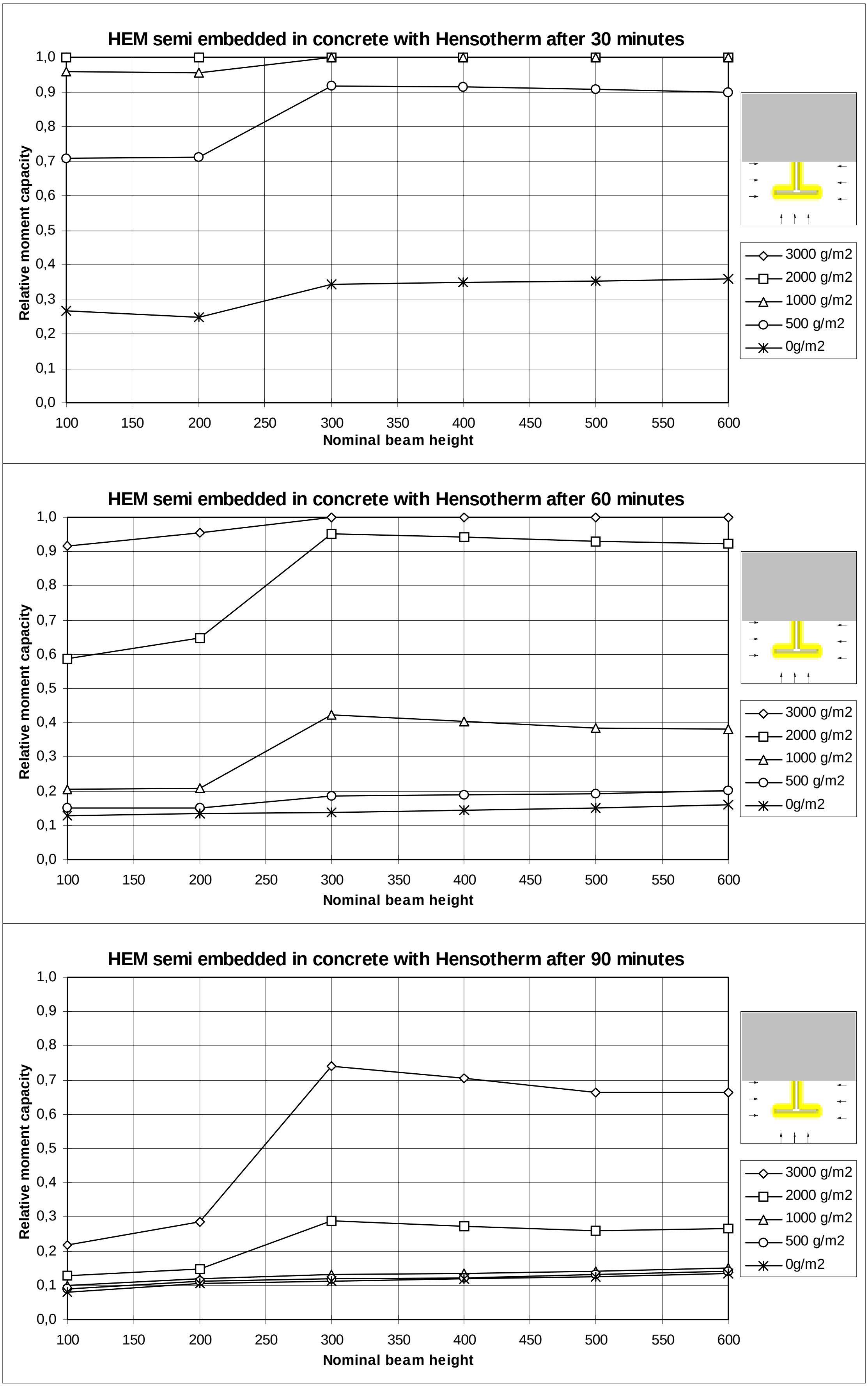


Figure 8.6 Relative moment capacity of HEM-beams semi embedded in concrete.

9 Steel Beam with Concrete on Top

9.1 Introduction

9.1.1 The Setup

The steel beam is placed so that only the top side of the beam is in contact with the concrete.

Since the cross-section is symmetrical the simulation was done with the left half replaced with an adiabatic line so that no heat passed to or from the left side. The dashdotted line in Figure 9.1 indicates the symmetry.

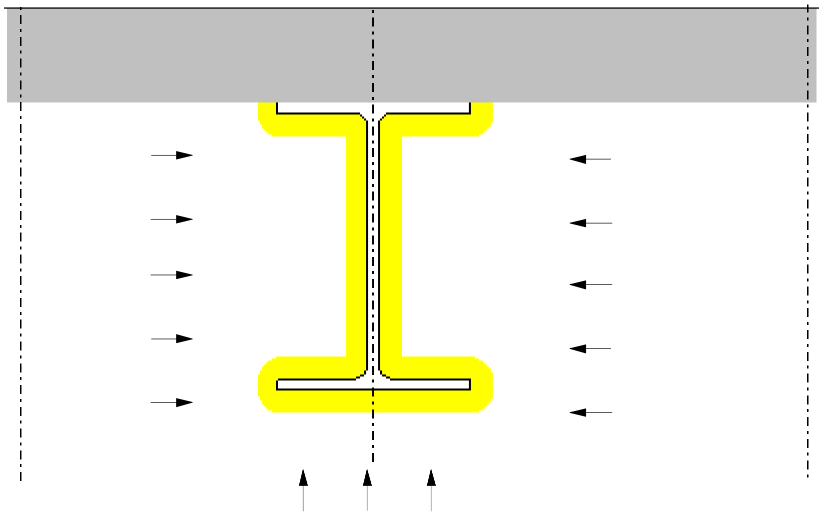


Figure 9.1 Steel beam with concrete on top.

To the right side of the beam an adiabatic line was placed 100 mm from the steel since the heatflow is quite one-dimensional that far away from the beam.

An adiabatic line was put 100 mm above the beam. The reason for this was that:

- 100 mm is a normal amount of concrete to use in this type of system of joists.
- An adiabatic layer lets through less heat than any material, and the results are thereby conservative no matter what type of flooring is placed on top of the concrete.

9.1.2 Relevancy

The calculated results are conservative when:

- Nothing or anything is placed on top of the concrete.
- The beam is in contact with a material with higher capacitivity and lower conductivity than concrete.

The results are not or might not be conservative when:

- Less that 100 mm of concrete is used on top of the beam.
- The beam is in contact with a material with lower capacitivity and/or higher conductivity than concrete.
- More or less steel than specified is in contact with the concrete.

9.1.3 F/A Versus A/F

One variable that normally is employed when fire resistances of steel beams are calculated is the F/A-factor. F is the circumference of the part of the steel that is exposed to the fire and A is the area of the whole cross-section of the steel beam. A/F is the inverse of F/A and they can both be seen in Figure 9.2 below.

One surprising fact that can be seen in the diagram below is that HEM-beams have their highest A/F value for beam heights around 300 mm. The reason for this is that the higher beams have approximately the same flange width, flange thickness and web thickness. It is only the height of the web that is increased to get the largest beams, and the A/F values can thereby have a maximum value for HEM-beams with heights around 300 mm.

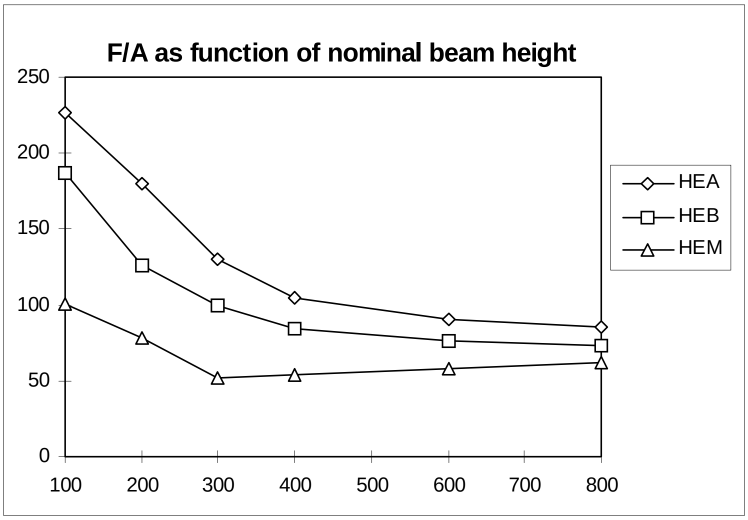


Figure 9.2a F/A as function of nominal beam height (m^{-1}).

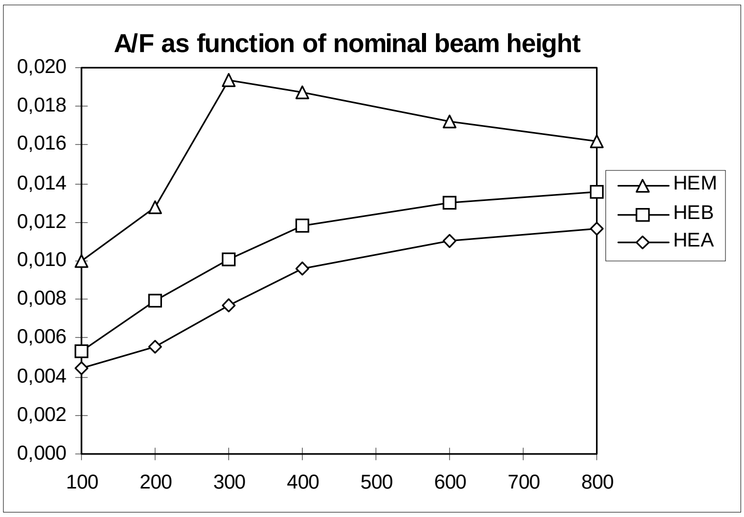


Figure 9.2b A/F as function of nominal beam height (m).

9.2 Results

9.2.1 General Comments

Putting a concrete system of joists on top of a steel beam is quite a quick and common way to build. Compared to a steel beam semi embedded in concrete the fire resistance is usually slightly lower but in some rare cases higher. Compared to a steel beam with 4-sided fire exposure the fire resistance has a tendency to be slightly higher but is sometimes lower. In many of the calculations the relative moment capacity is approximately proportional to A/F.

9.2.2 Structural Performance During Fire Exposure

The shape of the curves in the Figure 9.3 below are similar to the curve of relative strength as a function of temperature that is found in Figure 4.3 in chapter 4.2.3. There are basically two differences between the curves in the two figures.

- The curves below are rounded when they start to go down, but the material data curve drop is very sudden. The reason for this is that the fire temperature is climbing in the early stages, and that causes the steel to pass 400°C quite slowly. The temperature of the ISO 834 standard fire is shown in Figure 3.2 in chapter 3.2.1.
- The relative moment capacity does not go down to zero, instead it levels out around 5%. The reason for this can also be found in the temperature curve in Figure 3.2 in chapter 3.2.1. The ISO 834 fire temperature is around 1000°C after 90 minutes, and the steel does therefore not reach the 1200°C where it has no strength at all within the simulation time.
- The unexposed upper flange will imply a temperature gradient. Hence no uniform steel core temperature can be identified.

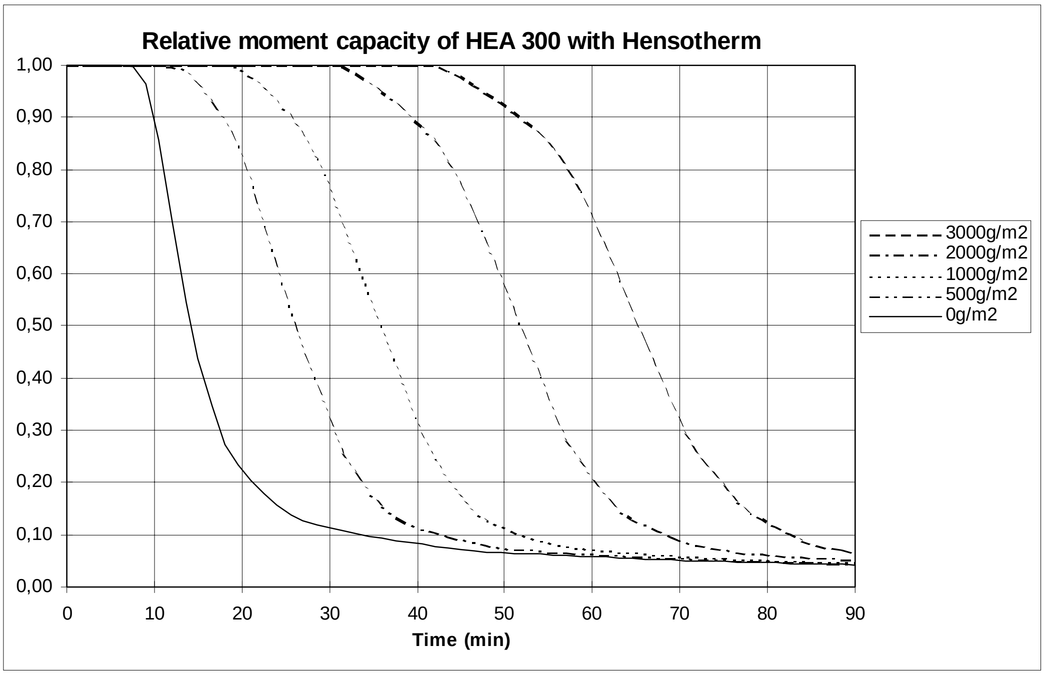


Figure 9.3 Relative moment capacity of HEA 300 with Hensotherm.

As can also be seen in Figure 9.3 on the previous page the use of Hensotherm does not prevent the beam from losing its moment capacity, but it slows down the process significantly. To include the figures for all the calculated beams would have made this report about twice as thick, so that was not realistic to do. Instead the figures have been analyzed and the following observations made:

- The relative moment capacity of all unprotected beams sooner or later level out around 5%, but it takes a little more time for beams with low F/A.
- Beams with low F/A respond more efficiently to fire protection with Hensotherm.

9.2.3 HEA-beams

The results of the calculations for HEA after 30, 60 and 90 minutes can be seen on the next page.

When designing for 30 minutes of fire it is for large beams suitable to use 1000 g/m^2 of Hensotherm.

After 60 minutes only beams with 3000 g/m^2 and large beams with 2000 g/m^2 of paint have enough moment capacity left to be useful.

After 90 minutes it is not possible to have more than 14% of the moment capacity left.

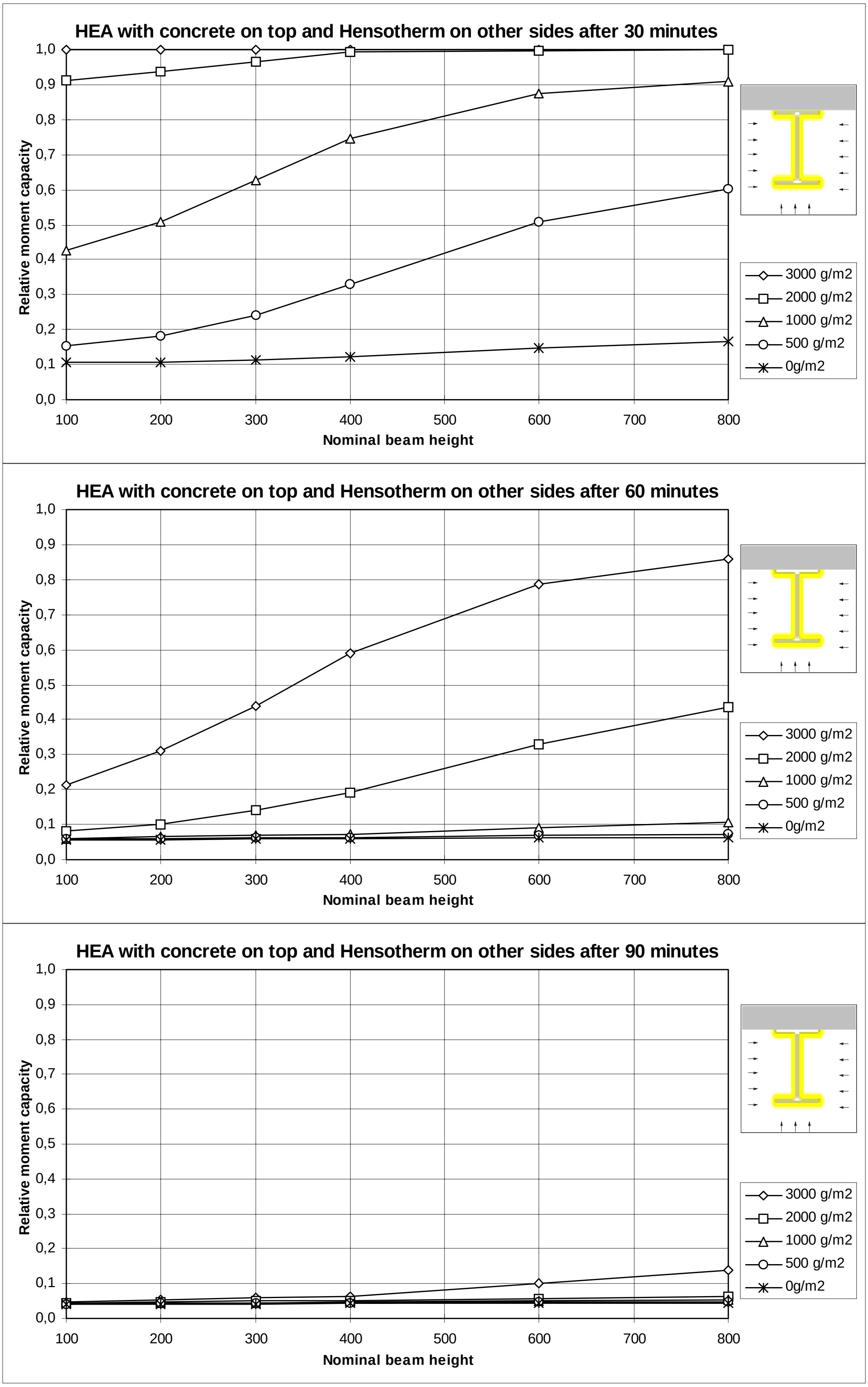


Figure 9.4 Relative moment capacity of HEA-beams with concrete on top.

9.2.4 HEB-beams

The results of the calculations for HEB after 30, 60 and 90 minutes can be seen on the next page. HEB-beams provide a better fire resistance than HEA-beams thanks to lower F/A-values.

When designing for 30 minutes of fire it is in most cases suitable to use 500 or 1000 g/m^2 of Hensotherm. Using more than 1000 g/m^2 of paint is only sometimes necessary for very small beams.

After 60 minutes only beams with 3000 g/m^2 and large beams with 2000 g/m^2 of paint have enough moment capacity left to be useful.

After 90 minutes it is not possible to have more than 25% of the moment capacity left.

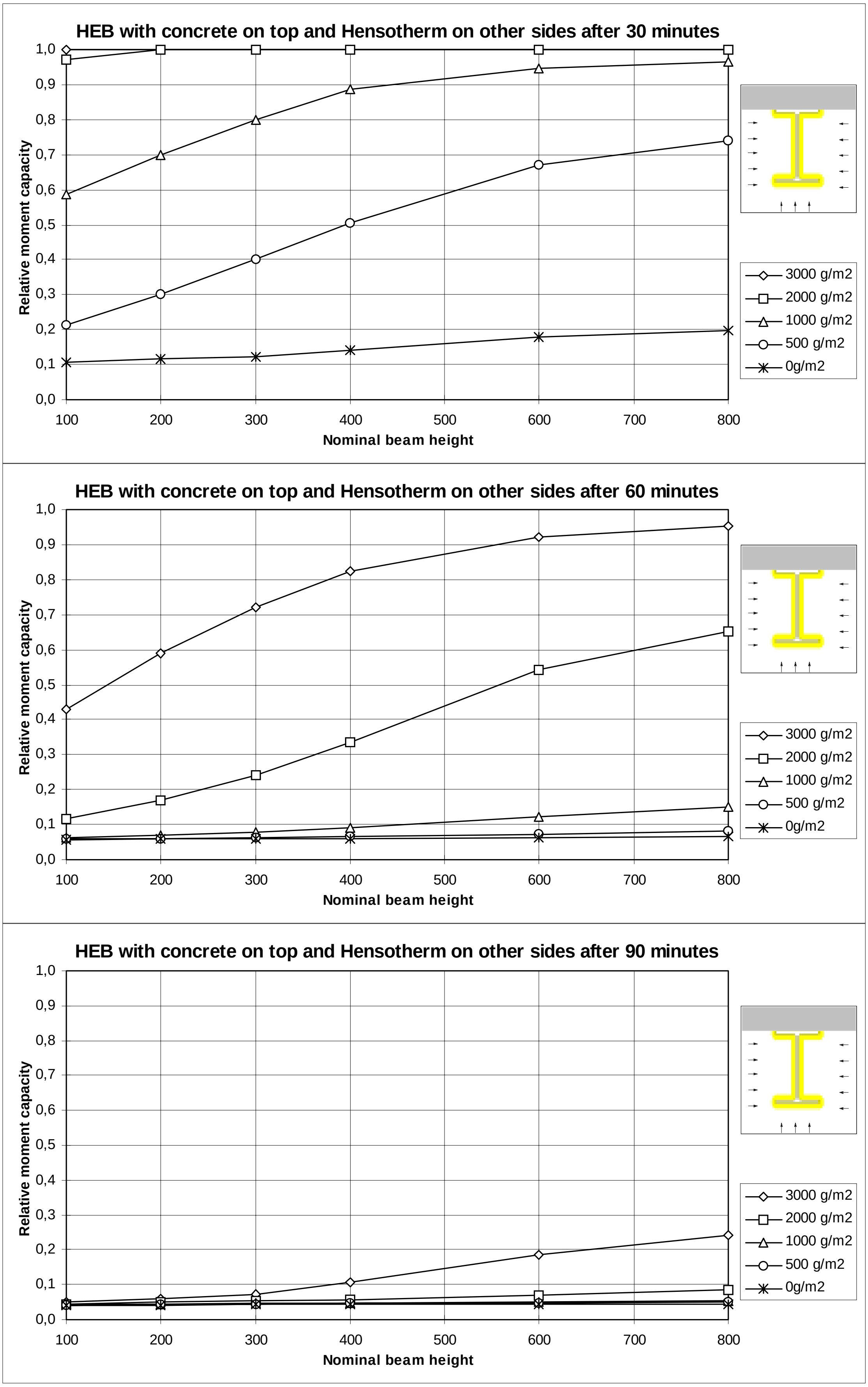


Figure 9.5 Relative moment capacity of HEB-beams with concrete on top.

9.2.5 HEM-beams

The results of the calculations for HEM after 30, 60 and 90 minutes can be seen on the next page. HEM-beams provide a better fire resistance than HEA and HEB thanks to lower F/A-values.

HEM-beams have a minimum F/A-ratio for HEM 300. This phenomenon reflects on the charts of Figure 9.6 which indicate a maximum relative bending moment capacity for this specific beam size.

When dimensioning for 30 minutes of fire it is in most cases suitable to use 500 g/m^2 of Hensotherm, but small beams might need slightly more.

After 60 minutes paint amounts between 1500 and 2500 g/m^2 can be estimated to be appropriate.

After 90 minutes it is only quite large beams with 3000 g/m^2 of paint that are useful.

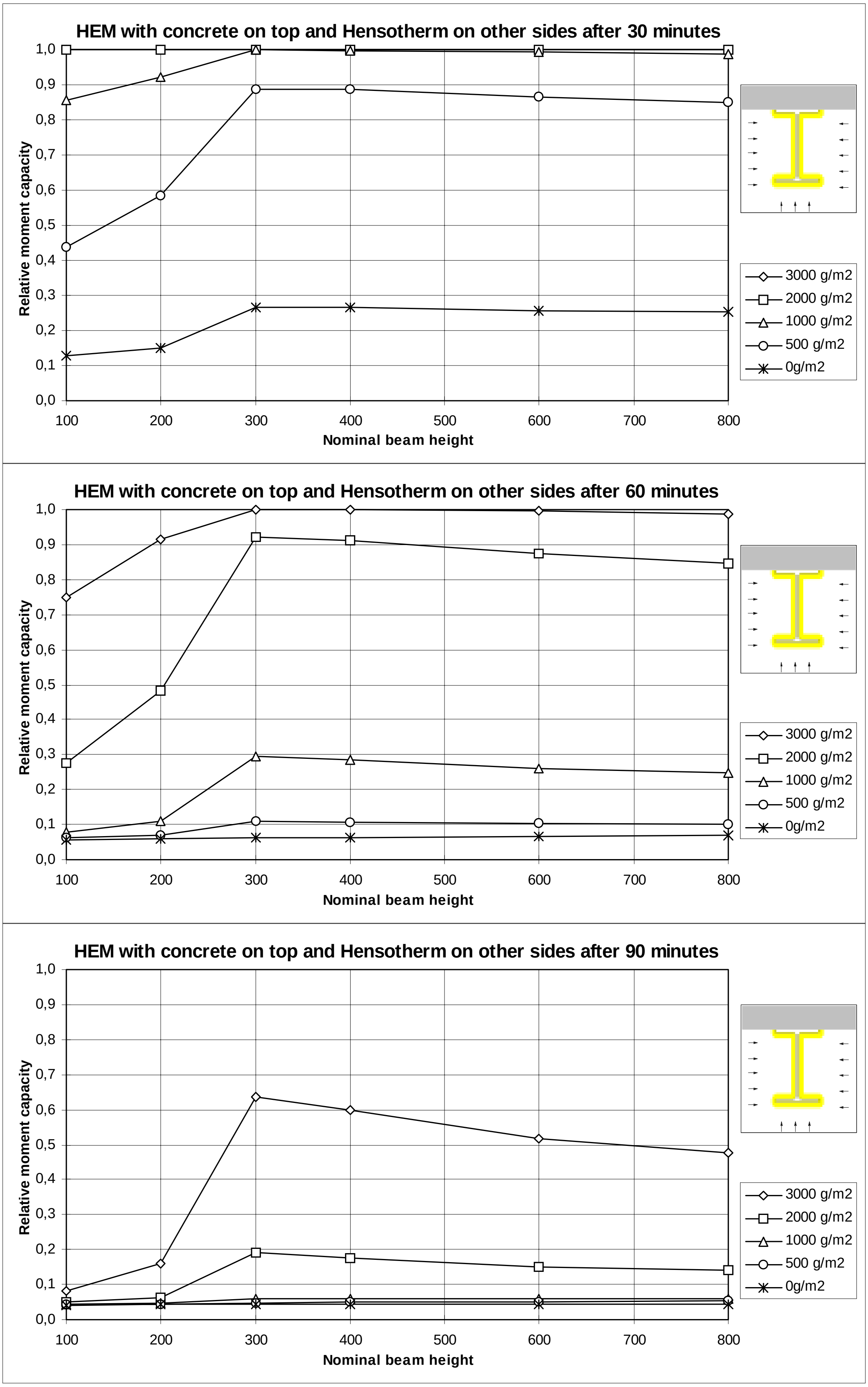


Figure 9.6 Relative moment capacity of HEM-beams with concrete on top.

10 Steel Beam with 4-sided Fire Exposure

10.1 Introduction

10.1.1 The Setup

The steel beam is placed so that it is completely surrounded by fire.

Since the cross-section is symmetrical the simulation was done with the left half replaced with an adiabatic line so that no heat passed to or from the left side. The dashdotted line in Figure 10.1 indicates the symmetry.

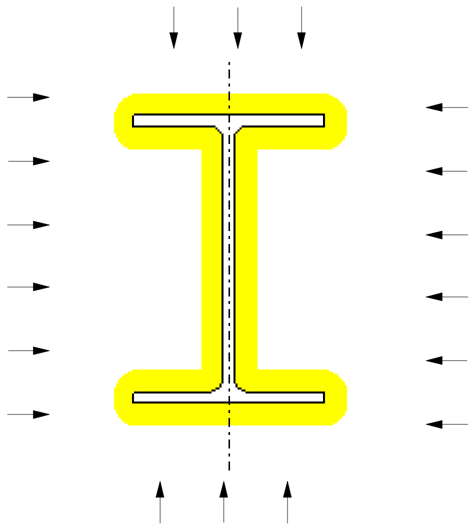


Figure 10.1 Steel beam with 4-sided fire exposure.

The cross-section has a horizontal symmetry axis as well, but if the top half had been replaced with an adiabatic line then the moment capacity calculation would not have been possible to perform.

10.1.2 Relevancy

The calculated results are only relevant for the beam type and paint amount specified. In order for the Hensotherm to work properly the beam needs 30 mm of air around it.

10.1.3 F/A Versus A/F

One variable that normally is employed when fire resistances of steel beams are calculated is the F/A-factor. F is the circumference of the part of the steel that is exposed to the fire and A is the area of the whole cross-section of the steel beam. A/F is the inverse of F/A and they can both be seen in Figure 10.2 below.

One surprising fact that can be seen in the diagram below is that HEM-beams have their biggest A/F value for beam heights around 300 mm. The reason for this is that the higher beams have approximately the same flange width, flange thickness and web thickness. It is only the height of the web that is increased to get the largest beams, and the A/F values can thereby have a maximum value for HEM-beams with heights around 300 mm.

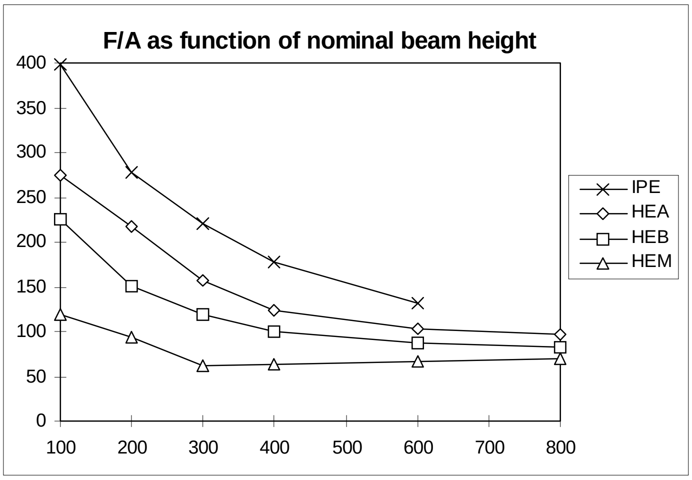


Figure 10.2a F/A as function of nominal beam height (m^{-1}).

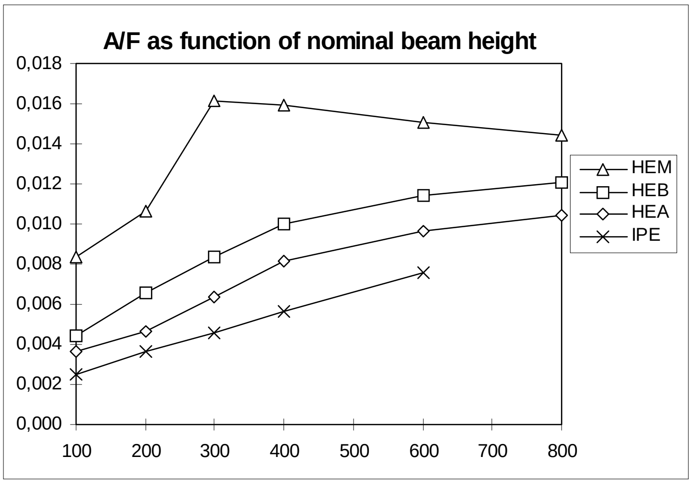


Figure 10.2b A/F as function of nominal beam height (m).

10.2 Results

10.2.1 General Comments

A steel beam with 4-sided fire exposure has, in most cases, slightly less fire resistance than a beam with concrete on top of it. It is thereby the most fire sensitive of the designs studied in this report, but it is still useful for some applications. In many of the calculations the relative moment capacity is approximately proportional to A/F.

In the days before computer simulations it was common to assume a uniform steel core temperature in the whole cross-section. That assumption is very close to the truth when a steel beam is surrounded by fire.

10.2.2 Structural Performance During Fire Exposure

The shape of the curves in Figure 10.3 below are similar to the curve of relative strength as a function of temperature that is found in Figure 4.3 in chapter 4.2.3. There are basically two differences between the curves in the two figures.

- The curves below are rounded when they start to go down, but the material data curve drop is very sudden. The reason for this is that the fire temperature is climbing in the early stages, and that causes the steel to pass 400°C quite slowly. The temperature of the ISO 834 standard fire is shown in Figure 3.2 in chapter 3.2.1.
- The relative moment capacity does not go down to zero, instead it levels out around 5%. The reason for this can also be found in the temperature curve in Figure 3.2 in chapter 3.2.1. The ISO 834 fire temperature is around 1000°C after 90 minutes, and the steel does therefore not reach the 1200°C where it has no strength at all within the simulation time.

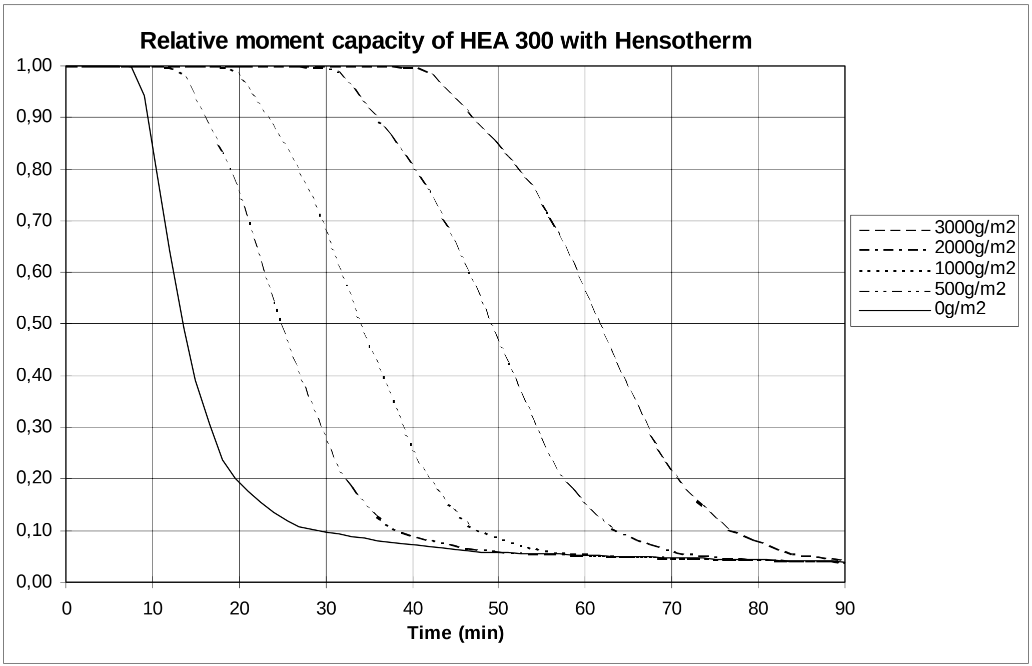


Figure 10.3 Relative moment capacity of HEA 300 with Hensotherm.

As can also be seen in Figure 10.3 on the previous page the use of Hensotherm does not prevent the beam from losing its moment capacity, but it slows down the process significantly. To include the figures for all the calculated beams would have made this report about twice as thick, so that was not realistic to do. Instead the figures have been analyzed and the following observations made:

- The relative moment capacity of all unprotected beams sooner or later level out around 5%, but it takes a little more time for beams with low F/A.
- Beams with low F/A respond more efficiently to fire protection with Hensotherm.

10.2.3 HEA-beams

The results of the calculations for HEA after 30, 60 and 90 minutes can be seen on the next page.

When designing for 30 minutes of fire it is in most cases suitable to use approximately 1000 g/m^2 of Hensotherm.

After 60 minutes only beams with 3000 g/m^2 and very large beams with 2000 g/m^2 of paint have enough moment capacity left to be useful.

After 90 minutes it is not possible to have more than 12% of the moment capacity left.

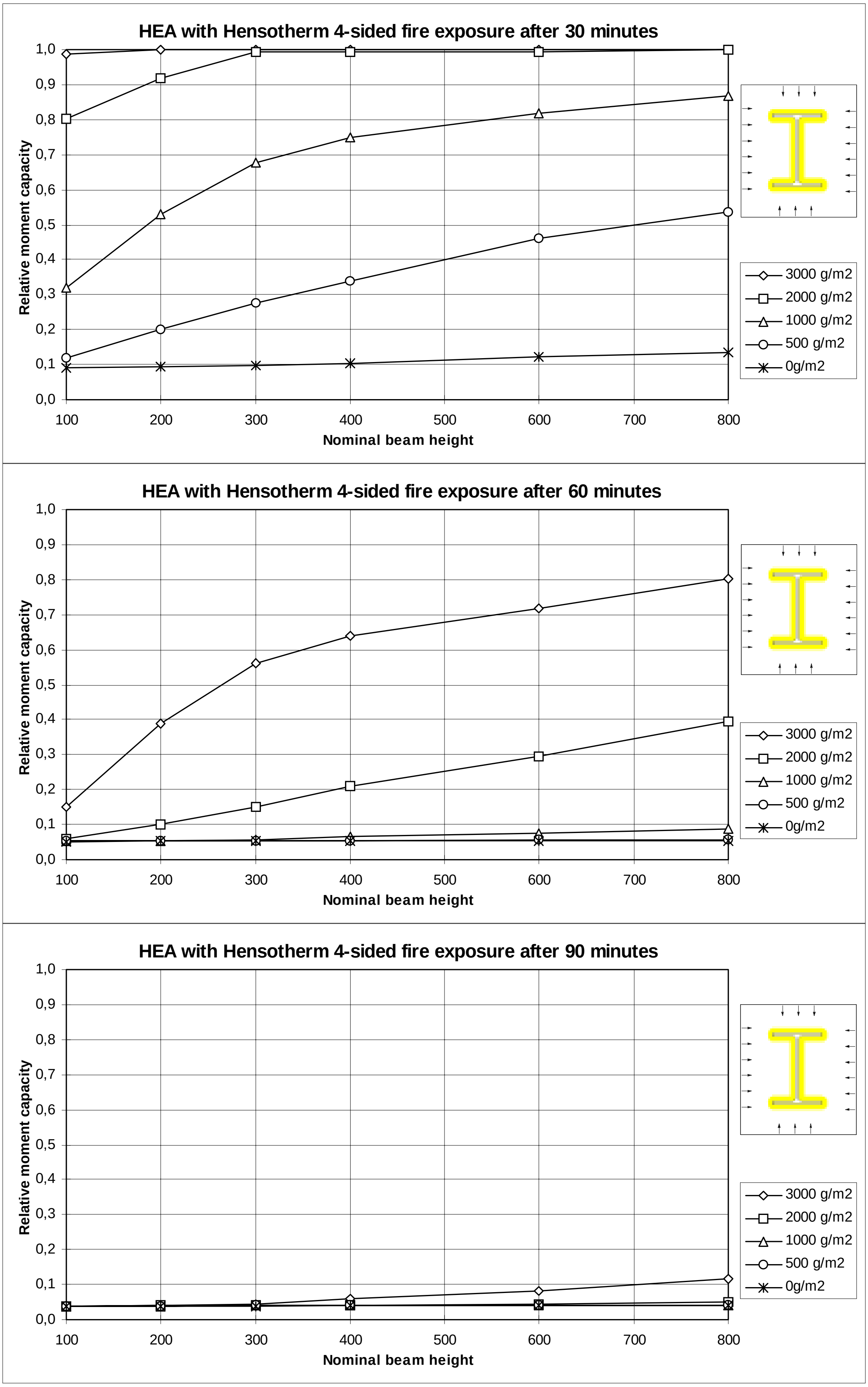


Figure 10.4 Relative moment capacity of HEA-beams with 4-sided fire exposure.

10.2.4 HEB-beams

The results of the calculations for HEB after 30, 60 and 90 minutes can be seen on the next page. HEB-beams provide a better fire resistance than HEA-beams thanks to lower F/A-values.

When designing for 30 minutes of fire it is in most cases suitable to use 500 or 1000 g/m^2 of Hensotherm. Using more than 1000 g/m^2 of paint is only sometimes necessary for very small beams.

After 60 minutes only beams with 3000 g/m^2 and large beams with 2000 g/m^2 of paint have enough moment capacity left to be useful.

After 90 minutes it is not possible to have more than 22% of the moment capacity left.

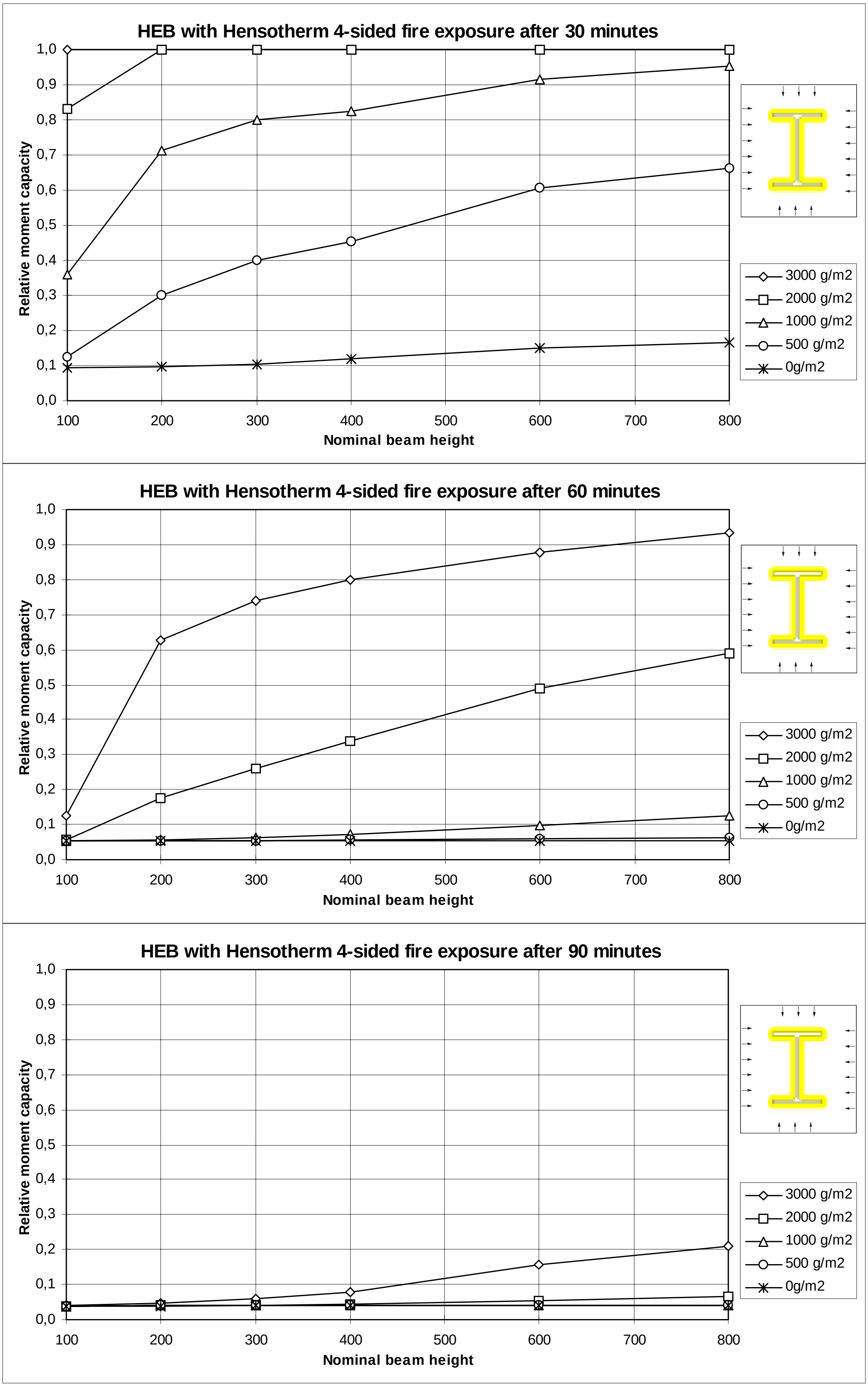


Figure 10.5 Relative moment capacity of HEB-beams with 4-sided fire exposure.

10.2.5 HEM-beams

The results of the calculations for HEM after 30, 60 and 90 minutes can be seen on the next page. HEM-beams provide a better fire resistance than HEA and HEB-beams thanks to lower F/A-values.

HEM-beams have a minimum F/A-ratio for HEM 300. This phenomenon reflects on the charts of Figure 10.6 which indicate a maximum relative bending moment capacity for this specific beam size.

When designing for 30 minutes of fire it is in most cases suitable to use 500 g/m^2 of Hensotherm, but small beams might need slightly more.

After 60 minutes paint amounts between 2000 and 3000 g/m^2 can be appropriate.

After 90 minutes it is only quite large beams with 3000 g/m^2 of paint that are useful.

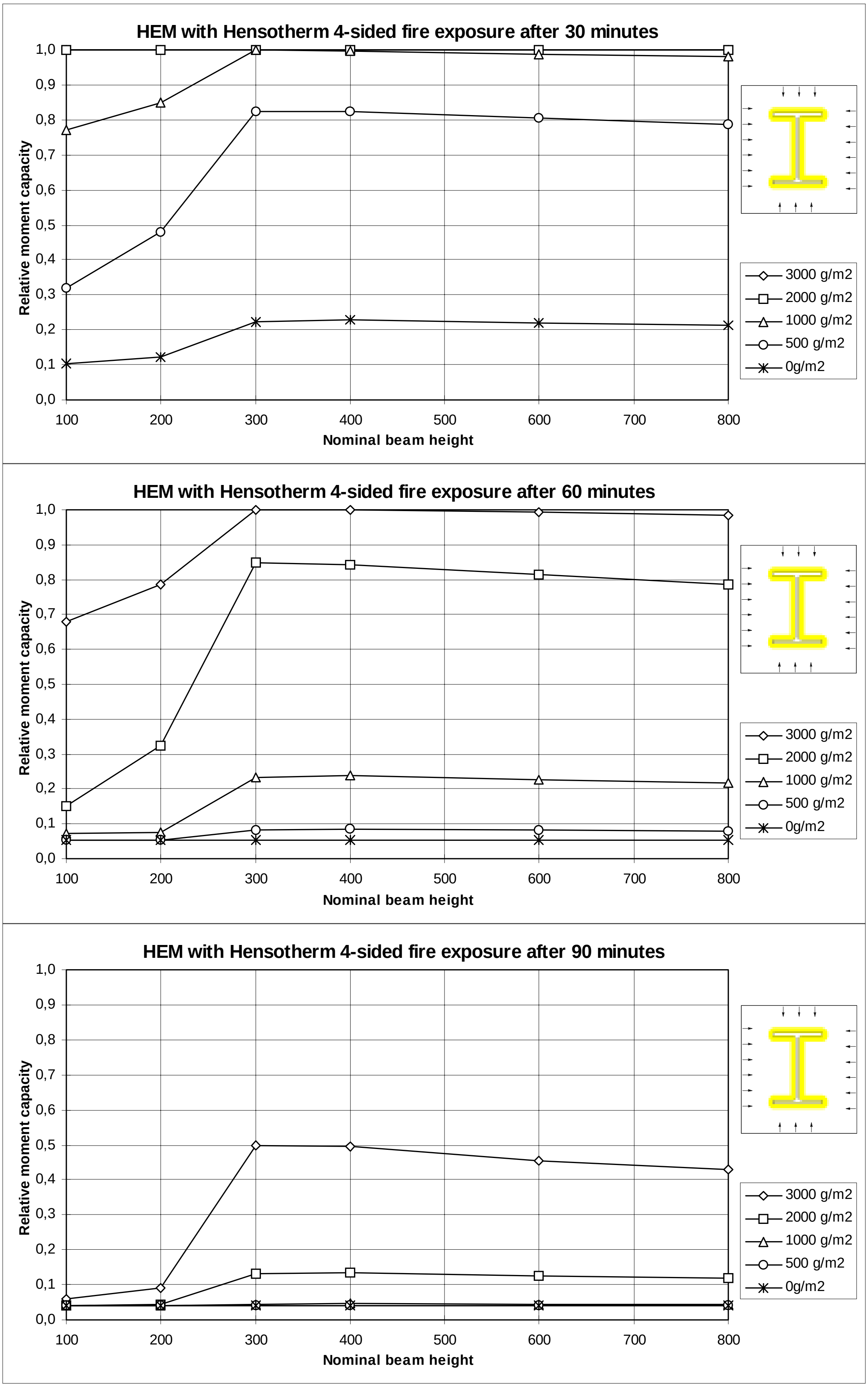


Figure 10.6 Relative moment capacity of HEM-beams with 4-sided fire exposure.

10.2.6 IPE-beams

The results of the calculations for IPE after 30, 60 and 90 minutes can be seen on the next page. IPE-beams do not have as good fire resistance as the other beam types, and the reason seems to be higher F/A-values. Note that the scale on the x-axis is different from the previous pages since IPE-beams are not available any larger than 600 mm high.

When designing for 30 minutes of fire it is in most cases suitable to use 1000 or 2000 g/m^2 of Hensotherm.

After 60 minutes only large beams with 3000 g/m^2 and very large beams with 2000 g/m^2 of paint have enough moment capacity left to be useful.

After 90 minutes it is not possible to have more than 9% of the moment capacity left.

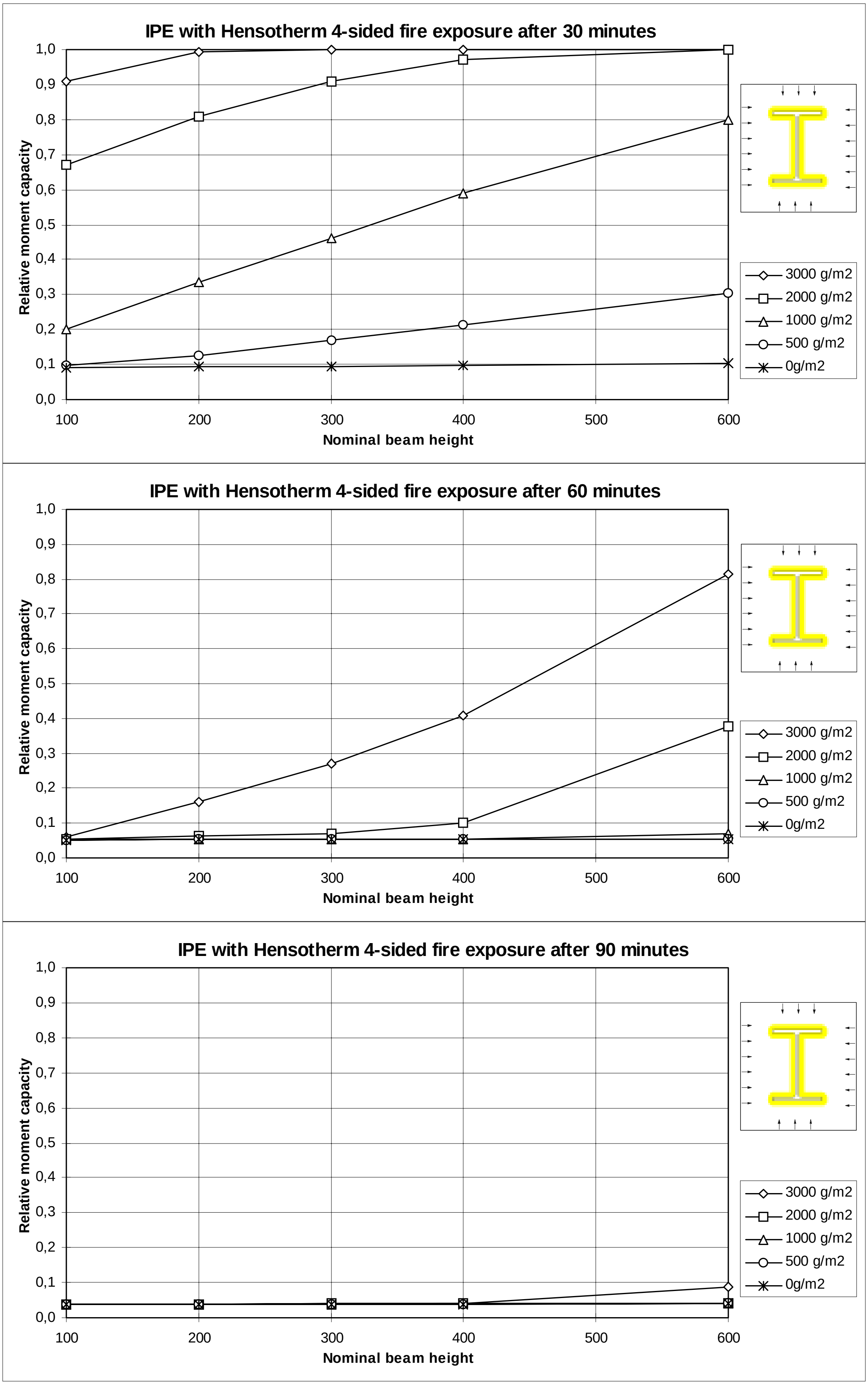


Figure 10.7 Relative moment capacity of IPE-beams with 4-sided fire exposure.

11 Design Table

11.1 Introduction

The design table can be seen on the next 13 pages. Interpolations can be made between different beam dimensions only with respect to the relative moment capacity, not the absolute moment capacity. For example: the relative moment capacity of HEA 340 can be found by interpolating between HEA 300 and HEA 400, but the moment capacity can not be found in the same way. Extrapolation of the results to include larger or smaller dimensions than studied in this report can not be done with sufficient accuracy. The variables used in the table are introduced here.

- M_o [kNm] is the moment capacity of the beam when it is not exposed to fire. It is calculated as f_{yd} multiplied by Z_z.

- f_{yd} [MPa] is the design yield strength of steel when designing for accidental loads with the risk of structural collapse taken into account. It is chosen to be 265 MPa since it is the value of steel type S275 with a maximum material thickness of 40 mm /8/. Most of the hot rolled beams available in Sweden are made from steel type S275.

- Z_z [mm^3] is the plastic bending resistance of the beam type as specified in construction tables such as *Byggformler och tabeller* /7/.

- A [mm^2] is the area of the cross-section of the beam according to /7/.

- F/A [1/m] is the fire exposed circumference divided by the area of the cross-section of the beam.

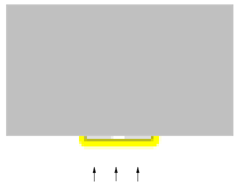
- Time [min] is the amount of time of that the beam has been exposed to ISO 834 standard fire.

- 0-3000 g/m2 is the amount of Hensotherm fire protection paint that is applied to the parts of the beam exposed to the fire.

- M [%] is the relative moment capacity calculated as described in chapter 5. It is valid for all kinds of construction steel.

- M [MPa] is the absolute moment capacity calculated by multiplying Mo [kNm] with M [%]. It is only valid for steel type S275.

11.2 Steel Beam Embedded in Concrete



11.2.1 HEA-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEA 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	22,00	30 min	12,74	57,9	21,89	99,5	22,00	100,0	22,00	100,0
A [mm2]	2124	60 min	5,48	24,9	9,41	42,8	17,86	81,2	22,00	100,0
F/A [1/m]	55	90 min	3,78	17,2	4,64	21,1	6,31	28,7	13,79	62,7

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEA 140		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	45,85	30 min	26,64	58,1	45,48	99,2	45,85	100,0	45,85	100,0
A [mm2]	3142	60 min	12,38	27,0	20,63	45,0	38,65	84,3	45,85	100,0
F/A [1/m]	50	90 min	9,40	20,5	11,00	24,0	14,58	31,8	33,01	72,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEA 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	113,7	30 min	68,9	60,6	112,8	99,2	113,7	100,0	113,7	100,0
A [mm2]	5383	60 min	32,7	28,8	54,8	48,2	98,2	86,4	113,7	100,0
F/A [1/m]	41	90 min	26,0	22,9	29,9	26,3	39,4	34,7	88,6	77,9

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEA 240		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	197,4	30 min	131,1	66,4	196,6	99,6	197,4	100,0	197,4	100,0
A [mm2]	7684	60 min	57,8	29,3	105,2	53,3	178,9	90,6	197,4	100,0
F/A [1/m]	34	90 min	46,4	23,5	53,7	27,2	74,8	37,9	168,4	85,3

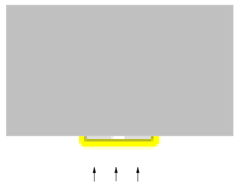
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEA 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	365,7	30 min	251,2	68,7	365,0	99,8	365,7	100,0	365,7	100,0
A [mm2]	11250	60 min	109,7	30,0	216,1	59,1	341,6	93,4	365,7	100,0
F/A [1/m]	29	90 min	88,9	24,3	104,2	28,5	155,1	42,4	331,7	90,7

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEA 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	678	30 min	550	81,0	678	100,0	678	100,0	678	100,0
A [mm2]	15900	60 min	250	36,8	509	75,0	660	97,3	678	100,0
F/A [1/m]	21	90 min	204	30,0	247	36,4	393	58,0	653	96,2

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEA 500		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1047	30 min	901	86,1	1047	100,0	1047	100,0	1047	100,0
A [mm2]	19750	60 min	431	41,2	839	80,2	1027	98,1	1047	100,0
F/A [1/m]	18	90 min	353	33,7	433	41,4	685	65,4	1024	97,8

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEA 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1418	30 min	1262	89,0	1418	100,0	1418	100,0	1418	100,0
A [mm2]	22650	60 min	666	47,0	1188	83,8	1398	98,6	1418	100,0
F/A [1/m]	16	90 min	554	39,1	675	47,6	1005	70,9	1392	98,2

11.2 Steel Beam Embedded in Concrete



11.2.2 HEB-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEB 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	27,56	30 min	17,23	62,5	27,56	100,0	27,56	100,0	27,56	100,0
A [mm2]	2604	60 min	7,06	25,6	13,53	49,1	24,20	87,8	27,56	100,0
F/A [1/m]	46	90 min	4,80	17,4	6,09	22,1	8,79	31,9	20,09	72,9

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEB 140		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	64,9	30 min	42,1	64,8	64,9	100,0	64,9	100,0	64,9	100,0
A [mm2]	4296	60 min	17,7	27,2	35,1	54,1	59,7	92,0	64,9	100,0
F/A [1/m]	38	90 min	13,0	20,1	16,0	24,7	23,7	36,5	55,3	85,1

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEB 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	170,4	30 min	121,5	71,3	170,4	100,0	170,4	100,0	170,4	100,0
A [mm2]	7808	60 min	50,4	29,6	105,5	61,9	161,4	94,7	170,4	100,0
F/A [1/m]	30	90 min	38,7	22,7	47,5	27,9	73,4	43,1	155,7	91,4

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEB 240		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	278,3	30 min	209,2	75,2	278,3	100,0	278,3	100,0	278,3	100,0
A [mm2]	10600	60 min	84,6	30,4	186,7	67,1	268,0	96,3	278,3	100,0
F/A [1/m]	26	90 min	65,1	23,4	81,2	29,2	133,3	47,9	263,5	94,7

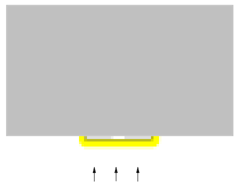
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEB 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	496	30 min	391	78,9	496	100,0	496	100,0	496	100,0
A [mm2]	14910	60 min	155	31,2	358	72,2	483	97,4	496	100,0
F/A [1/m]	23	90 min	120	24,3	153	30,9	266	53,7	479	96,6

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEB 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	856	30 min	749	87,5	856	100,0	856	100,0	856	100,0
A [mm2]	19780	60 min	329	38,4	710	82,9	847	98,9	856	100,0
F/A [1/m]	18	90 min	258	30,1	338	39,5	587	68,6	843	98,5

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEB 500		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1275	30 min	1162	91,2	1275	100,0	1275	100,0	1275	100,0
A [mm2]	23860	60 min	553	43,4	1115	87,5	1270	99,6	1275	100,0
F/A [1/m]	15	90 min	436	34,2	581	45,6	979	76,8	1271	99,7

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEB 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1704	30 min	1586	93,1	1704	100,0	1704	100,0	1704	100,0
A [mm2]	27000	60 min	837	49,1	1528	89,7	1701	99,8	1704	100,0
F/A [1/m]	13	90 min	673	39,5	884	51,9	1375	80,7	1701	99,8

11.2 Steel Beam Embedded in Concrete



11.2.3 HEM-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEM 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	62,5	30 min	51,5	82,3	62,5	100,0	62,5	100,0	62,5	100,0
A [mm2]	5324	60 min	18,9	30,3	49,4	79,0	62,1	99,3	62,5	100,0
F/A [1/m]	27	90 min	12,1	19,3	18,1	28,9	35,5	56,7	60,8	97,2

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEM 140		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	130,9	30 min	109,8	83,9	130,9	100,0	130,9	100,0	130,9	100,0
A [mm2]	8056	60 min	41,5	31,7	106,2	81,1	130,3	99,5	130,9	100,0
F/A [1/m]	24	90 min	28,5	21,8	41,6	31,8	81,3	62,1	129,7	99,1

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEM 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	302,9	30 min	265,6	87,7	302,9	100,0	302,9	100,0	302,9	100,0
A [mm2]	13130	60 min	102,7	33,9	257,8	85,1	302,3	99,8	302,9	100,0
F/A [1/m]	20	90 min	72,4	23,9	107,8	35,6	213,5	70,5	302,3	99,8

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEM 240		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	562	30 min	524	93,3	562	100,0	562	100,0	562	100,0
A [mm2]	19960	60 min	207	36,8	508	90,4	562	100,0	562	100,0
F/A [1/m]	16	90 min	139	24,8	233	41,4	452	80,5	562	100,0

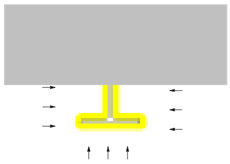
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEM 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1081	30 min	1047	96,8	1081	100,0	1081	100,0	1081	100,0
A [mm2]	30310	60 min	443	41,0	1022	94,5	1081	100,0	1081	100,0
F/A [1/m]	13	90 min	282	26,1	537	49,7	962	89,0	1081	100,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEM 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1529	30 min	1489	97,4	1529	100,0	1529	100,0	1529	100,0
A [mm2]	32580	60 min	702	45,9	1463	95,7	1529	100,0	1529	100,0
F/A [1/m]	12	90 min	472	30,9	849	55,5	1396	91,3	1529	100,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEM 500		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1879	30 min	1830	97,4	1879	100,0	1879	100,0	1879	100,0
A [mm2]	34430	60 min	945	50,3	1787	95,1	1879	100,0	1879	100,0
F/A [1/m]	11	90 min	675	35,9	1090	58,0	1683	89,6	1879	100,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2	
HEM 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	2324	30 min	2268	97,6	2324	100,0	2324	100,0	2324	100,0
A [mm2]	36370	60 min	1271	54,7	2224	95,7	2324	100,0	2324	100,0
F/A [1/m]	11	90 min	951	40,9	1443	62,1	2120	91,2	2324	100,0

11.3 Steel Beam Semi Embedded in Concrete



11.3.1 HEA-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	22,00	30 min	4,07	18,5	5,08	23,1	8,29	37,7	18,81	85,5	21,53	97,9
A [mm2]	2124	60 min	2,20	10,0	2,33	10,6	2,46	11,2	2,84	12,9	3,76	17,1
F/A [1/m]	137	90 min	1,47	6,7	1,52	6,9	1,58	7,2	1,69	7,7	1,78	8,1

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	113,69	30 min	20,24	17,8	24,67	21,7	41,38	36,4	95,84	84,3	111,07	97,7
A [mm2]	5383	60 min	12,73	11,2	13,30	11,7	13,87	12,2	15,35	13,5	20,69	18,2
F/A [1/m]	108	90 min	9,89	8,7	10,12	8,9	10,35	9,1	10,80	9,5	11,48	10,1

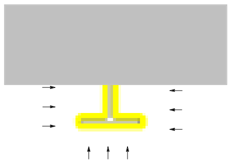
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	365,7	30 min	65,1	17,8	100,2	27,4	210,3	57,5	346,3	94,7	365,7	100,0
A [mm2]	11250	60 min	41,7	11,4	43,2	11,8	45,0	12,3	57,4	15,7	107,5	29,4
F/A [1/m]	78	90 min	34,0	9,3	34,4	9,4	35,1	9,6	36,6	10,0	38,4	10,5

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	678,4	30 min	137,0	20,2	290,4	42,8	551,5	81,3	678,4	100,0	678,4	100,0
A [mm2]	15900	60 min	88,2	13,0	91,6	13,5	97,7	14,4	172,3	25,4	411,8	60,7
F/A [1/m]	62	90 min	72,6	10,7	73,9	10,9	75,3	11,1	79,4	11,7	89,5	13,2

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 500		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1047	30 min	231	22,1	575	54,9	928	88,7	1047	100,0	1047	100,0
A [mm2]	19750	60 min	147	14,0	153	14,6	174	16,6	384	36,7	841	80,3
F/A [1/m]	55	90 min	122	11,7	126	12,0	128	12,2	136	13,0	176	16,8

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1418	30 min	345	24,3	866	61,1	1289	90,9	1418	100,0	1418	100,0
A [mm2]	22650	60 min	217	15,3	227	16,0	264	18,6	635	44,8	1211	85,4
F/A [1/m]	52	90 min	184	13,0	189	13,3	191	13,5	207	14,6	281	19,8

11.3 Steel Beam Semi Embedded in Concrete



11.3.2 HEB-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	27,56	30 min	5,37	19,5	7,77	28,2	15,05	54,6	25,80	93,6	27,56	100,0
A [mm2]	2604	60 min	2,95	10,7	3,17	11,5	3,39	12,3	4,30	15,6	6,81	24,7
F/A [1/m]	113	90 min	1,98	7,2	2,07	7,5	2,15	7,8	2,37	8,6	2,48	9,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	170,4	30 min	32,7	19,2	56,7	33,3	118,3	69,4	167,0	98,0	170,4	100,0
A [mm2]	7808	60 min	20,3	11,9	21,5	12,6	23,0	13,5	33,7	19,8	74,8	43,9
F/A [1/m]	76	90 min	15,8	9,3	16,4	9,6	16,9	9,9	18,1	10,6	19,9	11,7

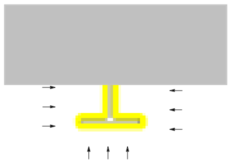
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	495,6	30 min	94,7	19,1	217,1	43,8	410,3	82,8	495,6	100,0	495,6	100,0
A [mm2]	14910	60 min	59,0	11,9	61,4	12,4	66,9	13,5	132,8	26,8	322,6	65,1
F/A [1/m]	60	90 min	47,6	9,6	49,1	9,9	50,1	10,1	53,5	10,8	63,4	12,8

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	856,0	30 min	190,9	22,3	520,4	60,8	784,1	91,6	856,0	100,0	856,0	100,0
A [mm2]	19780	60 min	114,7	13,4	120,7	14,1	145,5	17,0	387,7	45,3	747,2	87,3
F/A [1/m]	50	90 min	94,2	11,0	96,7	11,3	99,3	11,6	109,6	12,8	160,9	18,8

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 500		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1275	30 min	320	25,1	908	71,2	1215	95,3	1275	100,0	1275	100,0
A [mm2]	23860	60 min	180	14,1	194	15,2	251	19,7	780	61,2	1201	94,2
F/A [1/m]	46	90 min	150	11,8	156	12,2	161	12,6	185	14,5	329	25,8

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1704	30 min	469	27,5	1275	74,8	1644	96,5	1704	100,0	1704	100,0
A [mm2]	27000	60 min	262	15,4	281	16,5	370	21,7	1131	66,4	1629	95,6
F/A [1/m]	44	90 min	222	13,0	227	13,3	233	13,7	273	16,0	499	29,3

11.3 Steel Beam Semi Embedded in Concrete



11.3.3 HEM-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	62,54	30 min	16,70	26,7	44,34	70,9	59,98	95,9	62,54	100,0	62,54	100,0
A [mm2]	5324	60 min	8,01	12,8	9,51	15,2	12,82	20,5	36,65	58,6	57,29	91,6
F/A [1/m]	60	90 min	5,07	8,1	5,57	8,9	6,13	9,8	7,94	12,7	13,57	21,7

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	302,9	30 min	75,1	24,8	215,4	71,1	289,9	95,7	302,9	100,0	302,9	100,0
A [mm2]	13130	60 min	40,6	13,4	45,7	15,1	63,0	20,8	196,6	64,9	289,0	95,4
F/A [1/m]	47	90 min	32,1	10,6	33,9	11,2	35,7	11,8	45,1	14,9	86,0	28,4

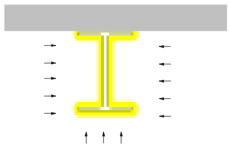
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1081	30 min	370	34,2	993	91,8	1081	100,0	1081	100,0	1081	100,0
A [mm2]	30310	60 min	149	13,8	202	18,7	457	42,3	1029	95,2	1081	100,0
F/A [1/m]	31	90 min	122	11,3	129	11,9	143	13,2	314	29,0	799	73,9

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1529	30 min	534	34,9	1399	91,5	1529	100,0	1529	100,0	1529	100,0
A [mm2]	32580	60 min	219	14,3	287	18,8	619	40,5	1440	94,2	1529	100,0
F/A [1/m]	32	90 min	179	11,7	188	12,3	205	13,4	419	27,4	1080	70,6

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 500		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1879	30 min	661	35,2	1704	90,7	1879	100,0	1879	100,0	1879	100,0
A [mm2]	34430	60 min	284	15,1	359	19,1	721	38,4	1744	92,8	1879	100,0
F/A [1/m]	32	90 min	235	12,5	244	13,0	263	14,0	489	26,0	1244	66,2

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	2324	30 min	832	35,8	2092	90,0	2322	99,9	2324	100,0	2324	100,0
A [mm2]	36370	60 min	374	16,1	467	20,1	890	38,3	2145	92,3	2324	100,0
F/A [1/m]	33	90 min	314	13,5	325	14,0	349	15,0	618	26,6	1539	66,2

11.4 Steel Beam with Concrete on Top



11.4.1 HEA-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	22,00	30 min	2,33	10,6	3,41	15,5	9,39	42,7	20,06	91,2	22,00	100,0
A [mm2]	2124	60 min	1,21	5,5	1,28	5,8	1,34	6,1	1,76	8,0	4,66	21,2
F/A [1/m]	227	90 min	0,90	4,1	0,92	4,2	0,95	4,3	0,97	4,4	1,03	4,7

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	113,69	30 min	12,28	10,8	20,80	18,3	57,75	50,8	106,52	93,7	113,69	100,0
A [mm2]	5383	60 min	6,48	5,7	6,82	6,0	7,39	6,5	11,37	10,0	35,36	31,1
F/A [1/m]	180	90 min	4,77	4,2	4,89	4,3	5,00	4,4	5,34	4,7	6,14	5,4

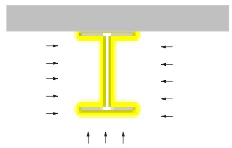
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	365,7	30 min	41,3	11,3	87,8	24,0	229,3	62,7	353,3	96,6	365,7	100,0
A [mm2]	11250	60 min	21,2	5,8	22,7	6,2	25,2	6,9	51,2	14,0	160,9	44,0
F/A [1/m]	130	90 min	15,4	4,2	16,1	4,4	16,5	4,5	17,9	4,9	21,6	5,9

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	678,4	30 min	83,4	12,3	223,9	33,0	506,1	74,6	675,0	99,5	678,4	100,0
A [mm2]	15900	60 min	40,7	6,0	42,7	6,3	48,8	7,2	128,9	19,0	400,3	59,0
F/A [1/m]	104	90 min	29,2	4,3	30,5	4,5	31,9	4,7	34,6	5,1	43,4	6,4

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1418	30 min	208	14,7	722	50,9	1242	87,6	1413	99,7	1418	100,0
A [mm2]	22650	60 min	88	6,2	96	6,8	130	9,2	465	32,8	1114	78,6
F/A [1/m]	91	90 min	61	4,3	65	4,6	69	4,9	81	5,7	145	10,2

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 800		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	2306	30 min	383	16,6	1388	60,2	2096	90,9	2303	99,9	2306	100,0
A [mm2]	28580	60 min	145	6,3	168	7,3	249	10,8	1008	43,7	1980	85,9
F/A [1/m]	86	90 min	101	4,4	111	4,8	120	5,2	148	6,4	316	13,7

11.4 Steel Beam with Concrete on Top



11.4.2 HEB-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	27,56	30 min	2,98	10,8	5,90	21,4	16,12	58,5	26,79	97,2	27,56	100,0
A [mm2]	2604	60 min	1,52	5,5	1,63	5,9	1,74	6,3	3,20	11,6	11,88	43,1
F/A [1/m]	187	90 min	1,16	4,2	1,16	4,2	1,19	4,3	1,24	4,5	1,38	5,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	170,4	30 min	19,8	11,6	51,1	30,0	119,3	70,0	170,4	100,0	170,4	100,0
A [mm2]	7808	60 min	9,9	5,8	10,4	6,1	11,6	6,8	29,0	17,0	100,5	59,0
F/A [1/m]	126	90 min	7,2	4,2	7,3	4,3	7,7	4,5	8,3	4,9	10,1	5,9

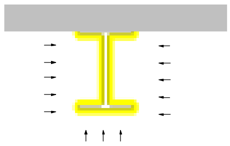
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	495,6	30 min	61,0	12,3	198,2	40,0	396,4	80,0	495,6	100,0	495,6	100,0
A [mm2]	14910	60 min	29,2	5,9	31,7	6,4	39,1	7,9	118,9	24,0	356,8	72,0
F/A [1/m]	99	90 min	21,3	4,3	21,8	4,4	22,8	4,6	25,8	5,2	36,2	7,3

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	856,0	30 min	121,5	14,2	433,1	50,6	760,1	88,8	856,0	100,0	856,0	100,0
A [mm2]	19780	60 min	52,2	6,1	57,3	6,7	78,7	9,2	287,6	33,6	705,3	82,4
F/A [1/m]	85	90 min	36,8	4,3	39,4	4,6	41,1	4,8	49,6	5,8	91,6	10,7

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1704	30 min	303	17,8	1142	67,0	1612	94,6	1704	100,0	1704	100,0
A [mm2]	27000	60 min	107	6,3	124	7,3	206	12,1	922	54,1	1573	92,3
F/A [1/m]	77	90 min	75	4,4	82	4,8	87	5,1	119	7,0	314	18,4

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 800		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	2703	30 min	535	19,8	2000	74,0	2606	96,4	2703	100,0	2703	100,0
A [mm2]	33420	60 min	176	6,5	219	8,1	408	15,1	1760	65,1	2579	95,4
F/A [1/m]	74	90 min	119	4,4	135	5,0	143	5,3	230	8,5	651	24,1

11.4 Steel Beam with Concrete on Top



11.4.3 HEM-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	62,54	30 min	8,01	12,8	27,39	43,8	53,53	85,6	62,54	100,0	62,54	100,0
A [mm2]	5324	60 min	3,56	5,7	3,94	6,3	4,94	7,9	17,26	27,6	46,84	74,9
F/A [1/m]	100	90 min	2,63	4,2	2,69	4,3	2,75	4,4	3,19	5,1	5,13	8,2

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	302,9	30 min	45,4	15,0	176,6	58,3	279,3	92,2	302,9	100,0	302,9	100,0
A [mm2]	13130	60 min	18,2	6,0	20,6	6,8	33,0	10,9	146,6	48,4	276,8	91,4
F/A [1/m]	78	90 min	13,0	4,3	13,6	4,5	14,2	4,7	19,4	6,4	48,2	15,9

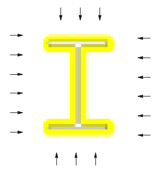
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1081	30 min	287	26,5	961	88,9	1081	100,0	1081	100,0	1081	100,0
A [mm2]	30310	60 min	68	6,3	118	10,9	320	29,6	996	92,1	1081	100,0
F/A [1/m]	52	90 min	49	4,5	52	4,8	65	6,0	205	19,0	688	63,6

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1529	30 min	407	26,6	1355	88,6	1526	99,8	1529	100,0	1529	100,0
A [mm2]	32580	60 min	98	6,4	164	10,7	437	28,6	1393	91,1	1529	100,0
F/A [1/m]	54	90 min	69	4,5	75	4,9	90	5,9	269	17,6	914	59,8

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	2324	30 min	597	25,7	2015	86,7	2308	99,3	2324	100,0	2324	100,0
A [mm2]	36370	60 min	153	6,6	237	10,2	607	26,1	2031	87,4	2317	99,7
F/A [1/m]	58	90 min	105	4,5	116	5,0	135	5,8	351	15,1	1204	51,8

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 800		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	3313	30 min	835	25,2	2812	84,9	3266	98,6	3313	100,0	3313	100,0
A [mm2]	40430	60 min	225	6,8	331	10,0	822	24,8	2799	84,5	3276	98,9
F/A [1/m]	62	90 min	149	4,5	172	5,2	192	5,8	470	14,2	1583	47,8

11.5 Steel Beam with 4-sided Fire Exposure



11.5.1 HEA-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	22,0	30 min	2,0	9,2	2,6	11,8	7,0	31,9	17,6	80,1	21,7	98,8
A [mm2]	2124	60 min	1,1	5,1	1,1	5,2	1,1	5,2	1,3	6,1	3,3	15,0
F/A [1/m]	274	90 min	0,9	3,9	0,9	3,9	0,9	3,9	0,9	3,9	0,9	3,9

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	113,7	30 min	10,7	9,4	22,7	20,0	60,3	53,0	104,6	92,0	113,7	100,0
A [mm2]	5383	60 min	5,9	5,2	5,9	5,2	6,0	5,3	11,4	10,0	44,3	39,0
F/A [1/m]	217	90 min	4,4	3,9	4,4	3,9	4,4	3,9	4,5	4,0	4,5	4,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	365,7	30 min	35,5	9,7	100,6	27,5	247,6	67,7	363,9	99,5	365,7	100,0
A [mm2]	11250	60 min	19,0	5,2	19,0	5,2	20,1	5,5	55,2	15,1	205,5	56,2
F/A [1/m]	157	90 min	14,3	3,9	14,6	4,0	14,6	4,0	14,6	4,0	16,1	4,4

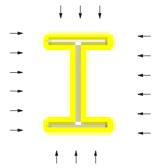
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	678,4	30 min	70,6	10,4	230,7	34,0	508,8	75,0	675,0	99,5	678,4	100,0
A [mm2]	15900	60 min	35,3	5,2	36,6	5,4	44,1	6,5	142,5	21,0	434,2	64,0
F/A [1/m]	123	90 min	27,1	4,0	27,1	4,0	27,1	4,0	28,5	4,2	40,7	6,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1418	30 min	173	12,2	652	46,0	1161	81,9	1411	99,5	1418	100,0
A [mm2]	22650	60 min	75	5,3	78	5,5	105	7,4	417	29,4	1018	71,8
F/A [1/m]	104	90 min	57	4,0	57	4,0	57	4,0	62	4,4	116	8,2

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEA 800		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	2306	30 min	314	13,6	1233	53,5	2003	86,9	2303	99,9	2306	100,0
A [mm2]	28580	60 min	122	5,3	131	5,7	201	8,7	908	39,4	1849	80,2
F/A [1/m]	96	90 min	92	4,0	92	4,0	95	4,1	113	4,9	265	11,5

11.5 Steel Beam with 4-sided Fire Exposure

11.5.2 HEB-beams



			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	27,6	30 min	2,6	9,4	3,4	12,5	9,9	36,0	22,9	83,0	27,6	100,0
A [mm2]	2604	60 min	1,4	5,2	1,4	5,2	1,4	5,2	1,6	5,7	3,4	12,5
F/A [1/m]	226	90 min	1,1	3,9	1,1	3,9	1,1	3,9	1,1	3,9	1,1	4,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	170,4	30 min	16,7	9,8	51,3	30,1	121,3	71,2	170,4	100,0	170,4	100,0
A [mm2]	7808	60 min	8,9	5,2	9,0	5,3	9,4	5,5	30,2	17,7	106,7	62,6
F/A [1/m]	151	90 min	6,6	3,9	6,8	4,0	6,8	4,0	6,8	4,0	7,8	4,6

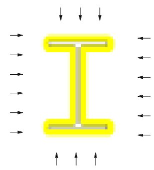
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	495,6	30 min	51,5	10,4	198,2	40,0	396,4	80,0	495,6	100,0	495,6	100,0
A [mm2]	14910	60 min	26,3	5,3	26,8	5,4	31,7	6,4	128,8	26,0	366,7	74,0
F/A [1/m]	119	90 min	19,8	4,0	19,8	4,0	19,8	4,0	20,8	4,2	29,7	6,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	856,0	30 min	101,9	11,9	387,7	45,3	707,0	82,6	856,0	100,0	856,0	100,0
A [mm2]	19780	60 min	45,4	5,3	47,1	5,5	61,6	7,2	291,0	34,0	684,8	80,0
F/A [1/m]	99	90 min	34,2	4,0	34,2	4,0	34,2	4,0	37,7	4,4	67,6	7,9

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1704	30 min	256	15,0	1033	60,6	1563	91,7	1704	100,0	1704	100,0
A [mm2]	27000	60 min	92	5,4	99	5,8	167	9,8	835	49,0	1496	87,8
F/A [1/m]	88	90 min	68	4,0	68	4,0	70	4,1	92	5,4	266	15,6

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEB 800		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	2703	30 min	446	16,5	1792	66,3	2576	95,3	2703	100,0	2703	100,0
A [mm2]	33420	60 min	146	5,4	170	6,3	341	12,6	1589	58,8	2525	93,4
F/A [1/m]	83	90 min	108	4,0	111	4,1	114	4,2	181	6,7	570	21,1

11.5 Steel Beam with 4-sided Fire Exposure



11.5.3 HEM-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	27,6	30 min	2,8	10,3	8,8	32,0	21,2	77,0	27,6	100,0	27,6	100,0
A [mm2]	5324	60 min	1,4	5,2	1,5	5,4	2,0	7,1	4,1	15,0	18,7	68,0
F/A [1/m]	119	90 min	1,1	4,0	1,1	4,0	1,1	4,0	1,2	4,2	1,7	6,0

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	170,4	30 min	20,6	12,1	81,8	48,0	144,7	84,9	170,4	100,0	170,4	100,0
A [mm2]	13130	60 min	9,0	5,3	9,4	5,5	12,8	7,5	55,2	32,4	133,8	78,5
F/A [1/m]	94	90 min	6,8	4,0	6,8	4,0	6,8	4,0	7,5	4,4	15,3	9,0

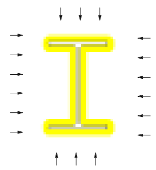
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	495,6	30 min	110,0	22,2	408,8	82,5	495,1	99,9	495,6	100,0	495,6	100,0
A [mm2]	30310	60 min	27,3	5,5	40,6	8,2	115,0	23,2	420,2	84,8	495,6	100,0
F/A [1/m]	62	90 min	20,3	4,1	20,3	4,1	22,3	4,5	64,9	13,1	246,8	49,8

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	856,0	30 min	195,2	22,8	707,0	82,6	852,5	99,6	856,0	100,0	856,0	100,0
A [mm2]	32580	60 min	47,1	5,5	71,9	8,4	204,6	23,9	722,4	84,4	855,1	99,9
F/A [1/m]	63	90 min	35,1	4,1	35,9	4,2	39,4	4,6	114,7	13,4	423,7	49,5

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	1704	30 min	377	22,1	1375	80,7	1685	98,9	1704	100,0	1704	100,0
A [mm2]	36370	60 min	94	5,5	140	8,2	385	22,6	1385	81,3	1692	99,3
F/A [1/m]	67	90 min	70	4,1	70	4,1	77	4,5	211	12,4	775	45,5

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
HEM 800		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	2703	30 min	578	21,4	2127	78,7	2654	98,2	2703	100,0	2703	100,0
A [mm2]	40430	60 min	149	5,5	216	8,0	584	21,6	2125	78,6	2660	98,4
F/A [1/m]	69	90 min	111	4,1	111	4,1	122	4,5	319	11,8	1157	42,8

11.5 Steel Beam with 4-sided Fire Exposure



11.5.4 IPE-beams

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
IPE 100		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	10,44	30 min	0,95	9,1	1,02	9,8	2,09	20,0	7,00	67,0	9,50	91,0
A [mm2]	1032	60 min	0,53	5,1	0,53	5,1	0,54	5,2	0,54	5,2	0,63	6,0
F/A [1/m]	399	90 min	0,41	3,9	0,41	3,9	0,41	3,9	0,41	3,9	0,41	3,9

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
IPE 200		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	58,6	30 min	5,4	9,3	7,3	12,4	19,6	33,4	47,4	81,0	58,3	99,5
A [mm2]	2848	60 min	3,0	5,2	3,0	5,2	3,0	5,2	3,7	6,4	9,4	16,0
F/A [1/m]	277	90 min	2,3	3,9	2,3	3,9	2,3	3,9	2,3	3,9	2,3	3,9

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
IPE 300		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	166,4	30 min	15,6	9,4	28,1	16,9	76,9	46,2	151,4	91,0	166,4	100,0
A [mm2]	5381	60 min	8,7	5,2	8,7	5,2	8,7	5,2	11,6	7,0	44,9	27,0
F/A [1/m]	220	90 min	6,5	3,9	6,5	3,9	6,5	3,9	6,7	4,0	6,7	4,0

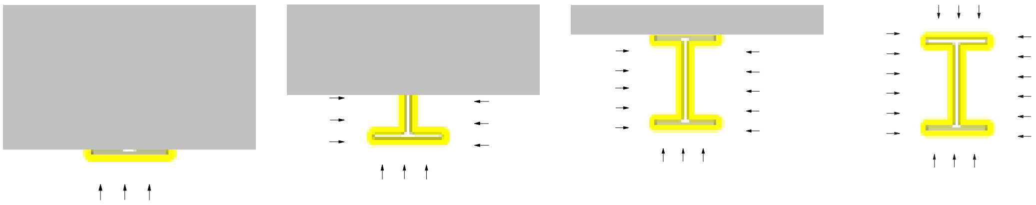
			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
IPE 400		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	347,2	30 min	33,3	9,6	74,3	21,4	204,8	59,0	337,4	97,2	347,2	100,0
A [mm2]	8446	60 min	18,1	5,2	18,1	5,2	18,4	5,3	34,7	10,0	141,6	40,8
F/A [1/m]	178	90 min	13,5	3,9	13,5	3,9	13,9	4,0	13,9	4,0	14,2	4,1

			0 g/m2		500 g/m2		1000 g/m2		2000 g/m2		3000 g/m2	
IPE 600		Time	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]	M [kNm]	M [%]
Mo [kNm]	930	30 min	95	10,2	283	30,4	744	80,0	930	100,0	930	100,0
A [mm2]	15600	60 min	48	5,2	49	5,3	63	6,8	351	37,7	757	81,4
F/A [1/m]	132	90 min	37	4,0	37	4,0	37	4,0	39	4,2	81	8,7

12 Conclusions

The plastic bending moment capacity for various durations of standard fire exposure of passively protected steel HEA, HEB and HEM-beams, partially embedded in concrete, was presented in chapter 11 for different application thicknesses of the intumescent product Hensotherm 4 KS.

In Figure 12.1 the studied degrees of concrete embeddment are displayed in terms of cases a through d. For obvious reasons the fire resistance is improved with extended concrete embeddment, thus indicating a significant fire resistance of case a whilst considerably lower ditto for case d.



Case a) Case b) Case c) Case d)

Figure 12.1 The cases studied in this report.

There are two phenomena that counteract each other. Hensotherm works more efficiently with slender beams, but slender beams have high F/A-factors and thereby low fire resistance. This means that a beam needs to have a low F/A-value to have a shape that results in good fire resistance but a high F/A-value in order for the fire protective paint to be as efficient as possible.

Under normal conditions HEA-beams are more efficient than HEB-beams which in turn are more efficient than HEM-beams. The reason is that slender beams have more moment capacity per cross-section area. When exposed to fire slenderness becomes a disadvantage since slender beams have much surface area per steel volume and thereby are heated more quickly. The result is that it is sometimes efficient to use a less slender beam type when designing a fire exposed structure.

The relative moment capacity is often approximately proportional to A/F.

The old assumption that the steel temperature is the same in the whole cross-section is very close to the truth in case d).

Case a) is a very efficient way of achieving very high fire resistance and often the only possible case if a design without intumescent paint is desired.

Regarding HSQ-beams this report confirms the usefulness of the previous design recommendations issued by Hensotherm /14/. In order for a HSQ-beam to have a high relative moment capacity when exposed to fire the beam should:

- Be as high as possible.
- Have a thick lower flange.
- Be as narrow as possible.

High beams are, except for HEM-beams, less slender than low beams of the same type and thereby have better fire resistance.

13 References

13.1 Books

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/2/ **J.P. Holman**: Heat transfer, Seventh edition, Singapore 1990.

/3/ **European Committee for Standardization**: Eurocode 3 Design of steel structures, Part 1.2 Structural Fire Design, Draft prENV 1993-1-2, August 1993.

/4/ **Yngve Anderberg**: FIRE DESIGN Computer program, integrated with SUPER-TEMPCALC for analyzing the load bearing capacity of thermally exposed concrete and steel beams and columns

/5/ **NFPA**: SFPE Handbook of Fire Protection Engineering, USA 1990.

/6/ **European Committee for Standardization**: Eurocode 1 Basis of design and actions on steel structures, Part 2.2 Actions on structures exposed to fire, ENV 1991-2-2:1994.

/7/ **Paul Johannesson, Bengt Vretblad**: Byggformler och tabeller, May 1969 / March 1995.

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/9/ **Fire Safety Design**: User's Manual for TCD 3.0 with Tempcalc®, December 1990.

/10/ **Sven-Erik Magnusson, Ove Pettersson, Jörgen Thor**: Brandteknisk dimensionering av stålkonstruktioner, Stålbyggnadsinstitutet 1974.

13.2 Brochures and Catalogues

/11/ **Tibnor**: Sortimentskatalog 90-91.

/12/ **Tibnor**: Stål lagersortiment. Prislista Nr 92 960102.

/13/ **Bröderna Edstrand**: Stål industrirör Feb.1995.

/14/ **Hensotherm®**: Projekteringsanvisningar för brandisolering av bärande stålkonstruktioner med Hensotherm.

13.3 Computer Programs

/15/ **Fire Safety Design**: TCD 3.0

/16/ **Microsoft**: Excel 5.0a

/17/ **Microsoft**: Word 6.0a

/18/ **Microsoft**: Power Point 4.0