STEEL TEMPERATURE CALCULATIONS IN PERFORMANCE BASED DESIGN

Advanced Techniques for Thermal Response Calculations with FE-Analysis

Joakim Sandström [a], Ulf Wickström [b]

[a] Luleå University of Technology/BrandskyddslagetAB, Karlstad, Sweden
[b] Luleå University of Technology/SP Technical Research Institute of Sweden, Borås, Sweden

Abstract

By using advanced FEA techniques, the predicted temperature in steel elements can be reduced significantly (see paper by Ulf Wickström). By in addition assuming a performance based fire exposure obtained with numerical fire models such as Fire Dynamics Simulator, FDS, the steel temperatures can be even further reduced.
Most calculation methods assume the fire exposure of the steel sections to be uniform. By using section factors A/V, i.e. the circumference over the area, and the most onerous of the fire exposing temperatures from computer fluid dynamics, CFD, calculations, the temperatures is over-estimated which leads to very conservative and costly solutions.
By considering the cooling effect of concrete structures and shadow effects, the temperatures can be reduced in the steel. By combining differentiated fire exposing temperatures from CFD calculations with consideration to shadow effects and the cooling of concrete, the temperature in the steel beam can be reduced even further.

Keywords: adiabatic surface temperature, CFD, FEA, shadow effect, thermal response

INTRODUCTION

Eurocode 3: Design of steel structures – Part 1-2: General rules – Structural fire design[1] contains various means of calculating temperature in fire exposed steel structures. Most calculation methods assume the fire exposure of the steel sections to be uniform while boundary temperatures from real fires in general are non-uniform[2]. By considering a non-uniform temperature exposure and an advanced FE-analysis set up, there can be a big difference in the calculated temperatures for the same cross section.
When calculating the steel temperature in a beam supporting a concrete slab, these methods for calculation can be illustrated.

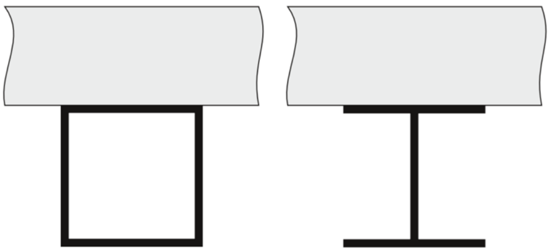

Fig. 1 Concrete slab supported by two different kind of beams

[1](EN 1993-1-2, 2005)
[2](Wickström, Jansson, & Touvinen, 2009)

The simplest method is to use section factors A_m/V, i.e. exposed surface area over the volume of an element, and the most onerous of the fire exposing temperatures from a real fire scenario. The steel temperature tends to gradually adopt the fire exposing temperatures. As the fire exposing temperature is the most onerous it is an over-estimation for the other sides of the steel leading to very conservative and costly solutions. It can be considered an over-estimation as the assumed fire exposure is more severe than the actual fire exposure for most sides of the element. Further, no heat is allowed to leave the cross section to the concrete giving two conservative assumptions.

There are several ways of increasing the accuracy of calculations and thereby often reducing the steel temperatures without reducing the overall safety level.

Firstly, by considering the concrete slab, heat can leave the cross section trough the upper flange. This reduces the temperature of the upper flange and to some extent, the web. The cooling effect has little or no impact on the lower flange.

Secondly, by considering the shadowing effects of the flanges in the H-sections the web and inside of the flanges is allowed to "see" other surfaces than only the fire. For simple spread sheet calculations this is done by changing the section factor, A_m/V, as described in Fig. 2. The effective heated surface, A_m, is reduced from the actual perimeter to the perimeter of a virtual box, $[A_m]_b$, resulting in a lower section factor denoted $[A_m/V]_b$.

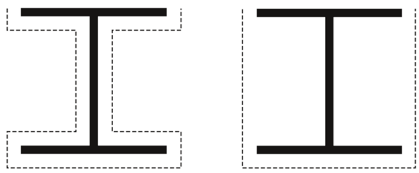

Fig. 2 The dotted line represents the heated area of the cross section. The left figure is heated with no consideration to shadow effects, whereas the right one does consider shadow effects

In a simplified numerical analysis with no regards to the shadow effects, the development of the steel temperature can be expressed according to EN 1993-1-2[3].

In an FE-analysis, considering the shadow effect can be done by adding a virtual representation of the box perimeter on a H-section creating a void on each side of the web. Together with the web and flanges, the virtual box perimeter creates a void where the inside of the virtual box perimeter can be modeled with a prescribed temperature. This way, the virtual box perimeter can imitate a black body recreating the fire exposure conditions that exists on the perimeter. A more practical description on how this is done is made in the section 2.

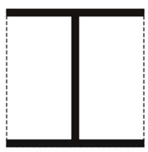

Fig. 3 The virtual box perimeter creates a void with the web and flanges; the dotted line represents the virtual box perimeter

Finally, the non-uniform fire exposure temperatures are considered along with the shadow effects in a FE-analysis.

1 CALCULATION OF BOUNDARY DATA

For calculations of steel temperature with non-uniform fire exposure, the fire exposure for each side of the beam and exposed sides of concrete has to be calculated. The boundary data

[3](EN 1993-1-2, 2005)

for the thermal analysis can be represented by adiabatic surface temperatures, AST, from FDS[4]which is calculated at the surfaces of the hollow beam and the ceiling as shown in Fig. 4.

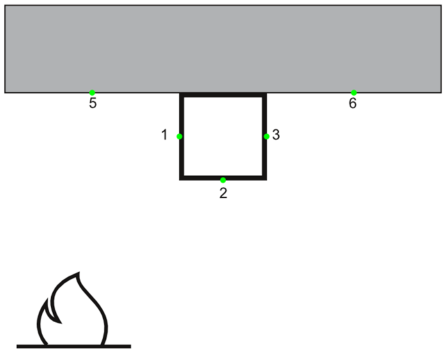

Fig. 4 Set of reference points for transferring data from FDS to FEA; reference point 1 is facing the burner

The modeling domain imitates a room similar to that stipulated in ISO 9705[5], a room with the dimensions 2.4 m x 3.6 m x 2.4 m and an opening of 0.8 m x 2 m in one end (see Fig. 5). A propane burner is located at one of the far end corners with an elevation of 0.65 m and a constant effect of 450 kW. ASTis obtained at the surface of a modeled hollow steel section with the dimensions 200 mm x 200 mm with flanges and web with a thicknessof 10 mm. The beam supports the concrete ceiling.

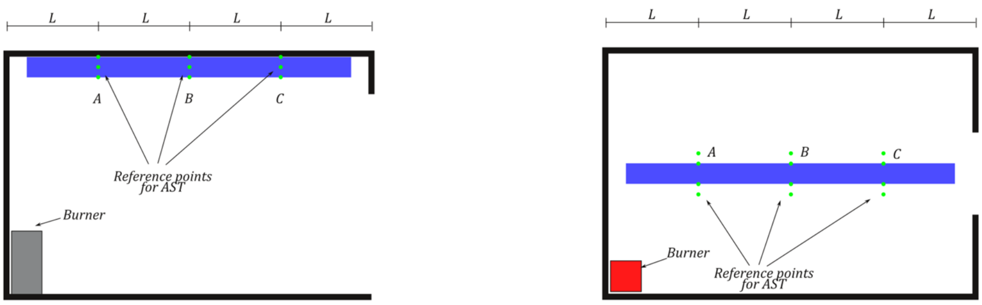

Fig. 5 Setup of calculation for obtaining coupling data for FEA

The data from this calculation represents the fire exposure to the beam. This fire exposure can be assumed equal for structural elements of approximately the same size and shape. As this is the case for the hollow and H-section, calculated T_{AST} can be used for both of the sections[6]. The H-section has the dimensions 200 mm x 200 x mm with flange and a web with a thickness of 10 mm.

The material properties and emissivity are taken from the Eurocodes[7,8] along with the convective properties for natural fires from EN 1991-1-2 (3.3.2)[9]assumed to 10 W/m²K for all surfaces.

2 EXAMPLES OF COUPLING

When coupling CFD calculations to thermal response calculations there are a few different methods available. The FE-analysis of method 2-5 is performed with TASEF[10].

[4](McGrattan, Klein, Hostikka, & Floyd, 2007)
[5](ISO 9705, 1993)
[6](Sandström, 2008)
[7](EN 1992-1-2, 2004)
[8](EN 1993-1-2, 2005)
[9](EN 1991-1-2, 2002)

2.1 Simplified Eurocode

Spread sheet calculation with fire exposure from a single, uniform temperature. Connection to concrete is ignored.

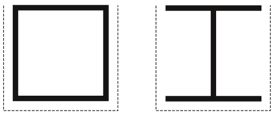

Fig. 6 Fire boundary in calculation 1; the dotted line represents fire exposure

2.2 Simplified FEA

Finite element calculation with fire exposure from a single, uniform temperature. No regards to shadow effects for the H-section and the connection to concrete is ignored.

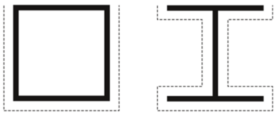

Fig. 7 Fire boundary in calculation 2; the dotted line represents fire exposure

2.3 Advanced FEA with uniform fire exposure

Fire exposure from a single, uniform temperature. Concrete is modeled in the calculations but not the shadow effect for the H-section.

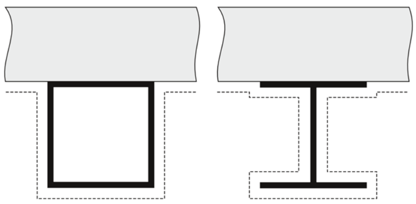

Fig. 8 Fire boundary in calculation 3; the dotted line represents fire exposure

2.4 Advanced FEA with uniform fire exposure and shadow effect

Same as above but with regards to shadow effects. This analysis is only performed for the H-section.

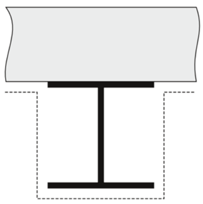

Fig. 9 Fire boundary in calculation 4; the dotted line represents fire exposure

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[10](Sterner & Wickström, 1990)

2.5 Advanced FEA with non-uniform fire exposure and shadow effect

Full analysis with different fire exposure temperature for each side. The fire exposure temperatures are the corresponding adiabatic surface temperatures for each side.

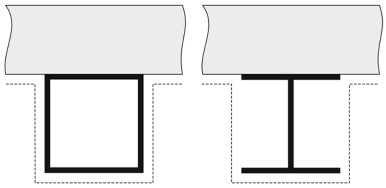

Fig. 10 Fire boundary in calculation 5; the dotted line represents fire exposure

3 RESULTS

3.1 Fire exposure temperature

The adiabatic surface temperatures in reference point set A are showed in Fig. 11. The highest adiabatic surface temperature is calculated under the bottom flange, i.e. reference point AST A-2, which is used as fire exposure temperature when assuming a uniform fire exposure temperature.

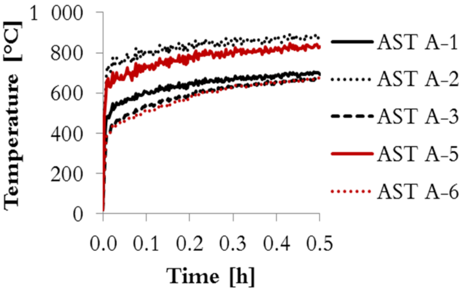

Fig. 11 Adiabatic surface temperatures in reference point set A from CFD calculations

3.2 Hollow section

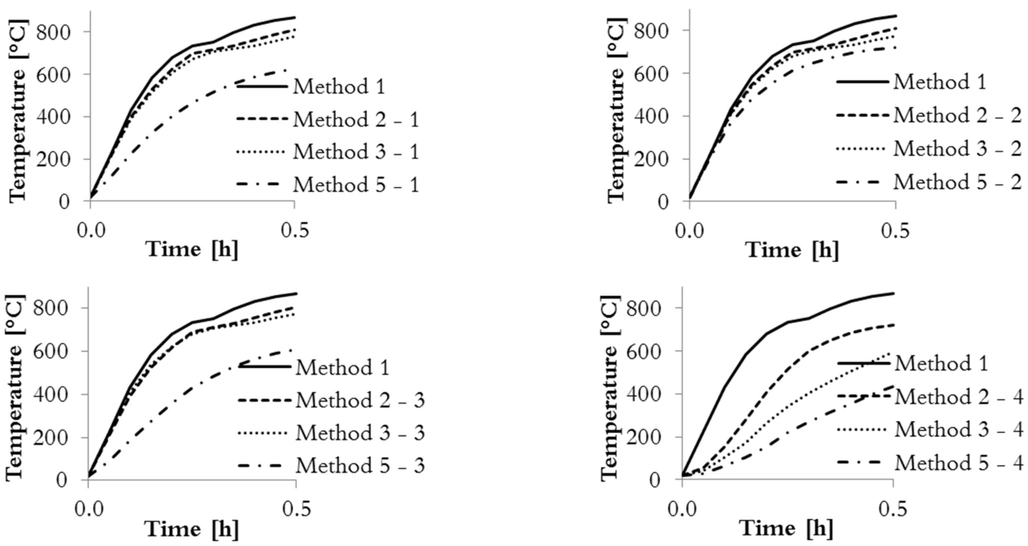

Fig. 12 Temperature development for each of the sides in the hollow section depending on the level of accuracy. Index 4 represents the upper flange in contact with concrete. The other indexes correspond to Fig. 4.

When calculating the temperature in the hollow section, the heat exchange in the void is considered at all times except for the simple spread sheet calculation. The temperature is calculated for all four sides of the hollow section following the same numbering as presented in Fig. 4 with the addition of side 4 which is facing the concrete.

Tab. 1 Temperature distribution in a hollow section with different levels of accuracy

Method	**Side 1**	**Side 2**	**Side 3**	**Side 4**
1 – simplified EC	877°C	877°C	877°C	877°C
2 – simplified FEA	811°C	809°C	807°C	719°C
3 – advanced FEA, uniform fire exposure	777°C	776°C	772°C	594°C
5 – advanced FEA, non-uniform fire exposure	628°C	719°C	611°C	436°C

3.3 H-section

The temperature in the H-section is calculated in the lower flange, the web and the upper flange numbered 2, 3 and 4 respectively.

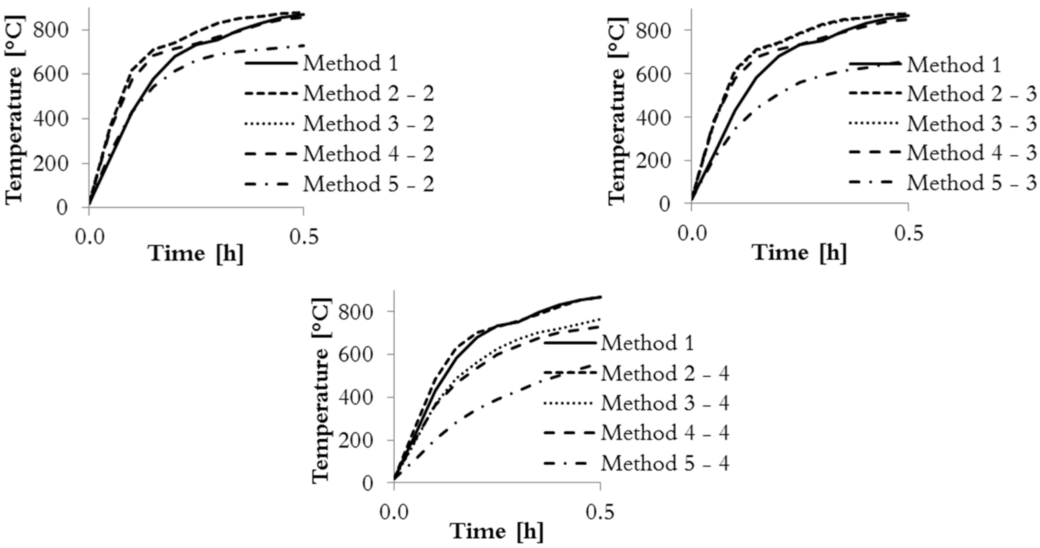

Fig. 13 Temperature development for each of the sides in the hollow section depending on the level of accuracy. Index 2, 3 and 4 represents the lower flange, the web and upper flange in contact with concrete respectively.

Tab. 2 Temperature distribution in a hollow section with different levels of accuracy

Method	**Lower flange**	**Web**	**Upper flange**
1 – simplified EC	869°C	869°C	869°C
2 – simplified FEA	877°C	877°C	868°C
3 – advanced FEA, uniform fire exposure	877°C	876°C	764°C
4 – advanced FEA, uniform fire exposure, shadow	857°C	851°C	731°C
5 – advanced FEA, non-uniform fire exposure, shadow	729°C	658°C	559°C

4 COMMENTS ON THE CALCULATIONS

By adopting a more advanced set up of boundary conditions, the steel temperature can be predicted with greater precision and becomes as rule reduced significantly. Only by using FEA considering the cooling effects of concrete on a hollow steel section, i.e. method 3, gives a temperature decrease in the lower flange of close to 100°C and in the upper flange of close to 300°C compared to the simplified method presented in EN 1993-1-2. For the H-section,

this difference is negligible for the lower flange and approximately 100°C for the upper flange.
When adopting different fire exposing temperatures the temperature is even better predicted. This way the analysis consider less onerous exposure on the sides not directly exposed to thermal radiation from the flame. This concept decreases the temperature and the difference compared to the simplified solution for the hollow section is 250°C for the lower flange and 450°C for the upper flange. For the H-section, this difference is 150°C for the lower flange and 300°C for the upper flange.

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