REDUCING DESIGN STEEL TEMPERATURE BY ACCURATE TEMPERATURE CALCULATIONS

Ulf Wickström[a,b], Alexandra Byström [a], Joakim Sandström [a], Milan Veljkovic[a]

[a]Luleå Univesity of Technology, Department of Civil Enviromental and Natural Resources Engineering, Luleå, Sweden
[b]Technical Research Institute of Sweden, SP Fire Technology, Borås, Sweden

Abstract

In this paper an un-insulated I-beam (HE400B) supporting a concrete slab was analyzed. The steel temperature was calculated with the simplest approach according to EC 3 and compared to temperatures calculated considering the cooling by the concrete. In addition the so called shadow effect was considered. The I-beam is then assumed not fully exposed to the incident radiation from the fire as the surfaces between the flanges will be partly shadowed. Temperatures of the I-beam after a fire exposure of 30 minutes was calculated and discussed. The calculations were performed with the finite element code Tasef(Sterner et al, 1990). The mean temperatures of the beam flanges were reduced by more than 200 °C (from 827 °C to 609 °C) when the cooling at the top of the beam and shadow effects were considered. The structure was supposed to be exposed to the standard time-temperature conditions according to EN1363-1 or ISO 834.

Keywords: shadow effect, steel structure.

INTRODUCTION

Eurocode 3: Design of steel structures –Part 1-2: General rules – Structural fire design contains various means of calculating temperature in fire exposed steel structures. For the most commonly used of the calculation methods the temperatures in the steel section are assumed uniform and the thermal properties are assumed constant. However, when following these assumptions the temperatures are often over-estimated which leads conservative and maybe unnecessary costly solutions. In particular the consequences of cooling of steel sections embedded in or in direct contact with concrete structures are not considered in the simplest approximated methods given in EC 3. Only the reduction of the exposed area is taken into account.

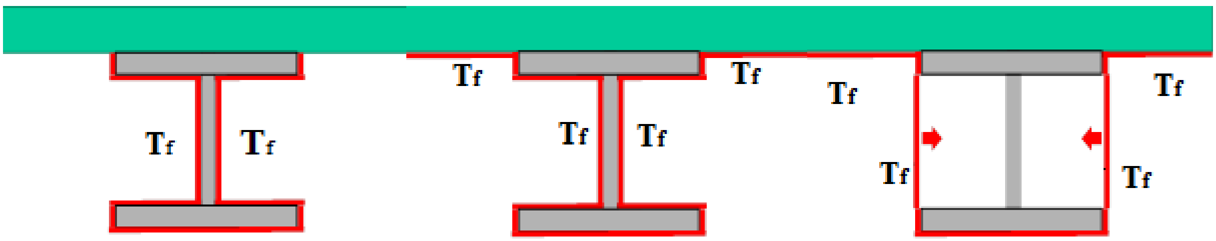
In this paper an un-insulated I-beam (HE400B) supporting a concrete slab was analyzed. The steel temperature was calculated with the simplest approach according to EC 3 and compared to temperatures calculated considering the cooling by the concrete. In addition the so called shadow effect was considered. The I-beam is then assumed not fully exposed to the incident radiation from the fire as the surfaces between the flanges will be partly shadowed. Temperatures of the I-beam after a fire exposure of 30 minutes was calculated and discussed. The calculations were performed with the finite element code Tasef[i] (Sterner et al, 1990). The mean temperatures of the beam flanges were reduced by more than 200 °C (from 827 °C to 609 °C) when the cooling at the top of the beam and shadoweffects were considered. The structure was supposed to be exposed to the standard time-temperature conditions according to EN1363-1 or ISO 834. Finally it is pointed out that by making more advanced fire modeling including CFD analyses the fire temperatures can be tailored for the particular problem and the calculated temperatures of the steel section can be even more accurate and in most cases further reduced.

1 THERMAL MODELING OF AN UNINSULATED I-BEAM

The thermal fire modeling of an uninsulated I-beam can be done more or less accurately. The simplest way is to assume that the beam section is uniformly heated on all exposed surfaces and that the steel at all times reaches the same uniform temperature level. This approximation is often used. The steel section can then be characterized by its section factor only, i.e. the ratio between the exposed area and the volume A/V, see Eurocode 3 (EN1993-1-2). In the case of a steel beam supporting a concrete slab as shown in Fig.1a only three sides are assumed to be exposed to fire while the fourth side is assumed to neither receive nor lose any heat. In other words it is perfectly insulated, constituting a so called adiabatic boundary. With the simplest assumptions the thermal properties of the steel is constant.

In reality, however, in case of fire heat will be conducted from the steel to the concrete which will reduce the temperature of the steel. In this case the temperature of the steel can no longer be assumed uniform and therefore numerical procedures are needed. Computer codes based on the Finite Element Method are most commonly used for this calculation purpose. By considering a calculation model as indicated in Fig.1b the cooling from the concrete slab, the top flange temperature in particular, will be considerably reduced as well as the average temperature of the steel section. This will be shown by the example below.

Further reduction of the steel temperature are obtained if the so called “shadow effect” is considered. The concept of shadow effects[ii](Wickström, 2001) was introduced in Eurocode 3 (EN 1993-1-2) to consider the fact that the incident heat radiation received by an open steel section like an I-section is not more than what is received by a so called boxed section. Therefore for the temperature calculation the thermal model is indicated in Fig.1c is applied. Then an artificial surface is introduced between the beam flanges. This surface is then prescribed to follow the fire time-temperature curve. The surface will radiate with an emissivity equal unity to the interior surfaces of the flanges and to the web. Convection may be calculated by assuming convection heat transfer coefficients of the surfaces. In the code Tasef(Sterner et al, 1990)which is used for the calculations reported below the different heat convection transfer coefficients may be applied to the various surfaces creating the void. The introduction of the concept of shadow effects has a similar effect on the temperature calculations as reducing the section factor for the radiation heat transfer part only. The effect on the convection part is not so obvious.



a) Uniform temperature model. No cooling.

b) Uneven temperature model. Cooling.

c) Uneven temperature model. Cooling. Shadow effect.

Fig. 1 Three levels of modeling accuracy of an I-beam supporting a concrete slab. The red lines indicates fire boundaries.

1.1 An example analyzed with the finite element code Tasef

To illustrate the importance of the various levels of approximations the temperature of an HE400A section was analyzed with finite element code Tasef. The code is a general code for calculating temperature but it is specialized for analyzing fire exposed structures. In particular the code can be used for calculating heat transfer by radiation and convection in voids or enclosures in structures.

In the example the steel beam supports a 200 mm concrete slab as shown in Fig. 1. The steel beam has a height of 400 mm, 150 mm wide and 40 mm thick flanges, and 30 mm thick web. The thermal properties of the concrete and the steel are according to Eurocode 2 (mean value) and 3, respectively. The boundary conditions are also according to Eurocode when applicable. The surface emissivity of the steel and the concrete are assumed generally to be 0.8.

The beam and a part of the slab were divided into finite element as indicated in Fig. 2. To model the shadow effect an artificial surface is introduced between the flanges as shown in the Fig. 2. The temperature of the inside surface the artificial surface is then prescribed to follow the fire time-temperature curve. The emissivity of the artificial surface shall be unity while the other surfaces around the void are assumed to 0.8 in this case. The heat transfer by convection is calculated by calculating a void gas temperature as the weighted average of the surrounding surface in such a way the total heat transfer between the gas and the surfaces vanishes. Different heat transfer coefficients can be prescribed to the various surfaces. In this case the convection heat transfer at the artificial surface is hard to estimate. Here it is assumed to be as high as h_{art} =50 W/(m^2 K) while for the other surfaces the heat transfer coefficient was assumed to be h_{void} =10 W/(m^2 K). These estimates are of course uncertain but as the radiation dominates at high temperatures the influence on the steel temperature development is expected to be limited.

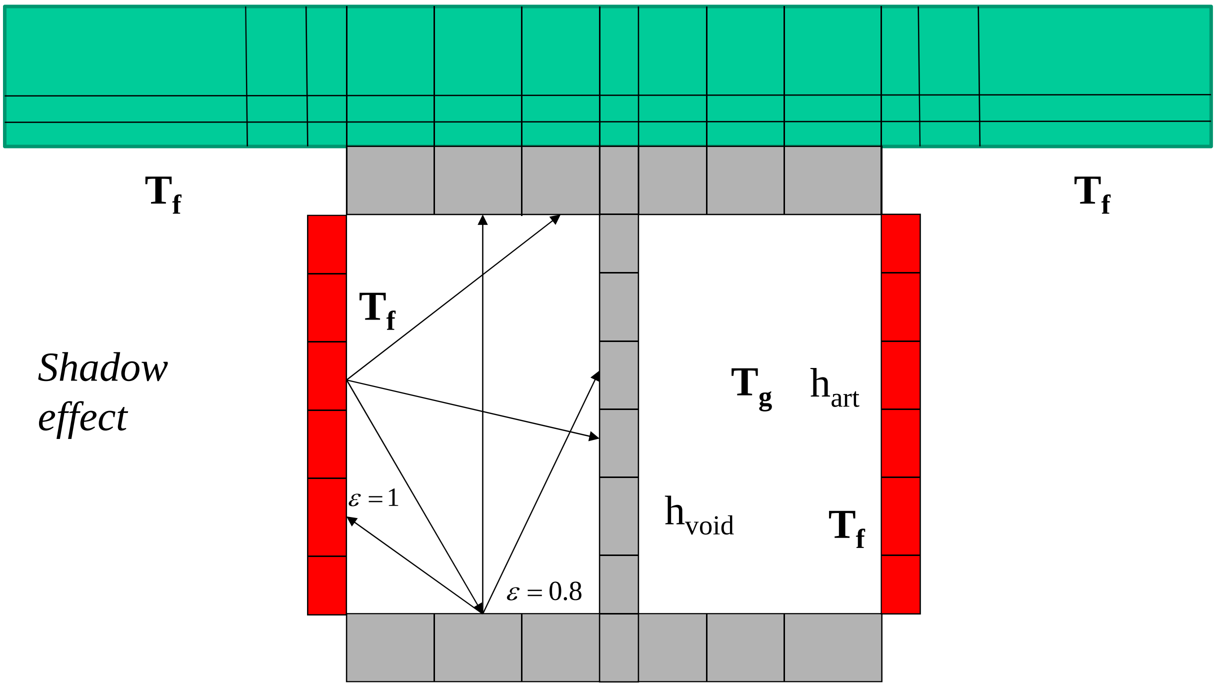


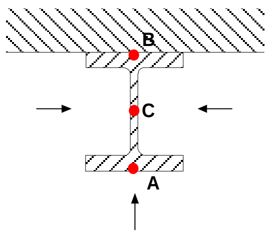
Fig. 2 Finite element model of the beam and slab. The left hand side indicates how the heat transfer by radiation is calculated between each of the element surfaces surrounding the void. The right hand side indicates how the heat is calculated by convection by first calculating the internal gas temperature as a weighted average of the surrounding surfaces.

Calculated temperatures after 30 minutes exposure according to the standard fire time-temperature curve according to EN 1361 are given in Tab 1. In all calculations the surface emissivity is assumed equal 0.8 to facilitate the comparisons of the results.

If the simplest method as given in Eurocode 3 is used assuming uniform temperature and constant thermal steel properties the calculated temperature becomes as high as 827 °C. If the cooling of the top flange and varying thermal properties of steel and concrete are considered in a finite element analysis a more accurate temperature distribution can be calculated. The

mean calculated temperature of the flanges then becomes 150 °C lower than the temperature calculated when assuming uniform temperature. The top flange temperature is reduced by almost 220 °C! Note that the middle web temperature is even higher than the lower flange temperature and that it is almost as high as the temperature obtained with the simplest method.
Finally when also considering the shadow effects the calculated steel temperatures become even lower. As shown in Tab 1 the average temperature of the flanges is now almost 220 °C lower than the uniform temperature calculated with the simplest method. The calculated bottom flange temperature is reduced by as much as 325 °C.

Tab 1 Example of calculated temperature in °C of an un-insulated steel I-beam HE400A after 30 min according to five different calculation models. The positions are indicated in the first column.



Position	Uniform temp Top ins EC	Uneven temp Top cooled Tasef	Uneven temp Top cooled Shadow effect Tasef
A - top flange	827	749	715
B – bottom flange	827	608	502
C - web	827	797	719
Mean (A+B)/2	**827**	**679**	**609**

2 CONCLUSION AND DISCUSSION

The Eurocodes contains simple methods for calculating temperature in structures. These are in general conservative and yields over-estimated steel temperatures and thereby under-estimated steel strengths. More accurate and precise estimates can be obtained by considering varying thermal properties and assuming more realistic boundary conditions like cooling from an adjacent structure and shadow effects. In this study only exposure conditions according to standard fire curve has been considered. Even lower steel temperatures can be estimated in some cases by applying more nuanced fire exposures like the parametric curves as presented in Eurocode 1 (EN1991-1-2 Annex A) or by applying advanced CFD calculations. For this purpose considerable interesting work has been carried out by Joakim Sandström using the code FDS. His work will also be presented at this conference.
Several types of insulated steel structures contain real voids where the heat transfer by radiation and convection must be calculated to obtain accurate predictions of steel temperature developments when exposed to fire Fig. 3 shows two examples indicating how an I-section can be insulated with boards of e.g. gypsum or calcium silicate.

REFERENCES

Sterner E. and Wickström U.,”TASEF – Temperature Analysis of Structures Exposed to Fire,” SP Report 1990:05, SP Technical Research Institute of Sweden, 1990.

Wickström, U. , “Calculation of heat transfer to structures exposed to fire – shadow effects”, Interflam 2001.