Influence of shadow effect on the strength of steel beams exposed to fire

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Abstract

In Eurocode 3: Design of steel structures –Part 1-2: General rules – Structural fire design, the temperatures in the steel section are assumed uniform and the thermal properties are assumed constant. This leads to conservative and possibly uneconomic designs. In particular, steel sections embedded in or in direct contact with concrete are not considered appropriately - only the reduction of the exposed area is taken into account. In addition, the shadow effect is rarely considered in structures with both concrete and asteel elements such as composite floors. It has been mainly used for stand-alone columns with I-cross section. In this paper, the temperature distributions in a steel beam with or without considering the shadow effect are calculated using the program TASEF. The resulting temperatures are then used to determine the fire duration under loading using a finite difference based computer program COMPSEF for the mechanical response. The differences in failure times reflect the savings that can be made using such 'advanced calculation models' permitted in Eurocode 3, when compared with the prescriptive methods included in the code.

Keywords: structural fire engineering, heat transfer, shadow effect, finite element method, finite difference method

1. Introduction

When modelling an uninsulated I-beam for fire exposure, Eurocode 3 [1] adopts the simplifying assumption that the beam section is uniformly heated on all exposed surfaces and that all steel has the same uniform temperature level. The steel section is then characterized by its section factor only. In the case of a steel beam supporting a concrete slab at the top, only three sides are assumed to be exposed to be perfectly insulated. In reality, heat is conducted from the steel to the concrete reducing 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. The Finite Element Method is most commonly used for this purpose. When concrete surrounds the steel partially or entirely, or when concrete filled hollow sections are used as in composite columns, it becomes imperative to use such methods.

Further reduction of the steel temperature is obtained if the so called "shadow effect" is considered. The concept of shadow effect was introduced by Wickström [2] to consider the fact that the incident heat radiation received by an open steel section like an I-section is not the same as what is received by a so called boxed section as indicated in Figure 1.

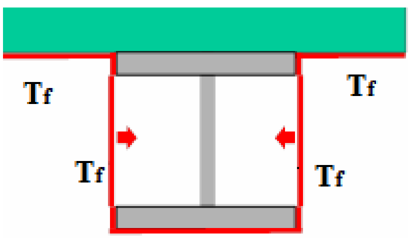

Fig. 1 Red lines indicate fire boundaries.

2. An I-Beam analysed by the finite element code TASEF

To illustrate the importance of the shadow effect, the temperature distribution in an HE400A section was analyzed with finite element program TASEF [3], a general code for calculating temperature distributions in fire exposed structures. In particular, TASEF 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 without composite action, as shown in Figure 1. The steel beam has a height of 400 mm, width of 150 mm, 40 mm thick flanges, and a 30 mm thick web. The thermal properties of the concrete and the steel are according to Eurocode 2 (mean value) [4] and Eurocode 3 [1], respectively. The boundary conditions are ISO fire on the underside of the floor assembly.

The surface emissivity of the steel and the concrete are assumed to be 0.8. To model the shadow effect an artificial surface is introduced between the flanges as shown in the Figure 2. The temperature of the inside surface of the artificial boundary is then prescribed to follow the fire time-temperature curve. The emissivity of the artificial surface is taken as unity.

The heat transfer by convection is evaluated by calculating a void gas temperature as the weighted average of the surrounding surface in such a way that the total heat transfer between the gas and the surfaces vanishes.

Calculated temperatures after 30 minutes exposure according to the standard fire time-temperature curve according to ISO fire are given in **Fejl! Henvisningskilde ikke fundet.**. If the simplest method as given in Eurocode 3 [1] is used, assuming uniform temperature and constant thermal steel properties the calculated temperature becomes 827 °C. If the cooling of the top flange and varying thermal properties of steel and concrete are considered in a finite element analysis, the mean calculated temperature of the flanges then become 150 °C

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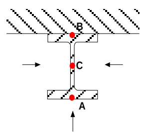
lower. The top flange temperature is reduced by almost 220 °C. Note that the middle web temperature is even higher than the lower flange temperature and that it is almost as high as the temperature obtained with the simplest method.

Finally when considering the shadow effects the calculated steel temperatures become even lower. As shown in Table 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.

Table 1. Comparison of temperatures at 30 min of ISO 834 fire

		Eurocode 3 [1]	No Shadow Effect	Shadow Effect
	A	827	709	661
	B	827	544	510
	C	827	714	666

The temperature distributions after 30 min of ISO 834 fire, obtained from the program, TASEF are shown in Figs 2 and 3.

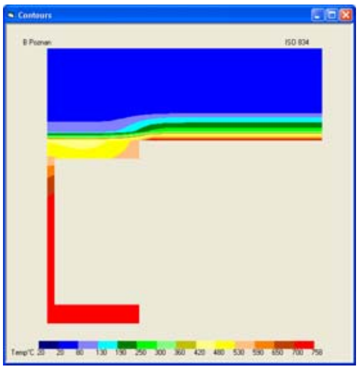


Fig. 2 Half-I-Beam with no shadow effect.

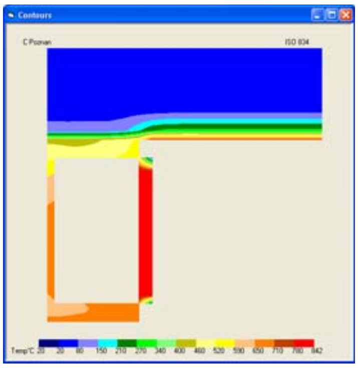


Fig. 3 Half-I-Beam with shadow effect.

3. Structural Response

The structural response of the I-beam for temperature distributions with and without the shadow effect has been analysed by the program COMPSEF, a finite difference based program developed at City University London [5]. The calculation procedure is based on the method developed by Virdi and Dowling [6] for the ultimate strength analysis of composite columns. COMPSEF only carries out structural analysis. The program uses thermal distributions directly imported from TASEF.

The procedure use accurate material properties at high temperatures. In the present case, Eurocode 2 and Eurocode 3 properties are used for concrete and steel, respectively. The steel and concrete geometry is also modelled precisely. For columns, second-order effects and imperfections are included.

The mechanical response under fire is divided into two sub-problems. For internal equilibrium, stress resultants are evaluated using numerical integration of temperature dependent stresses. External equilibrium involves the calculation of deflections using the finite differences and second-order iteration.

The method described is applied repeatedly, starting with a small time step and solving for the deflected shape, and then increasing the time until no convergence for the deflected shape is obtainable. The maximum time for which convergence is obtained is taken as the failure time.

For the present analysis, the beam length has been taken as 3.0 m. It is subjected to a uniformly distributed load of 300 kN/m. The analysis determines the time to failure. For the case shown in Figure 2, without the shadow effect, the failure time obtained was 30.0 minutes. However, taking into account the temperature distributions with the shadow effect, the time to failure increased to 35.4 minutes.

4. Conclusions

The paper has described how the shadow effect can be taken into account in determining the temperature distributions in a steel beam exposed to fire. The reduction in temperatures obtained by a more exact finite element analysis, using the program TASEF, is first due to the transmission of heat into the concrete slab supported by the beam. However, further significant reductions in temperatures are obtained by considering the shadow effect. The resulting improved structural performance, calculated by the finite difference based program COMPSEF, is reflected in the increase in time to failure from 30.0 min to 35.4 min due to the shadow effect. This difference could be significant in practical situations.

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