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Concrete and Composite Slabs in Fire

Discussion of the Load Bearing Characteristics

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Stresses due to Temperature Changes over the Cross-Section

The temperature distribution in concrete and composite slabs which are exposed to fire at one side is highly nonlinear. In addition, the thermal strains of concrete are not straight proportional to the temperature of the material. Therefore, also the strains in a concrete slab are distributed nonlinearly. Fig. 1 shows such a temperature and strain curve of a 100 mm thick unprotected concrete slab which is exposed to the standard fire curve (ISO 834).

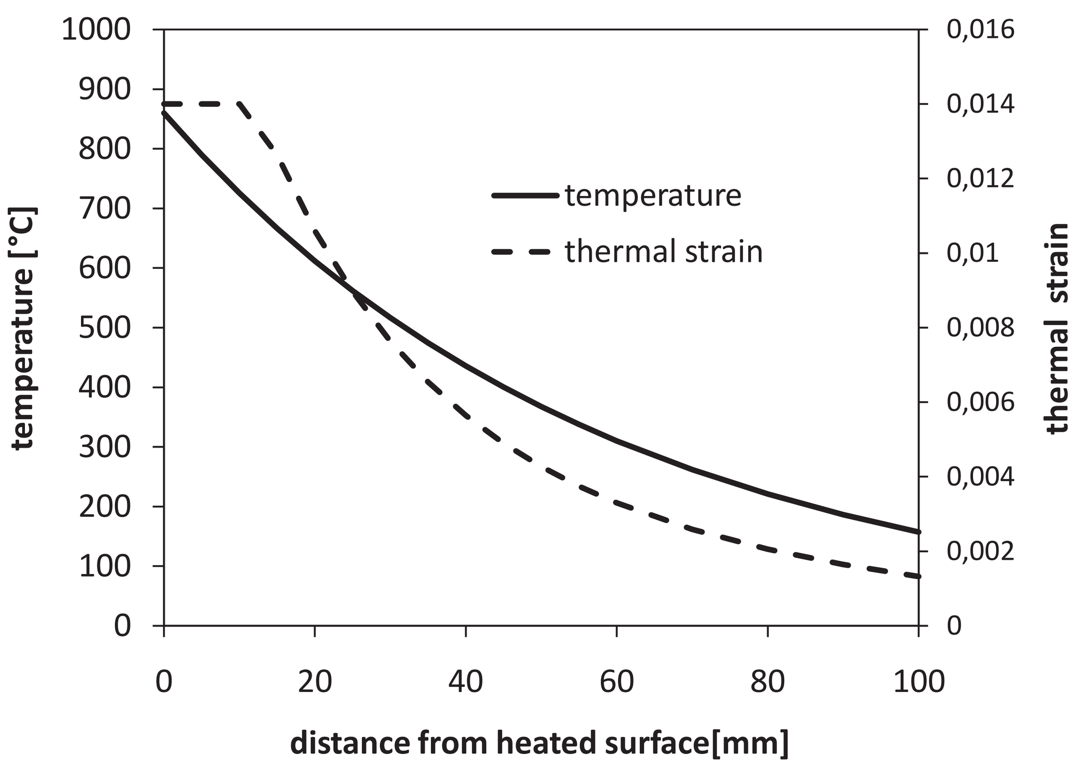

Fig. 1. Temperature and resulting strain distribution in a concrete slab

If these curves are used to analyse larger structures, a very high effort of calculation is necessary. A calculation by hand is virtually impossible. It is more practical to use linear strain distributions but not easy to find an appropriate approach. Furthermore, it is necessary to take into account that the nonlinear strain distribution leads to additional stresses. Related effects occur in hot-rolled steel sections during its production where non-uniform cooling generates self-equilibrating stresses. In contrast to steel sections a concrete slab cannot yield in such a way that these stresses can be neglected at design.

Internal Forces and load transfer

The temperature distribution over the depth of a cross-section leads to linear thermal strains which can be divided into a constant part $\Delta\varepsilon_{unif}$ and a linear strain gradient $\Delta\kappa$. In a simple beam which is horizontally unrestrained the constant part causes a longitudinal extension u_{unif} and the gradient causes a uniform curvature and bowing of the beam. An unrestrained beam with uniform curvature deforms to a circular arc. The arc length is the original length of the beam and the ends must move together (u_{grad}).

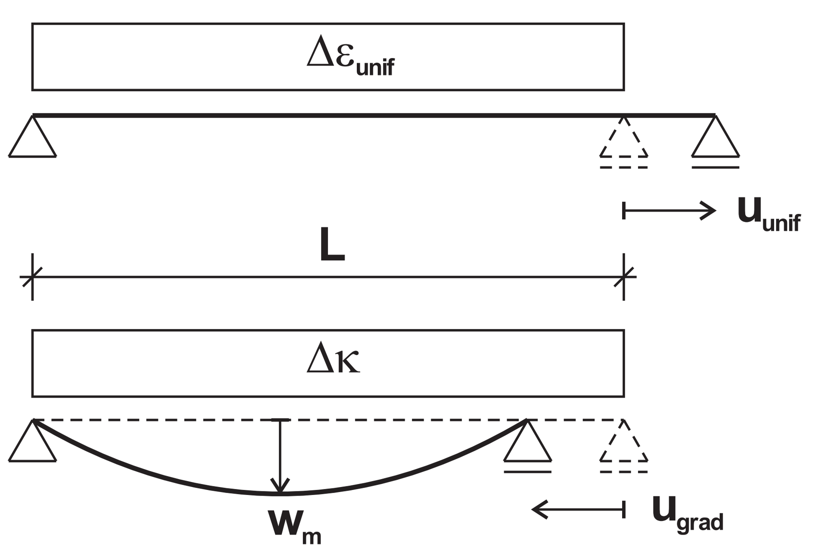

Fig. 2. Horizontal displacement of an unrestrained beam under uniform extension and curvature

If the beam is horizontally fixed on both ends, constraining forces occur. This can be visualized as an unrestrained beam which deforms under thermal loading and afterwards the support is shifted back to its initial position.

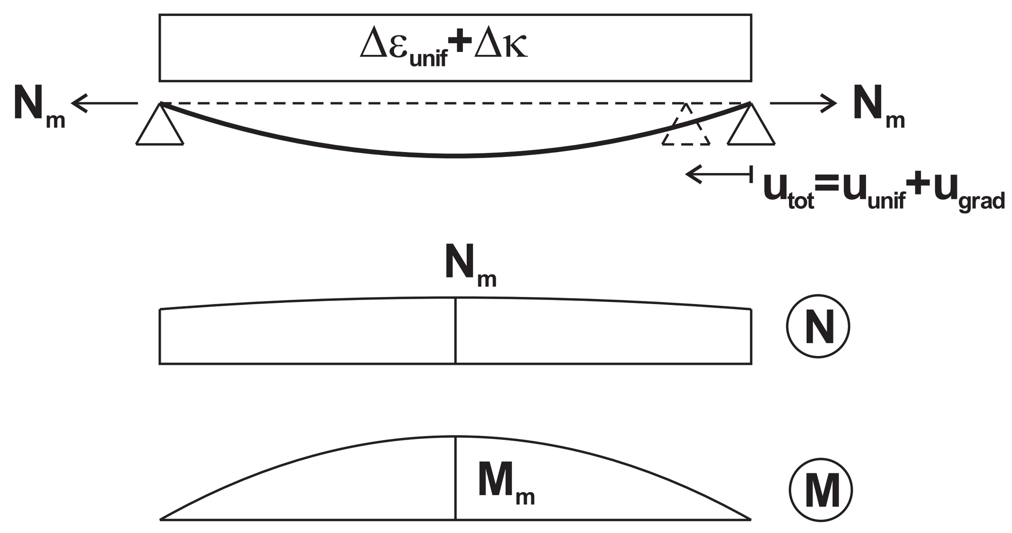

Fig. 3. Resulting constraining forces in a horizontally fixed beam

Slabs which are subjected to the fast heating of the standard fire curve will get a high curvature and in relation a small uniform extension. The curvature changes in both directions of the slab but even at unrestrained slabs the edges cannot move together. The deformations are restrained due to the development of a compression ring around the perimeter of the slab. In this case the thermal loading leads to a tensile force and a negative bending moment in the slab. The reinforcement already yields under thermal loading and the contribution to the transfer of mechanical loads becomes very small. It seems that mechanical loads like the dead load of the slab or working loads are mainly transferred by reduction of the bending moment. This kind of load transfer can be compared with the behaviour of prestressed concrete structures.

Tension Stiffening

In most engineering models only the reinforcement makes contribution to the load transfer because the concrete cracks at tension. Thus, the deflection of the slab only depends on thermal and mechanical strains of the reinforcement. But actually the concrete does not completely crack. Between the cracks stresses occur in the concrete and in the cracks the strains of the reinforcement increase. The slab becomes stiffer and the reinforcement is not stretched constantly. This so-called tension stiffening, which is well-known at ambient temperatures, also appears at elevated temperatures. For the design of beams and plates in bending, this effect does not influence the load bearing capacity but only the deflection. But in the engineering models using membrane action the load bearing capacity depends decisively on the deflection. Therefore tension stiffening must be included when the slabs are designed.

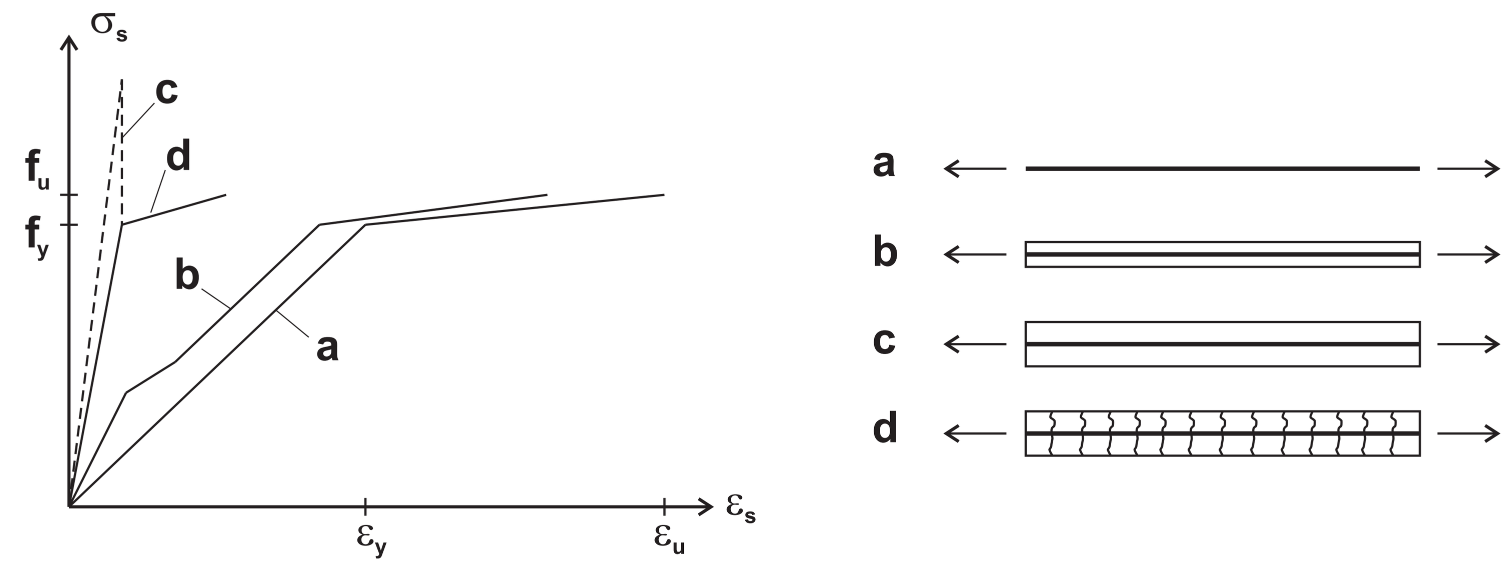

Fig. 4. Tension stiffening

Fig. 4 shows the stresses in a rebar related to its strain. Line a) is for a simple rebar without concrete. If the rebar is embedded in a small concrete section, the reinforcement ratio is high and the stress-strain curve of the rebar looks like line b). Line c) shows the behaviour of a slightly reinforced beam. In line d) the concrete beam is pre-cracked like it is the case at composite slabs in fire.