RECENT IMPROVEMENTS ON NUMERICAL METHODS IN STRUCTURAL FIRE SAFETY

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ABSTRACT

The fire resistance of composite members and complete structures can be determined on the basis of fire tests. Such fire tests are time-consuming and expensive. Therefore fire tests are less suitable for extensive parametrical studies concerning the load bearing capacity under fire conditions. In the future advanced calculation models according to the Eurocodes will become more and more important.

This contribution deals with the numerical simulation of ceilings and columns under fire conditions using the finite element method. For the three dimensional computations of the ceilings the software package *ABAQUS*® is used. The simulations of the columns are carried out with the finite element software *BoFire*.

In the calculations the nonlinear behaviour of the materials steel and concrete under high temperatures and in case of the ceilings a realistic approach for the steel/concrete interface between the steel beams and the concrete slab are taken into account.

For the ceilings a methodology and appropriate models are presented in order to carry out three-dimensional simulations of the fundamental load carrying mechanisms under fire conditions.

The investigation is focussed on structures with unprotected composite beams. In this context the *Cardington fire tests* must be mentioned, which were carried out in a steel-framed building at the Cardington test facility in the 90's.

The simulations of composite columns focus on special aspects concerning the interaction relationship between the normal force and the bending resistance under fire conditions. The target of the investigations is the development of a simple calculation procedure for the fire design of composite columns based on the simple calculation method provided by Eurocode 4 for the normal temperature design.

KEYWORDS

Slab, numerical simulation, unprotected composite beams, steel/concrete interface, fire design, composite columns, interaction curve, perfect plastic, strain dependent

NUMERICAL MODELING OF SLABS AND BEAMS

Introduction

The *Cardington fire tests* Newman & Robinson & Bailey (2000) showed that, under certain conditions, steel structures with protected columns, unprotected composite beams and unprotected composite slabs can survive a severe fire. Figure 1 shows the test building before the casting of the composite slabs (left) and the deformed structure following one of the fire tests (right).

Figure 1:   Cardington test building (left)
Structure following the test (right)

The numerical simulation problem comprises a thermal and a mechanical analysis. As the heating of the structure is independent of the mechanical loading both parts of the problem can be solved separately. The calculations are verified by comparisons with test results. The following example is taken from Hothan (2004).

Numerical Model and Simulation

The numerical calculations are carried out with the finite element program *ABAQUS*®. In the calculations the nonlinear behaviour of the building materials steel and concrete under high temperatures as well as a realistic approach for the steel/concrete interface between the steel beams and the concrete slab are taken into account. For the compressive stress-strain-relationship of concrete the material properties according to Eurocode 4 part 1-2 are used. Figure 2 shows a new assumption for the tensile stress-strain-relationship of concrete.

The reduction of the tensile strength of concrete after cracking can appear more or less abrupt. This behavior can be taken into account with the parameters b and c. The possible range of b is between 0 and 1. The value of c can range between 1 and d. The parameter d describes the strain when the tensile stress tends to zero.
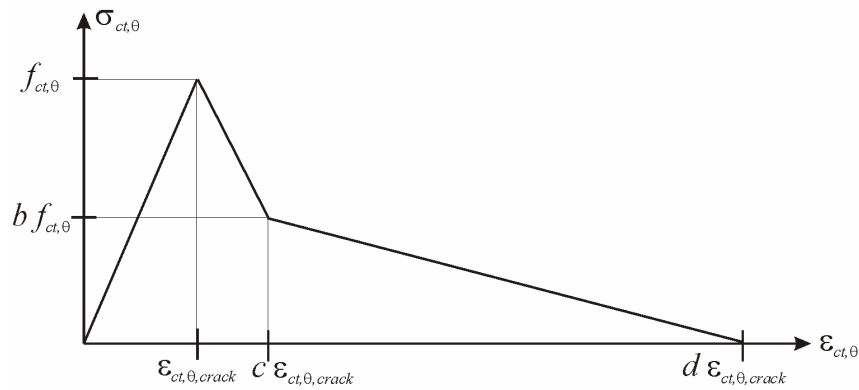
Figure 2:   Assumption for the tensile stress-strain-relationship of concrete

The behaviour of the steel/concrete-interface is modelled with nonlinear spring elements. The properties of the springs represent the temperature dependent load-slip characteristics of stud connectors under fire conditions. In Figure 3 the modelling of composite beam cross-section (left) and the temperature-dependent nonlinear spring characteristics of shear studs subjected to fire (right) are shown.
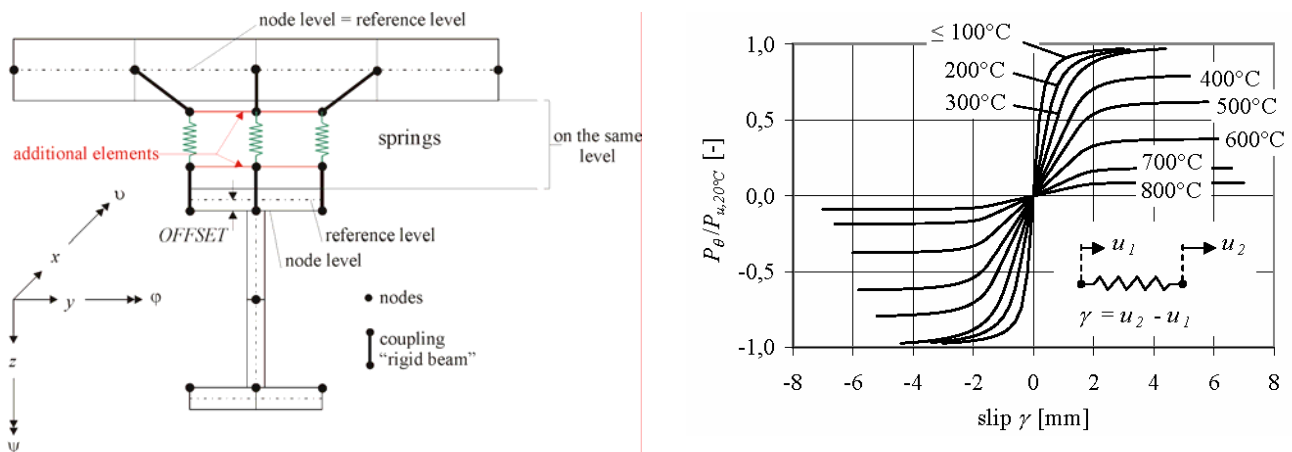

Figure 3:   Modelling of the beam cross-section and the steel/concrete interface (left)
Temperature-dependent nonlinear spring characteristics of shear studs subjected to fire (right)

Beside the spring elements the model comprises shell elements for the steel beam and the concrete slab. The concrete parts of the composite floor including the reinforcement are modelled with one layer of shell elements. The steel decking is modelled separately with shell elements. In this model it is possible to take into account the different load carrying characteristics of the composite floor in the longitudinal and the transverse direction of the ribs.

Results and Perspective

Using the described models it is possible to simulate the structural behaviour as it was observed in the fire tests. This includes the local buckling of the steel beam near the supports and the forming of a ring of compression in the composite slab.

Figure 4 (left) shows the connection between a beam and a column after the fire test. The test result is compared with the result of the related finite element simulation, see Figure 4 (right). Using shell elements for the steel beam it is possible to simulate local buckling close to reality.
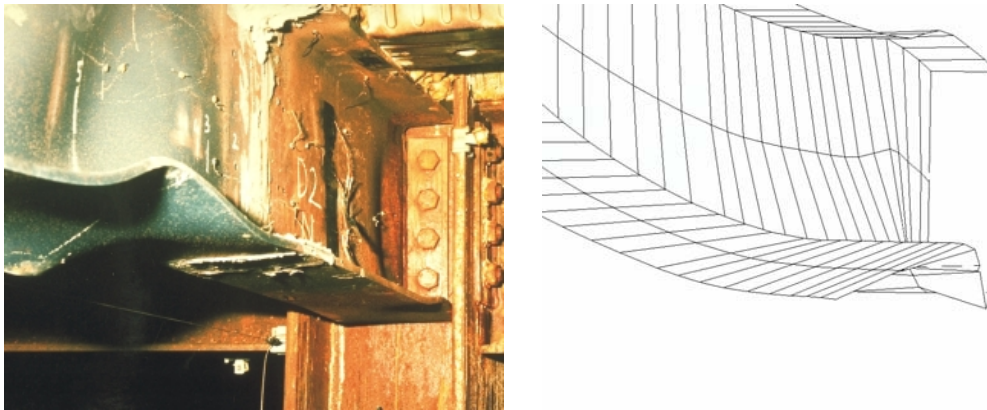
Figure 4:   Buckling of the steel beam near the support: Test (left)
FEM-simulation (right)

The three dimensional plot in Figure 5 (left) shows the model of a complete ceiling with the beams and the composite slab. The plot gives an overview of the elements and the applied boundary conditions. The hatching indicates the heated area of the restrained beam test. For the internal edges of the model symmetric boundary conditions are assumed.
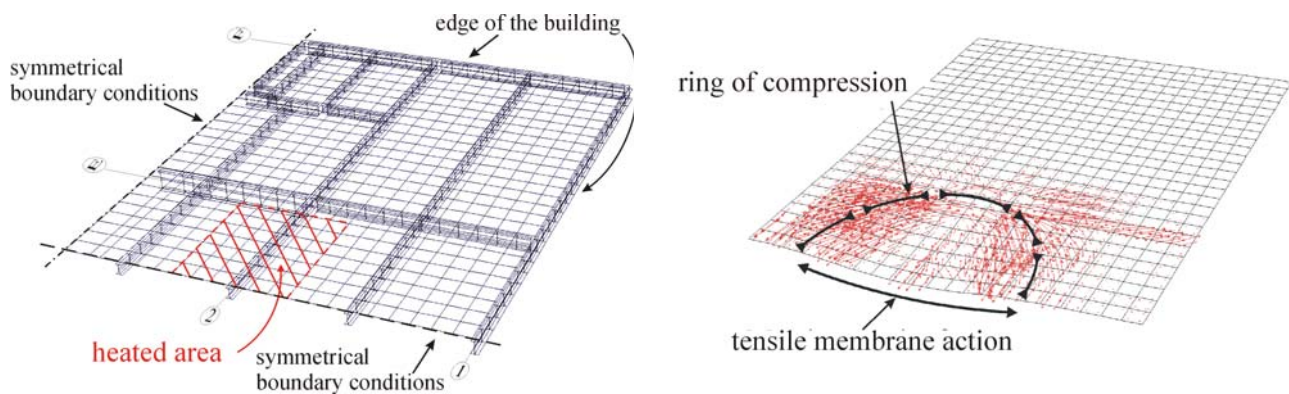

Figure 5:   Discretisation of a part of the ceiling (left)
Development of a ring of compression (right)

In Figure 5 (right) the forming of a compressive ring beam in the floor slab is visualized. With increasing deflections a tensile membrane action in the reinforcement of the slab is developing. The membrane forces in the deflected floor area are fastened in the compressive ring beam.

The presented models can be the basis of extensive parametric studies of the fire behaviour of ceilings. Fire tests and costs may be reduced using numerical simulations. So the presented models are essential for the developing and validation of simple calculation procedures for the fire design of such building structures. The knowledge of the fire behaviour observed in tests, which was also confirmed by the numerical simulations, may be used. In the future the economy of steel structures may be increased by reducing the passive fire protection measures in a responsible way.

NUMERICAL ANALYSIS OF COMPOSITE COLUMNS

Introduction

The design of composite elements in the fire situation is regulated in the European standard EN 1994-1-2. The herein given tabulated data and simplified calculation methods are just valid for a certain scope of application. For the design of columns out of this scope expensive fire tests must be performed. For composite columns the given simplified rules are limited to members in braced frames. The valid types of cross section are I-section with partially and totally concrete encasement or circular concrete filled hollow section.

The codes for the normal temperature design of composite elements offer a comparatively general verification method for any kind of static system and cross section. Thus it is the intention to adapt this method for the fire situation.

The following investigation deals with interaction curves of composite columns as an aspect of this adaptation process.

Normal temperature design of composite colums

In Europe, the verification with the European buckling curves is the most common design method to calculate the load bearing capacity of compression members for normal temperature design. Investigations by Lindner and Bergmann (1998) involved a new verification procedure, that is now included as a standard method in the German code DIN 18800-5 and the corresponding European document EN 1994-1-1 for normal temperature design of composite columns.
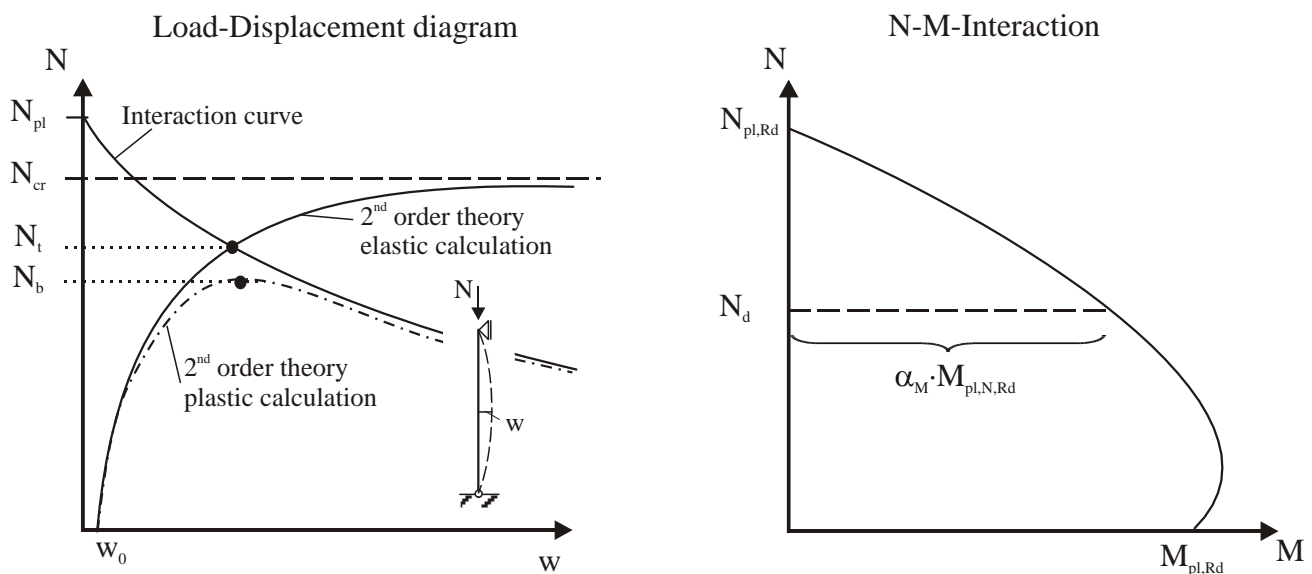

Figure 6: Load-Displacement diagram for compression members (left)
N-M-Interaction curve for composite cross sections (right)

Contrary to a calculation with the buckling curves the internal forces are calculated by a linear second order theory (see Figure 6 (left)), thus this method is taking the deformation into account. Normal force and corresponding bending moment are limited by the perfect plastic interaction curve as shown in Figure 6 (right). The effect of plastic stresses on the bending stiffness of the member is not considered (see Figure 6 (left)). The real load bearing capacity N_b is lower than the theoretical value N_t at the intersection point.

While the old procedure was intended for columns in braced frames this new second order method allows a more general application on composite columns.

The following investigations have been made for a special type of cross section: A concrete filled hollow section with an embedded massive profile (CHM). As no design rules exist for those kind of cross sections in the fire situation Schaumann and Kettner (2004) developed a catalogue with load bearing values for columns with a CHM cross sections with either an inner I- or X-section (see Figure 7).

Numerical methods for the thermal analysis of composite members

The numerical simulation program BOFIRE

Through the last years the authors evaluated the numerical simulation tool called *BOFIRE*. The basic implementation was done by Schaumann (1984). It is a transient, non-linear, incremental computer code based on the finite element method. The program includes two main calculation modules: one to calculate the development and the distribution of the temperature in the structural member (thermal response model) and another to consider the mechanical behavior of the structure, taking into account the change of material properties at elevated temperatures (mechanical response model). *BOFIRE* includes the required thermal and mechanical material properties of EN 1994-1-2 for steel and concrete.

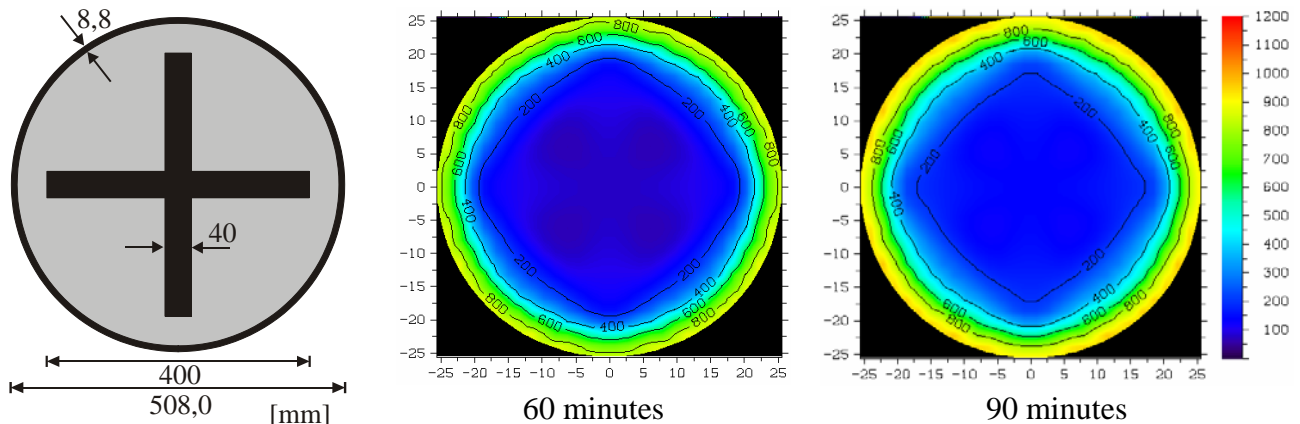

60 minutes   90 minutes

Figure 7: Heating of a composite cross section under ISO-fire

Starting point for the further mechanical analysis is the temperature distribution over the cross section at a defined point of time. The temperature profile is calculated with *BOFIRE* including a linear Finite Element Approach. Figure 7 shows the results of a 60 and 90 minutes temperature calculation under ISO-fire for a CHM cross section.

Interaction curves of composite columns

Mechanical material properties under fire conditions

Figure 8 shows the stress-strain relationship for steel and concrete as given in EN 1994-1-2. The stress values are related to the maximum stress level at room temperature. It is conspicuous, that the maximum stress level for the different materials and for different temperatures is not reached at the same strain value. As the considered cross section is a heated composite section with different materials and different temperatures it is not sufficient to consider just the maximum stress level, when calculating the limiting internal forces (interaction curve). Therefore the following strain dependent investigations are made.
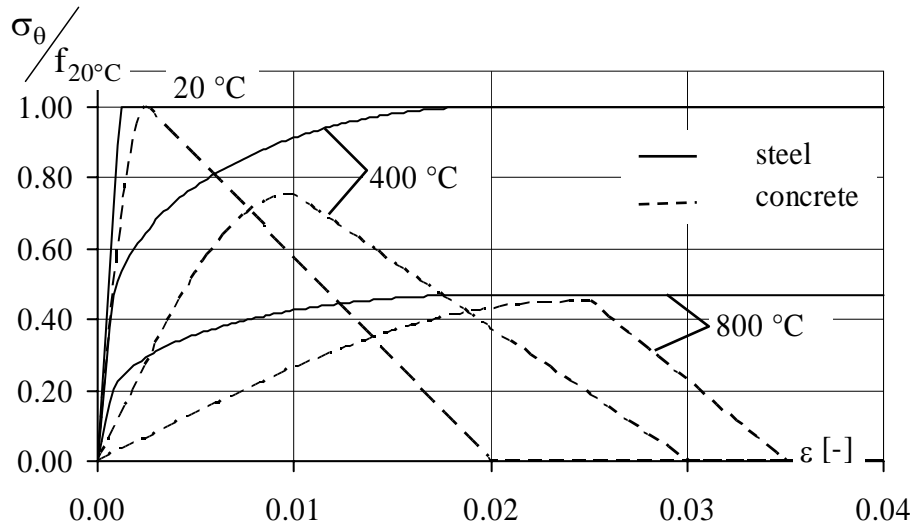
Figure 8: Stress-strain-relationship of steel and concrete given in EN 1994-1-2

Strain dependent interaction curves

For a determined temperature distribution at a certain point of time as given in Figure 7 the inner normal force can be integrated over the cross section for certain plain strains ε_0 assuming the Bernoulli hypothesis for plain cross sections. The result for compression strains is shown in Figure 9. The maximum normal force that is reached is smaller than the perfect plastic normal force calculated with the maximum stress levels. This is because of the descending stress-strain-relationship of the concrete. While parts of the cross section have not reached the maximum stress level, others are already on the descending part of the stress-strain relationship. With increasing strains more and more concrete parts crush and the curve converges to the inner normal force of the pure steel section given by the maximum stress level of steel.

The same phenomenon is observed for a given curvature κ and the plastic moment resistance.
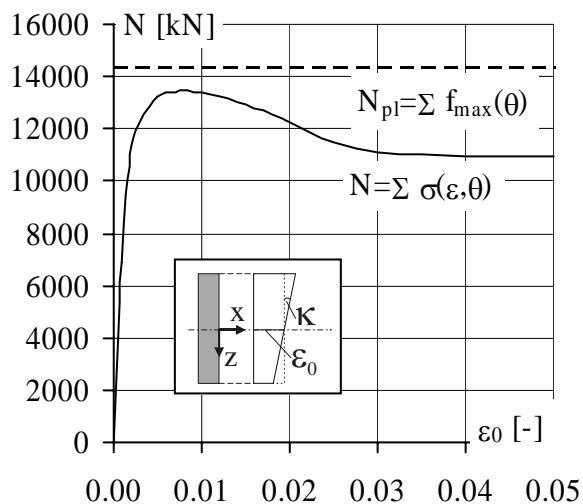

Figure 9: inner axial force integrated for a heated cross section (data see Figure 10) for different plain strains
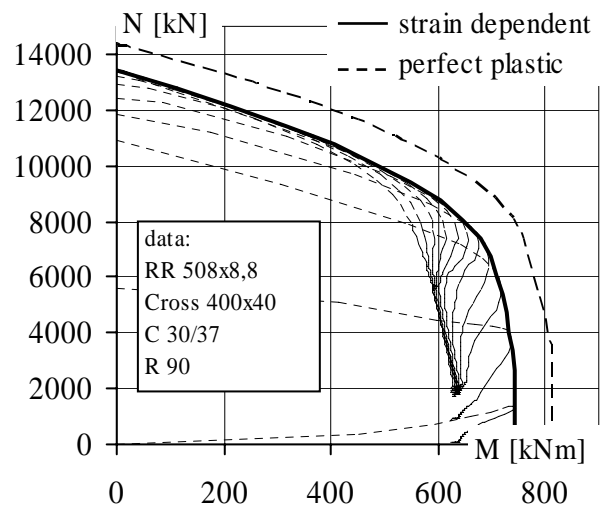
Figure 10: strain dependent and perfect plastic interaction curve under fire conditions

The integration of different strain distributions over the cross section leads to an array of curves for the normal force N and the bending moment M as shown in Figure 10. In this diagram each dotted line belongs to a constant value of the plain strain ε_0 and varying values of the curvature κ. The thick line is the enclosing graph of this array of curves and describes a strain dependent interaction curve for the presented CHM cross section.

Significance of strain dependent interaction curves for member verification

Compared to the perfect plastic interaction curve defined by the maximum stress level (Figure 10, dashed line) the limiting inner forces given by the strain dependent relationship are obviously smaller. Particularly for members with a high degree of utilization for the normal force the bending moment capacity reacts sensitively to the reduction of the interaction curve. This is important for the verification of more compact members without stability phenomena and has to be investigated for different types of cross section.

Furthermore analyses have to be carried out concerning the bending stiffness of compression members under fire conditions.

SUMMARY

Advanced calculation models are a suitable alternative instead of expensive and time-consuming fire tests. This paper presented numerical investigations on ceilings and columns under fire conditions. A three dimensional *ABAQUS*®-model was evaluated for slab structures with non-linear material properties and a realistic approach for the steel/concrete interface between the steel beam and the concrete slab. The investigations on composite columns applied to the N-M-interaction under fire conditions, particularly determined by a strain dependent approach. This leads to obviously smaller values than the perfect plastic approach, with is established for the normal temperature design.

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