PERFORMANCE-BASED FIRE SAFETY DESIGN OF DIFFERENT TYPES OF CONSTRUCTIONS IN GERMANY

Global Structure behaviour of Steel Constructions

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Abstract

The objective of this article is the illustration of the calculation of natural fires and fire resistance of structural members based on the Eurocodes of three types of special structures, in this case a railway bridge, a parking deck and an airplane hangar. The railway bridge has a width of nearly 70 meters and consists of steel beams and a massive concrete slab that are supported by massive columns and walls and for that reason can be compared to a tunnel. The parking deck was calculated on the basis the FE program ANSYS. The load-bearing capacity as well as the reactive internal forces in the case of fire were investigated. The load-bearing structure of the roof of the hangars is made of steel and is supported by steel columns. The choice of a fire scenario on the safe side is crucial for the design process of the unprotected steel structure.

Keywords: Natural Fires, Global structural behaviour, Steel, thermal and mechanical analysis, non-linear material properties, reactive internal forces

INTRODUCTION

Improvements in performance-based design allow for a more realistic and cost effective fire safety design of structures. Within the year 2012, the fire parts of the Eurocodes and the included methods for the calculation of natural fires and the resistance to fire of structural members are introduced into the German building laws. For that reason the application of these methods is generally permitted by the authorities having jurisdiction (AHJ) and it can be assumed that they will become more and more important in years to come.

Thereby simplified or general calculation methods of the according European standards for structural fire safety design can be used, depending on application case. To adopt this method of calculation finite element analysis is required, which considers nonlinear material properties and nonlinear thermal loads in structural elements. In this contribution the application of these methods using the FE-program ANSYS shall be described by means of two types of realistic building projects.

1 GENERAL PROCEDURE

The first step in fire safety design is the definition of design fires in the form of heat-release-time curves specially adapted to the building in question and the relevant fire scenarios. Subsequently, the effects of a design fire on a building and its load bearing structure are evaluated using simulation models, depending on the complexity of the building with zone or CFD-models. The temperatures calculated in these analyses are the basis of the simplified and advanced calculation methods of the Eurocodes.

In Germany the fire safety design of large railway structures like tunnels and stations can rely on special pre-defined design fires that were developed by the German railway services on the basis of Eurocode 1-1-2 (DIN EN 1991-1-2, 2010) and the specific geometric properties and fire loads of typical train cars.

Design fires for buildings like airplane hangars are not standardized in Germany and have to be derived for the special case. Similar to the design fires for train cars, the special geometric properties (like width and height of airplanes) are taken into account.

2 PROJECT EXAMPLE: TRAIN STATION "OSTKREUZ" IN BERLIN

2.1 Description of the Construction

The building in consideration is a crossing station in the city of Berlin, where the S-Bahn and long distance train lines intersect on two levels (see figure 1). The platform and the tracks supports of the upper level are made from steel girder grids supporting a concrete slab. The girders are single span beams carried by solid supports and supporting walls. The width of the superstructure is approx. 70 m and has almost the dimension of a tunnel.

A burning train located directly below the superstructure carrier represents the worst case fire scenario. The main task for the fire safety design of the superstructure was to prove that the steel parts of the structure withstand the effects of a fire long enough without loss of load carrying capacity and to devoid fire protection measures such as covering or coating.

2.2 Fire Scenarios and Design Fires

By means of a CFD simulation (computational fluid dynamics) the determination of temperature over the period of the fire is calculated using the program FDS (McGrattan, K. B. et al., 2010).

In fig. 2 the relevant time-temperature-curve of the train fire is shown. This time-temperature curve has been measured at the open carriage door one metre above the roof of the car.

Figure 1 Crossing station in Berlin with overlapping platforms (Source: Deutsche Bahn)

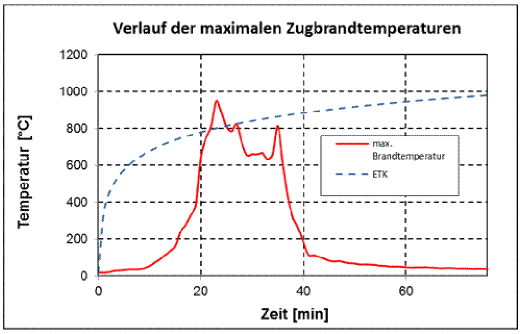

Figure 2 Development of the maximum fire temperature

The time period during which temperatures > 200 °C act on the structure, is approx. 25 minutes. At the time of the maximum impact 950 °C are reached for a short time. For comparison, the uniform-temperature-time-curve (UTTC) is also shown in Fig 2.

2.3 Thermal and Mechanical Analysis

The thermal and mechanical analysis was performed with the FE program ANSYS. The mechanical analysis examined the load bearing and deformation behaviour of the construction. The temperatures acting on the structure over the duration of the fire, as well as the mechanical loads and the non-linear temperature-dependent material properties were taken into account.

Fig. 3 shows the vertical deformation of the loaded cross member over the period of fire exposure. It is clearly visible how the course of the deformations corresponds with the natural fire curve of the thermal load (fig. 2). At the end of the fire, the influences of the temperatures on the load-bearing structure are getting smaller and the deformations are reduced.

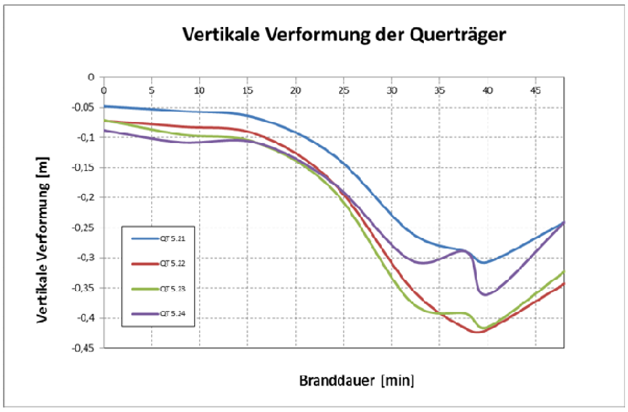

Fig. 3 Deformation of the cross-members during the time of the fire

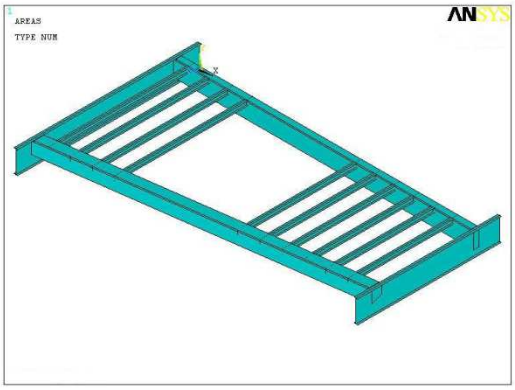

Fig. 4 Three-dimensional model of the steel girder grid of the platform level

The calculations showed that the failure criteria of the distortion were met over the entire period of stress. The results of the simulation show that the girder grid made from unprotected steel resists a natural train fire with temperatures above 900 °C and does not fail in the event of a fire. No fire protection measures such as insulating surface protection for the steel are required.

3 PROJECT EXAMPLE: PARKING DECK

3.1 Description of the Construction

The BBC Böblingen Center has a length of 190 m and a width of approx. 130 m. It consists of six floors. The ground floor and the first floor are intended for trade. Above this three levels of parking are located. The structure consists of steel-reinforced concrete, steel columns and composite beams. The steel girders of the composite slab and steel supports in the garage are to be classified in fire resistance class F 90. It is planned to provide the support beams and supports with an intumescent coating which allows a classification in fire resistance class F 30. Proof is required that the objectives with regard to stability are not compromised during the course of fire. This is done on the basis of natural fire scenarios, where it has to be ensured that the device successfully endures the entire fire load and does not fail.

3.2 Thermal and mechanical Analysis

As fire scenario a burning of 8 cars in parking deck 1 was analyzed. The fire flashover time from car to car was established at 10 minutes. The resulting load temperatures of the burn-up of the cars for the structure were determined using a general nature fire model (CFD simulation). The steel frame is protected with a layer of intumescent coating with the fire resistance rating R 30. The thermal material properties of the coating, such as the thermal conductivity and heat capacity, are specified according to (Dorn 2003).
The warming and the carrying- and distortion behavior of the structure was then simulated according to the General calculation method with the help of ANSYS.
The results were evaluated and compared with selected failure criteria. It was found that the failure criteria for bending and deformation were not exceeded.

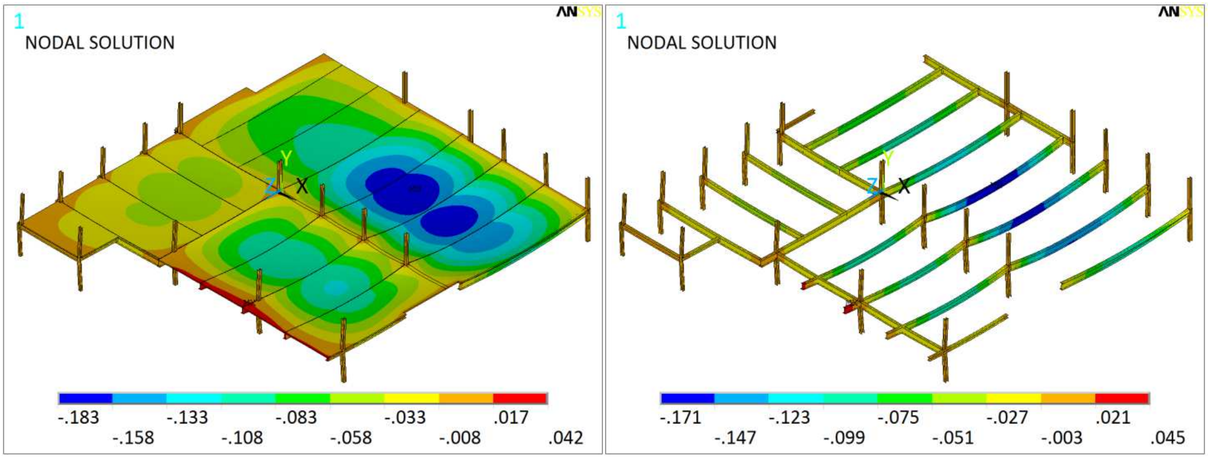

Fig. 5 Deformation in the vertical direction to the 90th minute (left - total system; right - steel construction)

As a result of the compressions in the connections occurring in the heating phase of the fire there will be tensile stresses during the cooling phase. These restraining forces must be considered when the connections are determined. The restraining forces are calculated by multiplying the normal tension with the respective tensioned cross sectional area of the connection. The maximum restraining forces amounted to up to 1300 kN, so that an assessment of the connections for these restraining forces was not possible. As a result, cleats were arranged below the carriers in the connection area, taking over the bearing in the failure of the connection.

4 PROJECT EXAMPLE: AIRCRAFT HANGAR

4.1 Description of the Construction

The hangar discussed here has the outer dimensions of 83.40 m width and 77.60 m depth and an inner area of 6,472 m². The hangar has a horizontally orientated roof, which is supported by the main load-bearing system which consists of an external two truss girders on steel supports. The hangar has a mean interior height of approximately 18.10 m.

4.2 Safety Objectives

Alike to the train station, the main objective that has to be fulfilled by the fire safety design of the construction was a sufficient structural safety in case of fire. Therefore the results from CFD-Simulations should be used for the structural fire design of the steel structure according to the simplified calculation procedures of Eurocode 3 (columns and roof structure). The objective was to use the least possible amount of fire protection measures.

4.3 Fire Scenarios

The fire scenarios are compiled according to the various aircrafts that are to be serviced in the hangar:

- Scenario 1: fire in the cabin of a B747-400 with participation of part of the wings (plastics and kerosene fire), fire surface 100 m², fires in a height of approx. 6 m.
- Scenario 2: cabin fire in a B747-400 in the upper-deck (plastics) without participation of the wings, fire area 50 m², fires in a height of approx. 8 m.
- Scenario 3: local fire, for example larger car or a similar major technical device or storage good, fire area 10 m², fires at a height of 4.0 m.

4.4 Design Fires

To ensure design fires on the safe side, the relevant input parameters must be adopted conservatively, so that all relevant fire events are covered.
It is conservatively assumed that the heat release rate is not reduced after the depletion of the fire load but will remain at the maximum rate of heat release. For that reason, only the nature of the fire load, but not the amount is significant the for the fire safety design. This leads to the fact that the safety objectives in the building will be proven when a stationary state, i.e. a balance of the energy supplied by the fire and the energy dissipated by the smoke and heat exhaust measures is reached. In all fire scenarios extinguishing measures, for example, by the extinguishing system or the airport fire brigade, are not considered to have a direct effect on the heat release rate. They are accounted for conservatively by the partial factor $\gamma_{fi,HRR}$ according to (DIN EN 1991-1-2, 2010).
According to the literature such as the (vfdb-Leitfaden, 2009), area-specific heat release rates of between 150 kW/m² and 500 kW/m² are realistic. In individual cases also values over 600 kW/m² can occur especially in plastics and lubricants. This adds up to the following design fires for the defined fire scenarios (partial safety factors in accordance with (DIN EN 1991-1-2, 2010)):

- Scenario 1 (Fire in cabin + wing): q‘ = 600 kW/m²
- Q‘max [kW] = 600 kW/m² * 100 m² * 1,075 = 64500 kW after approx. 930 s
- Scenario 2 (Fire in upper-deck cabin): q‘=450 kW/m²
- Q‘max [kW] = 450 kW/m² * 50 m² * 1,075 = 24187.5 kW after approx. 720 s
- Scenario 3 (Local fire at support): q‘=500 kW/m²
- Q‘max [kW] = 500 kW/m² * 10 m² * 1,075 = 5375 kW

The mean value of the heat of combustion of the fuel mixture was derived from the specific parameters of the individual substances to be approximately 27 MJ/kg.
The results of the fire simulations carried out have proven to be decisive for the roof structure. Because of the height and the width of an aircrafts and their necessary distance to the steel columns of the building, there was no relevant increase in temperature in their vicinity during the fire simulations. Since no fire scenario could be ruled out, the effects of a localized fire event in the immediate vicinity of the columns were analysed. The temperatures resulting from such a fire were calculated with a Plume-model in accordance with Heskestad (DIN EN 1991-1-2, 2010) using a maximum heat release rate of 5 MW.

4.5 Fire Safety Design

In a next step, a thermal analysis in 3-D was undertaken for the steel columns using the temperatures evolving from the localized fire as thermal load. Here, segments of a height of 2 metres were assumed to receive the same thermal load. It was taken into account that the components were protected by a protective coating up to a height of 8 m.
A thermal analysis for the structure of the roof was not necessary, since the temperatures recorded in the CFD simulation were only at about 400 °C. This temperature is well below the critical temperature of the structural members made of steel, as a result a fire safety design was only required for the columns. This design was carried out using the simplified calculation procedures on resistance level of Eurocodes 3 part 1-2 (DIN EN 1993-1-2, 2005). This was done in the most unfavourable area of the components regarding the internal forces and thermal loads. A fire safety design was not necessary for all stiffening components because they were protected from a critical warming by protective coatings.

5 SUMMARY AND ACKNOWLEDGMENT

The application of computational design methods of the Euorcodes for complete or partial structures can only be performed with powerful FEM programs that are able to depict and calculate the non-linearities of material build-ups and design loads. The heat generation in the

cross section of the components is done by FEM programs as well. Usually a thermal analysis of two-dimensional models is of sufficient accuracy due to the material properties of steel that lead to quick uniform temperatures.
Depending on the complexity of the analysed structures the simplified or general calculation methods of the Eurocode. In the first case, the internal force in the fire case can be calculated using simple standard software, in the latter case more complex 3-D mechanical analysis is required.
With the rapid development and the increasing capacity of the computer coupled analysis of 3-D models will be possible in the future. Further research in these areas will extend the possibilities of the design of constructions, reduce the cost of planning the implementation of a project, and shorten the time for the realisation of buildings by the reduced structural fire protection at the same level of safety.
We would like to thank hkm Management AG and the Deutsche Bahn AG for the excellent cooperation.

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