1.1. Design fires for structural engineering

M. Gillie
School of Engineering, University of Edinburgh, Edinburgh, UK

F. Wald & K. Horová
Czech Technical University in Prague, Czech Republic

1.1.1 THE NATURE OF BUILDING FIRES

1.1.1.1 General

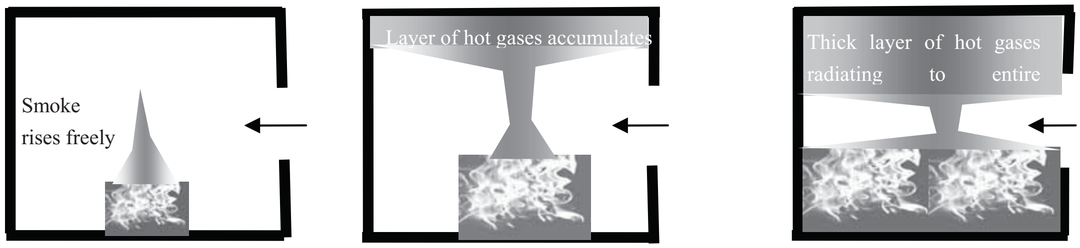
To design structures to resist fire loading, some assessment of the likely gas temperatures to which they may be subjected is required. The first part of this paper summarizes the nature of fires that occur in buildings with reference to relevant tests. The study of fire dynamics is a subject in its own right so only an overview of the available knowledge as applicable to the design of building structures can be given here. For a complete survey of fire dynamics see Drysdale (1998).

Since fire is a highly complex phenomenon and the various factors affecting its behaviour are unlikely to be known with any certainty for most structures, it is necessary to develop models of building fires that simultaneously account for the likely variation in the possible fires that could occur, and are sufficiently simple to apply in design. The second part of the paper discusses the various ways in which building fires may be modelled. In the final section of the paper three compartment fire tests are reviewed and the results from these tests compared with the predictions of gas temperatures that the various models of compartment fires make.

1.1.1.2 Fires in small compartments

Most building structures are divided into a number of compartments such as offices, meeting rooms etc. From a fire safety perspective these divisions are significant for two reasons. Firstly they provide a means of preventing fire spread and hence often allow a structure to be designed on the assumption that a fire will only occur in a single compartment. Secondly a fire occurring within a compartment will develop in a different manner to a fire in an unrestricted space. Historically most research into the behaviour of compartment fires has focussed on small compartments and assumed a reasonably uniform distribution of fuel. This work has informed most of the design fires currently used in structural design and will be discussed in this section. The following section will consider the behaviour of fires in the larger compartments that are increasingly present in modern structures.

Immediately after ignition the behaviour of a fire in a small compartment will not be affected by the compartment boundaries. However, hot gases will not be free to escape from the compartment but, due to buoyancy effects, will begin rapidly to accumulate in a layer under the ceiling. As the fire grows in size and the layer of gases develops, a point will be reached when the downward radiation from the smoke layer becomes sufficiently intense to ignite objects distant from the seat of the fire. Assuming a sufficient supply of air, this will result in full involvement of all combustible materials in the fire. The transition from localised to fully involved burning tends to be rapid and is known as “flashover”. The above process is indicated in Fig. 1. After flashover, the rate of heat release within the compartment is controlled by the rate of supply of air through openings such as doors and windows. This is a ventilation controlled fire and in sufficiently small compartments will result in fairly uniform temperatures at any level within the compartment.



a) Early stage compartment fire unaffected by compartment

b) Pre-flashover fire

c) Flashover results in fully involved burning.

Figure 1.1.1. The growth of a compartment fire.

1.1.1.3 Fully-developed fires

The rate of heat release rate in fully-developed (flashed-over) fire in buildings is normally controlled by the amount of oxygen available. The most widely quoted relationship between the rate at which fuel in consumed in ventilation controlled fires and degree of ventilation is that of Kawagoe (1958), reported, for example, in Rasbash *et al* (2004) as

$$\dot{m} = KA\sqrt{H} \tag{1.1.1}$$

where A is the area of ventilation opening and H its height. Kawagoe derived this result from fire tests in compartments containing wooden cribs. The value of constant the K is somewhat uncertain but is often quoted between 0.5 and $0.9\text{kgs}^{-1}\text{kg}^{5/2}$, depending on the size and shape of the ventilation opening. Various more refined versions of relationships similar to Kawagoe's are available. By multiplying the rate of mass loss by the heat of combustion of the fuel, h_c, an estimate of the rate of heat release within a compartment fire can be obtained as

$$\dot{q} = KA\sqrt{H}\,h_c \tag{1.1.2}$$

Typical value of h_c for various fuels are shown in Table 1.1.1.

Table 1.1.1. Heat of combustion, h_c, of common fuels. Obtained from DiNenno (2002), Drysdale(1998) and EN 1991-1-2, 2004.

Fuel	Heat of combustion
MJ/kg	
Wood (Beech)	19.5
Wood (Pine)	17.5
Leather	20
Wool	20.5
Nylon	30
Polyester	24-30
Alcohols	30
Petroleum	45
Diesel	45
Coal	30

1.1.1.4 Fire in large compartments and travelling fires

Experimental and analytical evidence increasingly suggests that in larger fire compartments, such as typical office spaces, the assumption of uniform temperatures at any level within the compartment is not valid. Instead, fires in larger compartments will tend to travel within the compartment as fuel is consumed at a rate governed by the available ventilation. This causes variations in gas temperatures within such compartments that are not present in older descriptions of compartment fires.

The first clear evidence of this was presented by Cooke (1998) who undertook a number of fire tests with uniform fire loads of wooden cribs in a long, thin (4.5×8.75×2.75m high) compartment in which ventilation was provided at one end. The results showed a clear progression of temperature within the compartment. Peak values occurred near the source of ventilation early in the fire and then progressed away from the opening as fuel was consumed. This progression occurred even when ignition was distant from the source of ventilation. The progression of the peak temperature from the front to the rear of compartment took 20-30min, with higher levels of ventilation resulting in more rapid fire spread.

Similarly Welch *et al* (2007) report on a series of fire tests undertaken in a 12×12×3m high compartment in which a combination of wood and plastic fuel was burnt. Ventilation was provided either along one or two walls of the compartment. The tests were heavily instrumented which allowed both temperature and heat-flux maps to produced after various periods of burning. Although the differences in temperature were modest, when converted to incident heat-fluxes on the compartment ceiling, very significant differences arose as a result of the T^4 dependence of radiation.

Correspondingly, the effect of non-uniform gas temperatures on structural temperatures has been shown to be significant in recent work by Gillie and Stratford (2007) who reported on temperatures in a concrete slab above a fire compartment. Lower surface concrete temperatures varied by as much as 400°C despite a compartment size of only 3.5m by 4.5m.

The above results have all been recorded in compartments that are still small in comparison the many modern office spaces and so highlight the need for a new approach to defining design fire for structural fire engineering.

1.1.2 DESIGN FIRES

1.1.2.1 The nominal standard fire

The nominal standard fire curve is the best known and most widely used method of estimating temperatures in compartment fires. It assumes that the temperature in a fire compartment is uniform and that it increases indefinitely according to a logarithmic relationship with time, see Figure 1.1.2. The nominal standard fire curve has been incorporated, with minor differences, into a number of design standards worldwide. In EN 1991-1-2, 2002 the gas temperature, θ in °C, at time t in minutes, is given as

$$\theta = 20 + 345\left[\log(8t+1)\right] \tag{1.1.3}$$

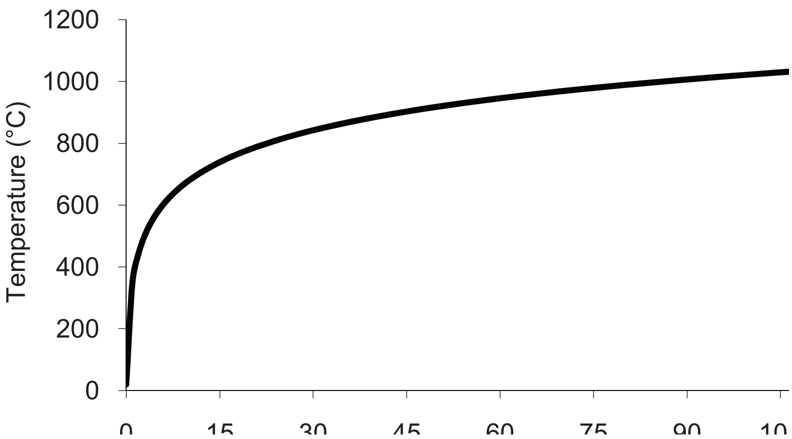


Figure 1.1.2. The nominal standard fire curve as defined in EN 1991-1-2.

This form of temperature-time relationship was originally derived from measurements of tests taken early in the 20th century and has been shown to have only a very limited similarity to the temperatures in real compartment fires. Notable shortcomings in the Standard Fire curve include the lack of a cooling branch and no dependence on either fuel load or the available ventilation. Thus it is often referred to as a "nominal" temperature-time curve.

Until recently almost all structural fire design was based on prescriptive methods where there is no requirement to make an explicit assessment of the likely response of a structure to fire. Instead, fire protection is specified based on tests of single structural elements subject to Standard Fires. The relationship between such single element tests and real, global structural behaviour in fire is limited at best so the crude nature of the Standard Fire curve is not seen as problematical for prescriptive design.

Over the last ten to fifteen years, performance-based methods have been introduced to structural fire engineering. These do require the designer to make assessments of structural behaviour in fire, as assessments are made for other types of loading. Adopting the Standard Fire curve in performance-based design is difficult to justify on scientific grounds due to its lack of similarity with real fires and cannot be advised. Despite this, its use remains widespread, partly due to its ubiquity in other branches of fire engineering and partly due to the high and sustained temperatures that it predicts being seen as conservative.

1.1.2.2. Heat balance and Zone models

Recognising that the Standard Fire curve was not physically reasonable, researchers in Sweden in the 1970s (Pettersson *et al,* 1976) developed a method of predicting fire temperatures by considering the heat balance in a fire compartment. By assuming

- the temperature within a fire compartment is uniform,
- all available fuel is burnt within the compartment,
- and that the thermal properties of the compartment walls are uniform,

the heat balance can be expressed as

$$\dot{q}_c = \dot{q}_L + \dot{q}_W + \dot{q}_R \tag{1.1.4}$$

where $\dot{q}_c$ is the rate of heat release due to combustion, $\dot{q}_L$ is the rate of heat loss due to the replacement of hot gases by cold, $\dot{q}_W$ the rate of heat loss through the compartment boundaries and $\dot{q}_R$ the rate of heat loss due to radiation through the compartment openings. By evaluating these terms it is possible to arrive at a differential equation that relates the temperature within the compartment to the fuel load, the available ventilation and thermal properties of the compartment walls. The solution to this equation cannot be expressed explicitly so compartment temperatures based on Pettersson's approach are normally presented graphically for various fire loads and ventilation conditions, e.g. Drysdale (1998) or Buchanan (2000).

The lack of an explicit solution to Petterson's model was addressed in EN 1991-1-2 by instead using a parametric approach that fits a curve to the experimental data originally used to validate Petterson's approach. The input variables are very similar and take account of fire load, ventilation conditions and the thermal properties of the compartment. Additionally, a fire growth rate is included and different behaviour is predicted for ventilation and fuel controlled fires. Full details of how to use this approach are given in EN 1991-1-2 and are also presented by Franssen and Zaharia (2005) in a rather clearer manner. A comparison of predicted gas temperatures for a typical compartment with various ventilation conditions is shown in Figure 1.1.3.

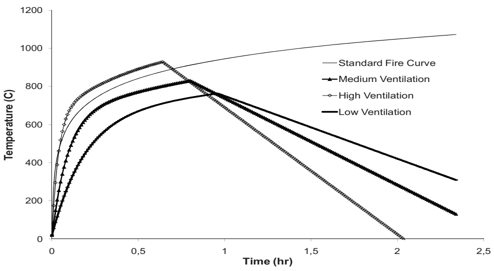


Figure 1.1.3. Predicted temperatures within a compartment for various ventilation conditions using the parametric approach. The Standard Fire curve is shown for comparison.

Petterson's model is the simplest example of a class of compartment fire models known collectively as "zone models". These all represent compartment temperatures by considering energy, mass and momentum conservation with various levels of sophistication. One-zone models, such as Pettersson's assume that all the gases within a compartment are at an equal temperature, whereas "two-zone" models divide the gases into an upper, hot zone and a lower, cooler zone. The more sophisticated zone models allow for factors such as compartment boundaries with varying thermal properties and multiple compartment openings to be included in analyses. Models that account the interaction between fires in more than one compartment are also available. All but the simplest zone models require numerical solutions

Approaches such as these remove some of the shortcomings of the Standard Fire test. Notably cooling behaviour is included and the effects of compartment geometry and ventilation conditions are accounted for. Thus, their use in performance-based design can be justified on the basis that the key factors affecting fire behaviour are included in the predictions of gas temperatures. Since the models are also reasonably straightforward to use they are attractive for routine designs where more onerous calculations would not be economic.

Despite their benefits, heat-balance and zone models do have restrictions on their applicability and fail to capture some aspects of fire behaviour. The most significant simplification is the assumption that at any level within a compartment gas temperatures are uniform. This has always been regarded as a reasonable assumption for small compartments – the EN 1991-1-2 parametric equation is applicable for compartments up to 500 m^2 floor area – although the recent work discussed above suggests significant variations in temperature will occur even in small compartments. For compartments larger than around 500 m^2 uniform burning, and therefore temperatures, are unlikely because of restrictions on air supply to the fire. If simple heat balance estimates are applied to large compartments, a more severe fire than is in fact likely will be predicted because peak temperatures will not be reached simultaneously across the whole area of the compartment (Cooke, 1998).

1.1.3 COMPUTATIONAL FLUID DYNAMICS

Computational Fluid Dynamics (CFD) models of fire growth and behaviour have been available for some years. CFD modelling is a numerical approach to representing fluids that divides a fluid domain into small volumes and considers conservation of mass, energy etc. within each volume. Software exists that can represent the very wide range of physical phenomena known to affect fire behaviour including compartment geometry, heat release rates of burning fuel, complex ventilation conditions, turbulent gas flow, soot production and many others. Using such software is complex and time-consuming and for this reason CFD models are currently little used in design work.

If the greater resolution of fire behaviour available from CFD models is considered to worth the additional effort, great care must be taken when obtaining and interpreting predictions as the output can be influenced hugely by even minor differences in input data. Obtaining the full range of input data needed in a sufficiently accurate and precise manner will be impractical for most structural engineering problems. The implications of not having the correct input data was highlighted in a recent study where Rein *et al* (2007a) compared the blind predictions of a fire in a very well defined compartment by nine different analysts using CFD methods. The predictions varied very widely. Rein *et al* concluded that at present CFD predictions of fire growth are not sufficiently reliable to be used in engineering design unless directly supported by experimental validation. However, they also noted that if the use of CFD models is restricted to predicting gas temperatures for a given fire heat release rate, good predictions can be made. The use of CFD in this way is likely to be advantageous for structures with complex compartment geometries for which the use of zone models can not be justified.

1.1.4. COMPARISON TO FIRE TESTS

1.4.1. Cardington fire test 2003

The structural integrity fire test, large scale test No. 7, was carried out in a centrally located compartment of the building, enclosing a plan area of 11 m by 7 m on the 4th floor. The preparatory works took four months. The fire compartment was bounded with walls made of three layers of plasterboard (15 mm + 12,5 mm + 15 mm) with a thermal conductivity of between 0,19 - 0,24 Wm^{-1}K^{-1}. In the external wall the plasterboard is fixed to a 0,9 m high brick wall. The opening of 1,27 m high and 9 m length simulated an open window to ventilate the compartment and allow for observation of the element behaviour. The ventilation condition was chosen to produce a fire of the required severity in terms of maximum temperature and overall duration. The columns, external joints and connected beam, about 1,0 m from the joints, were fire protected to prevent global structural instability. The fire protection used was 18 - 22 mm of Cafco300 vermiculite-cement spray, with a thermal conductivity of 0,078 Wm^{-1}K^{-1}.

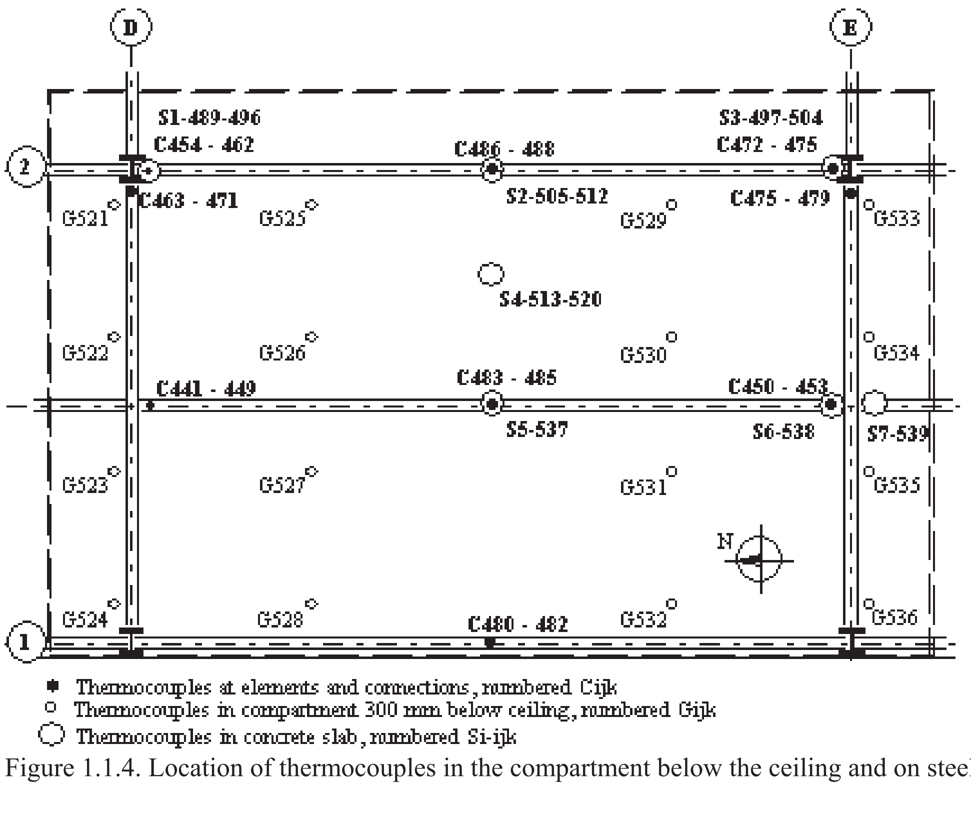


Figure 1.1.4. Location of thermocouples in the compartment below the ceiling and on steel structure.

The geometry and measured material properties of the flooring system are summarised by Wald et al (Wald et al, 2003). . Wooden cribs with moisture content 14 % were used to provide a fire load of 40 kg/m^2. The instrumentation used included thermocouples, strain gauges and displacement transducers. A total of 133 thermocouples were used to monitor the temperature of the connections, the steel beams within the compartment, the temperature distribution through the slab and the atmosphere temperature within the compartment, see Figure 1.1.4.

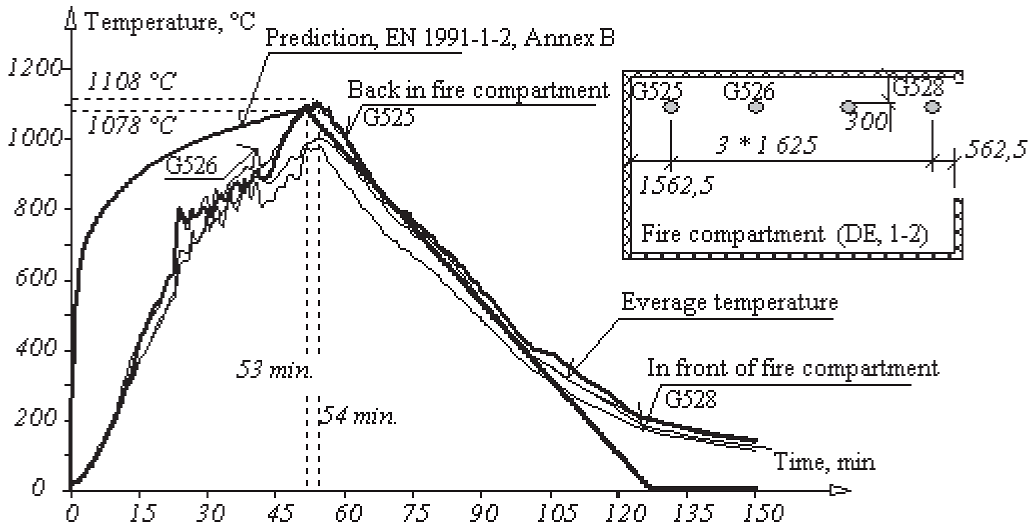


Figure 1.1.5. Comparison of the prediction of the gas temperature to the measured temperatures.

The quantity of fuel and the dimensions of the opening in the facade wall were designed to achieve a representative fire in an office building. Figure 1.1.5 shows the measured time-temperature curve within the compartment. In the initial stages of the fire the temperature within the compartment grows rapidly to reach a maximum temperature of 1107,8 C after about 54 min. The maximum recorded compartment temperature occurred near the wall of the compartment. Figure 1.1.5 also compares the temperatures predicted by the parametric curve given in EN 1991-1-2: 2003 with the test results. The parametric curve predicts a maximum temperature of 1078 °C after 53 min and this compares well with the test results, see (Wald et al, 2004).

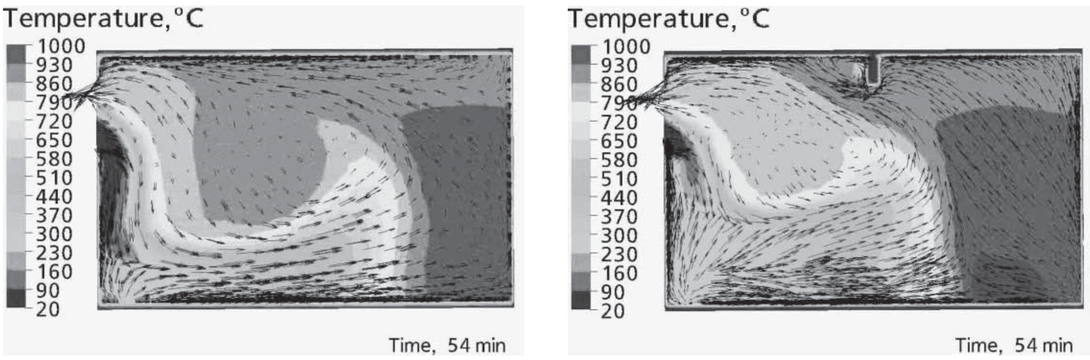


Figure 1.1.7. The influence of the secondary beam in the ceiling simulated by CFD code Almeida et al (2007).

The influence of the secondary beam with 0,5 m height placed at the ceiling in the draining and in the distribution of temperatures of the involving fluid was simulated by CFD code, see Figure 1.1.6 from Numerical simulation of the 7th Cardington Compartment Fire Test using a full conjugate heat transfer approach. The study confirming the difference till 10 % lead to the conclusion that the beam affected the results quite significantly. This was due to the manner in which the beam changed the flow pattern. Figure 1.1.7 shows the velocity field at the symmetry plane, for both simulations (with and without beam). Analysis of this results revealed that the vortex from the simulation with the beam was reduced in the middle back of the compartment and was directed towards the opening as time proceeded. The presence of the beam showed to have a significant role in the general vortex development, thus affecting the velocity and temperature field.

1.4.2. Ostrava fire test 2006

The structure of Ostrava fire test was composed of tree storey steel structure with the composite slabs, the beam-to-beam and beam-to-column header plate connections, and the diagonal wind bracings. Internal size of fire compartment was designed 3,80 x 5,95 m with height of 2,78 m. The structure of enclosure was made from the light silicate and ceramic bricks. Opening of 2400 x 1400 mm ventilated the room during the fire. The doors of fire compartment 1400 x 1970 mm and columns were equipped by the fire isolation by boards, see Figure 1.1.6.

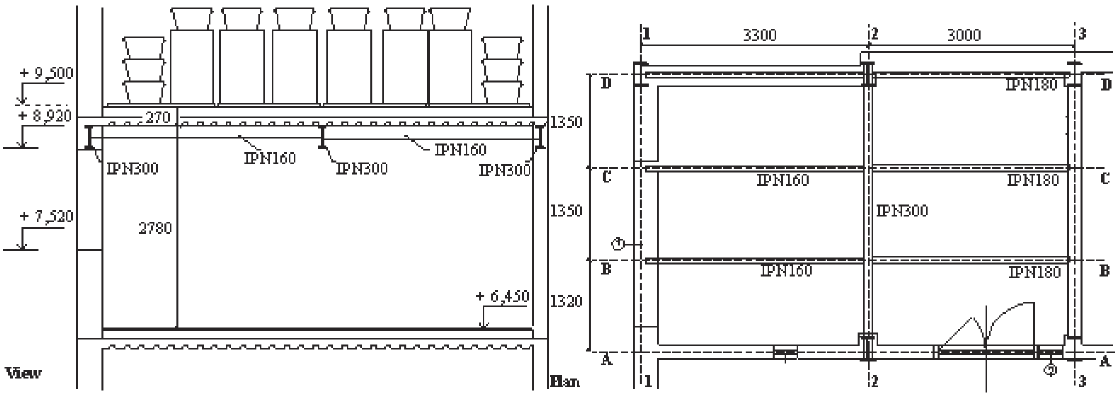


Figure 1.1.6. Geometry of the fire compartment.

Fire load was represented by the unwrought timber bars 50 x 50 mm of length 1 m from softwood with moisture till 13% For the compartment fire were the bars placed into eight piles.

The gas temperature in the fire compartment was measured by four thermocouples 300 mm below ceiling, marked at Figure 1.1.7 as TGi. Two thermocouples were placed in front of the fire compartment 0,5 m and 1 m from front wall.

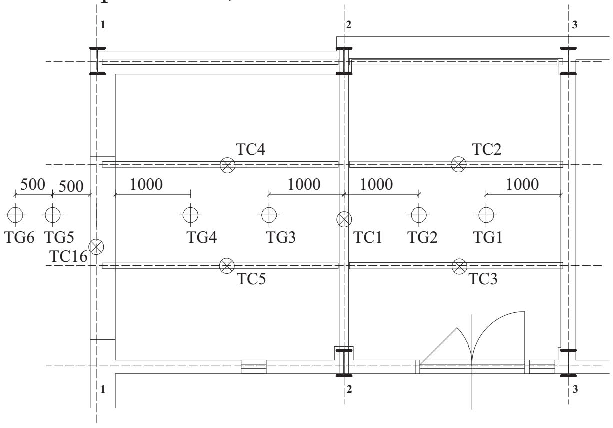


Figure 1.1.7. The position of the thermocouples for recording of gas and beams temperatures.

Figure 1.1.9 shoes the comparison of the predicted gas temperature in the fire compartment by parametric fire curve according to EN 1993-1-2:2005 Annex A, and of the predicted primary beam temperature to the measured values.

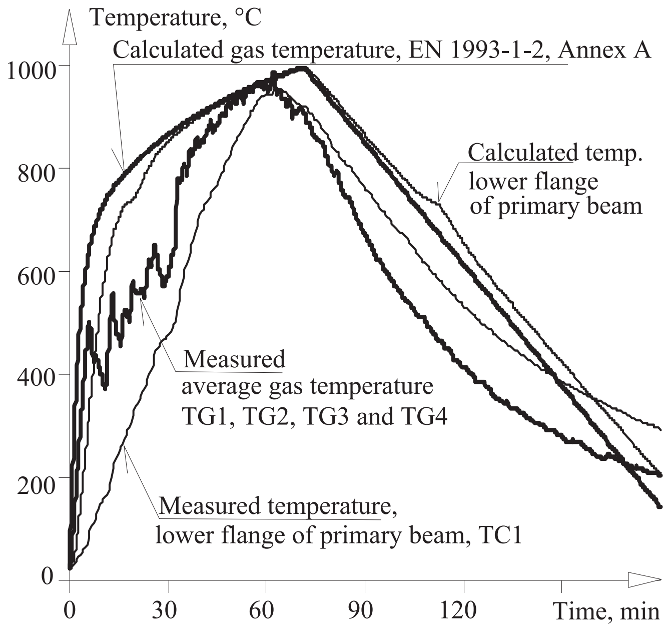


Figure 1.1.9. Comparison of the predicted temperature by the parametric fire curve to the measured average gas temperature and primary beam temperature.

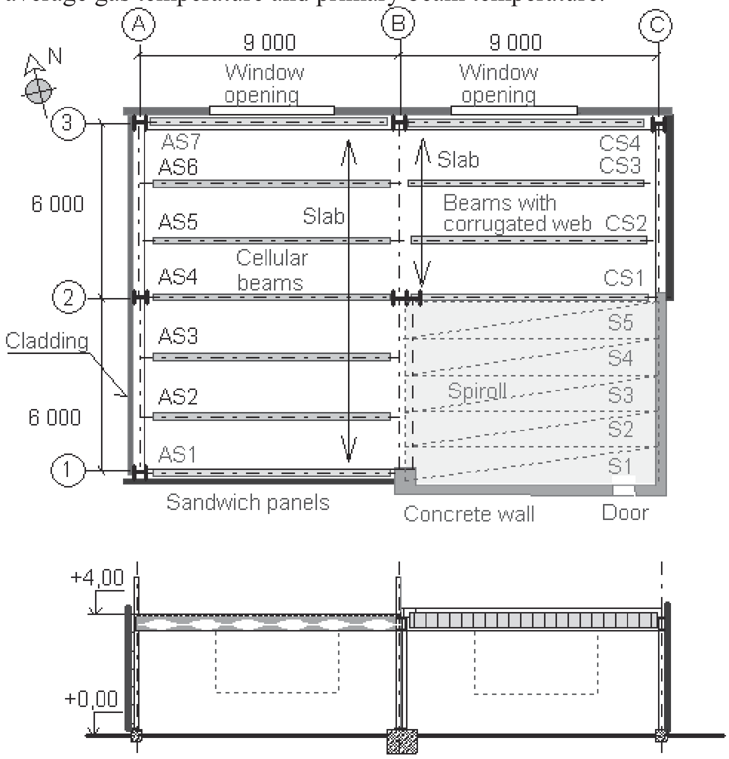


Figure 1.1.10. Fire compartment with description of the major floor and wall structures.

1.4.3. Mokrsko fire test 2008

The structure in Mokrsko fire test represents one floor of the administrative building of size 18 x 12 m, see Figure 1.1.10. The composite slab on the castellated beams was designed with a span 9 to 12 m and on beams with corrugated webs with a span 9 to 6 m. The deck was a simple trapezoidal composite slab of thickness 60 mm with the height over the rib 120 mm with sheeting . Two walls were composed from cladding, linear trays, mineral wool and external corrugated sheets. In two 6 m spans were compared the system with the internal grid and horizontal sheeting and with vertical sheeting without the internal grid. Two other walls are made of sandwich panels of thickness 150 mm filled with mineral wool. In front of the concrete wall was brick over by plaster blocks. The fire protection of columns, primary and edge beams as well as bracings was designed for R60 by board protection 2 x 15 mm Promatect H. The fire load created 15 m^3 unwrought wooden cribs 50 × 50 mm of length 1 m of softwood. The cribs were placed into 50 piles. The openings of height 2,54 m and total length 8,00 m with parapet 1 m ventilated the compartment. To allow a smooth development of fire no glassing was installed.

The gas temperature in the fire compartment was measured by 14 jacketed 3 mm thermocouples located 0,5 m below the ceiling in the level of the beams lower flanges. Two thermocouples were placed in the openings. The temperature profile along the compartment height was measured between the window and in the back of the fire compartment below the backward secondary beam. The location of the thermocouples is shown in Figure 1.1.11.

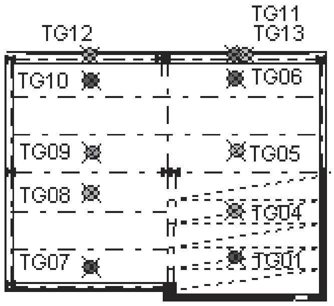


Figure 1.1.11. Location of thermocouples below the ceiling and in the window openings.

Figure 1.1.12 shows the comparison of prediction of the gas temperature by nominal and parametric fire curve to the measured average temperatures from part and whole fire compartment. The sensitivity of the prediction by zone model to the combustion factor *m* for fire growth rate coefficient t_α = 300 s is documented on Figure 1.1.13.

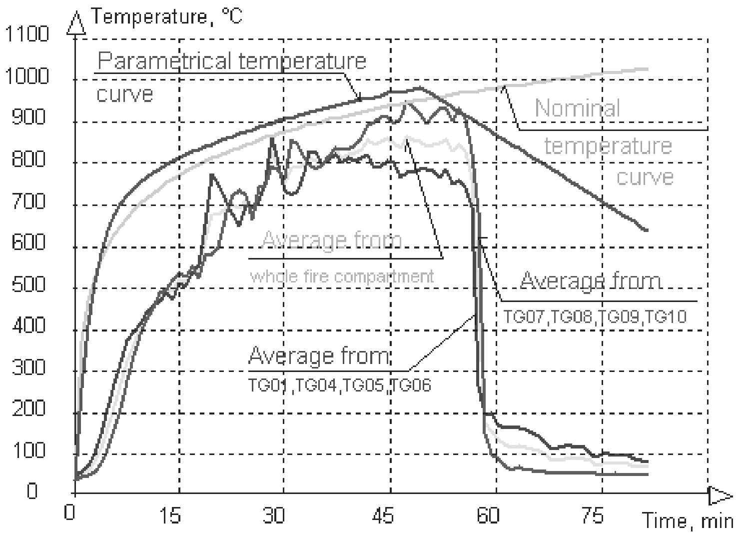


Figure 1.1.12. Comparison of prediction of the gas temperature by nominal and parametric fire curve to the measured average temperatures from part and whole fire compartment measure 500 mm under the ceiling.

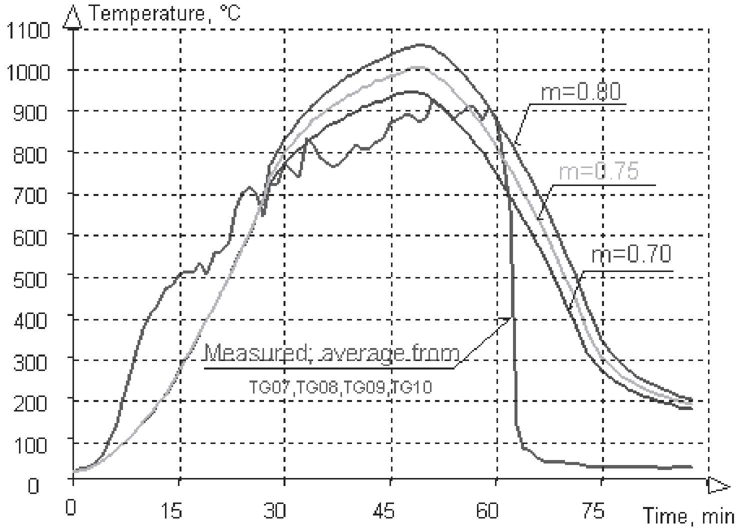


Figure 1.1.13. Prediction by zone model with different combustion factors *m* for fire growth rate coefficient $t_\alpha = 300$ s.

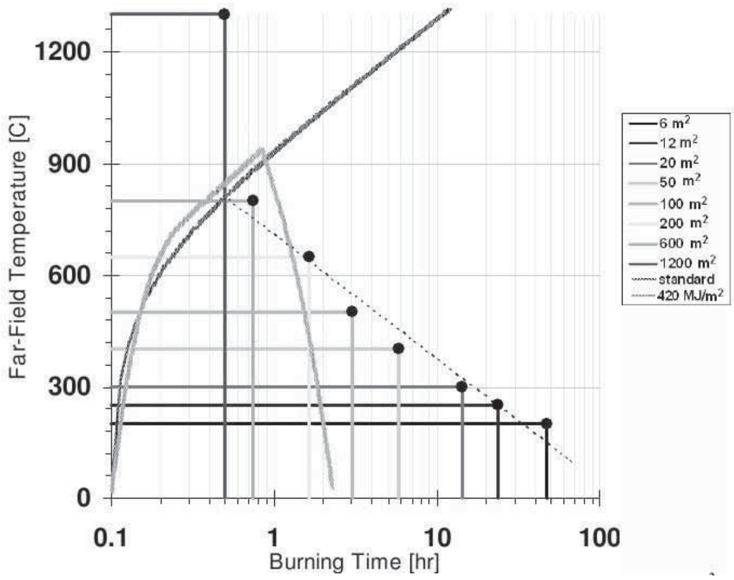


Figure 1.1.14. Predictions of far-field temperatures for different sizes of travelling fire in a 1250 m^2 compartment using a near-field/far-field approach. The nominal standard fire curve and parametric curve predictions for a fire load 420 MJ/m^2 are shown for comparison (Rein, 2007b).

1.1.5. FURTHER DEVELOPMENTS

The recently acknowledged variability of temperatures in large fire compartments, have led researchers to begin developing new approaches to modelling compartment fire behaviour that are more sophisticated than the simple heat-balance approach but avoid the complexities and uncertainties of CFD models. Rein *et al.*(2007b) proposed a model consisting of "near-field" and "far-field" temperatures where the far-field temperatures result from hot gases and near-field temperatures from direct impingement of a flame. They proposed that the duration of exposure to near-field temperatures in well a ventilated fire is governed by the available fuel load and that for office fires this will be of the order of 15 minutes. Exposure to far-field temperatures was found to be around 10 times longer and dependent on the size of the fire (itself governed by the ventilation conditions) and geometry of the compartment. This method produces predictions of fire size, temperature and rate of travel based on fuel load and ventilation and thus appears to offer a useful method for predicting gas temperatures in large compartments that avoids the assumption on uniform temperatures present in other methods.

However, it is still under active development and will probably be refined further. Figure 1.1.14 shows predictions of far-field temperatures for an example case. If should be noted that in addition to the temperatures shown in this figure, structural elements may experience short exposure to near-field temperatures. This will be of the order 1250°C.

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