

Modelling of Structures in Fire: an Example of the Boundary Condition

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ABSTRACT

The collapse of the World Trade Center Towers 1, 2 and 7 on September 11th 2001 has highlighted the need for proper understanding of the behaviour of structures in the event of a fire. A detailed analysis of the fires and the behaviour of the structures followed the events revealing numerous gaps of knowledge and uncertainties within the methodologies that are generally used by engineers and that are meant to deliver building designs that can be deemed as safe. Detailed modelling of the fire can only be achieved via Computational Fluid Dynamics (CFD) and of the structure using Finite Element Models. The integration of both models implies an adequate understanding of the boundary condition. This paper will analyse the boundary condition between the gas phase environment generated by the fire and the solid phase representing the structural members and protective elements. As an application example the performance of high-rise steel framed structures in the event of a large uncontrolled fire will be evaluated using the Fire Dynamics Simulator (FDS) CFD code and ABAQUS Finite Element Model.

1. INTRODUCTION

From the perspective of a Fire Safety, the design of a building can be approached in two different ways. The first is for the building to comply with existing regulations, and the second one is to achieve certain safety goals. Regulations have not been developed to fully specify the design of unique and complex buildings such as high rises and even, in the event that they existed, they are of questionable effectiveness. Furthermore, if a scenario such as the one of September 11th, 2001 needs to be considered as a possible event during the life of the building, design on the basis of safety goals is the only path that can be followed.

The schematic presented in Figure 1 could represent the behaviour of a building in the event of a fire. It could be argued that the safety objective should be that the time to evacuation (t_e) at each compartment (i.e. room of origin, floor, building) be much smaller than time necessary to reach untenable conditions in the particular compartment (t_f). Characteristic values of t_e and t_f can be established for different levels of containment, room of origin, floor, building. Furthermore, it is necessary for the evacuation time to be much smaller than the time when structural integrity starts to be compromised (t_s).

In summary:

$$\begin{aligned}t_e &\ll t_f \\ t_e &\ll t_s\end{aligned}$$

It could be added to these goals that full structural collapse is an undesirable event, therefore:

$$t_s \rightarrow \infty$$

Although these criteria for safety times can be considered as a simplified statement, it is clear that it describes well the main goals of fire protection.

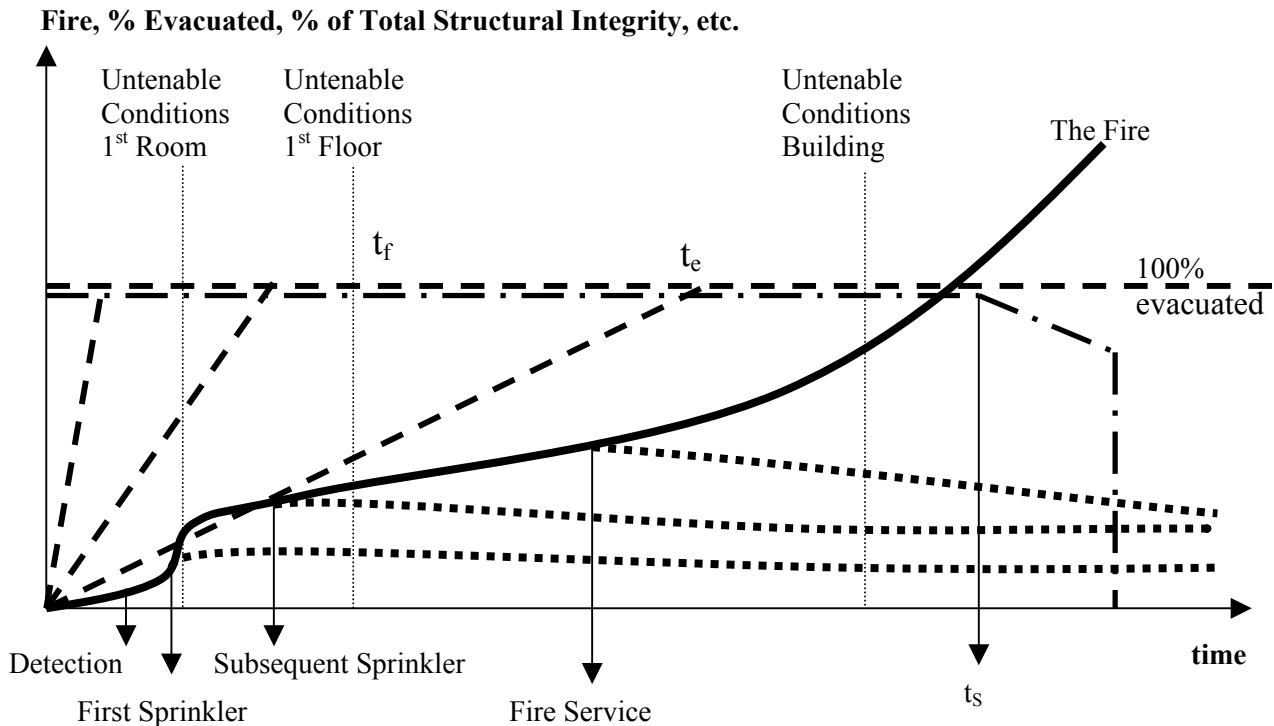


Figure 1 Schematic of the sequence of events following the onset of a fire in a multiple story building. The thick line corresponds to the “fire size,” the dotted lines to the possible outcome of the different forms of intervention (sprinkler activation, fire service). The dashed lines are the percentage of people evacuated, with the ultimate goal of 100% represented by a horizontal dashed line. The dashed & dotted line corresponds to the percentage of the full structural integrity of the building.

With the objective of achieving these goals a number of safety strategies are put in place. These include those strategies that are meant to increase t_f which include active systems, such as sprinklers, or the intervention of the fire service. As shown by Figure 1 (dotted lines), success of these strategies can result in control or suppression of the fire. Passive protection such as thermal insulation of structural elements becomes part of the design with the purpose of increasing t_s . Finally, but most important, evacuation protocols and routes are design to minimize t_e at all stages of the building. It is important to note that within the estimation of t_e the safe operations of the fire service need to be included.

The events following the attack on the World Trade Center showed that these safety goals were not attained and illustrated why it is essential to have the best possible understanding of how structures will behave in the event of a fire. For this purpose an adequate understanding of the nature of the possible event and the characteristic of the structure and its safety systems is necessary. This requires a detailed understanding of the fire conditions, the interactions between the fire and the structural elements and the sequence of the intervention and evacuation processes. Different methodologies and tools have been developed to study each of these aspects. This paper will concentrate on a methodology that can be used to assess the boundary condition between the structural elements and the fire. An application example from a fictitious building that resembles an existing high rise will be used to illustrate this methodology.

1.1 The Boundary Condition

Fire resistance calculations have been conducted in the past and are being conducted currently on the basis of a simulation of the fire by means of Temperature vs. Time curves. Whatever temperature evolution is used [1,2] the methodology is the same. A heat flux is imposed on the structural element on the basis of a boundary condition defined by the gas phase temperature. The gas phase temperature is assumed to be that of the fire compartment. Then the energy equation of the structural element can be solved [3]. The energy equation can be of two forms depending on the thermal thickness of the material:

$$\rho_s C p_s V_s \frac{dT}{dt} = A_s \dot{q}_s'' \quad (\text{Thermally Thin Material- i.e. Steel})$$

$$\rho_s C p_s \frac{\partial T}{\partial t} = k_s \frac{\partial^2 T}{\partial x^2} \quad (\text{Thermally Thick Material – i.e. Concrete})$$

Where the boundary condition for both cases corresponds to the input from the fire and is given by:

$$\dot{q}_s'' = h(T_g - T_s) + \varepsilon_g \sigma T_g^4 - \varepsilon_s T_s^4 \quad (\text{Thermally Thin Material})$$

$$\dot{q}_s'' = h(T_g - T_s) + \varepsilon_g \sigma T_g^4 - \varepsilon_s T_s^4 = -k_s \left. \frac{\partial T}{\partial x} \right|_{x=0} \quad (\text{Thermally Thick Material})$$

Where T_g is the imposed temperature of the gas as defined by the Temperature vs. Time curves. The emissivity of the solid surface is given by ε_s and that of the gas by ε_g . For simplicity heat exchanges with the outside environment have been ignored but could be included in these expressions. For the thermally thin elements A_s will be the exposed area. The unexposed area can be ignored or treated as a loss to some ambient temperature. For the thermally thick materials the boundary condition at the other end will be fixed based on the conditions established for this side of the element. If a fire is present at the other side then a similar boundary condition will be included at this end, if no fire is imposed a heat loss to an ambient temperature can be used.

A very different way of defining the boundary condition is by assuming that the surface temperature of the structural element is that of the gas. This is a simpler boundary condition that requires the introduction of less parameters, but currently is consistently deemed as not describing properly the physics of the heat transfer process.

The concept of Temperature vs. Time curves implies a number of simplifications of which the main are:

- The compartment fire temperature is homogeneous with no spatial differences worth considering.
- The radiation field is in thermal equilibrium within the gas phase, i.e. there is no radiation exchange between soot particles and the gas, and thus gas temperatures can be used to establish radiative heat fluxes.
- The optical depth within the gas phase is much smaller than the characteristic length scales of the compartment. Thus heat radiation can be treated as a local phenomenon.

The computation of the emissivity (ε_g) is also subject to various simplifications that vary with the author. A common assumption states that the emissivity increases exponentially with the thickness of the emitting gas and thus Petterson et al [1] postulates that

$$\varepsilon_g = 1 - \exp(-\kappa x_g) \quad (1)$$

Where κ is an emission (or absorption) coefficient and x_g the thickness of the emitting layer. This approach carries the further assumptions that single emitting temperature and gas phase emissivity is sufficient to describe radiative heat exchange. The radiative component needs to account for all sources of radiation, thus a more complete way to describe the above boundary condition will be:

$$\dot{q}_S'' = h(T_g - T_S) + \dot{q}_{r,T}'' - \varepsilon_s \sigma T_S^4 \quad (2)$$

Where the net heat input to the structural element is \dot{q}_S'' , $h(T_g - T_S)$ is the convective contribution, $\varepsilon_s \sigma T_S^4$ is the surface re-radiation and the term $\dot{q}_{r,T}''$ conglomerates all radiative inputs. Radiative inputs can come from the hot gases, soot, other surfaces or the flame, furthermore, they are attenuated by the absorption through the gas phase. It is important to note that absorption is a function of the soot volume fraction and temperature through the soot absorption coefficient (κ):

$$\kappa = C f_s T \quad (3)$$

Where C is a constant, f_s the soot volume fraction and T the temperature. Thus if the soot volume fraction is high and the distance from the flame or other hot element is large, equation (1) shows that all energy from these emitting bodies will be absorbed by the smoke before reaching the target. The assumption that the hot gases adjacent to the structural element are the main contributors to its heating might then be appropriate and there is no need to resort to equation (2). Furthermore, if far from the flames, thermal equilibrium between soot and gas phase in the smoke might also be accurate.

The relevance of each of these assumptions can be evaluated for each specific scenario but to understand the validity of these simplifications it worth briefly reviewing some basic concepts of compartment fires, this will be done in the following section.

2. THE COMPARTMENT FIRE

A fire has a significant effect on a structure but the characteristics of the compartment that encloses the flames also have an impact on the nature of the fire. Temperatures within the compartment and duration of the fire are defined by the supply of fuel and oxidizer as well as being affected by heat transfer through the compartment boundaries. Fuel generation in turn is the result of energy feedback from the flames, hot surfaces and combustion products thus the heat input to fuel surfaces can be described by an expression of the form of equation (1).

A fire undergoes a series of processes from its inception, through spread and growth to its fully developed stage. A singularity in the growth process is the event of “flashover.” Here, “flashover” is defined as a transition, usually rapid, in which the fire distinctly grows bigger in the compartment. The “fully-developed” state is where all of the fuel available is involved to its maximum extent according to oxygen or fuel limitations. The growth of a fire is generally described through a two-zone model where the fire through a cold lower zone entrains air and products of combustion migrate to an upper layer. Pressure in a compartment fire is considered to be atmospheric and flows occur at vents due to hydrostatic pressure differences [4,5]. Following “flashover” the fire becomes fully developed fire. In this case the flow can be modelled via a single zone and the use of the ideal gas law in conjunction with conservation of energy and mass.

The fully developed compartment fire is defined as the ultimate (not always maximum) state of burning and either the fuel available or the ventilation determines its characteristics. The fuel available is determined by the burning rate and the ventilation is generally defined by a ventilation factor that is associated to the size of the openings of the compartment. Although significant research has been done to establish the characteristics of fully developed compartment fires [6] many questions related to the quantitative input required for the modelling of structural behaviour remain with no answer.

The thermal inertia of structural elements is significantly larger than that of the gas phase, thus characteristic times for temperature changes within the solids are much longer than those required for temperature changes in the gas phase. Furthermore, the presence of thermal insulation can result in very minor temperature changes throughout the entire fire growth period. This particular interaction between solid and gas phases generally allows using time averages for the gas phase temperatures and to assume that the fire can be considered as fully developed for all thermal calculations related to the structures. This assumption eliminates the need to establish hot and cold areas and thus allows treatment of the fire simply as an homogeneous temperature throughout the compartment. This translates to defining the characteristic length scale of equation (1) as the characteristic size of the compartment (x_g). Fully developed fires have been studied for many years. Quintiere [6] presents a comprehensive review of the existing body of work thus only a brief description of the relevant concepts will be presented here.

A clarification needs to be made here, both the standard temperature time curve (ISO-834) and the parametric curves developed by Petterson et al [1] insist on establishing a temperature evolution with time. In the growth period this implies a developing fire that is inconsistent with the single layer treatment that is used to establish the heat input to the structural elements. Furthermore, Petterson *et al* [1] make a significant effort to describe the different stages of the fire. Their tests and computations result in a series of temperature time curves that are intended to represent fires for different fuel loads and ventilation conditions, but only the region of maximum temperature and the decay stage are consistent with the assumptions of the thermal model.

The International Counsel for Buildings (C.I.B.) took a different approach in their study of compartment fires. The C.I.B. undertook one of the most comprehensive studies on the subject [7-9]. Wood cribs were used as fuel and although this arrangement has particular burning characteristics the observations illustrate the main factors controlling a fully developed fire. This study used room height scales of $H=0.5$ to 1.5 m, and the cribs nearly covered the entire floor. For wooden cribs in a compartment, the area of the vertical shafts of the crib, $(HA_o/A)_{\text{crib}}$, and the ventilation factor of the compartment, $A/A_o\sqrt{H_o}$, control the oxygen flow through the crib. H being the height of the vertical shafts of the crib, H_0 the height of the compartment opening, A_0 the area of the vertical shaft or the compartment opening and A the surface area of the crib or the room floor. For limited oxygen the ventilation factor controls the burning rate and a constant burning rate is observed for different vertical shaft areas. With sufficient oxygen, the exposed surface area of the sticks controls the burning rate and therefore the burning rate increases with $(HA_o/A)_{\text{crib}}$.

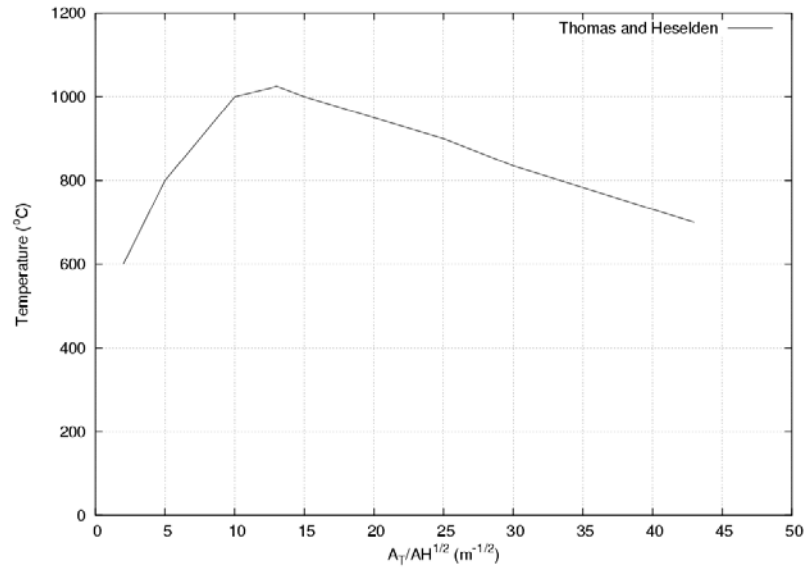


Figure 2 Time mean temperature near the ceiling [7]. Where A_T is the total area excluding floor an opening, A the window area and H the height of the window. The fuel loads for these tests are in the range 20-40 kg/m² that is smaller but nevertheless comparable to what would be expected in a modern office.

If the burning rate can be established then, knowing the heat of combustion, the energy release rate can be calculated and thus the temperature of the compartment. Then a correction could be made to establish the fraction of the energy that remains within the compartment. Figure 2 represents the curve fit presented by Thomas and Heselden [7] that gives estimates of the temperatures that could be expected for wood cribs in small-scale (1 m high) compartments. The actual data has some scatter which Law and O'Brien [10] suggest to be a result of some particularly extreme experimental conditions. The results are expressed in terms of the ventilation-factor and surface area and are hoped to be scale independent. As can be seen in Figure 2, this study only provides a single average temperature for each condition instead of a temporal evolution of the temperature. Despite being less information this is consistent with the assumptions of the thermal model. The extent of the period characterized by the peak temperature can be defined as a function of the empirical burning rates and the duration of the decay can be estimated using a simple energy balance for the compartment. Torero et al. [11] performed this analysis for the WTC 1 & 2 Towers.

The C.I.B. work consisted of a parametric study that included more than one hundred experiments thus allows for a reasonable level of confidence to be associated to the data. Nevertheless, the data presented is limited to average values and does not address the spatial temperature distributions within the compartment nor the proximity of the flames to the structural elements. Drastic temperature variations within the compartment have been suspected for many years but very few experiments exist to demonstrate the significance of these variations. Numerical modelling can serve to describe the significance of these variations. Figure 3 shows the simulations corresponding to the same fire embedded in compartments with three different aspect ratios. It can be observed that temperature variations greater than 600°C exist throughout the compartment. Furthermore, analysis of the soot volume fractions show also well defined distributions. These observations seem to further establish that the basic premise of a single compartment temperature might be over simplified. The obvious consequence of this is the need to compute the local temperatures and to solve the radiative transport equation. This can only be done using appropriate compartment fire models or through experimental characterization of the radiative fluxes to the different surfaces.

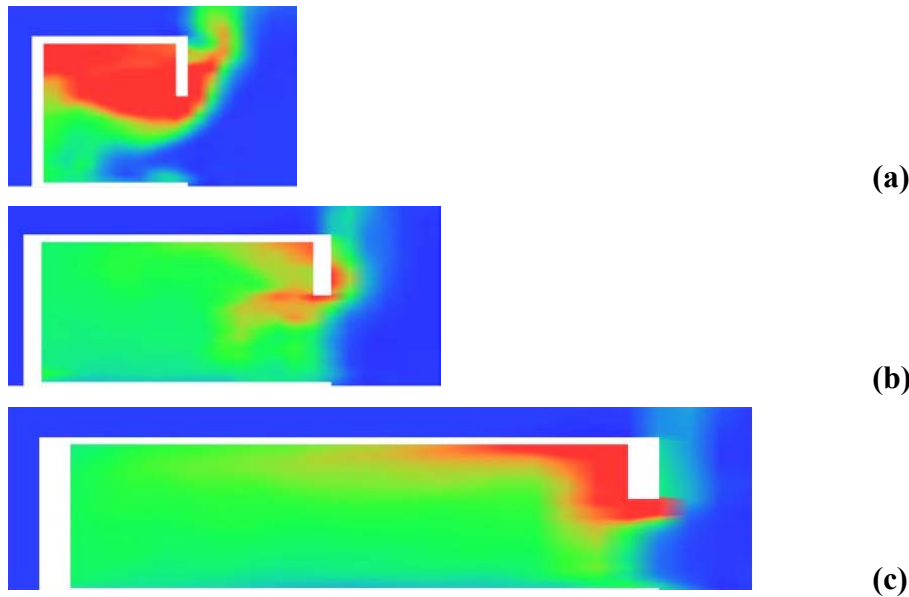


Figure 3 Example of three FDS calculations of a compartment fire. The temperature legend is not presented because the emphasis is on the spatial distribution of the temperatures not on the quantitative values. The red is approximately 1000°C and the green 400°C. For all three cases the compartment cross section is 4m x 4m x 4m and the lengths is (a) 4m, (b) 8m and (c) 16m. For all cases the heat release rate per unit area is 1000 kW/m² propane fire distributed throughout the surface. All surfaces concrete, the grid size is approximately 0.3m to 0.5m in all directions. The ventilation opening is 4m width by 2.5m height.

3. THE STRUCTURE

Traditional design of structures for fire is based on single element or sub-assembly testing in the standard furnace [2]. This approach allows uniform testing of structural elements and other fire resisting components. However, a defining behaviour of structural frames in fire is the response of the frame to restrained thermal expansion effects and resulting geometrically non-linear response which cannot be captured by simple unrestrained standard furnace tests on single beams, slabs or columns. Designing structures based on critical temperatures and failure of single elements as a result of material degradation does not address the forces and possible collapse mechanisms experienced by an integrated whole frame structure during a fire. As a direct result of the Cardington Frame fire tests, new understanding of the behaviour of structures in fire has been developed [12,13]. This understanding has now been broadened so that structures in fire design has a real engineering basis and is not reliant on results from single element testing in the standard furnace. The type of analysis advocated includes detailed modelling of the time evolution of the structure as the temperature increases, this is generally done by means of a dynamic analysis using finite element codes [12,13].

A landmark series of tests conducted at Cardington (UK) provided the opportunity to establish the validity of this approach. The main conclusions of the tests and the subsequent research projects were that composite framed structures possess reserves of strength by adopting large displacement configurations with catenary action in beams and tensile membrane behaviour in the slab [12, 14, 15]. Furthermore, for most of the duration before runaway failure (not observed at Cardington), thermal expansion and thermal bowing of the structural elements rather than material degradation or gravity loading govern the response to fire [13]. Large deflections were not a sign of instability and local buckling of beams helped thermal strains to move directly into deflections rather than cause high stress states in the structure. Near failure, gravity loads and strength will again become critical factors.

A thorough understanding of the whole frame response to fire as a result of such analyses allows structural detailing to be incorporated in the design addressing the structural weaknesses as a result of fire. This leads to more robust fire resistance design based on quantified structural behaviour.

4. METHODOLOGY AND EXAMPLE

Through the present paper a methodology that allows an analysis of a structure in the event of a fire will be presented and will be illustrated with an example from a fictitious high-rise building. The methodology requires:

1. Identification of the building areas the structure is most sensitive to a fire and that could lead to the collapse of the structure (i.e. global failure)
2. Identification of the critical compartments where a fire can result in high temperatures and prolonged exposure (long burning times).
3. Modelling the time evolution of the fire using the NIST developed Fire Dynamics Simulator (FDS) [16].
4. Establishing a methodology to transfer characteristic time dependent heat-fluxes from the numerical simulations of the flow to the structure.
5. Modelling of the structure using a finite element code (ABAQUS [17]).

4.1 The Example

As an example a fictitious high-rise building has been analysed and a series of structural components have been identified as critical to the global stability of the building. In parallel numerical modelling of the potential fires in the areas where these components are present have allowed identification of those components that have the potential to be exposed to the most severe fire conditions. In the process of identifying these areas geometrical factors (ventilation and aspect ratio) and fuel loading have been considered. These analyses covers points (1) and (2) of the method. Detailed modelling of the potential fires within those compartments was conducted using FDS [16]. All the appropriate sensitivity analyses were conducted but will not be presented here since the objective is the illustration of the method and not the description of how to properly conduct such an analysis.

For the purpose of this presentation only a single critical area would be identified. In general the analysis of more than one area might be necessary. The particular area identified is presented in Figure 4. This area meets both requirements stipulated in points (1) and (2) of the methodology. Within this compartment there are three columns that represent the critical structural elements. In this particular case the three columns support of a truss system from which a single column that covers the entire height of the building emerges. The large frontal opening provided significant ventilation, while the particular geometry allowed for concentration of the heat in the back right-hand corner. A global analysis of the structure that included several floors and incorporates floor slabs as well as steel structural elements indicated that failure of this truss or the columns associated to it will lead to global failure of the building.

Figure 5 presents the time evolution of the gas phase temperature at one particular column location. These temperatures were obtained by assigning thermocouples (in FDS) in the gas phase adjacent to the column of interest. The fuel used for these particular simulations is kerosene and the extent of the fuel coverage was varied seeking the worst-case conditions. The scenario intended to simulate the leakage of a fuel pipe in the event of an intentional fire. Fuel pipes are many times present in buildings where power generation units are available. It can be seen in Figure 5 that given the nature of the fuel the fire spreads rapidly and steady state conditions are achieved. An infinite supply of fuel was assumed. This is not realistic but is a good way to establish the time period where structure integrity could be expected. The

simulation was conducted only for 600 seconds since clearly the variation of the temperature with time was negligible at this point. It is important to note that the evolution of the temperatures of the compartment walls, ceiling and floors was not monitored in detail. Heat feedback from the solid boundaries of the compartment will affect the burning rate and thus continuous evolution of the temperature will occur. Nevertheless, these changes were estimated to be small. This will be explained in detail later.

NIST

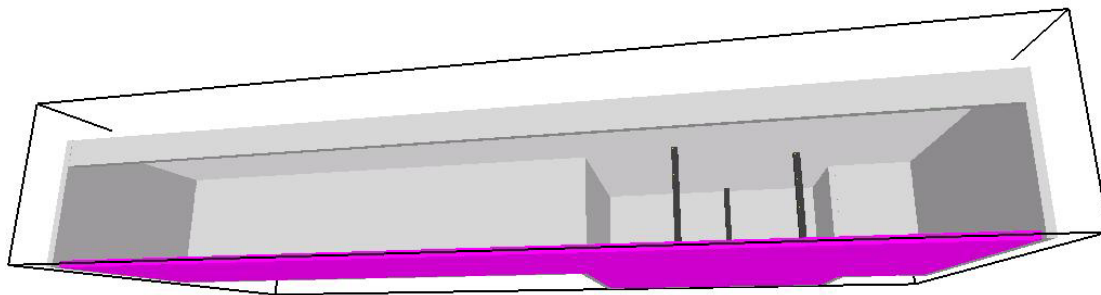


Figure 4 Schematic of the compartment where the critical fire conditions were observed. The large frontal opening provided significant ventilation, while the particular geometry allowed for concentration of the heat in the back right-hand corner. The three columns in black represent the critical structural elements that in this particular case support of a truss system from which a single column that covers the entire height of the building emerges.

It is important to note that Figure 5 shows a significant spatial evolution of the temperature along the height of the column. The temperature difference between the floor of the compartment and the ceiling is about 800°C. An important aspect of this analysis was to identify that gas phase temperatures of the order of 1200°C could only be achieved in compartments where the ceiling height exceeded the typical modern construction height of approximately 3 to 4 m. For regular compartments the aspect ratio of the rooms implied that these temperatures could only be achieved very close to windows (Figure 3). The particular building studied had no major structural elements in its outer region. The particular geometry of the room illustrated in Figure 4 resulted in the highest temperatures being present in the region where the main structural elements were present.

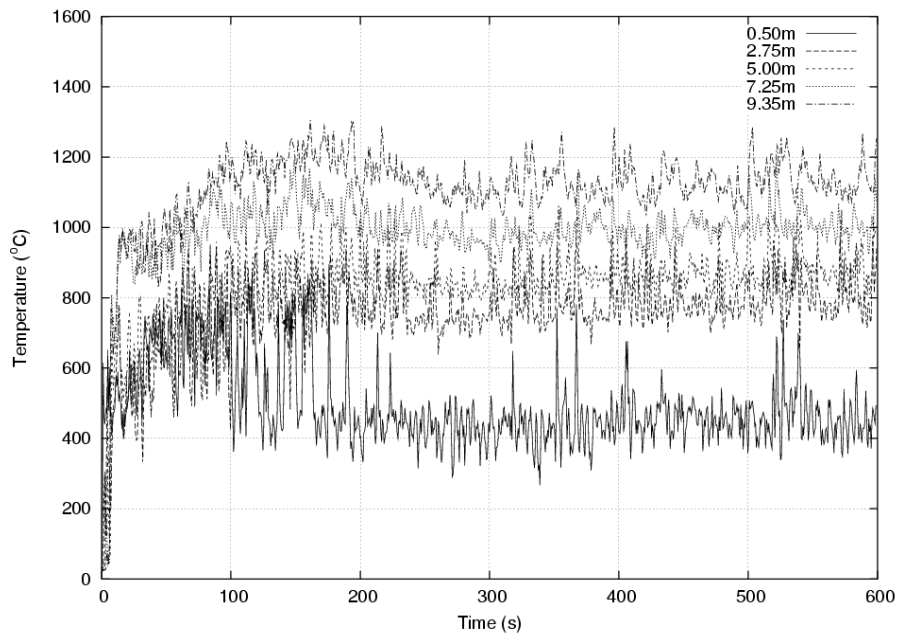


Figure 5 Gas phase temperatures as extracted from FDS thermocouples adjacent to one of the columns of interest. It can be noted that a significant spatial variation of the temperature can be observed while the time evolution is limited to the first few seconds after ignition. The heights indicated in the legend are measured from the floor of the compartment.

The rapid evolution of the fire towards steady state conditions implied that for this particular fire scenario there was no need to establish a “Temperature vs Time” curve. Instead it was important to establish the spatial evolution of the temperature fields. Temperatures were thus averaged over time. Figure 6 shows a typical distribution of the temperature field for the columns studied while figure 7 shows a schematic representation of the temperatures within the compartment. The results presented in Figures 6 and 7 represent the worst-case scenario. Ventilation and fuel supply were varied until maximum temperatures were observed in the area of interest. It is important to note that clear trends can be established and the critical scenario can be well established.

It is important to note that the spatial distribution of the temperature could have a significant effect on the outcome of the structural model. It could be argued that an homogeneous compartment temperature that corresponds to the peak value observed could be a worst case scenario, nevertheless the dynamic behaviour of the structure is complex and mostly defined by stresses generated by restrained thermal expansion, thus cold boundaries to a heated structural element could result in a more critical scenario. For this reason the actual temperature distributions will be used for this study. A benchmark case, using peak temperatures homogeneously distributed, will have to be conducted as part of a sensitivity analysis.

Heat transfer from the gas phase to the columns was conducted via a total heat transfer coefficient that included a linearized component for radiation. The total heat transfer coefficient was defined as $45 \text{ W/m}^2\text{K}$ [3]. The evolution of the temperatures of the structures and trusses of interest was established via a simplified analysis. The columns were treated as fins and no thermal insulation was included. In the event of insulated structural elements the appropriate heat transfer model for the solid phase will have to be incorporated. Structural finite element codes such as ABAQUS [17] have adequate solid phase heat transfer models that could be adapted easily for the present application.

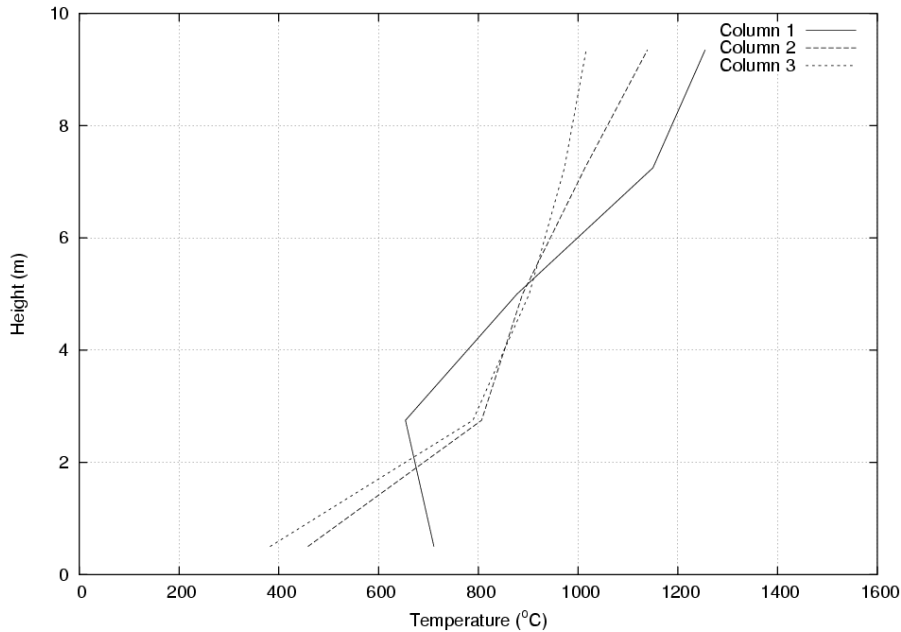


Figure 6 Average gas phase temperatures for the regions adjacent to the three columns of interest.

The problem was divided into two different parts, a transient analysis and a steady state analysis. It is important to note that this treatment is not necessary since a numerical code can resolve the transient problem completely. Nevertheless, for practical applications it is important to establish analytical methodologies that could enable the designer to concentrate on a parametric study of the different scenarios instead of investing all resources in a complete numerical analysis of the problem. For this particular application, the gain of a transient numerical analysis was deemed marginal, given the thermal inertia of the structural elements, thus a simple methodology to couple the numerical simulations of the gas phase to those of the solid phase was developed.

The steady state temperature distributions along the structural elements were obtained by treating the columns as fins. This analysis will not be presented here since it could be found in any heat transfer text. The time to reach steady state conditions was established by conducting a lumped analysis of the cross section and defining a characteristic time to steady state conditions as the time to reach 90% of the steady state temperature. The results were compared with a numerical transient solution showing that the methodology adequately represented the time evolution of the columns and also that a linear temperature rise was an adequate representation of the temperature histories. Thus, the time dependent temperature evolution of the different steel structural elements was established in this fashion and a set of typical results is presented in Figure 8.

For practical purposes functions of the form $T(x,t)$ were generated that represented the best fits to the different temperature distributions. These functions could then be used as inputs to the finite element modelling of the structural behaviour. In Figure 8 the ISO-834 Temperature vs. Time curve is presented showing that the solid phase temperatures can achieve more severe conditions than those given by the standard fire.

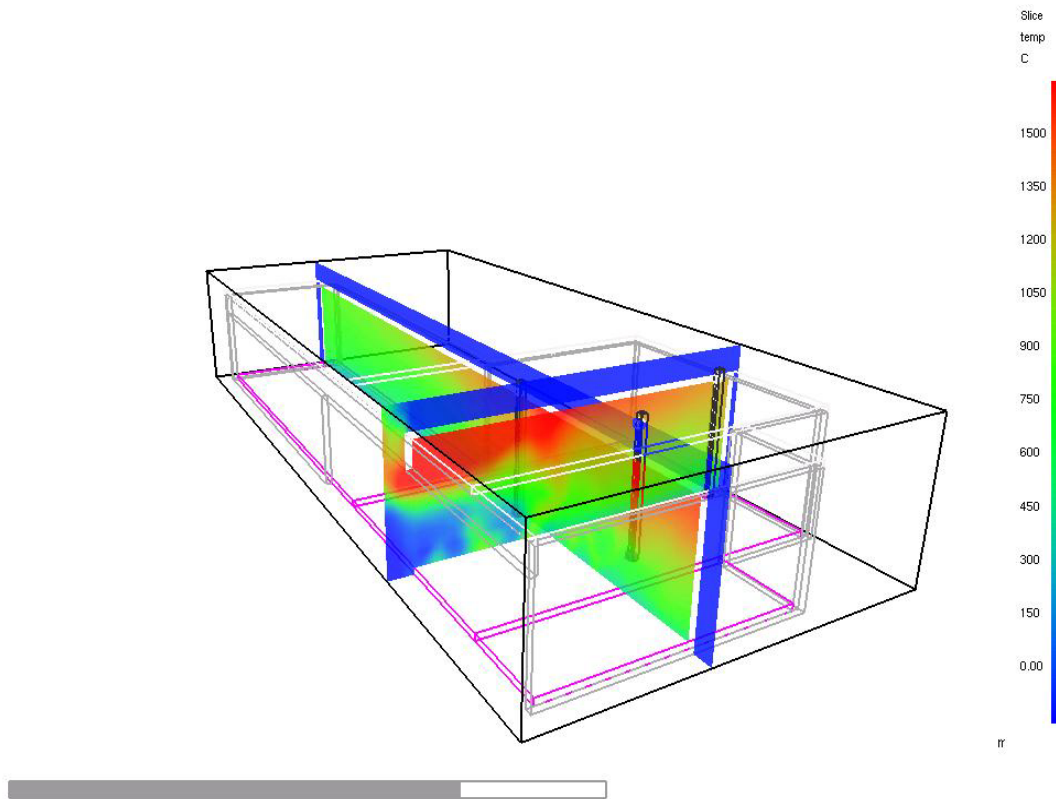


Figure 7 FDS representation of the temperature distributions within the compartment showing the drastic spatial variations and the concentration of the maximum temperatures in the region of interest.

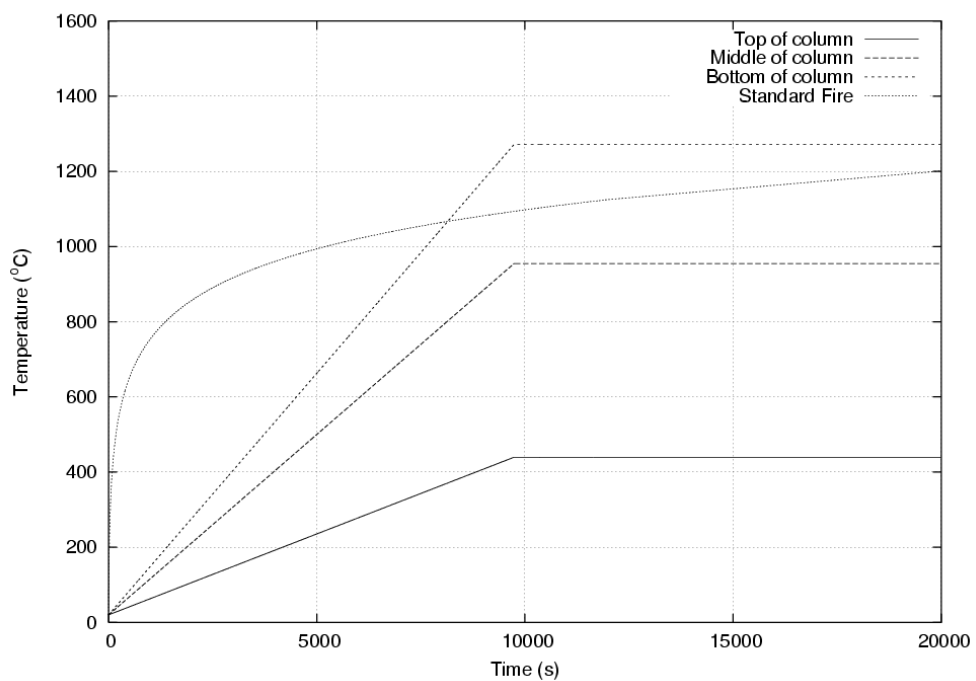


Figure 8 Time dependent evolution of the temperature of the structural elements. Three characteristic cases are presented together with the standard ISO-834 “temperature vs. time” curve.

The structural behaviour was then modelled using ABAQUS [17]. The methodology followed has been described elsewhere thus will not be presented here [12,13]. Figure 9 shows a schematic of the structural element analysed. A two dimensional model of this particular structural element will be presented here but it is important to note that a three dimensional analysis that included a large part of the building also accompanied this study.

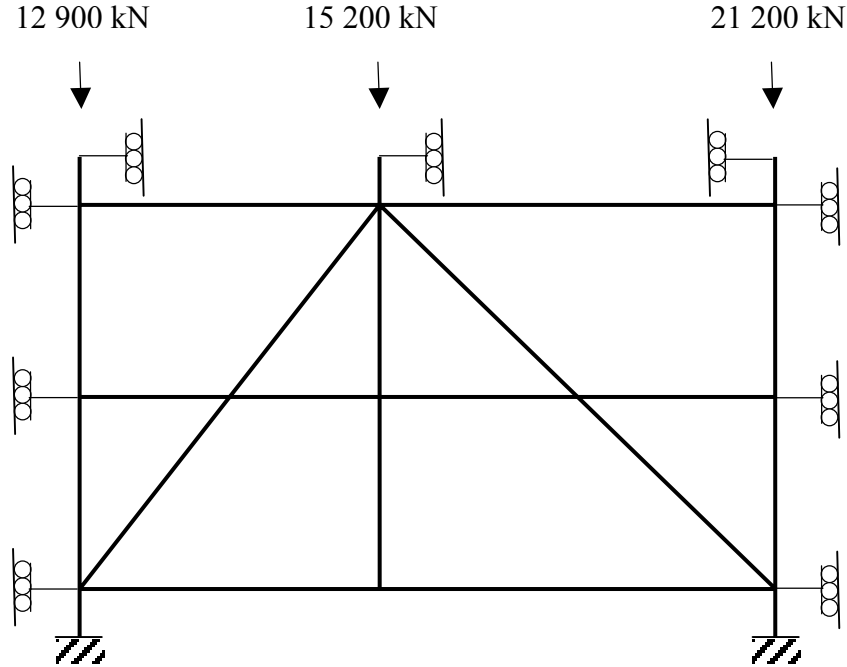


Figure 9 Truss model. The loads applied correspond to those established from the building geometry. This truss is immersed in the compartment studied and is supported by two of the three columns indicated in Figure 4.

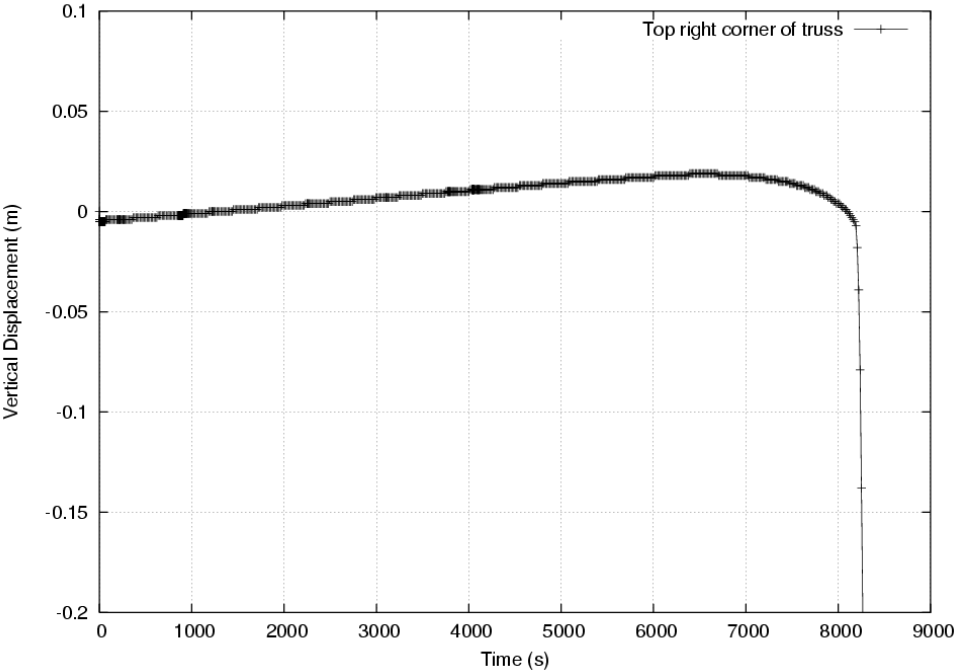


Figure 10 Evolution of the vertical deformation for the top right corner (Figure 9).

Figure 10 presents the evolution of the vertical deformations for the top right corner of the truss. As it can be seen, initially there is a small negative deformation due to the static loading of the truss. As the temperature increases thermal expansion effects appear and an upwards vertical displacement can be observed. At approximately 7000 seconds the deflections start reverting their direction until approximately at 8000 seconds runaway conditions can be identified. For the purpose of this study this will be the definition of collapse. It is important to note that for this particular case, Figure 8 shows that failure occurs when the top part of the truss has reached approximately 1000K while the bottom part of the truss is at approximately 600K. This information is essential to establish the value of t_S , as indicated in Figure 1. This is clear evidence of the importance of a proper description of the temperature distributions within the structural elements.

5. CONCLUSIONS

A fictitious scenario has been analysed to illustrate a methodology for the calculation of the time available in a fire before global structural failure, t_S . This paper has emphasized on the importance of the use of detailed modelling of the fire that can only be achieved via Computational Fluid Dynamics (CFD) and of the structure using Finite Element Models. The dynamic behaviour of the structure coupled with the non-homogeneous distribution of the gas phase temperatures requires an analysis that goes beyond the establishment of single average compartment temperatures of the use of test furnaces with characteristic Temperature vs. Time curves. The importance of thermal expansion as a dominant mechanism controlling the behaviour of structures in the event of a fire [12] has been re-emphasized.

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