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Modelling of the thermal stresses of concrete structural elements in tall buildings under natural fires

Modelado de las solicitaciones de los elementos estructurales de hormigón en edificios de gran altura en incendios reales

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SUMMARY

The fire of the Windsor Building in Madrid represents a paradigm in High Rise Building Fires. The present work analyses the origin, growth and propagation conditions of natural fires in tall buildings. The study has been focused on the determination of the thermal exposure conditions (temperatures T, heat fluxes *q"*, etc.) on the structural members of high rise buildings, at end use conditions, under natural fires using fire computer modelling techniques.

Work allowed: 1) validate the predictive capacity of the fluid-dynamics computer models used, 2) apply these models to a specific fire scenario to assess the thermal and the mechanical response of the structural members of a high rise building.

RESUMEN

El incendio de la Torre Windsor de Madrid constituye un suceso paradigmatico de incendios en edificios de gran altura. En el presente Estudio se analizan las condiciones de origen, desarrollo y propagacion de incendios reales en este tipo de edificaciones, asi como la determinacion de las condiciones de exposición` (temperaturas T, flujos de calor q", etc.) a las que se encuentran sometidos los elementos estructurales, en condiciones de uso final en este tipo de estructuras, mediante la utilización de técnicas de modelado y simulación computacional de incendios.

Los trabajos realizados, se centraron en aquellas actuaciones que: 1) permitieran validar la capacidad predictiva de los modelos de fluido-dinámica empleados, 2) la aplicación de los modelos ajustados y validados a un escenario de incendio en condiciones de uso final en un edificio de gran altura, para la predicción de la respuesta mecánica de la trama estructural.

458-8

Keywords: CFD modelling, room fires, fire spread, thermal stresses, structural behaviour.

Palabras Clave: *modelado CFD, incendios en recintos cerrados, propagación interior, solicitaciones térmicas, respuesta estructural.*

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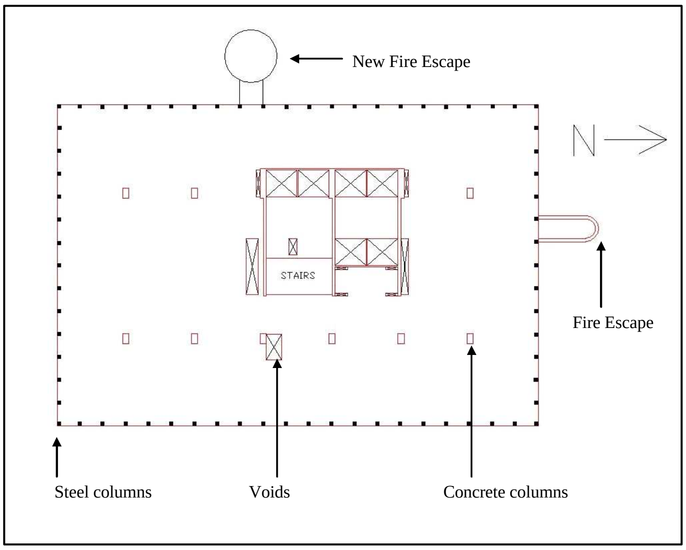
1. INTRODUCTION

When the effects of fires in a building are examined by utilizing of modelling tools and computational simulation, it should be recognised, firstly, that the behaviour of a structure in case of fire is strongly related to the effect that the fire can have on the individual structural elements that compose it, but secondly, that the redundancy inside the structure can permit that the loads be redistributed even when individual structural members fail.

In the present work, the fire in the Windsor Tower is taken as a basis to carry out different types of analysis: 1) determination of the initiation and development of the first phases of the fire, considering as reference the fire in the office of origin (2109), and 2) the propagation on the floor of the fire, selecting the 21st floor. This permits determination of the severity reached as a result of the completely developed fire, due to the combustion of the materials present.

Subsequently, calculations were carried out by means of an FEM (Finite Element Method) model, using the thermal loads calculated to determine the gas-phase boundary conditions to the structural members. The use of this type of study permits calculation of the global impact of the temperature into the structure, focusing on, by means of detailed analysis, the behaviour of the elements composing the main structural frame.



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1. Floor plan of the Windsor Tower.

2. DESCRIPTION OF THE BUILDING

On 12-13 February 2005, the Windsor Tower was involved in a major fire, of duration 18-20 hours. This broke out in an office on the 21st floor of the building, causing extensive structural damage to the upper floors of the building. The Windsor Tower was built in 1978 and was at one time the tallest building in Madrid.

The upper section of the building, above floor three, was a tower block containing offices and consisted of a concrete core, several interior concrete columns, exterior steel columns and a concrete waffle slab floor with permanent clay formwork (see Figure 1).

At the time of the fire a programme of fire protection upgrading was being undertaken, and the steel columns up to the second transfer floor had been protected, except on the 9th floor where two adjacent sides of the building remained unprotected due to the sequential nature of the upgrades to the building. An additional fire escape was also added to the west side of the building.

3. MODELLING AND COMPUTATIONAL SIMULATION OF THE FIRE

The modelling of the fire is a very complex undertaking due to the large number of variables involved. When applying fire exposures to a structure, a number of methods are available (1), as described below.

The simplest approach is to specify a uniform temperature for the surface of the structural elements. This temperature can either be estimated from observational or experimental data, taking into account for example the colour of the flames or the post-fire condition of the exposed materials. In the case of the Windsor Tower, video evidence is consistent with gas-phase temperatures reaching around 800-1000°C after flashover.

In the absence of measurements, it is possible to represent the approximate conditions of fire development by means of modelling tools and computational simulation of the fires. Within these are different approaches based on steady-state and transient simulations.

In the present work, the main tool used for this study was the Computational Fire Model 'Fire Dynamics Simulator (FDS)', version 4 (2). This model has been developed by the Building and Fire Research Laboratory of the National Institute of Standards and Technology – NIST

(USA), in cooperation with VTT Building and Transport, Finland.

FDS is a Computational Fluid Dynamics (CFD) model that was designed specifically for reproduction of fire phenomena, which has been widely and validated (3, 4) in the international scientific community as tool for the analysis and prediction of the evolution of fires in enclosures. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires [1], [2], [3], [4], [5].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0 \qquad [1]$$

$$\frac{\partial \rho Y_l}{dt} + \vec{u} \cdot \nabla \rho Y_l = -\rho Y_l \nabla \cdot \vec{u} + \nabla \cdot \rho D_l \nabla Y_l + \dot{m}_l''' \qquad [2]$$

$$\frac{\partial}{\partial t}(\rho \bar{u}) + \nabla \cdot \rho \bar{u}\bar{u} = -\nabla p + \rho \bar{f}_T + \nabla \cdot \tau_{ij} \qquad [3]$$

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot \rho h \bar{u} = \frac{Dp}{Dt} + \dot{q}''' - \nabla \cdot \bar{q}_r + \nabla \cdot k \nabla T + \nabla \cdot \sum_l h_l (\rho D)_l \nabla Y_l \qquad [4]$$

$$p_0 = R \rho T \sum_l \frac{Y_l}{M_l} \qquad [5]$$

Where: [1] Equation of conservation of mass, [2] Equation of conservation of species, [3] Equation of conservation of momentum (Navier-Stokes), [4] Equation of conservation of energy, [5] Equation of state.

The core algorithm is an explicit predictor-corrector scheme, second-order accurate in space and time. Turbulence is treated by means of the Smagorinsky form of Large Eddy Simulation (LES).

3.1 Analysis of the validation of the predictive capability of the model

Before commencing the analysis of the scenario of the floor fire, the mechanisms of validating of the predictive capability of the computational simulation model were developed, taking for a reference the full-scale fire tests carried out in a tall building at Dalmarnock (Glasgow, UK), a study lead by the University of Edinburgh (UK) (4).

The results produced by the simulations showed a great disparity between the prediction of the simulation models and the experimental measurements, nevertheless, the results obtained in the simulations of the general behaviour of the fire are deemed sufficiently reliable to be utilized in a simplified engineering analysis.

In order to improve the predictive capability of the model, the sensitivities of the outputs have been previously analysed with FDS and have improved the parameters introduced to the model to advance to the maximum the calculations of the dynamics of the fire (5). Likewise, the influence of the turbulence was studied and the spatial refinement in the accuracy of the results (6, 7).

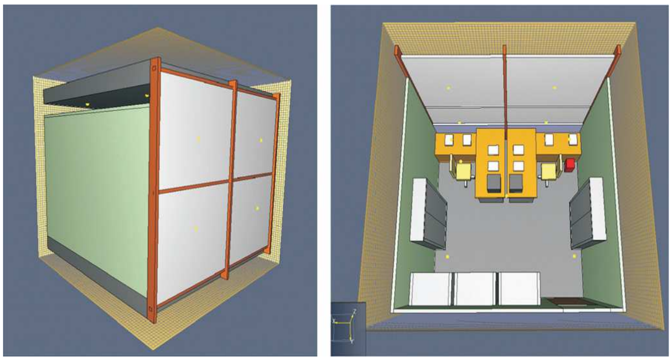
This analysis has permitted to determine a consensus on the importance of the correct selection of the input parameters of the model and the spatial refinement of the grid, in the accuracy of the results for the calculations of the fire dynamics.

3.2 Study of fire in the room of origin

Before trying to establish a study to understand the progression of the fire through the interior of the building, it was decided to focus attention on the fire development in the room of origin of the fire, with the purpose of understanding the fire development in terms of heat release rate.

The resulting technical elements of this analysis, besides obtaining useful results for the analysis in all the floor and between floors, facilitate verification of the hypothesis of the fire origin, and assist in determining the importance of the different factors that influence the fire growth in an enclosure: dimensions of the enclosure, power of the ignition source, characteristics, distribution and types of flammable materials, conditions of ventilation, etc.

The computational model of the room of fire origin was developed in a versatile manner, such that the characteristics of the materials could be easily changed along with other factors affecting the fire (e.g. the time of window breakage) so as to study their influence in the progress of the fire (Figure 2).



2. Computational model of the room of fire origin.

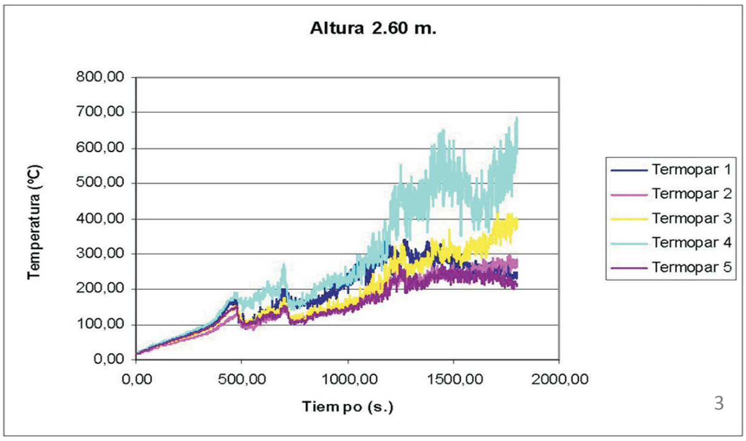
Informes de la Construcción, Vol. 63, 522, 83-91, abril-junio 2011. ISSN: 0020-0883. eISSN: 1988-3234. doi: 10. 3989/ic.09.005

Thus the initial focus of the study was on the fire development in room 2109, the origin of the fire, making it possible to use refined grids for the CFD simulation. In this model the conditions of the room before the fire were represented with a computational grid having a uniform cell size of 5 cm side, with 512,000 cells in the domain.

Once the computational domain was established, the characteristics of the materials

Table 1. Characteristics of the materials of the compartment linings

Ref.	Thickness (mm)	Density (Kg/m3)	Specific heat (KJ/KgºK)	Tig (ºC)	HRR (kW/m^2)
Walls (5)	9.5	440	1,47	326	243.36
Floor	6	750	---	290	374
Ceiling tile	13	1440	---	325	38.92



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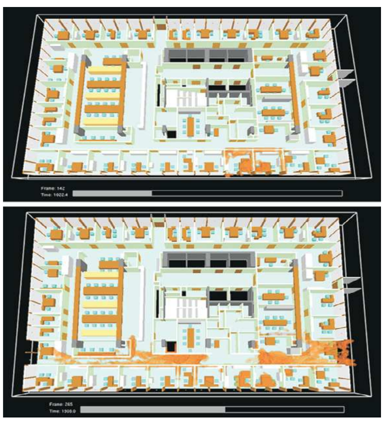
3. Temperatures registered in the model of office 2109.

4. Propagation of the fire on the floor of origin.

of the interior finish were defined, with the heat release rate taken from the NIST cone calorimeter test in the research work 'Cook County Administration Building Fire, 69 West Washington, Chicago, Illinois, October 17, 2003: Heat Release Rate Experiments and FDS Simulations' (8). Table 1 summarises the characteristics of the materials of the linings of the office.



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To define the total heat release rate of these elements, the tests of National Institute of Standard and Technology NIST (USA) on 'Two Panel Workstation Fire Test' (9) were studied. To characterize this element there was added also, amongst other parameters, an ignition temperature of 200 ºC.

Due to the importance of the definition of the window breaking times and for lack of more information, in this initial stage of the study two situations of ventilation were analysed: heat detectors were placed upon the glass which broke on having reached 150 ºC, and the glasses partition were eliminated from the start.

Once all the input parameters were implemented in the model, the study proceeded to the calculation of the development of the fire dynamics of the fire in the floor. Figure 3 is an example of the values registered for temperature by the low thermocouples under the most unfavourable conditions during the first 1,800 seconds of the development of the fire simulation.

The results of the initial analysis demonstrated that it was possible to reach the status of a fully developed fire in this office from small sources of ignition, such as the wastebasket.

During the fire development there was verified the generalized ignition in the auxiliary desk close to the wastebasket before the first 30 minutes, and the breaking of the top windows in this interval of time, as well as the spread to the adjacent enclosures to the office 2109 across the nearest wall to the wastebasket.

3.3 Fire development on floor 21

The floor of the building was built around a central core of reinforced concrete, and steel columns were utilised around the perimeter. The reinforced concrete core was centred on the longer north-south facing axis but was slightly off-centred with regards to the east-west axis. The core housed the stairwells, lift shafts and service ducts.

With the object of the present paper, the preliminary studies in the 21st floor were centred in two specific targets, on the one hand (1) to study and to analyse the fire development in this floor and for other (2) to allow the calculation of the total heat release rate parametric curves representative of the real fires completely developed in the floor.

In the Figure 4, a representation of the floor that will be object of this study with its initial layout can be observed. For the model a uniform grid size of 20 cm was adopted over the whole computational domain, with 729,000 cells in total. The office containing the ignition source, which was analysed in the initial study, above, is marked in the figure.

In this sense, it is apparent that attention must be paid to the conditions of oxygen depletion due to the fast growth of the fire, first in the room and later in the rest of the floor. This problem was solved by more detailed analyses by means of the introduction of the building ventilation system; however, these are not presented here due to lack of space.

From the results obtained in the simulations, the total heat release rate curves were calculated in the floor for the conditions analysed. This data provided an indicator of the magnitude and severity of the fire, of great importance to the analysis of the thermal stresses in the structural elements.

An analysis was realized to examine the results arising from the parametric curves of heat release rate, in relation to the conditions of thermal attack (temperature, heat flux, etc.) necessary for collapsing the structure.

For the calculation process, the conditions of final use of the 21st floor were simplified, considering only the structural elements together with the heat release rate curves previously calculated, taking these to be representative of the natural fire development. In the model, the characteristics curves of heat release rate were provided as an effective “design fire”, placed over the whole surface of the floor.

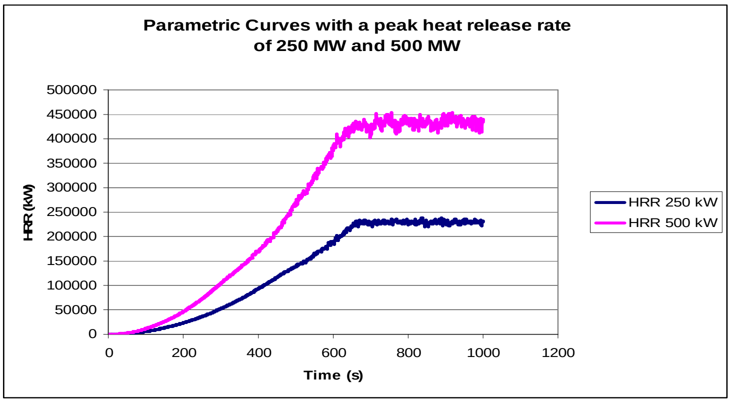
Different characteristic curves were studied; in this paper two extreme options will be described. The first one was mentioned in the previous paragraph, with a growth t-squared of approximately 225MW.

The second curve selected was approximately double the previous one in the value of the peak (500 MW) with the purpose of considering an extremely severe situation (due, for example, to uncertainties in the modelling process). (see Figure 13). It should be noted that the size of this latter fire deliberately exceeds the approximate upper limit on a whole-floor ventilation-controlled fire, obtained from the expression $\dot{m} = 5.5 A_w \sqrt{h}$ (kg/min), which is of the order of 350MW). In any case, when the height of the opening of ventilation, h, is equal to two metres, this value is evaluated on the order of 493 MW, approximately the same as the 500 MW upper limit.

Subsequently, parametric curves were fit to the predictions of the FDS model matching the expected magnitude of fully developed fires, with considerable temperatures achieved reaching up to 1160°C, for the heat release rate curve reaching 500 MW.

5. Parametric curves for the adopted heat release rates.

6. Thermocouple temperatures from simulations of central nucleus zone of building.



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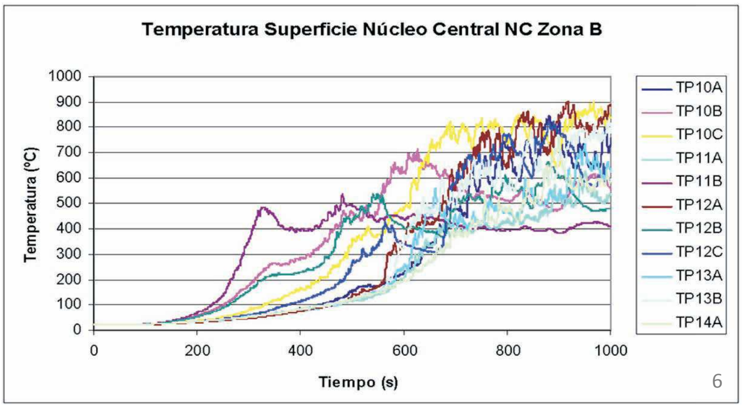

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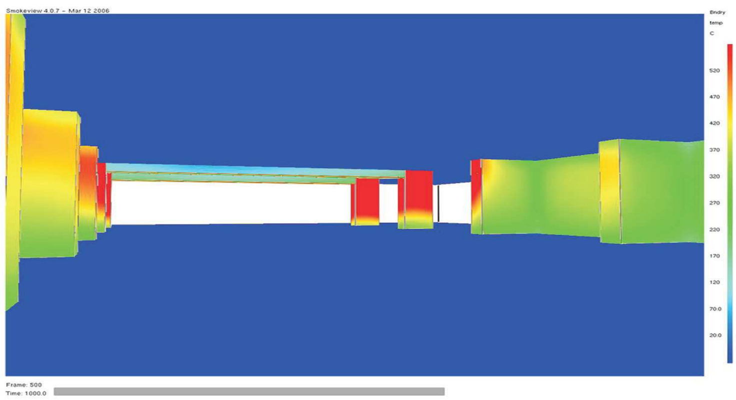

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Figure 6 provides a selection of the results of the temperatures registered by the thermocouples in the simulations of the central core of the building. The maximum values reached by the internal temperatures are found to be in agreement with the values estimated from the evaluation of the structural condition after the fire. Figure 7 presents an overview of the thermal response in the structural elements after applying the 500 MW heat release rate curve.

These results inform the consideration of the required input values for the finite element analysis, to determine the response of the structure, a process that is typically complex and that is explained more to the detail subsequently.

4. MODELLING AND SIMULATION OF THE STRUCTURAL RESPONSE

In many cases, is neither necessary nor desirable to base the geometry of the model in the totality of the structure. A simplified model consisting of one or several floors provides a large quantity of information that can be extrapolated to the remainder of the building (11).

When we examine fire propagation models, including those pertaining to vertical propagation, the main point of interest is in the magnitude and time for which the individual elements are subjected to the thermal exposures. Although a model of a complete floor can provide this information, if it is known that the directional effects of the wind were not significant, as in the present case of study, is possible to employ symmetrical plans to reduce the size of the domain. It is reasonable to assume that if the floor is divided into rooms along the axes of symmetry then each room of the floor is going to be affected in a similar way (time to flashover and extinction, for example); thus these techniques will be adopted in subsequent analysis of vertical propagation in the following studies.

Likewise, in creating the finite element model of the structure, there is little benefit representing the three-dimensional form of the complete floor. Moreover to reduce the number of elements required, wherever possible, instead of utilizing solid elements, "beam", "shell" or "membrane" elements are specified. Also, the overall model can be simplified by taking a slice of the section of the floor and analysing it as a beam, as is a common practice in structural engineering.

While this approximation can preclude taking into account many of the load redistributions that commonly take place in a three-dimensional structure, the simplified models can be used to examine factors such as the failure of an individual structural element. For example, the effect of the failure of the unprotected steel columns exposed to fire on the exterior floor can be examined by simplifying the floorslab as a beam extending between the concrete core and the steel perimeter columns.

4.1. Modelling the concrete response during the fire

In finite element modelling of reinforced concrete as structural members certain material properties require careful attention. Firstly, the concrete itself is a good insulator, therefore the thermal penetration into the depth of the member will be low. Additionally, the reinforced concrete is composed of concrete and reinforcement steel. The strength properties of the concrete and the reinforcement steel are temperature dependent, and when we load a beam of reinforced concrete it will behave first elastically and then plastically after yielding.

4.2. Modes of failure of the Windsor Tower

There exist a great number of possible manners of failure for the Tower Windsor, and is probable that a variety of these actually occurred in practice. Some of these are:

1. The collapse of the floor as a consequence of the prior failure of the columns of steel of the perimeter. This hypothesis supposes that the floor is forced to work as a cantilever projecting from the structural core.

2. Collapse of the floor between the core and the columns exterior to the core. This hypothesis supposes that because of the large facilities void existing in the floorslab in the region external to the core, the floor area was insufficient to support the large pulling forces originating from the failure of the floor exterior to these columns.

The nature of multi-floor fires is undoubtedly important, and is probable that if the fire had been concentrated on a single floor that the majority of the building would have was accommodated by means of load redistributions.

4.3. Structural model of the Windsor Tower

Modelling the behaviour of a complete building is a very complex task, and is often desirable to begin with individual elements of the structure and later to increase the level of complexity the model. In the case of the Windsor Tower, the first structural element to model was the floorslab, but given the manner of its construction this cannot simply be represented as a membrane borne by beams.

Rather, from examination of the building plans, it is evident that the floorslab acts as a network of beams. This can be modelled as primary beams bearing secondary beams. Nevertheless, the secondary and primary beams do not necessarily extend in the same direction, i.e. while in one section of the building the main beams run north to south, in another they are from east to west.

It is also necessary to make suppositions about the conditions of boundary connections in the model of the beam. Where the beam unites with the concrete core of the building it can be assumed that there is a rigid connection with the beam while in the union with the column we can assume that the connection is pinned. In spite of the fact that the column is absorbed in the slab, the relatively small size of this (140 x 120 mm) suggests that is improbable that it will resist any transmitted moment of the floor (Figure 8).

Once the structure has been defined, it is necessary to examine the effect of the heat exposure, specifically the evolution of the thermal response in the depth of the material, that is to say, the degree of penetration of the thermal wave into the concrete structural elements and the temperatures attained by the steel of the reinforcement. This makes it necessary to examine the profile of temperature inside the cross-section of the beams.

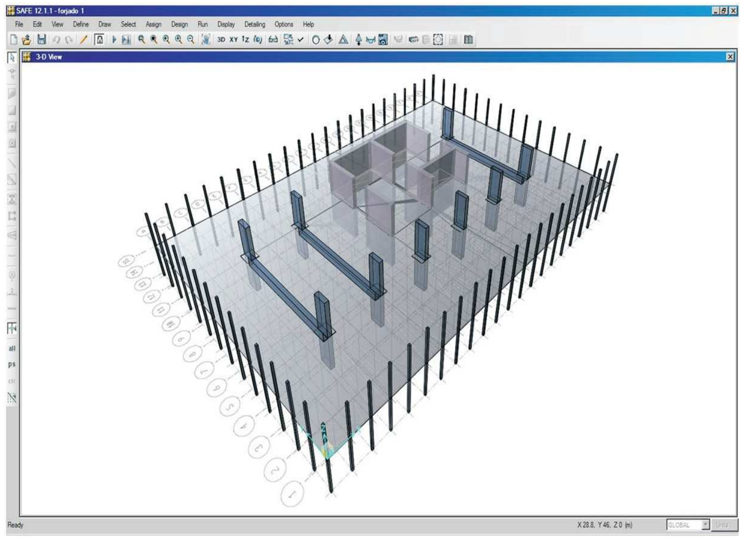
The tools utilized for the structural calculations with FEM were the models ABAQUS, SAP2000 and SAFE. Although it could be expected that an element type "beam" could be used to model the primary beams, the limitations for represent the thermal effects give an appreciation that this it will in fact be required to adopt shell elements. With these, the temperature can be defined to sufficient depths into the element. The concrete beam has been therefore modelled as a shell element, narrow and deep.

4.4. Analysis

The models of development of the fire in the floor of origin have been described previously by (13), these simulations being focussed on the aspect of the failure with the two aforementioned heat release curves.

Also the uncertainties in the characteristics and the distribution of the flammable materials, for which the calculations were processed with fuel supply velocities that correspond approximately to double what would be expected to sustain a ventilation controlled fire [$m=5.5A_w\sqrt{h}$], with a heat release rate plateau of 350 MW, based on the supposition of a window height equal to half of the distance from the floor to the ceiling, the latter being 3 m.

When the fire had progressed, after some time, some of the Aluminium panels in the lower part of the window openings were lost, giving access to more ventilation, but in this phase the fire load may have been substantially diminished due to its consumption.



8. Structural model of floor 21.

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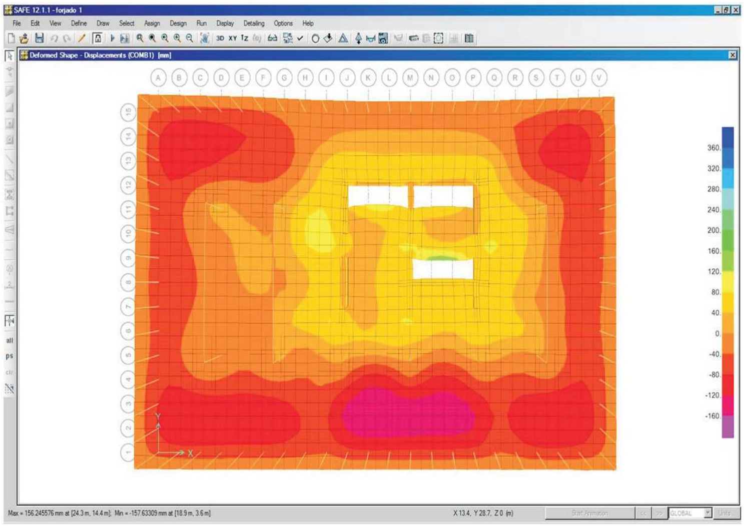
In the course of the fire, based on these suppositions of ventilation, the maximum computed gas-phase temperatures exceeded 1100C, and the corresponding temperatures in the surface of the concrete columns were approximately 200C smaller.

Here, small variations of the predictions exist according to uncertainties in the envisaged total heat release rate of the fire, though these are mitigated from the moment that the limit of ventilation-controlled burning is exceeded, with the additional flammable volatiles being consumed chiefly externally to the compartment.

These estimations are also supported by the post-fire analysis of the resistance of the concrete (14), which confirmed that the peak temperature in the surface of the columns and the floorslabs had exceeded 800C. It is also possible to do an analysis to obtain temperatures on the surface of the concrete by a methodology based on examining changes of colouring in the concrete and the changes in its internal microstructure.

In examining the behaviour of the structure using the FEM code a very important parameter is the definition of the internal temperatures in the structure. The ABAQUS finite element program is well able to calculate the thermal response based on the known exposures at the boundary, considering temperatures and fluid flows, but normally solid elements is required for this, which are inefficient in the structural model. Therefore, the thermal response has been examined using independent thermal models, as previously described. Using shell elements, different temperatures are specified for each layer, encompassing also the reinforcement bar. The depth of the elements into the material is a vital parameter in relation to the progression of the thermal flow into the material.

When the thermal flows have very limited penetration the distribution of the temperature inside a given structure an adequate representation will only be possible with a sufficient number of nodes to properly resolve it. With insufficient nodes the effect of the warming-up will tend to exaggerate the thermal evolution against time.



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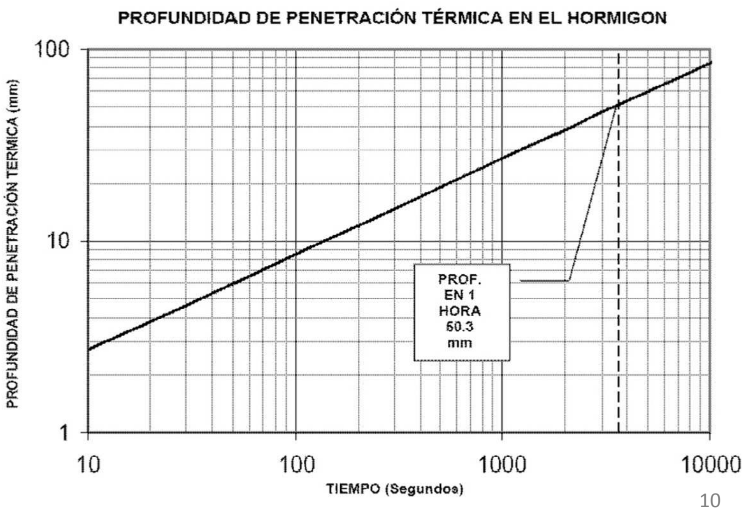

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The strength specified for the structural elements was 24.5 MPa in the columns and walls, 29.4 MPa in the beams and 17.2 MPa in the floor slabs, although there were some variants on the matter in practice (13). Considering a normal concrete of silicaceous aggregate, the density was taken as 2400 kg/m^3, the thermal conductivity as 1.2 W/m/K and the specific heat as 880 J/kg/K, giving a thermal diffusion of 0,57x10^{-6} m^2/s.

Figure 9 presents an example of the results of the chief deflections in the model for one of the conditions of thermal attack studied. The results obtained are consistent with the first mechanism of failure discussed earlier. Figure presents an example of the evolution of the thermal penetration into the depth of the material with time. The data of the complete duration of the fire are not known precisely, but evidence exists that the main phase lasted for around an hour (14); this yields some results of thermal penetration of around 50 mm.

Comparing these results with the studies carried out on the strength of the concrete after the fire suggests that the thermal penetration had exceeded a depth of 200 mm in small regions of the ceiling, based on the criterion of a 500C isotherm (15). In this case there can of course be secondary effects, including heating originating from the sides of the beams which conform to the reticulated formwork (dimensions of 100x200 mm, excluding the upper slab).

Using a shell element type de5 node to represent defects, the domain of the model of the beam of 230 mm of height and the joint with the slab of 58 mm, the thermal wave travels through the floorslab in approximately 1400 s. Figure 10 suggests that a resolution of 10 mm should be appropriate to adequately describe adequate the thermal response of the floors at least in the first 100 seconds of the simulation.

5. CONCLUSIONS

The initial phase of the investigative work demonstrated the capacity of the computational fire models to undertake the analysis of the development of a fire inside small enclosures, such as the room of origin, as part of the larger zone of the complete floorplan.

It has been shown, in qualitative terms, how the fire could grow and spread from the room of origin, and this then provided a basis for establishing a representation of a possible full-floor fire. Besides analyzing the development of the fire, these models permitted comparison of the computed thermal exposures with those that it was assessed the structure had been submitted to. These thermal loads were employed in the subsequent phases to analyze the mechanical response (stresses and deformations) of the structure via finite elements models (FEM).

A global study has been carried out to assess the behavior of the main concrete structure of the Windsor Tower. This has permitted an appraisal of the impact of representative thermal exposures, referencing data obtained from the assessment of the structure after the fire and various methods based on computational simulation models of the fire. The thermal response of the structure was subsequently evaluated, in order to define the boundary conditions for the structural models, encompassing FEM. Based on this, a strategy has been developed to determine the mechanical response of the structure, with a view to analyzing the possible mechanisms of failure in relation to the effects of the fire.

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