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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

J. A. Capote Abreu(*), D. Alvear(*), M. Lazaro(*), J. Crespo(*), I. Fletcher(**), S. Welch(**), J. Torero(**)

SUMMARY

The fire of the Windsor Building in Madrid represents a paradigm in High Rise Building Fires. The present Work analyzes 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 exposicion (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 utilizacion de tecnicas de modelado y simulacion computacional de incendios.

Los trabajos realizados, se centraron en aquellas actuaciones que: 1) permitieran validar la capacidad predictiva de los modelos de fluido-dinamica 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 prediccion de la respuesta mecanica de la trama estructural.

458-8

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

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

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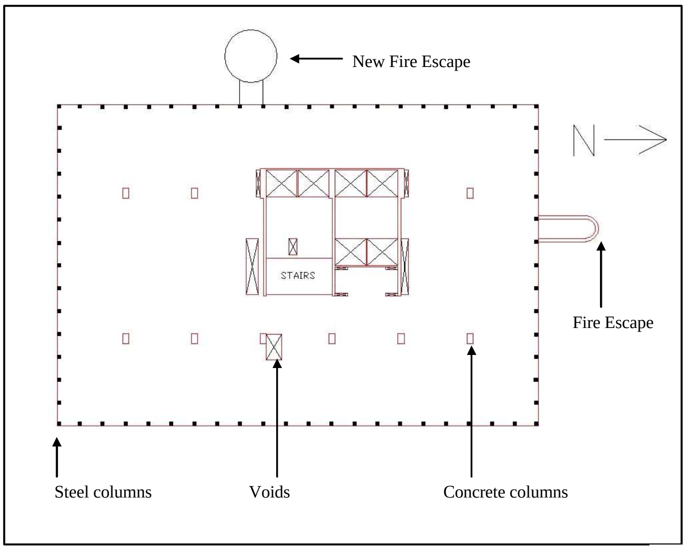
1. INTRODUCTION

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 very connected with the effect that the fire can have on the structural elements that compose it and second, that the redundancy inside the structure can permit that the loads be distributed 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 start 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 present materials.

Subsequently calculations were carried out by means of an FEM (Finite Element Method) model, using the thermal loads calculated to provide of 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 inside the structure, focusing on, by means of detailed analysis, the behaviour of the elements inside the 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 discipline due to the large number of variables involved. When applying fire exposures to a structure, a number of methods are available [4], 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 study, the main tool used for this study was the Computational Fire Model 'Fire Dynamics Simulator (FDS)', version 4 [1]. 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. The Smokeview software [2] was used to display the result of the FDS simulations and create images and animations of these results.

'Fire Dynamics Simulator (FDS)' is a Computational Fluid Dynamics (CFD) model that was designed specifically for fire simulations. 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.

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

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

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

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

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

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 processes of validation of the predictive capability of the computational simulation model was 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 of simulation and the experimental measurements, nevertheless, the results obtained in the simulations of the general behavior of the fire are deemed sufficiently reliable to be utilized in a simplified engineering analysis.

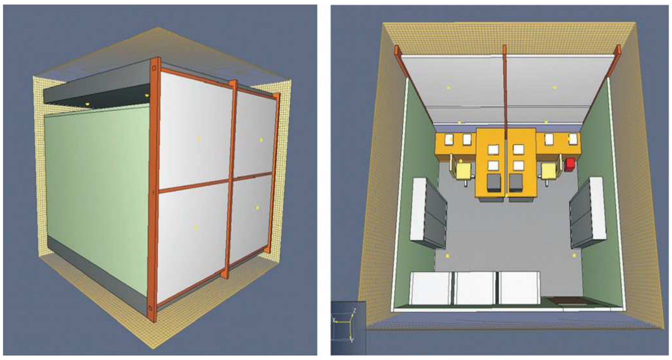
In order to improve the predictive capability of the model, the sensitivities exit choice have been previously analysed with FDS and have improved the parameters introduced to the model to advance to the maximum the calculations of the dynamics of the fire (5). Likewise, the influence of the turbulence was studied and the spatial refinement in the accuracy of the results (6, 7). This analysis have permitted to determine a consensus on the importance of the correct selection of the input parameters of in the model and the spatial refinement of the grid, in the accuracy of the results of the calculations of the dynamics of the fire.

3.2 Study of fire in the room of origin

Before trying to establish a study to understand the development 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 plant and between plants, facilitate verification of the hypothesis of the fire origin, and assist in determining the importance of the different factors that influence in the growth in an enclosure: dimensions of the enclosure, power of the ignition source, characteristics, distribution and types of flammable materials, conditions of ventilation, etc.

In the model the conditions of the room before the fire have been represented with two desks with its respective auxiliary desks in the position of the figure, three filing cabinets in front of the window and another two filing cabinets in the lateral walls. In addition each workstation had a computer and a papers tray, along with a wastebasket. Figure 2 shows a representation of the room model develop with FDS.



2. Computational model of the room of fire origin.

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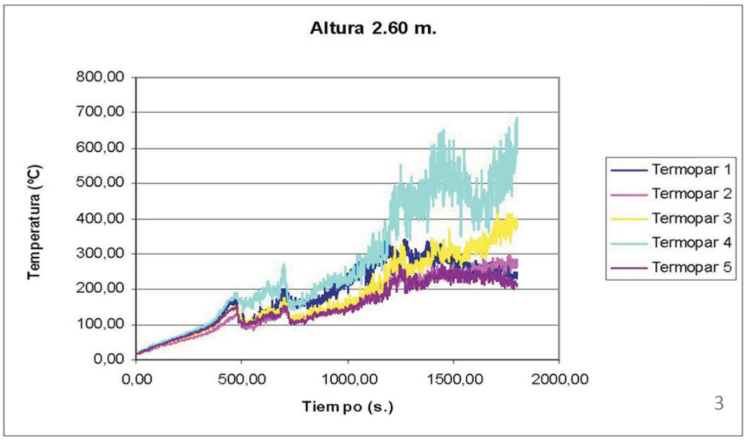
The initial focus of the study was on the fire development in room 2109, the origin of the fire, making it possible to use refined grids for the CFD simulation. In this model the conditions of the room before the fire have been represented with a computational grid having a uniform cell size of 5 cm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

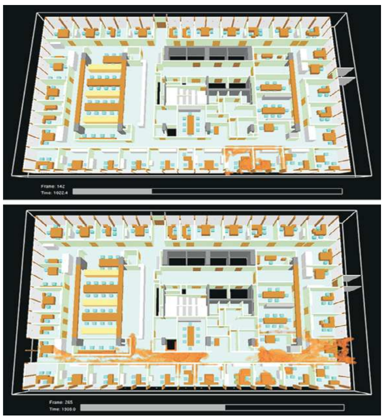
Once the computational domain was established, the characteristics of the materials of the interior finish were defined, with the heat release rate taken from the NIST cone calorimeter test in the research work 'Cook County Administration Building Fire, 69 West Washington, Chicago, Illinois, October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

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



3. Temperatures registered in the model of office 2109.



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

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. Figure 4 shows this heat release rate curve. To characterize this element there was added also, between 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 analyzed: (1) heat detectors were placed upon the glass which broke on having reached 150 ºC, and (2) 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. The Figure 3 is an example of the values of 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 analyze 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 analyzed 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 reasons of space.

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

An analysis was realized to examine the results provided by 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 characteristics curves were studied; in this paper two extreme options of them 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 the double of the previous one in the value of peak (500 MW) with the purpose of considering an extremely severe situation (due, for example, to uncertainties in the modeling 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).

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, when the heat release rate curve is of value 500 MW.

5. Parametric curves for the adopted heat release rates.

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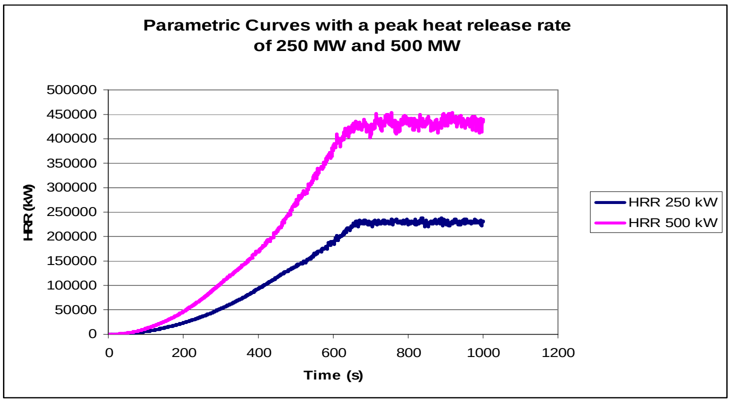
6. Thermocouple temperatures from simulations of central nucleus zone of building.



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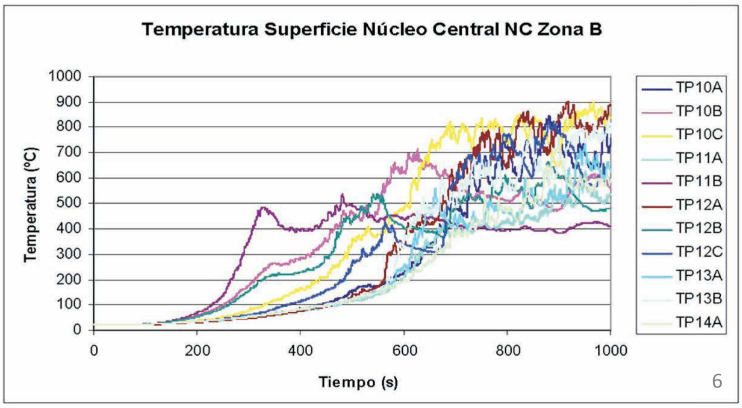

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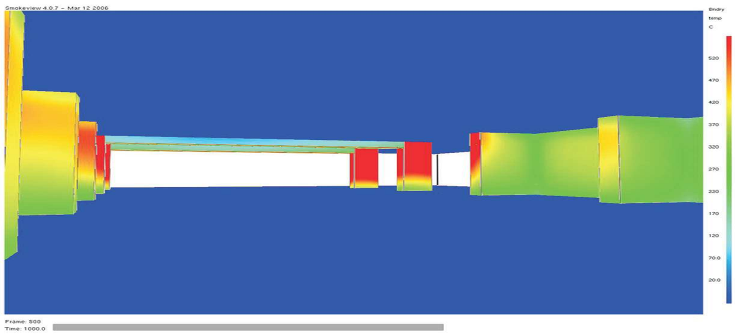

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Figure 6 provides a selection of the results of the temperatures registered by the thermocouples in the simulations of the central nucleus zone of the building. The maximum values reached by the internal temperatures are found to be in agreement with the values estimated after 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 parameter curve of heat release rate 500 MW.

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

En muchos casos, no es necesario ni deseablebasar la geometría del modelo en latotalidad de la estructura. Un dominio mássimplificado, consistente en una o variasplantas, proporciona una gran cantidad deinformación que puede ser extrapolada alresto de la edificación (10).C

uando examinamos modelos de propagaciónde incendios, incluyendo aquellos de propagaciónvertical de las llamas, el principal focode interés recae en la magnitud y el tiempo enque los elementos individuales están sujetosa la exposición térmica. Aunque un modelode una planta completa puede proporcionaresta información, si se conoce que los efectosdireccionales del viento no fueron relevantes,como en el presente caso de estudio, es posibleemplear planos simétricos para reducirel tamaño del dominio. Es razonable asumirque si la planta se divide en cuartos a travésde ejes de simetría entonces cada cuarto de laplanta va a estar afectado de manera similar(tiempos de flashover y extinción, por ejemplo),por lo que estas técnicas serán empleadasen análisis posteriores de propagación verticalen siguientes estudios.

De la misma forma, al crear un modelo de elementosfinitos de la estructura, de nuevo puedeser poco ventajoso crear un modelo tridimensionalde la planta completa. Igualmente parareducir el número de elementos necesario,donde sea posible, en vez de utilizar elementostipo sólido, se pueden utilizar elementostipo “beam”, “shell” o “membrane”. Además,el modelo puede ser simplificado tomandoun plano de corte de la sección de la planta yanalizándola como una viga, como es prácticacomún en ingeniería estructural.

Mientras esta aproximación puede excluircontabilizar muchas de las redistribuciones decarga que comúnmente tienen lugar en unaestructura tridimensional, puede ser utilizadapara, en modelos simplificados, examinar factorescomo el fallo de un elemento individualdentro de la estructura. Por ejemplo, el efectodel fallo de los pilares de acero sin proteccióncontra el fuego sobre el forjado de entrepisopuede ser examinado simplificando el forjadocomo una viga extendida entre el núcleo dehormigón y la columna de acero.

4.1. Modelling the concrete response during the fire

En el modelado por elementos finitos delhormig⍰ armado como miembro estructuralexisten ciertas propiedades inherentes al materialque requieren una cuidadosa atenci⍰.En primer lugar, el hormig⍰ es un buenaislante, por tanto la penetraci⍰ t□micadentro del miembro ser□baja. As□mismo, elhormig⍰ armado es un material compuestoconsistente tanto en hormig⍰ como en elacero de refuerzo. Las propiedades tanto delhormig⍰ como del acero de refuerzo sondependientes de la temperatura, y cuandocargamos una viga de hormig⍰ armado secomportar□primero el□ticamente y luegopl□ticamente despu□ de ceder.

4.2. Modes of failure of the Windsor Tower

Existen un gran n□ero posible de modosde fallo para la Torre Windsor, y es probableque una variedad de estos ocurrieran en lapr□tica. Algunos de estos son:

1. Colapso del entrepiso a causa del falloprevio de las columnas de acero delper□etro. Esta hip⍰esis supone que elentrepiso se vio forzado a trabajar comoun voladizo partiendo del n□leo.
2. Colapso del forjado entre el n□leo y lospilares exteriores al n□leo. Esta hip⍰esissupone que producto de los grandesespacios vac□s existentes en esta zonapor encontrarse los patinillos, el □ea delentrepiso capaz de soportar las grandesfuerzas de tracci⍰ que se originaron porel fallo del entrepiso exterior a los pilaresno era suficiente.

La naturaleza multi-pisos del incendio esindudablemente importante, y es probableque si el incendio sólo se hubiese concentradoen una planta, la mayoría del edificiohubiese sobrevivido intacto. Una evidencia aeste planteamiento se encuentra en el robustocomportamiento sobre la novena planta,donde el fallo local de los pilares perimetralesde acero fue reacomodado medianteredistribución local.

4.3. Structural model of the Windsor Tower

El modelado del comportamiento de unaestructura completa es una tarea muy compleja,y es a menudo deseable empezar conelementos individuales de la estructura ydespués incrementar el nivel de complejidad del modelo. En el caso de la Torre Windsor,el primer elemento estructural a modelarfue el forjado dado que la naturaleza de laconstrucci� del entrepiso, hace que este nopuede ser simplemente modelado como unamembrana soportada por vigas.

Examinando los planos, resulta evidente queel forjado act□ como una red de vigas. Estopuede ser modelado como vigas primarias quesoportan vigas secundarias. Sin embargo, las vigasprimarias y secundarias no necesariamentese extienden en la misma direcci�, esto quieredecir que, mientras en una secci� del edificiolas vigas principales corren de norte a sur, enotra secci� corren de este a oeste.

Es tambi□ necesario hacer suposicionesacerca de las condiciones de frontera en elmodelo de la viga. Donde la viga se une conel n□leo de hormig� del edificio se puedeasumir que existe empotramiento de la vigamientras que en la uni� con el pilar podemosasumir que la conexi� es una articulaci�.A pesar de que la columna est□embebida enel forjado, el tama� relativamente peque�de □ta (140 x 120 mm) da a entender que esimprobable que resista cualquier momentotrasmitido del forjado (Figura 8).

Una vez que ha sido definida la estructura,es necesario examinar el efecto delcalentamiento sobre ella, espec□icamentela evoluci� del calentamiento dentro delmaterial, es decir, el grado de penetraci�del flujo t□mico en el elemento de hormig�estructural y las temperaturas a las cuales hasido expuesto el acero de refuerzo. Esto hacenecesario examinar el perfil de temperaturadentro de la secci� de la viga.

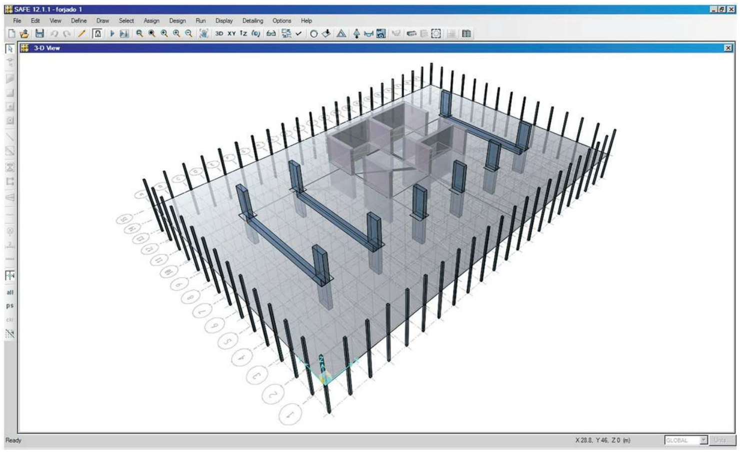
La herramientas utilizadas para el c□culoestructural mediante FEM fueron los modelosABAQUS, SAP2000 y SAFE. Aunque pudiesepensarse que un elemento tipo *beam* se podr□utilizar para modelar las vigas primarias,las limitaciones para representar los efectost□micos dan a entender que es m□ pr□ticoutilizar elementos tipo *shell*. Con esto, la temperaturapuede definirse a un n□ero mayorde profundidades dentro del elemento. La vigade hormig� ha sido por tanto modelada comoun elemento *shell* estrecho y profundo.

4.4. Analysis

Los modelos de desarrollo del incendio en laplanta donde se originó el mismo han sidodescritos anteriormente por (11), focalizándoseestas simulaciones en la atención alaspecto del fallo de ventilación con los doscasos expresados.

También se han considerado las incertidumbresen las características y la distribuciónde los materiales combustibles, por lo quelos cálculos fueron procesados con velocidadesde suministro de combustible que secorresponden aproximadamente a dos veceslo que se podría esperar para tener una ventilación controlada [m� = 5.5Aw h],con unavelocidad de cesión de calor por piso de 350MW, basado en la suposición de una alturade ventana de la mitad de la distancia delsuelo al techo de 3 m.

8. Structural model of the 21st floor.



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Mientras transcurría el incendio, pasadoalgún tiempo, algunos de los paneles dealuminio localizados en la base de lasaperturas se perdieron, dando acceso a aunmás ventilación, pero en esta etapa la cargade combustible del incendio puede habersido sustancialmente disminuida debido asu consumo.

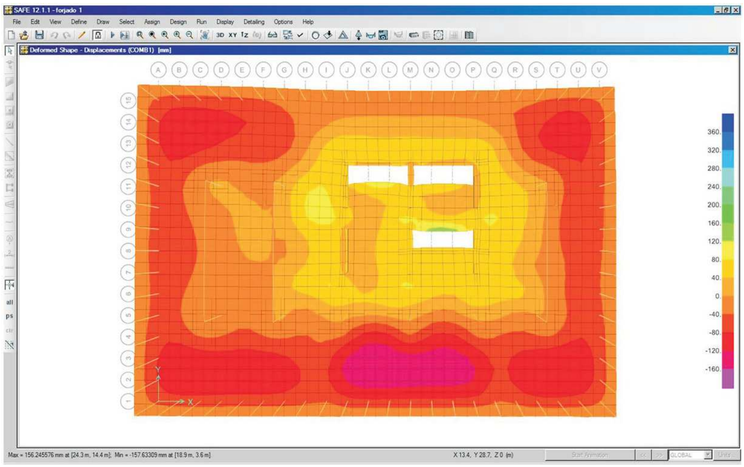
Basados en estas suposiciones de ventilación,las temperaturas máximas calculadas de lafase-gas exceden los 1.100 ºC y las temperaturascorrespondientes en la superficie de lospilares de hormigón fueron aproximadamente200 ºC menores.

Aquí existen pequeñas variaciones de estapredicción respecto al tamaño del incendioprevisible, lo cual estuvo condicionadoa partir del momento en que el límite deventilación controlada fue excedido y elcombustible extra ardió principalmente fueradel compartimiento.

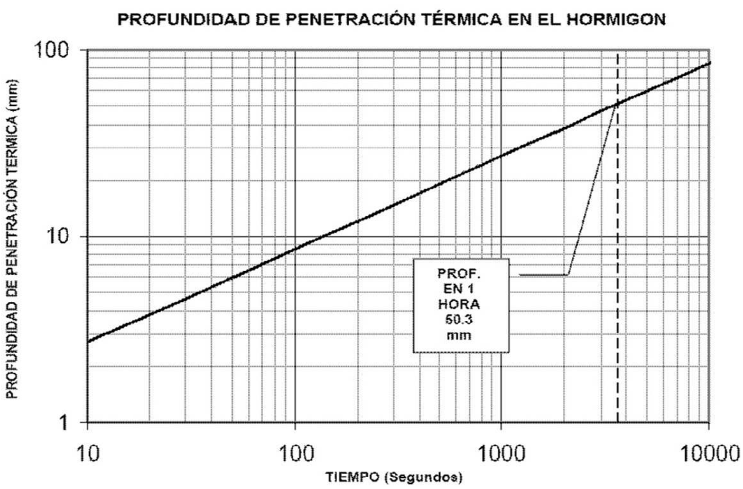
Estas estimaciones están además soportadaspor el análisis post-incendio de las resistenciasdel hormigón (12), que confirmaronque la temperatura en la superficie de lascolumnas y forjados había excedido los 800ºC. Es también posible hacer un estimado delas temperaturas en la superficie del hormigónbasado en la metodología de examinar loscambios de coloración en el hormigón y loscambios en la microestructura interna.

Examinando el comportamiento de la estructurausando los códigos del FEM, un dato muyimportante es la entrada de las condiciones detemperatura en la estructura. Los programasde elementos finitos como ABAQUS puedenpor supuesto calcular la respuesta térmicabasada en la exposición para las condicionesde borde conocidas, tanto temperaturas comoflujos, pero normalmente se necesita el usode elementos tipo bloque, los cuales sonineficientes en la modelación estructural. Portanto, la respuesta térmica ha sido examinadausando modelos térmicos independientesanteriormente descritos. Usando elementostipo shell, se especifican distintas temperaturasa cada capa, y por lo tanto las barras derefuerzo. Una consideración importante aquíes la profundidad del elemento en relacióna la profundidad del flujo térmico que sepropaga dentro del material.

Si este último es muy superficial, entoncesla distribución de la temperatura dentro dela estructura no podrá ser adecuadamente representada a menos de que existan suficientesnodos para resolverlo. Si la cantidad de nodos son insuficientes, el efecto delcalentamiento tenderá a ser exagerado y



9. Deflections in the 21st floor.



10. Thermal penetration depth against time

estopodría tener un efecto que repercutirá en elmodelo mecánico.

Por tanto, con el fin de mostrar esta modelaciónse ha realizado un cálculo sencillo de laevolución de la penetración térmica frente altiempo. La resistencia especificada para la estructurafue 24.5 MPa en los pilares y paredes,29.4 MPa en las vigas y 17.2 MPa en el forjadode entrepiso, aunque hubo algunas variantesal respecto en la práctica (13). Considerandoun hormigón normal de agregados silicios, ladensidad fue tomada como 2400 kg/m^3, laconductividad térmica como 1.2 W/m/K y elcalor específico como 880 J/kg/K, dando unadifusión térmica de 0,57x10.

La Figura 9 muestra los resultados del patrónde deflexiones del modelo para una de lascondiciones de ataque térmico estudiadas.Los resultados obtenidos concuerdan con elmodo de fallo 1 comentado anteriormente. LaFigura 10 muestra la evolución de la penetración térmica en la profundidad a lo largo deltiempo. Los datos de la duración del incendiono fueron completamente precisados, peroexisten evidencias que las fases principalesde éste duraron alrededor de una hora (14);arrojando unos resultados de penetración dealrededor de 50 mm.

Comparando con estudios realizados a laresistencia del hormigón después del fuegosugieren que en pequeñas regiones deltecho, basado en el criterio de la isoterma500 ºC, había excedido una profundidad de200 mm (15). En este caso puede haber porsupuesto efectos transversales incluyendocalentamiento proveniente de las caras delas vigas que conforman el forjado reticular(dimensiones de 100x200 mm, excluyendola losa superior).

Usando por defecto un elemento tipo shell de5 nodos, el espaciamiento en el modelo de laviga de 230 mm de altura y el acoplamientocon la losa de 58 mm, la onda térmica recorreel forjado en aproximadamente 1.400 s. LaFigura 10 sugiere que al menos en los 100primeros segundos sea usada una resolucióndе 10 mm para poder describir adecuadamentela respuesta térmica del forjado en lasimulación.

5. CONCLUSIONS

The initial phase of the investigative work has 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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