In Proc. Proc. Int. Congress Fire Safety in Tall Buildings, Santander, Spain, 19 October 2006

Analysis of thermal fields generated by natural fires on the structural elements of Tall Buildings

Jorge A. Capote[1] (capotej@unican.es); Daniel Alvear[1] (alveard@unican.es); Mariano Lázaro[1] (lazarom@unican.es); Pablo Espina[1] (espinap@unican.es); Ian Fletcher[2] (ian.fletcher@ed.ac.uk); Stephen Welch[2] (s.welch@ed.ac.uk); José L. Torero[2] (j.torero@ed.ac.uk)

[1]Group GIDAI. Dpto. de Transportes y Tecnología de Proyectos y Procesos. University of Cantabria. Ave. Los Castros, s/n. 39005 Santander (Spain). Tf.: +34 942 201826. Fax: +34 942 201873.
[2]BRE Centre for Fire Safety Engineering. School of Engineering and Electronics. The University of Edinburgh. The King's Buildings EH9 3JL Edinburgh (U.K.). Tf.: +44 (0) 131 6507161. Fax: +44 (0) 131 6506781

ABSTRACT

The Windsor Tower in Madrid was involved in a major fire, on 12-13 February 2005, which caused extensive structural damage to the upper floors of the building. This fire has provoked intense interest amongst researchers hoping to better understand the performance of concrete structures in fire. A research team integrated for Group GIDAI (University of Cantabria – Spain) and BRE Centre for Fire Safety Engineering (The Edinburgh University – UK) has begun a study with the purpose of properly characterising the fire and the performance of the structure.

The objectives of the study are (1) to analyze the fire growth conditions in order to understand the fire propagation mechanisms between floors of the building, using computational fire modelling, and (2) to evaluate the response of the structure to the fire.

The research undertaken on the fire propagation on the 21st floor, the origin of the fire, has allowed assessment of the severity conditions reached as consequence of the fully-developed fire, due the combustion of the present flammable materials. Starting from these results, characteristic curves of heat release rate representative of the real fire have been determined, to facilitate study of the thermal attack (temperatures, heat flux, etc.) on the structural elements. The tools used for this purpose were the Fire Dynamics Simulator (FDS) LES code, developed at the National Institute of Standards and Technology (NIST), and the SOFIE RANS code. These results will allow, in the next stages, to make use of finite element methods to obtain the corresponding thermal and mechanical state (stress and strain) of each element due to these conditions.

1.- INTRODUCTION

In the late evening of the Saturday 12th February 2005 a fire started on the 21st storey of the Windsor Tower, Madrid. This fire proceeded to engulf all levels above the 4th storey and burnt uncontrollably for about 16 hours. Severe damage was caused throughout the building including a partial collapse of the upper storeys of the 106m tall tower.

The building, owned by Asón Inmobiliaria, was constructed during the period 1974-1978 for use as commercial office space. It was located at 65 Calle Raimundo Fernández Villaverde in the heart of the commercial and banking district of Madrid, north of the city centre. The tower was originally designed by Alas Casariego Arquitectos and was constructed by OTEP Internacional S.A.. At the time of construction it was the tallest building in Madrid but by the time of the fire was the 8th tallest.

The building was undergoing a major refurbishment designed to bring the structure in-line with the current national fire safety regulations. Both passive and active fire safety improvements were due to be installed. Sections of the work had been completed but much of the work, especially on the upper floors, was yet to start. Also as part of the refurbishment a new fully-glazed external facade had been fitted.

Fig. 1 Visualization of the Windsor building after the fire. (Source: Cuerpo de bomberos de la Comunidad de Madrid).

The fire services arrived on-site shortly after the fire began and attempted to tackle the blaze. However they quickly retreated as they could not halt the fire spread putting the safety of fire crew was at risk. The fire quickly spread to the uppermost floors of the building but more unusually also spread to floors below the point of ignition. The fire stood out spectacularly against the night sky and by morning had reached the lower floors of the building before burning out on the 5th floor. Due to the intensity and length of the blaze there was concern of a complete global collapse.

The timing of the events that took place during the fire are quoted in various source materials, however the values given vary according to the source. Nevertheless, the sequence of events is consistent for all reports covering the event. The following times are quoted from information included in several sources:

11:05 am	Building surveillance system signals an alarm in office 2109 on the 21st storey
11:20 am	Fire Brigade (Civil defence) called
11:24 am	First fire-fighters arrive onsite
11:35 am	Fire brigade begins initial engagement with the fire, having climbed the stairs to reach the 21st storey
12.20 am	Fire has spread up the 28th storey
01.15 am	North-east section of building collapses on upper storeys, including the concrete portal frame adjoining the façade
02:00 am	Occasional blue flames are seen coming from east and south building facades. Fire spread below the 21st floor
02:13 am	Perimeter flooring above 25th floor collapses, large collapse of middle section at 20th floor
03:00 am	Fire less ferocious in upper floors but large segments of the structure continue to fall both inside and outside the building
03:30 am	Fire spread below 16th floor, crossing below Technical Storey 2
04:00 am	Fire intensity increases on storeys below ignition floor, especially 14 and 15. Floors at upper levels collapse
05:30 am	Fire spread below 12th floor
07:00 am	Fire Services consider the blaze to be under control although numerous hotspots still exist throughout the building

Table 1. The timing of the events (Source: 'Fire in the Windsor building, Madrid. Survey of the fire resistance and residual bearing capacity of the structure after the fire', Intemac Report NIT 2-05, December 2005 and http://www.structuralfiresafety.org/).

In this paper we present an abstract of the research work. Initially, we studied the fire development in the office 2109, the origin of the fire, and the next stage was the fire propagation on the 21st floor. This has allowed assessment of the possible severity conditions reached as consequence of the fully-developed fire, due the combustion of the present flammable materials.

Starting from these results, characteristic curves of heat release rate representative of the real fire have been determined, to facilitate study of the thermal attack (temperatures, heat flux, etc.) on the structural elements.

2.- COMPUTATIONAL FIRE MODEL: FIRE DYNAMICS SIMULATOR (FDS)

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.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0 \qquad \text{Conservation of Mass}$$

$$\frac{\partial \rho Y_l}{dt} + \vec{u} \cdot \nabla \rho Y_l = -\rho Y_l \nabla \cdot \vec{u} + \nabla \cdot \rho D_l \nabla Y_l + \dot{m}_l''' \qquad \text{Conservation of Species}$$

$$\frac{\partial}{\partial t}(\rho \bar{u}) + \nabla \cdot \rho \bar{u}\bar{u} = -\nabla p + \rho \bar{f}_T + \nabla \cdot \tau_{ij} \qquad \text{Conservation of Momentum (Navier-Stokes)}$$

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

$$p_0 = R \rho T \sum_l \frac{Y_l}{M_l} \qquad \text{Eq. of State for a Perfect Gas}$$

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). It is possible to perform a Direct Numerical Simulation (DNS) if the underlying numerical grid is fine enough. LES is the default mode of operation.

For most applications, FDS uses a "mixture fraction" combustion model. The mixture fraction is a conserved scalar quantity that is defined as the fraction of gas at a given point in the flow field that originated as fuel. The model assumes that combustion is mixing-controlled, and that the reaction of fuel and oxygen is infinitely fast.

Radiative heat transfer is included in the model via the solution of the radiation transport equation for a non-scattering gray gas. In a limited number of cases, a wide-band model can be used in place of the gray gas model. The radiation equation is solved using a technique similar to a finite volume method for convective transport, thus the name given to it is the Finite Volume Method (FVM).

3.- ANALYSIS OF FIRE DEVELOPMENT IN 2109 OFFICE

The research team decided to focus initial attention on the fire development in room 2109, the origin of the fire, with the purpose of understanding the fire development inside the building and determinate flame spread conditions, the time when the windows broke, etc. Some representative material properties were established from the literature, which whilst not providing a means of establishing a forensic interpretation of the fire development, do permit an initial assessment of possible spread mechanisms and times. In addition, material properties and other conditions (e.g. window failure times) can easily be varied to study their influence on the progress of the fire.

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.

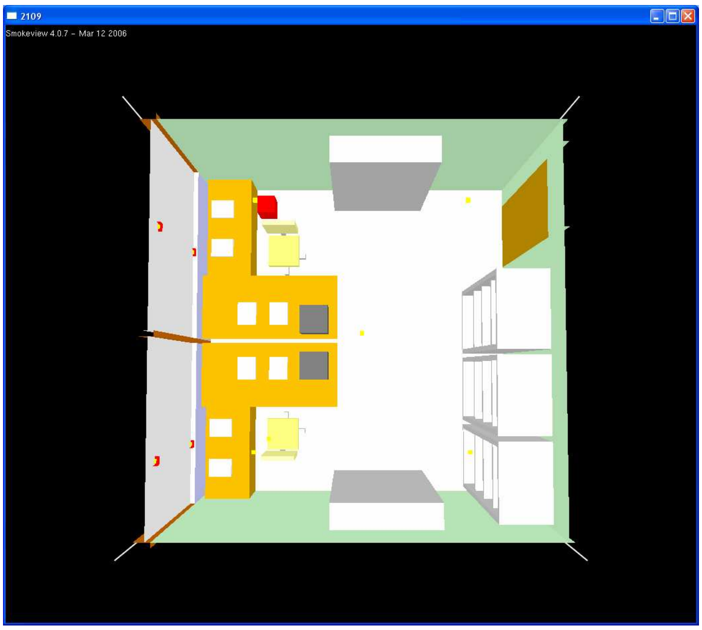


Fig. 2 Visualization of the office in which the fire began.

The Figure 2 shows a representation of the room model develop with FDS. 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. This office had 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.

The floor slab material was concrete. The interior finish included carpeted floor, ceiling tiles and wall coverings. The characteristic parameters of the ceiling tiles were represented by a fibre mineral material 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' [5]. In the cone calorimeter tests of that study, the heat release rate per unit area of the ceiling tile had a peak of 38.92 kW/m^2 at 22 s and the heat release rate per unit area of the carpeting had a peak of 374 kW/m^2 at 45 s.

For the walls, the parameters used correspond with "Plywood" material whose heat release rate per unit area had a peak of 243 kW/m^2 at 575 s. The properties of this material have been obtained of the program 'FIRESTAR Project CEN TC256' [7] and can be observed in the Figure 3 together with the curves of the different covering materials.

Table 2 shows a summary of the covering materials properties that have been used in the simulation of the fire scenario.

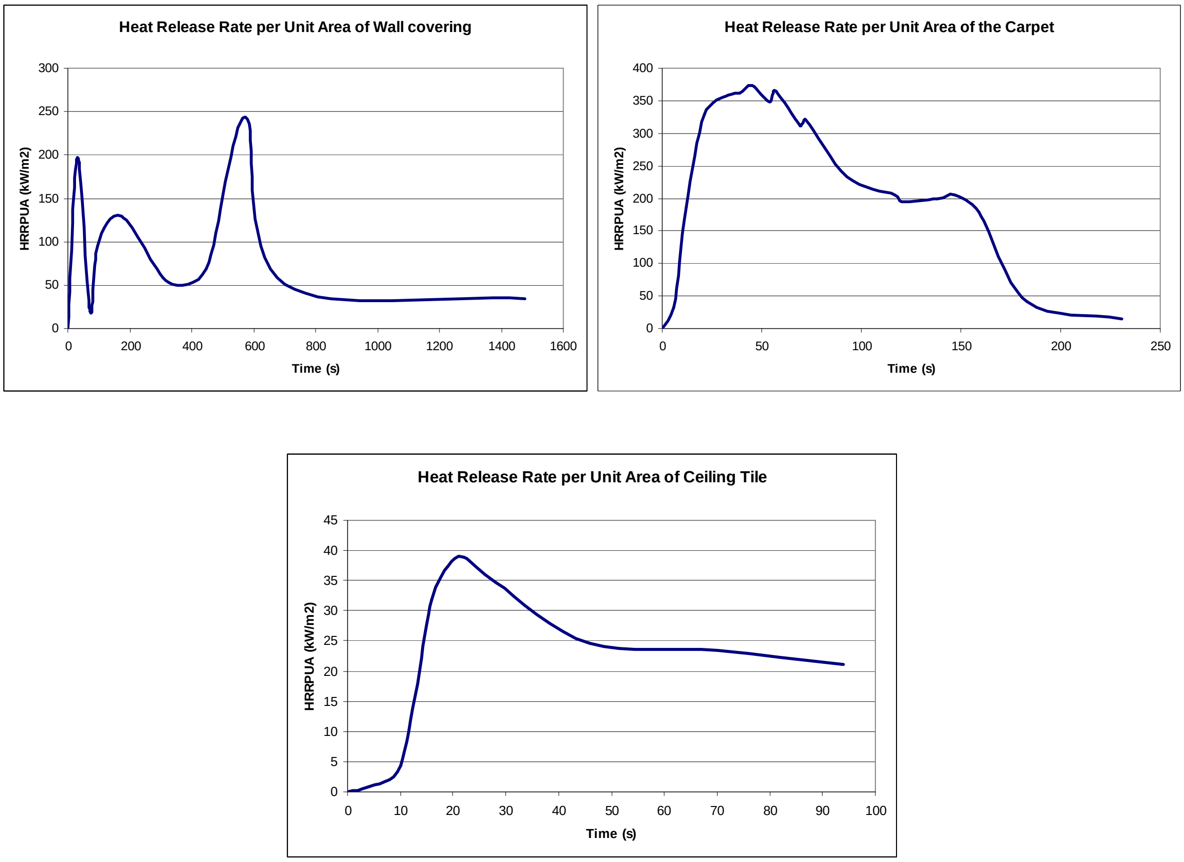


Fig. 3 Heat Release Rate per unit area of the covering materials. (Sources: 'FIRESTARR Project CEN TC256' and 'Cook County Administration Building Fire, 69 West Washington, Chicago, Illinois, October 17, 2003: Heat Release Rate Experiments and FDS Simulations; D. Madrzykowski and W.D. Walton; NIST (USA)'.)

	Thickness (mm)	Density (Kg/m3)	Specific heat (KJ/KgºK)	Ignition Temperature (ºC)
Walls[1]	9.5	440	1,47	326
Floor[2]	6	750	---	290
Ceiling tile[2]	13	1440	---	325

Table 2. Characteristics of the covering materials. (Sources: [1]FIRESTARR Project CEN TC256. [2]Cook County Administration Building Fire, 69 West Washington, Chicago, Illinois, October 17, 2003: Heat Release Rate Experiments and FDS Simulations; D. Madrzykowski and W.D. Walton; NIST (USA).)

After defining the characteristics of the covering materials, we proceeded to analyze the characteristics of the furniture elements. The workstation included two desks and its auxiliary desk, the computer and the paper tray of both desks.

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' [6] 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. The filing cabinets characteristics were introduced using the information of the NIST database tests [6], proposing a heat release rate peak of 3.6 MW at 425 s.

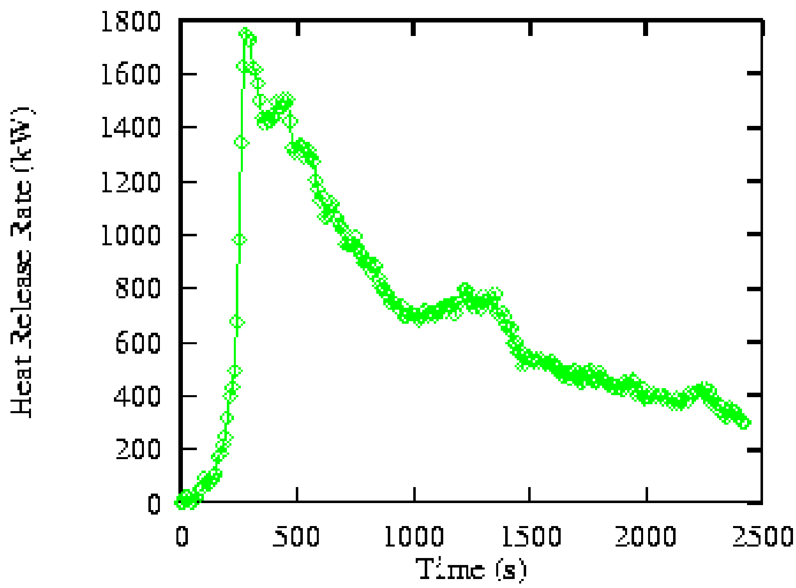


Fig. 4 Workstation heat release rate. (Source: NIST Standard Reference Database)

The fire origin was prescribed in a wastebasket close to the auxiliary desk, with the purpose of representing the similar conditions of the real fire. To define its heat release rate curve several documents were used [3, 5, 8, 9], although finally the curve of the experiment included in the document 'Heat Release Rate Tests of Plastic Trash Containers' [3] was selected, but with a smaller peak value in order to consider the rest of studied documents. Figure 5 shows the heat release rate selected.

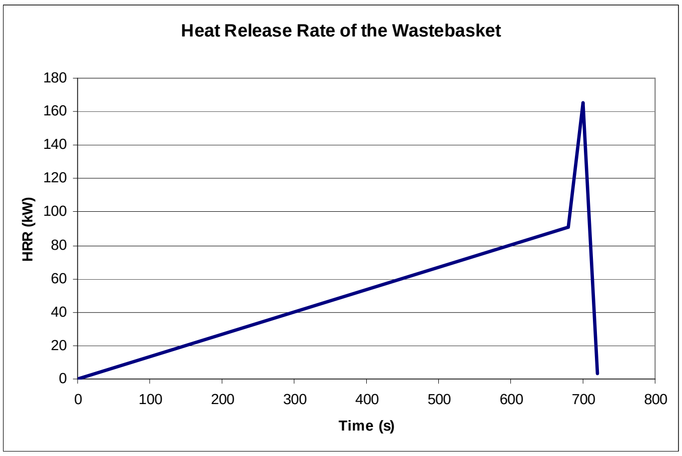


Fig. 5 Wastebasket heat release rate curve. (Source: "Heat Release Rate Tests of Plastic Trash Containers", D.W. Stroup and D. Madrzykowski, Building and Fire Research Laboratory, National Institute of Standards and Technology, REPORT OF TEST FR 4018, April 24, 2003.)

After defining the characteristics of all the combustible materials, the properties of the glass curtain wall, the windows and the perimetric steel columns were specified, taking their default characteristics from the FDS database. Also in the lower part of the window, fire-proofing elements were introduced in some zones of the building. The characteristic parameters of these elements were considered to be "MARINITE" material, taking as a reference the parameters of the model database.

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.

The results in both cases were similar as can be observed in the Figures 6 and 7.

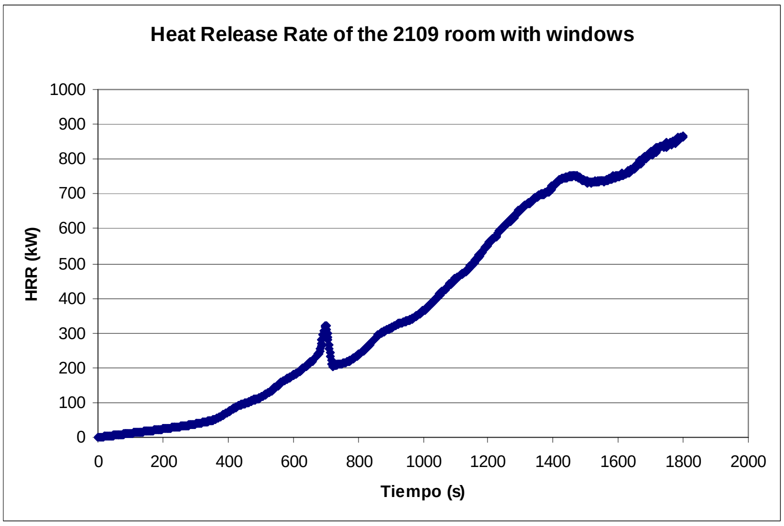


Fig. 6. Total Heat Release Rate of the 2109 room with windows.

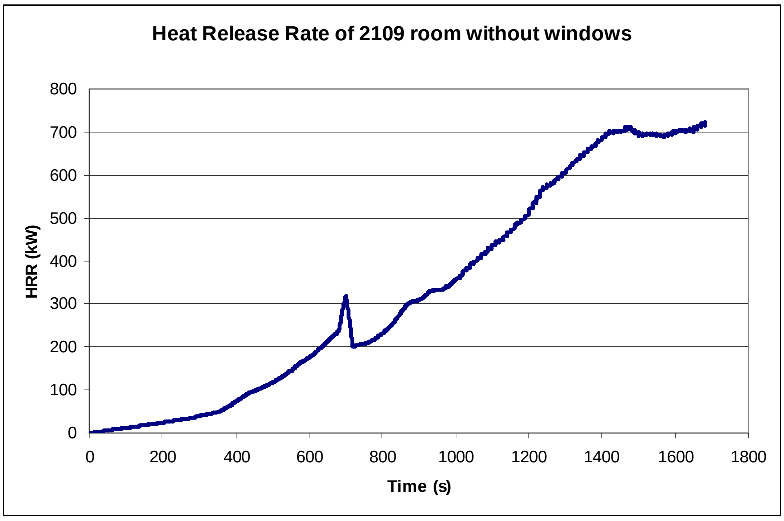


Fig. 7. Total Heat Release Rate of the 2109 room without windows.

The results of the analysis in 2109 room demonstrated that it was possible to reach phases of fire completely developed 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.

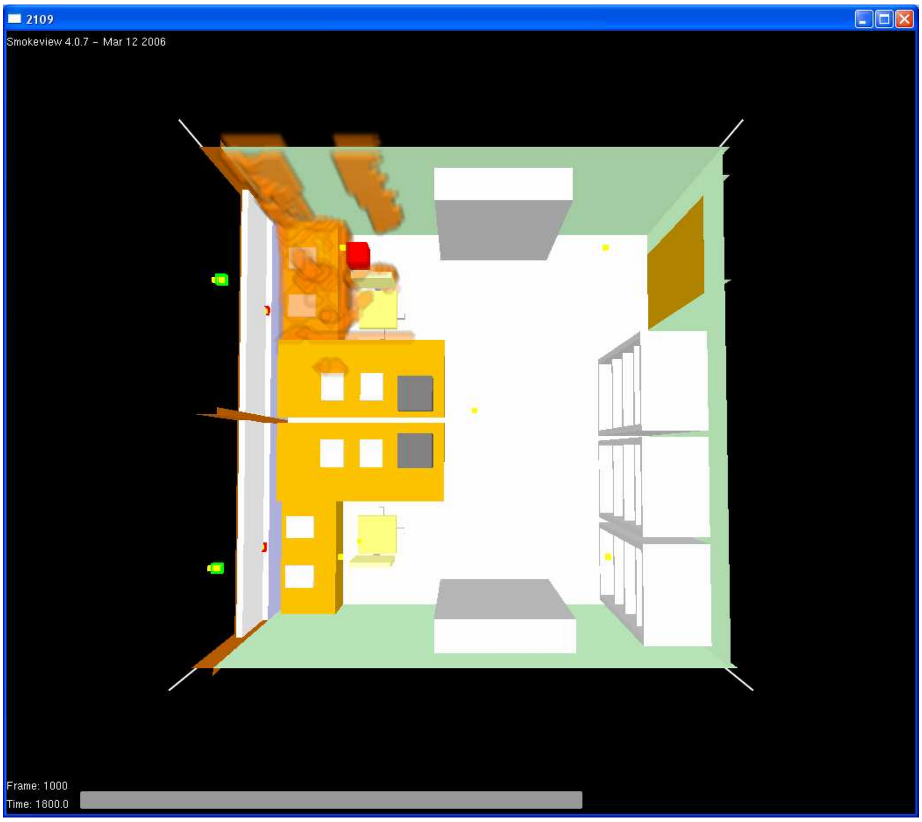


Fig. 8. Smokeview visualization of the heat release rate per unit volume in the fire development (1800 s).

4.- ANALYSIS OF THE FIRE DEVELOPMENT IN THE 21st FLOOR

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. This floor also contained reinforced concrete columns outside the core, but these did not extend to the facade. The composite steel and concrete beams, found outside the core, were anchored into the reinforced concrete columns at an east-west aspect. The beams were anchored to the columns by means of steel plates with rods welded at the comers.

In the Figure 9, 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.

The 21st floor has been divided into smaller modular rooms with several offices situated around the perimeter of the building and further rooms within the building. The rooms are divided across 'Plywood' panels; some workstations are located in the central left part and there are a central core of concrete in which are located the elevators, the stairs, the toilets and some meeting rooms (see Figure 9).

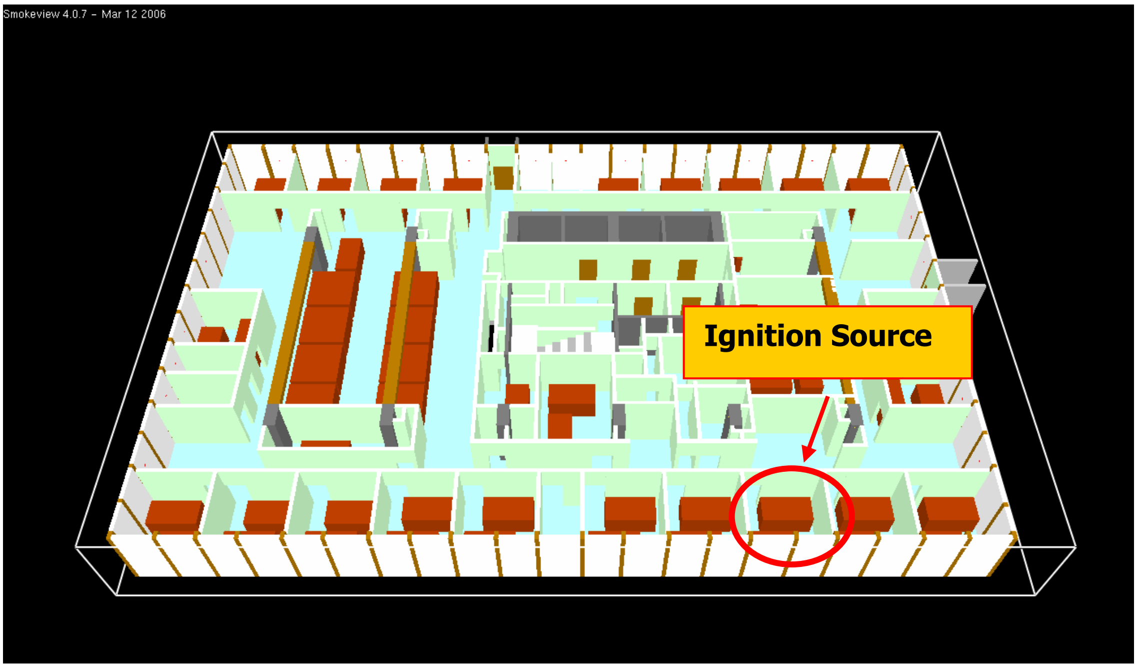


Fig. 9. General view of the 21st floor, with ignition source location.

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. From these results, in later phases, more detailed analyses will be developed that allow verification of the spread conditions on this floor and the spread to other floors of the building.

The characteristics of the covering elements present in the 21st floor correspond to those previously described for office 2109, except in case of the carpet, for which the heat release rate has been modified to match that of the FDS database. The Table 3 shows the principal characteristics of these covering materials.

Ref.	Thickness (mm)	Density (Kg/m3)	Specific heat (KJ/KgºK)	Ignition Temperature (ºC)
Walls[1]	9.5	440	1,47	326
Floor[2]	6	750	---	290
ceiling tile[3]	13	1440	---	325

Table 3 Characteristics of the covering materials. (Sources: [1]FIRESTARR Project CEN TC256. [2]FDS Database. [3]Cook County Administration Building Fire, 69 West Washington, Chicago, Illinois, October 17, 2003: Heat Release Rate Experiments and FDS Simulations; D. Madrzykowski and W.D. Walton; NIST.)

In this case the beginning of the fire corresponds directly with the combustion of the workstation which includes all its elements, for which information from several NIST tests [6] of one or more workstations was used. In the Figure 10 it is possible to see the heat release rate of two workstations tests adopted.

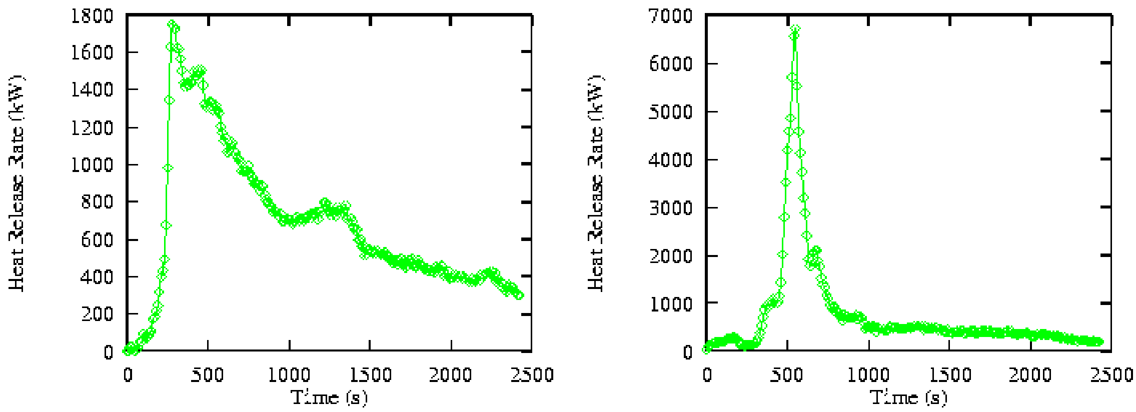
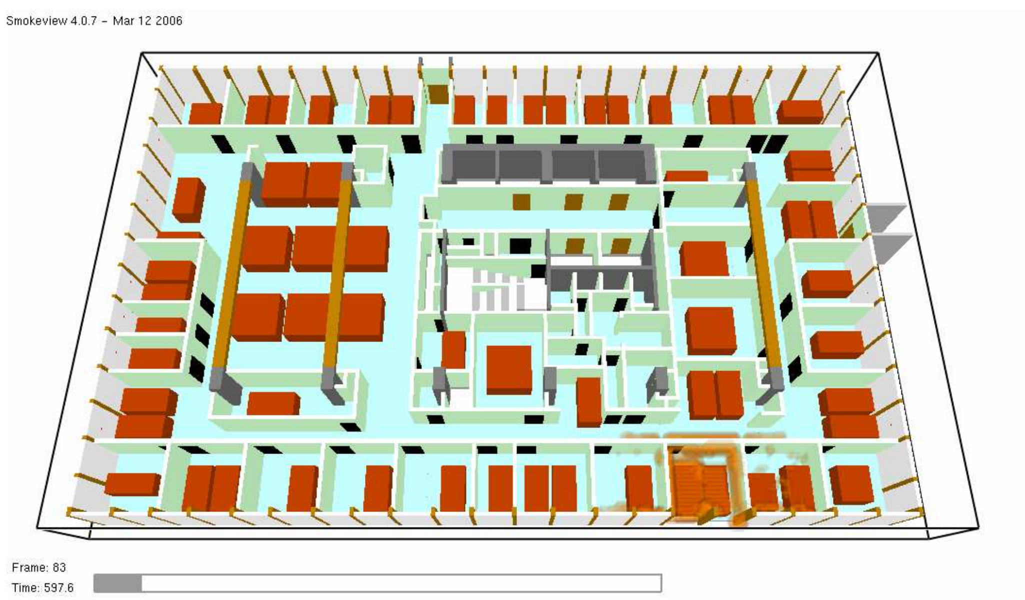


Fig. 10 Heat release rate of the workstations. To the left side two panel workstation and to the right three panel workstation (Source: NIST Standard Reference Database).

It can be seen in Figure 11 that the development of the fire was produced both across the walls and within the corridor. Different simulations of the fire development were produced under different conditions of ventilation, which proved to be a critical factor in the fire evolution.

In this way, 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.



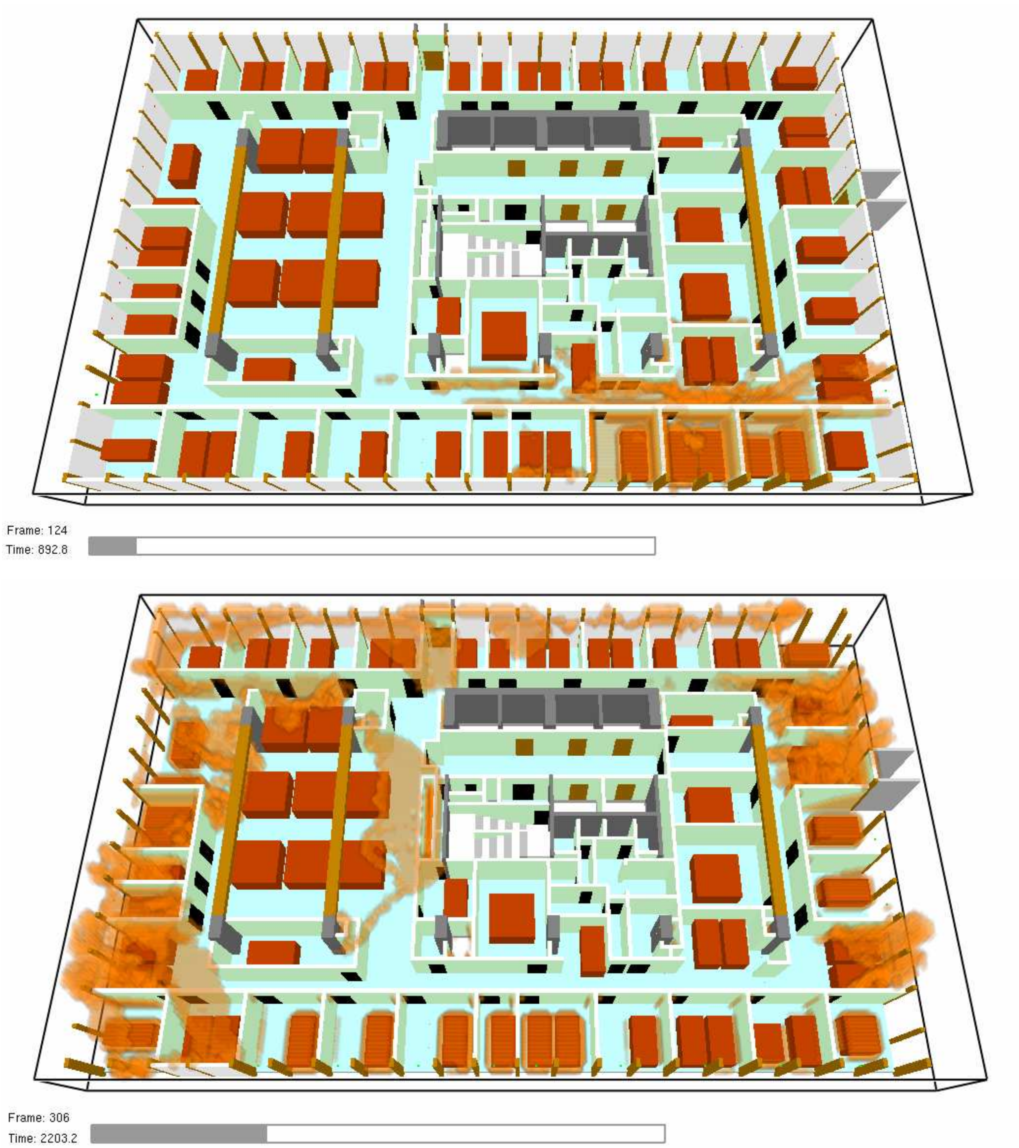


Fig. 11 Fire development in the 21st floor with a window break temperature of 90 ºC.

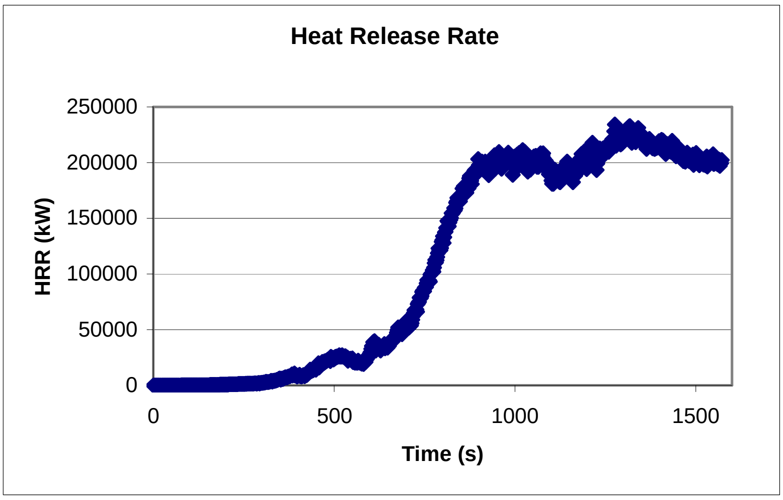


Fig. 12 Results of the model FDS for Heat Release Rate in the 21st floor.

From the results of the previous simulations, the heat release rate curve that was developed in the floor was calculated. This information provides an indicator of the magnitude and severity of the fire and it is of great interest for the analysis of thermal response in the structural elements. In the Figure 12 it is possible to observe the curve mentioned previously.

5.-ANALYSIS OF THE STRUCTURAL RESPONSE USING PARAMETRIC CURVES

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 a 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 $\dot{m} = 5.5A_w\sqrt{h}$ (kg/min), which is of the order of 350MW).

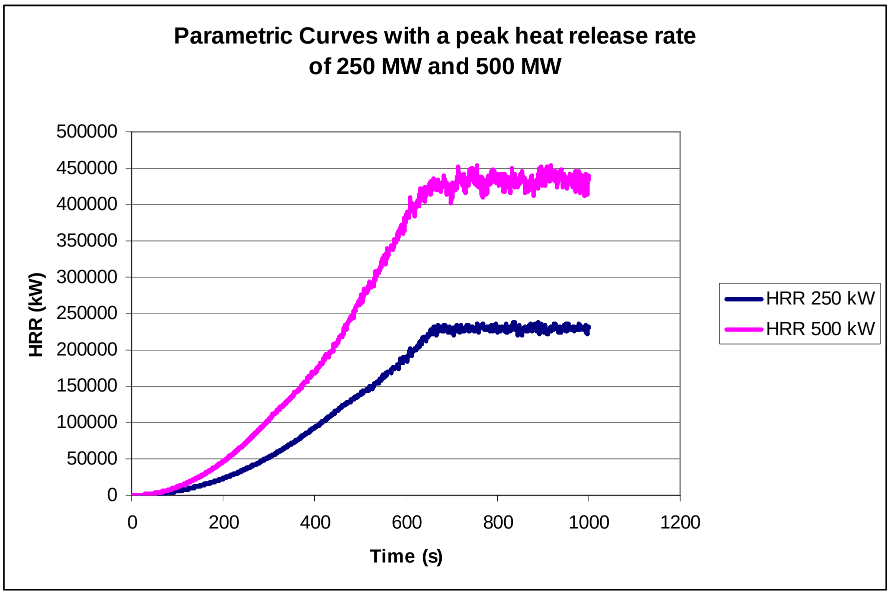


Fig. 13 Characteristics curves with a peak heat release rate of 250 MW and 500 MW.

As was expected due to the magnitudes of completely developed fires, such as the selected ones from the characteristics curves, the resulting environmental temperatures were of a considerable value, reaching 1160 ºC. In the first of the cases studied the major temperatures on the surface of the structural elements were produced in the column of the central core of concrete, reaching 678ºC.

As the characteristic curve of heat release rate was increasing, the value of the temperature of these elements was increasing too, being obtained in both cases values of temperature until 966 ºC.

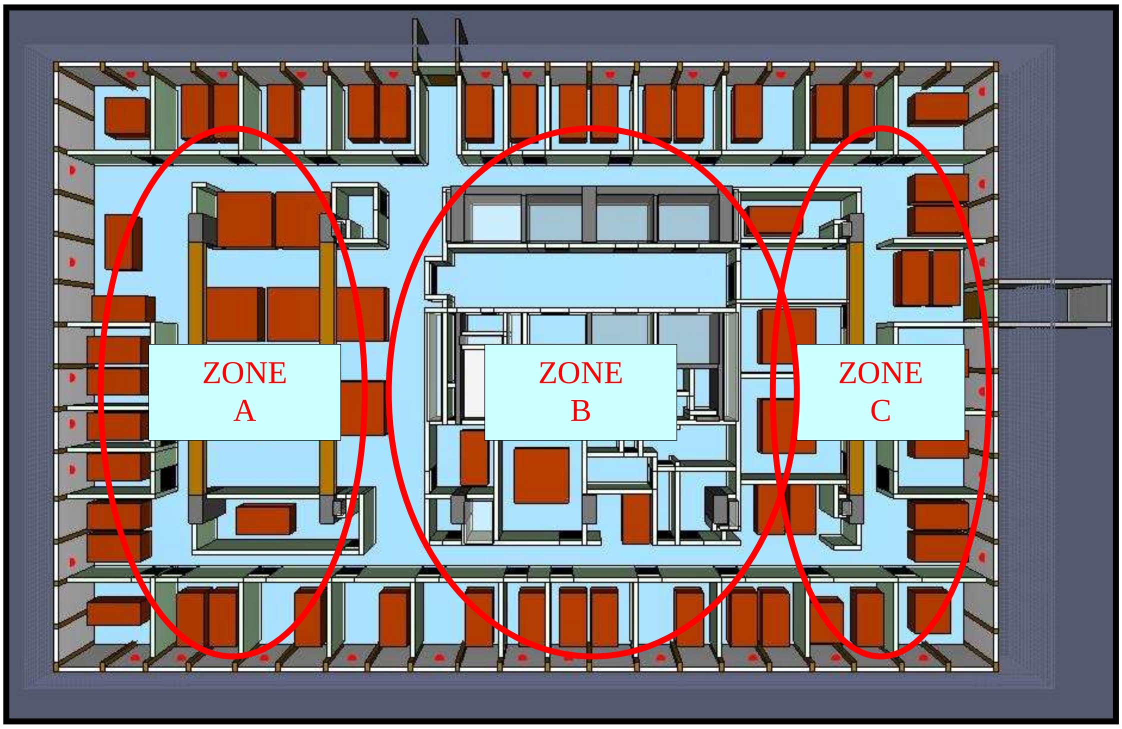


Fig. 14 Zones for the structural analysis in the 21st floor.

The floor has been divided in three zones to be able to obtain information of the temperatures in the columns in concrete zones (see Figure 14). For the case of the characteristic curve of 500 MW, the temperatures of the columns of the Zone A can be seen in Figure 15, Zone B in Figure 16 and Zone C in Figure 17.

The next phases of the study will centre on improving the previous analyses and once the possible conditions of the origin floor of the fire are established the spread of the fire among the floors must be analysed, considering the system of ventilation, the curtain wall, etc.

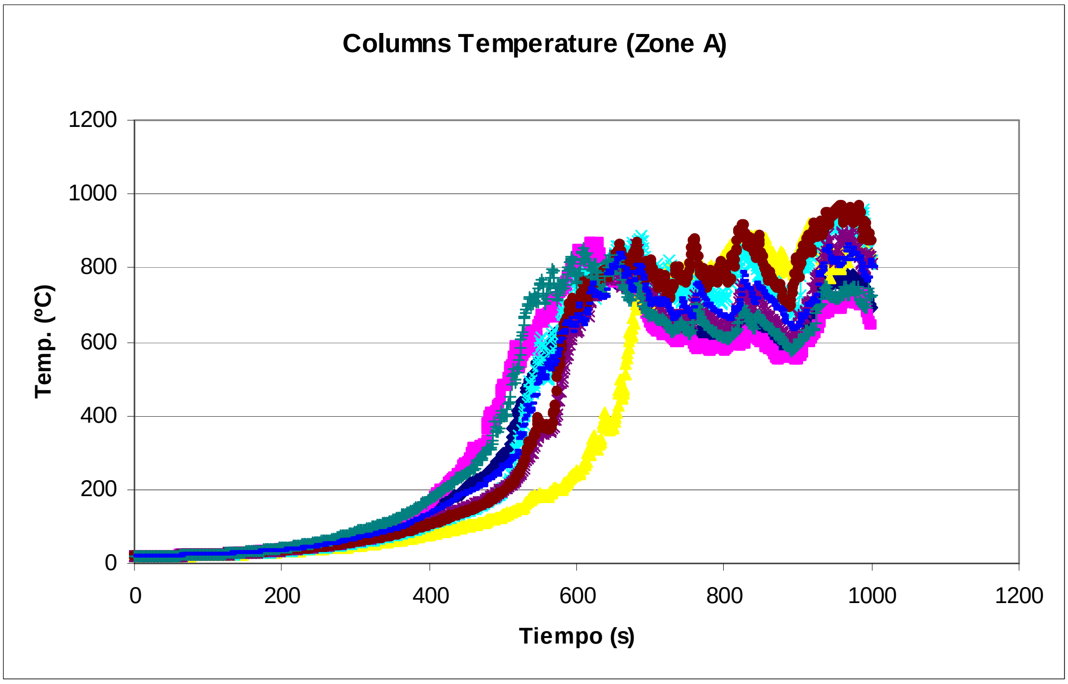


Fig. 15 Temperatures of the columns of the Zone A.

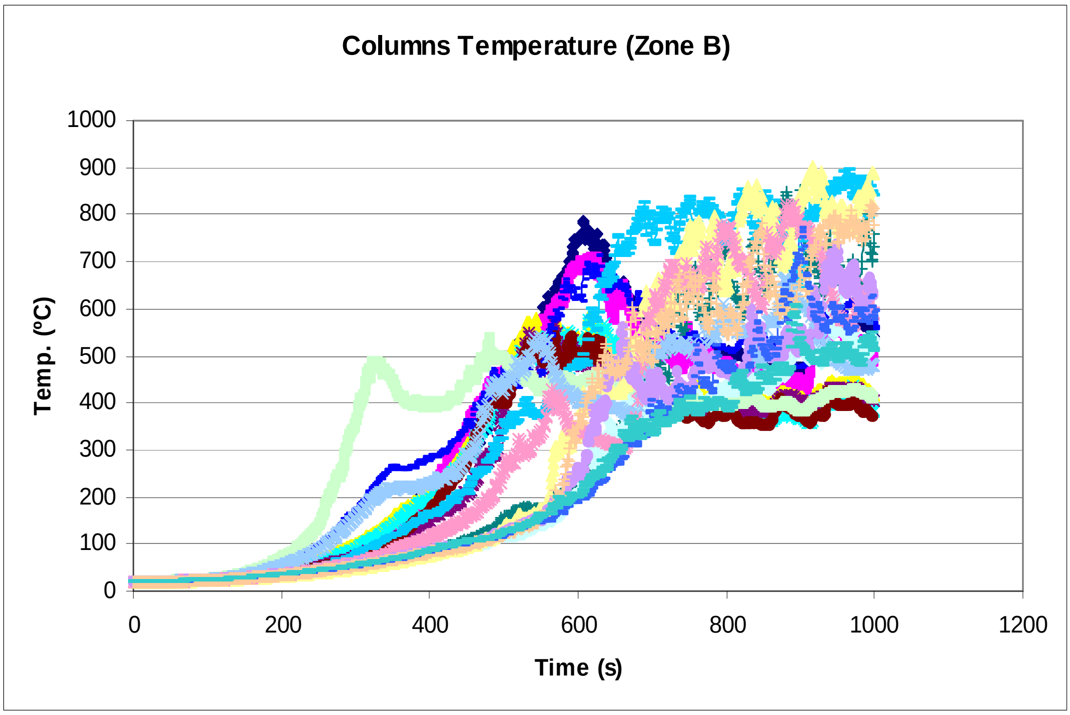


Fig. 16 Temperatures of the columns of the Zone B.

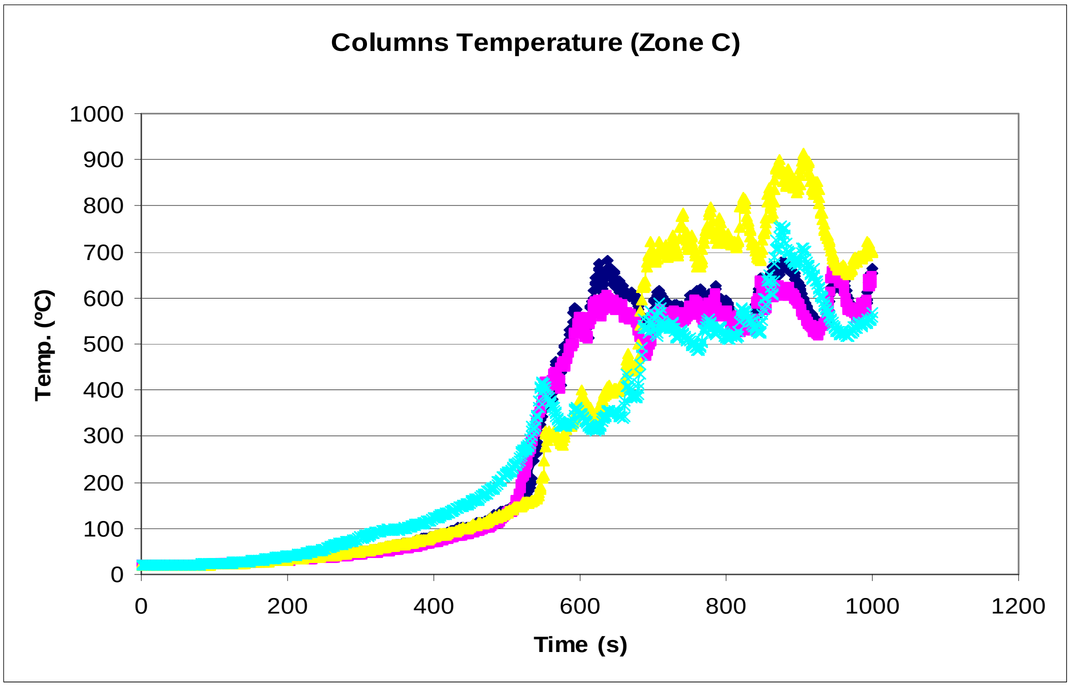


Fig. 17 Temperatures of the columns of the Zone C.

In the Figure 18 it is possible to observe the temperature on the surface of the structural elements after 1800 s for the case of the second characteristic curve selected.

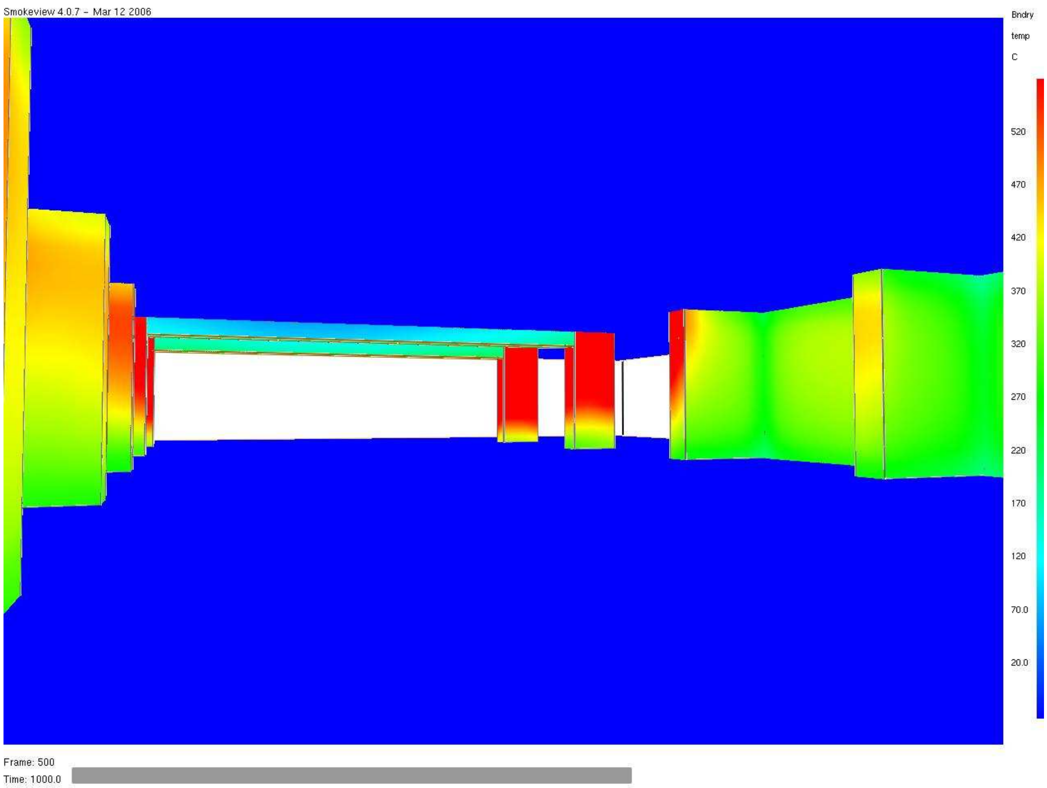


Fig. 18 Results of the model for the conditions of thermal attack on the structural elements in case of the characteristic curve of HRRpeak=500 MW.

6.-CONCLUSIONS

The initial stage of the research works has demonstrated the capacity of the computational fire models, including CFD, to realize the analysis of natural fires development inside both in a small enclosure, as a room, and in a bigger enclosure as an entire floor. 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. Furthermore, these models allow analysis of the impact of the fire, calculating the thermal conditions to which the structure will be submitted. These thermal exposures will be used in later phases to analyze the mechanical response (stress and strain) of the structure in more detail by means of finite elements models.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of The Concrete Centre/British Cement Association (UK), EPSRC (UK), el Instituto Español del Cemento y sus Aplicaciones – IECA, Financiera y Minera Corporation– FYM, and the Ministry of Education and Science of the Government of Spain, as well as to all those persons, public and private institutions whose support made this research project possible.

REFERENCES

[1] “Fire Dynamics Simulator (Version 4) – Technical Reference Guide”, Kevin McGrattan, National Institute of Standards and Technology (NIST). 2005.
[2] “Smokeview (Version 4) – User’s Guide”, Glenn P. Forney and Kevin McGrattan, National Institute of Standards and Technology (NIST). 2005.
[3] “Heat Release Rate Tests of Plastic Trash Containers”, D.W. Stroup and D. Madrzykowski, Building and Fire Research Laboratory, National Institute of Standards and Technology, REPORT OF TEST FR 4018, April 24, 2003.
[4] “Full-Scale Flammability Measures for Electronic Equipment”, Matthew Bundy and Thomas Ohlemiller, Building and Fire Research Laboratory, National Institute of Standards and Technology, NIST Technical Note 1461, August 2004.
[5] “Cook County Administration Building Fire, 69 West Washington, Chicago, Illinois, October 17, 2003: Heat Release Rate Experiments and FDS Simulations”, D. Madrzykowski and W.D. Walton, Building and Fire Research Laboratory, National Institute of Standards and Technology, NIST Special Publication SP-1021, July 2004
[6] NIST Standard Reference Database Number 75, January 1999 Release
[7] FIRESTARR Final Report. CEN TC256 / CENELEC TC9x JWG Fireprotection. 2001.
[8] Karlsson & Quintiere “Enclosure Fire Dynamics” CRC Press 2000 pg 255 – 305
[9] “The SFPE Handbook of Fire Protection Engineers”, Society of Fire Protection Engineers, SFPE and National Fire Protection Association, NFPA.