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MULTI-STOREY FIRE ANALYSIS FOR HIGH-RISE BUILDINGS

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ABSTRACT

This work proposes a novel methodology to determine the design fire of modern buildings that are outside the range of applicability of nominal methods. Structural engineers face the problem of how to characterize the fire environment to be used in the design stage of buildings. This question is addressed here in the context of complex high-rise buildings where the resulting fire environments pose unique features that are not necessarily accounted for in traditional design fires. A comprehensive analysis of the fire environment, with the objective of maximizing the challenge to the structural elements is proposed to understand the particular fire dynamics of the building. The results must be expressed in simple terms without loss of generality in order to be of valuable engineering use. The methodology combines computational fluid dynamics and engineering simplifications such as using steady-state temperatures and dividing the fire environment into near and far fields. Both, fully distributed fires and travelling fires are investigated. The methodology is applied to a real building to illustrate the importance of this analysis and the comparison with the results from the standards.

1 INTRODUCTION

Structural engineers and building regulations are gradually moving towards greater use of performance based design. This is especially true for large or prestigious buildings, which are constantly seeking better, more robust and more reliable methodologies to establish stronger correlations between the designs and the actual performance of the building. In the light of a series of very serious and costly fires in tall buildings in recent years[1], the need for large structures being robust is achieving greater importance in the eyes of insurers, clients and the general public. New methodologies aimed at a better understanding of both the fire and structural behaviour of such buildings are therefore sought.

Structural fire engineers face the problem of how to characterize the fire environment to be used in the design stage of the building. Modern high-rise buildings include complex and non-conventional architectonical elements and designs that can lead to fire environments diverging significantly from those used in the development of current codes and standards as well as many engineering calculations. Atria, large enclosures, high ceilings, connected floors, glazed façades, and others are not exceptional features of modern architecture and their effects are not necessarily included in traditional design fires. These distinctive characteristics of high-rises and other modern buildings influence the fire environment but have not been included in the current state of the art.

The simplest way to represent any fire is the standard fire curve[2], which was developed at the end of the XIX century as a breakthrough that led to the concept of fire resistance rating. This one curve expresses the heating of any fire as a logarithmic increase of gas temperature with time. The standard curve offers a very simplistic method that neglects the real behaviour of natural fires. Ingberg[3] addressed this shortfall and proposed in 1928 to extrapolate the results from the standard fire by linking fire severity to the area under the curve. Most regulatory bodies accepted Ingberg's approach. However, when compared to real fires, these approaches seem inappropriate as they took no account of the ventilation, the compartment size or boundary wall linings, all of which dictate the severity of a fire. Petterson *et al.*[4] consulted some experimental data and calculated a family of fire curves that take into consideration the effects of ventilation and the thermal inertia of the compartment's lining. This work led to the adoption of the parametric fire curves, which provide more sensible estimates of fire severity for a given compartment but are not exempt of important shortfalls and limitations[5].

In the context of modern high rises, the most important limitation of the current nominal approaches is in their range of validity. The application domain of the standard fire curve, the parametric curves and the natural fires are strongly linked to the experimental compartments that gave origin to these curves, i.e. simple, rectangular and of relatively small size. For example, Eurocode[6] states that the design equations are only valid for compartments with floor areas up to 500 m^2 and heights up to 4 m. The enclosure must have no openings on the ceiling, and the compartment linings were also restricted to thermal inertia between 1000 and 2200 $J/m^2s^{1/2}K$, which meant that highly conductive lining, like glass facades, and highly insulated materials could not be taken into account. As a result, common features in modern construction like large enclosures, high ceilings, atria, large open spaces, connected multiple floors and glass facades are excluded from the range of applicability of current methodologies.

An important aspect of structural design for fire is that it poses different challenges than other fire safety strategies. Characteristic time scales for heating of structural elements are long (order of dozens of minutes), thus rapidly changing fires used for the design of egress, alarm and suppression are not relevant. Furthermore, issues such as spatial resolution of the fire have dissimilar relevance and the fire properties of interest are different. These differences increase the complexity of the fire safety design process in some areas but can allow greater simplification in others. What is important is that any proposed design fire would be generated on the basis of what is consistent with the detail of the structural design to be conducted. If a detailed finite element simulation of the structure is to be conducted, then the level of detail required might be significant enough to justify the use of a field model for the gas phase.

This work proposes a novel methodology to define the design fire environment for structural analysis of buildings that are outside the range of applicability of nominal methods. The case study illustrates the importance of this analysis in modern high-rise and the potential consequences of an incomplete understanding of each individual scenario.

2 METHODOLOGY

During a fire, heat transfer from the fire to structural elements results in an increase in temperature. As compared to the 'cold' behaviour, this increase in temperature leads to a significant loss of strength of the material and the resulting thermal expansions in the system (and the subsequent contraction during the cooling phase). The evolution of the structural response depends on the interactions of all the constructions elements during the fire. For large and complex structures, it is largely agreed that the state-of-the-art in structural fire engineering states that the mechanical responses of the structural elements are to be considered together to capture force redistribution and thermal restraints, while the more conventional engineering method of studying isolated elements is rather limited and in decline. The resulting heating to the elements is dictated by the time evolution of the heat flux to the material. The heat flux from the fire can be approximately calculated using the temperature induced in the gas phase. Thus, the fire temperature and the duration of the fire (T-t curves) are the two variables to study in the design fire stage. Other fire variables such as heat transfer coefficients, soot concentrations, etc. are also necessary for the proper calculation of heat fluxes to the structure [7]. Here, for simplicity of the method, focus is given only to the time evolution of the fire temperature with the understanding that this is only an approximation to the complex problem.

This paper proposes a novel methodology to define the design fire in non-conventional enclosures containing elements that make the design to fall outside the validity range of the conventional design fires. The following three elements are the core behind the methodology: a) the understanding of fire dynamics within the particular building under design; b) the definition of the fire environment in a comprehensive but simple format, without unnecessary details and avoiding the excess of degrees of freedom; c) the investigation of fully distributed fires as well as travelling fires, allowing the structural engineer to chose a fire scenario that is consistent with the detail needed by the structural models.

Significant differences in the geometry lead to potentially significant differences in the fire behaviour. The understanding of fire dynamics within the particular building is especially important to improve the design. Complex compartments contain sufficient particularities that make the fire behaviour within them unique. With such remarkable architectural features mentioned above (*e.g.* atrium and glass facades) the fire dynamics observed in one building does not necessary correspond to the fire dynamics resulting in a different building. Systematic investigations of the effect of fire size, fire location and ventilation conditions must be conducted in order to identify and generate a comprehensive range of fire environments. This process has to be biased towards worst case scenarios, and emphasis is on the definition of the most challenging ones in structural terms. The question to be answered is what is the worst fire for the structure? And, what is the sensitivity of this scenario to all relevant variables? Ultimately, it is the structural engineer who has to decide on this after having explored and quantified the fire dynamics.

In order to be of practical use, the fire environment must be defined in simple terms but without loss of generality. This requires focusing on the dominant effects dictating the structural response, mostly long term and high temperature fire conditions. The larger the enclosures and the lower the thermal inertial of the linings, the faster the cooling phase is since the smoke layer spreads over larger areas and heat dissipates faster. For these reasons, the growth and decay phases of the fire are not considered here. Due to its short duration and lower temperature, the growth phase can be included within more developed fire phases. The cooling is not neglected from a structural perspective, it is only eliminated from the fire environment, but assumed an instantaneously decay to ambient air temperature.

Computational fluid dynamics (CFD) is a particularly well suited tool for the task proposed here. However, this presents two major drawbacks. Firstly the large computational times required to solve the fire evolution within large enclosures, and secondly the cumbersome amount of data provided as output which needs to be condensed if it is to characterize the fire environment in simple terms. Original solutions to these are presented in the next section.

Traditional methods emphasize very intense post-flashover fires. But there is a certain size beyond which the flashover regime cannot span the whole enclosure. When this happens, the resulting fire will spread from one location to another and will not produce a uniform fire environment. Travelling fires, like those observed before the WTC collapsed[8], produce thermal environments of lower temperature that last for many hours, thus representing long-cool fires.

In this study, two kinds of fire are investigated as extreme conditions with distinctive behaviours; well distributed fires and localized spreading fires. A distributed fire burns uniformly within the enclosure and generates high temperatures for relatively short durations. Since a well-distributed fire engulfs most of the structural elements, these are exposed to the high temperatures of the flames (near field). A localized fire burns locally but spreads with time along the enclosure, generating lower temperatures for longer times. A structural element is exposed to the near field temperatures for a shorter time when the fire is in the vicinity of that particular element, while exposed for a longer time to the far-field temperatures.

3 UNDERSTANDING THE BUILDING'S FIRE DYNAMICS

A detailed study of the fire dynamics in the building under design provides the understanding of realistic fire environment that then leads to an adequate definition of the scenarios to be used in the structural design. Together with the simplified temperature/time curve already mentions with no growing and decaying phases, this methodology aims at reducing the unnecessary degrees of freedom to allow focusing on the dominant parameters in large enclosures. As mention before, CFD is a particularly well suited for analysis in larger and complex enclosure but the two major drawbacks must be overcome. Here, two solutions are presented here.

First, the large computational times required to solve the fire evolution within large enclosures can be reduced by setting constant fire sizes and using the steady-sate gas phase results, instead of running long simulations with a transient hear release rate. Setting the fire heat released rate to the required constant value, steady-state conditions are reached in the compartment rapidly, within a dozen seconds for most large enclosures (see results from the case study). This allows conducting the many simulations required in a reasonable time.

Second, the cumbersome amount of data provided as output from CFD needs to be condensed if it is to characterize the fire environment in simple terms. The 3D transient fields of temperature, velocities and species in the enclosure provide an amount of information that is impossible to assimilate as a whole in a practical manner. The analysis proposed here classifies the effect of a fire on structural elements into the near field and the far field. The near field is when the structural element is exposed directly to the flames of the fire, and the far field when exposed to the hot gases (i.e. smoke layer) away from the flames. See Fig. 1. This division of the thermal field allows to overcome a well-know inaccuracy of fire model; calculation of the flame temperature. For the accuracy levels required in the structural design of buildings, the temperature of a flame is more or less constant and about 1300 or 1500 °C for typical fire in office building[5]. This fundamental fact can be easily overestimated or underestimate by CFD models that required many approximation and sub-models to simulate the region near the flame, the most challenging. However, it is the temperature of the smoke layer as it travels along large enclosures that can vary greatly from flame temperatures to ambient, and it is calculating these the CFD models do better (because in large space it is transport dominated).

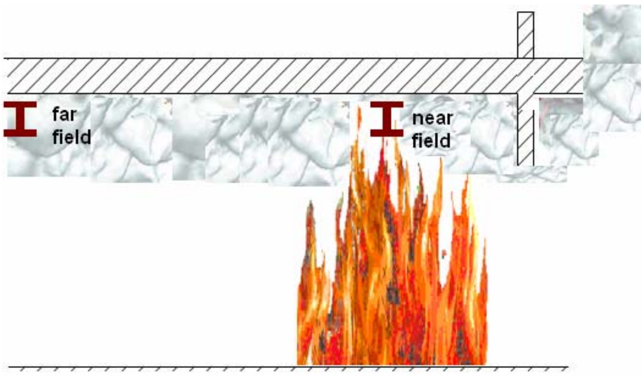

Figure 1. Representation of the near and far fields in an enclosure fire.

The computational model FDS[9] is used here to simulate the fire environment. A systematic variation of the fuel, spread and ventilation parameters within reasonable ranges was conducted to understand the behavior of the fire in the enclosure. The predictions are post-processed to condense the complex 3D temperature fields into a representative pair of maximum temperatures for each scenario (near field and far field). This methodology has the benefit of robustness, transparency and ease of interpretation at the expenses of spatial resolution. Detailed spatial resolution is not relevant to the investigation of the general fire dynamics.

4 CASE STUDY

The above mention methodology is applied here to a real high-rise design to illustrate the importance of this analysis in modern buildings. The development subdivided into three- storey blocks called 'villages'. Each village is then internally connected by an atrium which is open to all levels. Three sides of this building, north, west, east are facades covered with glass windows, whereas the south side is an interior wall. A village (Fig. 2) is composed of 50 x 25 m^2 floors with a ceiling height of 3 m. The atrium, the 1250 m^2 surface area of per floor and the glazed façades, clearly make the design to lay outside the applicability range of the codes[5].

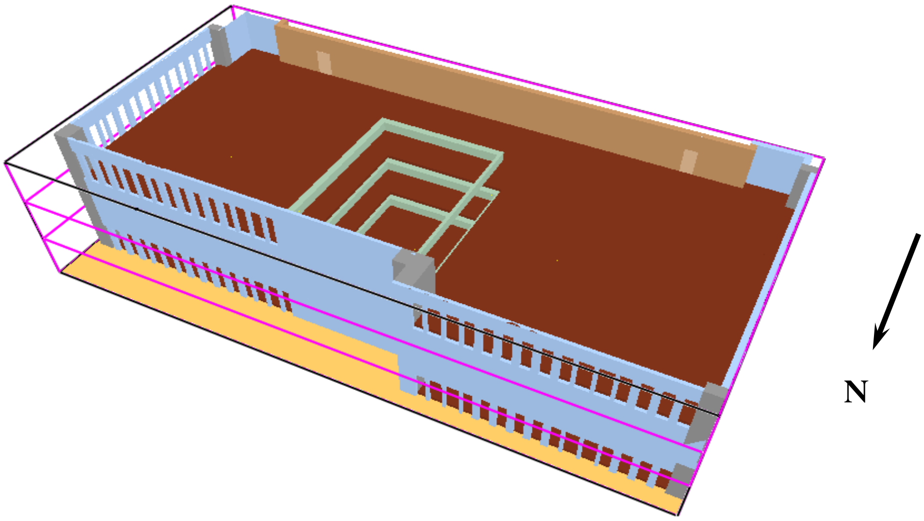

Figure 2. The 3-story village under study, show here with 60% ventilation on façades

The design fire depends on the expected fuel load in the building, which in turn depends on its occupancy and type. The building is for office space, and thus the load has been assumed to be that of a typical office; 25kg/m^2 of cellulose-type fuel with an effective heat of combustion of fuel to be 16 kJ/g (resulting in an equivalent load of 400 MJ/m^2). The mass burning rate per unit area in typical office building fires ranges from 20 to 40 g/m^2s[11] and thus the corresponding heat release rate per unit area ranges from 320 to 640 kW/m^2.

Preliminary simulations were carried out to determine the best grid size possible with the computational resources available. The grid size was systematically reduced until it was not possible to achieve a result due to limitations in a reasonable maximum computing time (*i.e.* a few days). The best grid size was found to be 25x25x12.5 cm, which resulted in a total of 2 million grid cells. The first series of simulations was conducted to study the transient heating of the gas phase. The temperature field reaches approximately steady-state after 10 s of simulated time for a well-distributed fire of 500 kW/m^2, and within 5 s for a heat release rate 1500 kW/m^2. Thus, a total simulation time around 15 s was chosen for the simulations requiring an approximate computing time of 30 hr in our PC cluster.

A systematic variation of the fuel, spread and ventilation parameters was conducted. It is observed that the atrium acts like a chimney linking the bottom and the top floor fires. For large fires, the ventilation pattern is such that the top floor is ventilation limited and the bottom floor is fuel limited. The chimney effect created by the atrium transports the heat from the bottom to the top and results in high temperatures homogeneously distributed in the upper floor. The resulting temperatures are dominated by the fire at the lower level, and thus, a worst case scenario must focus on a fire on the bottom floor.

5 FULLY-DISTRIBUTED FIRES

Well-distributed fires assumed a fire al over one or more floors, and produce the hottest fire environments, subjecting large parts of the structure to direct contact with flames or near flame temperatures (near field). For this reason, they are typically studied as design fires. An intense fire of several MW burning uniformly distributed over a few m^2 would last for only a dozen minutes given the typical office fire load, resulting in an intense by short blaze.

In the first set of simulations, fully distributed fires over one or more floors were investigated. There are four main locations for design fires: bottom fire, top fire, bottom and top fire and all fire when the fuel is loaded on all of these three floors. Eight main ventilation scenarios were considered.

Most of the results show flames at the ventilations openings, indicating an under-ventilated fire due to the large fire of the fires. Nevertheless, the exiting flames are specific to the upper floor and not the bottom floor, which suggests that the fire ventilation is dominated by the flames on the lower level. This was explored and showed that the atrium acts like a chimney linking the bottom and the top floor fires. The ventilation pattern is such that the top floor is ventilation limited and the bottom floor is fuel limited (see Fig 3).

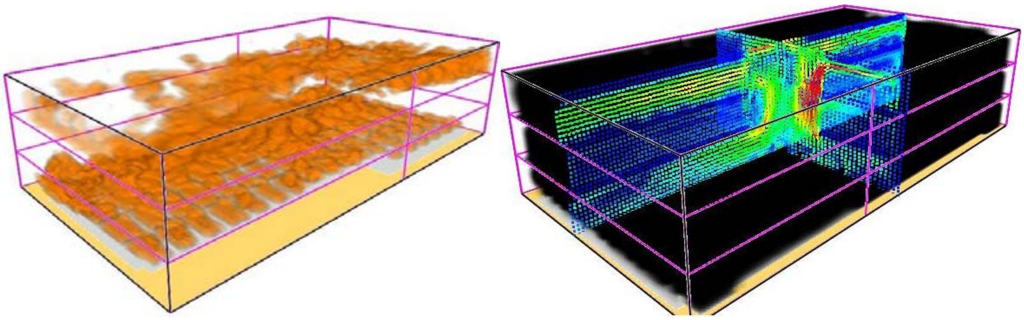

Figure 3. Simulation results showing the flames (left) and the velocity field (right) for a 1000 kW/m^2 fire on two floors for ventilation on top and bottom floors.

The highest temperature reached in the simulations is 1500 °C, indicative of flames exposure. It was observed in the vicinity of the atrium (see Fig. 4) at a few locations on the bottom if there is a fire there, and at the top of the atrium, where the smoke from any fire tends to accumulate. However, for top floor fire, temperature in the bottom floor is always very small.

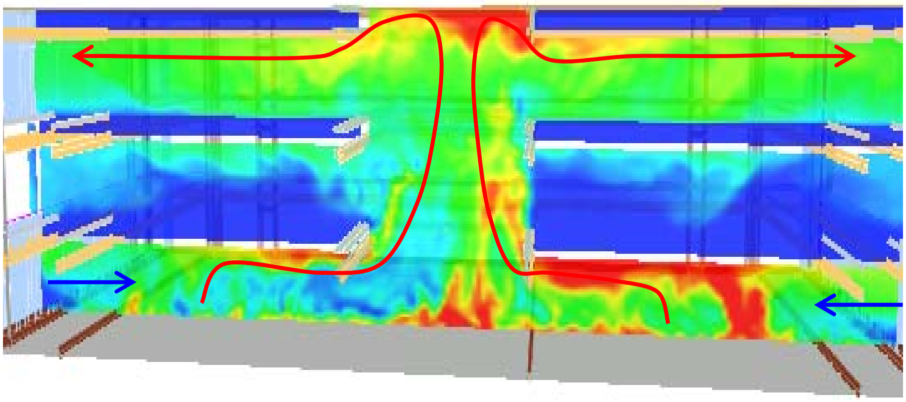

Figure 4. Temperature map for a 500 kW/m^2 well-distributed fire on the bottom floor with top and bottom floor ventilation. The atrium acts as a chimney, linking the bottom and the top floors.

The results in Table 1 and 2 are the maximum temperatures found near the top and bottom of the atrium when fires are on the bottom or/and top floors. Given large size of the fires, flames extend long distances and reach the atrium space, so the maximum temperatures found correspond to a mixture of near and far field temperatures. In general, a temperature below 1000 C is far-field and above near field. Table 1 is for well-distributed fires over one story and Table 2 for two-stories burning simultaneously. All simulations showed fundamentally the same trend in the spatial distribution of temperatures; that the hottest spot in the building was on the top floor near the atrium, and that over any one floor, the highest temperatures were near the ceiling. A fire on the top floor has virtually no impact on the bottom floor. A modification of the ventilation changes the far-field temperatures in the top floor by no more than 100 °C, while the bottom floor temperature remains the same at near the maximum observed in the whole building.

Table 1 Maximum temperatures near the atrium for 500 kW/m² well-distributed fires over one story. Red is near-field.

	Bottom Floor Fire		Top Floor Fire	
Ventilation location	bottom floor (°C)	top floor (°C)	Bottom floor (°C)	top floor (°C)
Bottom	1300	300	100	900
Top	1100	500	25	1200
Bottom & Middle	1300	700	100	900
Bottom & Top	**1400**	**1000**	25	1200
Middle& Top	1100	400	25	1200
North Façade	1300	900	35	1150
West & East Façade	**1500**	900	25	1150
All	**1500**	**1100**	25	1200

Table 2. Maximum temperatures near the atrium for 500 kW/m² well-distributed fires over two stories. Red is near-field.

Fire type	Bottom & Top Floor Fires		All Floors on Fire	
Ventilation	Temperature on the bottom floor (°C)	Temperature on the top floor (°C)	Temperature on the bottom floor (°C)	Temperature on the top floor (°C)
Bottom	1200	900	1200	900
Top	1000	**1150**	800	1200
Bottom & Middle	**1400**	900	1300	1000
Bottom & Top	**1400**	1000	**1350**	**1200**
Middle & Top	1000	1100	900	1200
North Façade	1300	1100	1300	1000
West & East Façades	1200	1100	1300	1000
All	**1400**	1100	**1400**	900

When the heat released is change, the results indicate that the characteristic temperature increases with the imposed heat release rate. Table 3 shows the range of temperature at the top of the atrium (away from the flames, so far-field) for fires of different heat released rate on the top and bottom floors. The worst ventilation conditions are systematically archived when the top and bottom floors are open. When a third floor is open, the middle one, the ventilation has the global effect of diminishing the maximum temperatures. This behaviour is explained by the chimney effect of the atrium that guarantees under ventilated conditions on the upper level while it is well ventilated on the bottom, and implies that the resulting temperatures are dominated by the fire at the lower level.

With this data, it is concluded that the more challenging conditions for a well-distributed fire would be a two-story fire, on top and the bottom floors, with only the ventilation of these floors open.

Table 3. Range of far-field temperatures at the top of the atrium for well-distributed fires over the top and bottom floors

HRRPU / Ventilation	500 kW/m²	1000 kW/m²	1500 kW/m²
Bottom	500-650 °C	600-700 °C	600-800 °C
Middle	**600-700** °C	600-800 °C	600-800 °C
Top	**500-700** °C	600-700 °C	600-700 °C
Bottom & middle	500-650 °C	600-700 °C	600-800 °C
Bottom & top	**550-700** °C	**650-900** °C	**700-1000** °C
Middle & top	**500-700** °C	**650-900** °C	700-900 °C
West	**500-700** °C	600-800 °C	600-800 °C
North	550-650 °C	700-800 °C	700-800 °C
East	**600-700** °C	700-800 °C	700-900 °C
West & North	500-650 °C	650-850 °C	700-900 °C
West & East	**600-700** °C	650-800 °C	700-900 °C

North &East	500-650 °C	750-850 °C	700-900 °C
All	500-600 °C	700-800 °C	700-900 °C

Well-distributed fires lead to very intense but also very short burning times, and although the imposed heat release rates in this study are realistic, a well-distributed fire over a large surface is not realistic and given the short durations, it could not be the worst case scenario for the structure. Fire durations can be estimated for each heat released rate in a simple manner. Assuming an average fuel load typical of office buildings of 25 kg/m^2 and an effective heat of combustion of 16 kJ/g, the burning time depends only on the heat released rate per unit area. For example, for 500 kW/m^2, the mass burning rate of 30 g/m^{2}s and thus the fire duration is approximately 14 min to burn a typical office. As the heat released rate of the fire is increased, the burning time is reduced (linearly). This leads to a divergence respect to the standard fire curve which predicts very intense temperatures for very long times; a condition that might be observed in small enclosure but is not realistic in large open spaces.

The realistic nature of well-distributed fires for large enclosure is further questioned when it is considered the huge total fire size resulting from these scenarios. For the building under study, owing to the large areas of 1250 m^2 on each floor, with a heat release rate per unit area of 500 kW/m^2, the total heat release rate of a 3-storey fire would be around 2000 MW, a fire size that has rarely, if ever, been observed. Localized and travelling fires would produce differential heating of the structure and could lead to realistic and more severe conditions.

6 TRAVELLING FIRES

As was observed in the study of the World Trade Centre collapse[8], fires in large office spaces generally do not burn across the entire floor simultaneously but will instead spread as fuel is sequentially ignited and consumed. This situation is of great relevance in this study because of the large and complex geometry of the villages.

When a small fire is in the vicinity of a structural element, the temperature corresponds to the near field (in the order of 1300°C). This heating would last for about 10 min to 20 min for typical office fuel loads (in the range from 20 to 40 kg/m^2) independently of the fire size. As reported before, for the average office building, a heat released rate per unit area of 500 kW/m^2 fire lasts for approximately 14 min to burn. As the fire travels away from the element, the far field surrounds it and temperatures from 700 °C down to 200 °C are sustained, albeit for a period approximately ten times longer.

To study the thermal fields produced by travelling fires without conducting long fire simulations that will take weeks to run each, the effects of small localized fires, burning within a small area and rapidly reaching steady-state, are used here and extrapolated to reconstruct the thermal field of small travelling fires. The temperature profile generated by a localized fire peaks at the centre and gradually decays as the smoke plume spreads over the ceiling (Fig 5). The peak value at the center of the fire can be considered as the near field or flame temperature, whereas the far field is not one characteristic temperature but a gradual decay from peak to ambient along a characteristic length which is a function of the heat released rate and the fire area. The far field temperature is here defined as the average temperature near the ceiling at a distance of ¼ the difference between the fire length and the floor maximum length, where the lengths are given by the square root of the area.

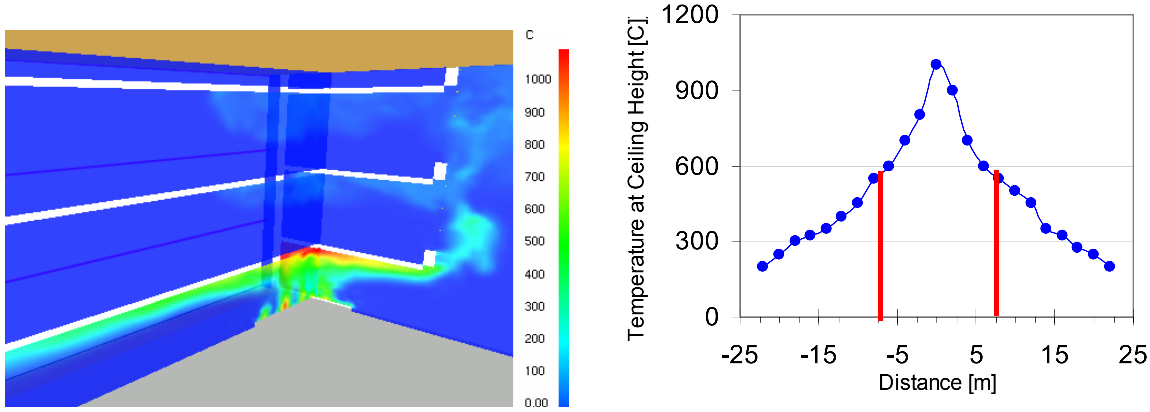

Figure 5. Temperature profile in the horizontal direction for a localized fire of 50 m^2 and 500 kW/m^2.

Assuming an average burning rate typical of office buildings of 30 g/m^{2}s and an effective heat of combustion of 16 kJ/g[11], the heat released rate per unit area is fixed to 500 kW/m^2. With the heat released rate per unit area fixed, the size of a travelling fire is only characterized by its surface area. Several scenarios were simulated for 500 kW/m^2 and varying the surface area of the fire from 6 to 600 m^2. These fire sizes results in heat released rates from 3 to 300 MW, respectably. The fires were located either on the bottom or top floors. Temperatures right above the flames were observed to be in the range 1100-1300 °C (near field) and the temperatures on the top floor away from the flames (far field) are between 200 and 800 °C. The results and have been summarized in Table 4.

The variation of the ventilation for small travelling fires (smaller than 200 m^2) shows that the maximum temperature is reached for small ventilation, between 5% to 10 % of the total glazed facades. But over the whole range of ventilation, only a maximum variation of 100 °C in the near field is seen, indicative of well ventilated fire due to the large space of the village. For larger fires, above 200 m^2, the effect of the ventilation is similar to that of well-distributed fires and has been studied in the previous section of this paper.

The results obtained for static small fires can be analytically extrapolated to evaluate the effect of spreading fires. The total surface area of each floor of the village is 1250 m^2, and a fire of 500 kW/m^2 takes 14 min to burn out, as previously calculated. Thus, assuming a linear relationship between surface area and burning time, a spreading fire of 20 m^2 (10 MW) will take about 14 hr to burn a entire floor while a fire of 100 m^2 (50 MW) will take approximately 2.8 hr. A travelling fire is characterised by its surface areas or by its spread speed, since these two are related to the fire load and the burning rate. These times estimation will vary with a more detailed calculations of fire spread but it serves as to capture the time scales involved.

When the small fire is in the vicinity of a structural element, the temperature corresponds to the near field (around 1300 °C) and last for approximately 13 min. When the fire is away from the structural element, the temperature corresponds to the far field and lasts ten times longer (see values in Table 4).

Table 4. Far field temperature ranges and durations for different spreading fires

Fire size(m^2)	6	12	20	50	100	200	600
Spread speed (m/s)	0.003	0.004	0.054	0.085	0.012	0.017	0.03
Time for entire floor (hr)	47	23.5	14	5.6	2.8	1.4	0.5
Far field temperature (°C)	200	250	300	400	500	650	800

The family of travelling-fire curves that this method generates is plotted in Fig. 6 for the different fire sizes. One family like this one is generated per each fuel load assumed. This figure contains the core of the fire environments that this methodology produces, and it is the kind of information that the designer and the structural engineer needs to calculate the mechanical response of the building under fire.

Note that Table 4 and Fig 6 show only the far-field temperatures, but a structural element will feel both the far-field and near-field for different period of time; the near field for a short time (14 min for 500 kW/m2) and the far field for the longer time shown in the Table 2.

The results in Fig. 6 are also compared to the standard fire curve, showing the divergence with the travelling fire curves after 1 hr of burning time. The standard curves extend to a region of temperatures and burning times that for the present building cannot be explained in terms of realistic fire dynamics. It also compares to the parametric fire curve that are typically used in the structural design. It was used to represent a compartment fire, assuming 25% of the available glazing breaks and a fire load of 420 MJ/m² (equivalent fire load to the one used here). It shows agreement with the 600 m^2 travelling fire calculated by our methodology.

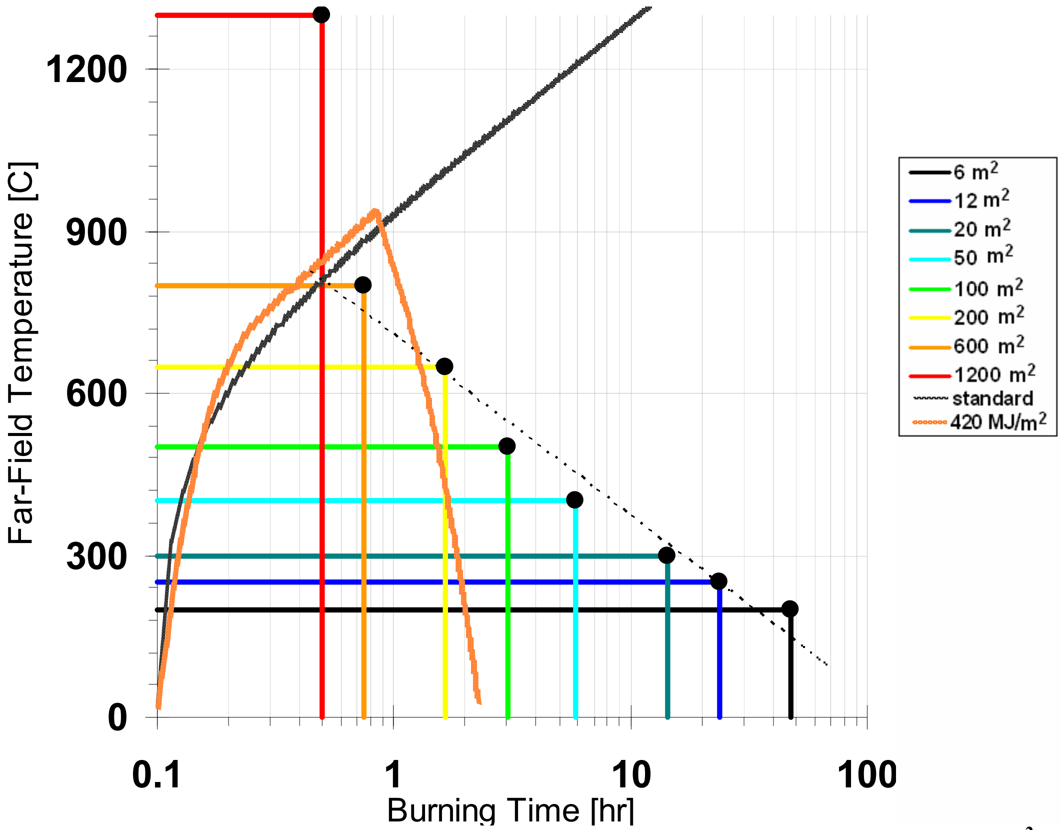

Figure 6. Time evolution of the temperatures for travelling fires of different size (legend in m^2) and comparison with standard curve and the parametric curve for 420 MJ/m^2 and 25% ventilation[10].

7 CONCLUSIONS

This work proposes a novel methodology to determine the design fire of those buildings that are outside the range of applicability of nominal current methods. The fire environment is studied using a novel methodology combining computational fluid dynamics and engineering simplifications.

Three elements are the core behind the methodology: the understanding of fire dynamics within the particular building; the definition of the fire environment in a comprehensive but simple format; and the investigation of fully distributed fires as well as travelling fires. To overcome the difficulties of using CFD in this methodology, two solutions are proposed and test; the use of steady-state temperature to avoid running lengthy simulations and the condensation of the complex output fields into near and far-field temperatures.

The methodology is presented and applied to a real building design to illustrate the importance of this analysis in modern high-rise buildings and the potential consequences of an incomplete understanding..

The results indicates that the fire dynamics of the building are dominated by a fire at the bottom floor with the atrium allowing for significant heating of the top floor through the rising smoke plume (chimney effect). Conversely a fire on the top floor has virtually no impact on the bottom floor. Worst case scenario was identified to compromise a fire on the bottom floor (and the top floor too for multi-story fires) having ventilations on the bottom and top façades only.

The study looked at both well-distributed and travelling fires. The analysis indicates than a travelling fire through the bottom of the atrium leads to marginally lower temperatures than a uniform fire all over the floor. However, the spreading process can result in a much longer fire and thus could be considered a worse scenario than a well-distributed fire. Comparison with the standard fire curve shows extreme divergence respect to the travelling fire curves after 1 hr of burning time. The standard curve is shown to extend into a temperature/time range that cannot be explained in terms of fire dynamics. Comparison to the parametric fire curve used in structural design shows agreement with the 600 m^2 travelling fire captured by our methodology. The meaning of this agreement needs to be further investigated.

Regarding the practical application, future work will assess the structural response of the building using the fire environments reported here to quantify the level of protection and structural detailed needed. The methodology is still under development but its core is presented and applied here. It needs further research and more detail study of the assumptions behind. In particular, the calculation of burning times for travelling fires and the definition of the far-field in localized fires needs to be revisited. The application of the method to more real cases will speed up the process.

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