Even 'Clouds' Can Burn

Fire engineering simulation for a safe, innovative and high-performance architectural design - a case study

Antonio Fioravanti[1], Eolo Avincola[2], Gabriele Novembri[3]
Dept. DICEA - Sapienza University of Rome, Italy
[1,3]http://www.dicea.uniroma1.it
[1]antonio.fioravanti@uniroma1.it, [2]eoloavincola@gmail.com, [3]gabriele.novembri@uniroma1.it

Abstract. *Architecture, nowadays, is an even more demanding activity in which complexity is the keyword: complex forms, complex functions and complex structures require sophisticated facilities and components, for example, 'The Cloud' of D. and M. Fuksas in Rome. These complexities can give rise to numerous risks, among which fire is frequently a central problem.*
The fire safety norms do not involve an approach integrated with other instruments or building model (BIM), but provide a list of information and constraints. These codes are now shifting away from a prescriptive-based towards a performance-based method due to recent progress in fire safety engineering.
Following this approach, a case study simulation of a multi-purpose centre was carried out in Tivoli, near Rome. This simulation allowed greater freedom in architectural composition, a lower risk to people, a larger number of material and building components used and higher safety standards to be achieved. The model is based on the FDS (Fire Dynamics Simulator) language, a simulation code for low-speed flows, focused on smoke, particle and heat transport by fire.

Keywords. *Architectural design; computational fluid-dynamics; fire propagation; fire safety; smoke propagation.*

FIRE AND ARCHITECTURAL DESIGN

Architecture has always been a demanding activity, but in present times, has had to face intertwined problems in which complexity is the keyword: complex forms, complex functions and complex structures require sophisticated facilities and components. These complexities can give rise to numerous risks, among which fire is frequently a central problem (Harper, 2004).

Existing fire safety regulations and codes (Balaban et al., 2012) very often actually represent as many limitations imposed on architectural needs such as space layout, free form space, distribution path, space occupancy and aesthetic quality. Fire safety, more specifically smoke and heat extraction, requires optimization and careful analysis in the early design phases. These norms are the average of real fire safety cases, and so in some specific cases, they are more demanding than strictly necessary with regard to devices or shape layout, while in others they could actually be insufficient.

An impressive example of the impact of fire regulations on architecture is represented by the recent design competition for the new Rome Conference Centre in 1998. It is situated near the old one, in the district of the *Esposizione Universale Roma - EUR* (Rome Universal Exhibition) planned for 1942 where, according to Mussolini's town plan, important ministries would subsequently be transferred. The old Conference Centre was designed by Adalberto Libera in 1939 and is a reflection of late Italian rationalist style tinted with a superficial, ironical and monumental classicism. There were numerous important responses to the 1998 competition call and several high quality projects were selected. Many were based on mimicking the symmetrical and constrained layout resulting from a simplistic interpretation of the apparently elementary nature of the EUR buildings. Another important motivation was the difficulty to take into account current safety rules regarding structure, plant engineering and evacuation paths in a free form space configuration.

In many cases, this design logic led to the various conference halls being situated as low as possible and for fire fighting purposes to use water cisterns (filled with water) at the top of the building. These design solutions had the following consequences: overloading at the building top, which is a design solution to be avoided in view of the seismic nature of Italian territory; an obstruction of the visual permeability between inside and outside in order to respect the fire resistance of the walls; the denial of whole roof level availability and limited panoramic view due to the presence of cisterns. Other examples are: the Twin Towers, which had cisterns on the roof that unfortunately failed to cope with the combined effect of fire and the abrasion of the intumescent paint protecting the steel structure; or the first HKSBC projects in which water inside the pillars was thought to cool the structure at the price of adding permanent loads.

The engineering approach makes it possible to exceed the limits prescribed by the codes and at the same time rigorously respect safety as the norms regulate only average scenarios. This approach allows designers to have a greater compositional freedom, obtaining innovative and high-performance buildings in which fire safety has become an essential element of architectural conformation. In other words, fire engineering is used to allow fire safety to be demonstrated, despite its peculiar form and dimension like the new Congress Palace in Rome designed by D. and M. Fuksas - familiarly called "The Cloud" [1, 2]. In this case, it was possible to use fire engineering simulation techniques to demonstrate that the danger, in the case of fire, was very low as the space enclosed by the 'glass box' could be considered an open space and as the thinness of the membrane enveloping 'The Cloud' renders the fire load negligible.

This approach has allowed modifications to be avoided during the detailed building design phase that might compromise the identity of the project.

FIRE SAFETY PRESCRIPTIVE APPROACH

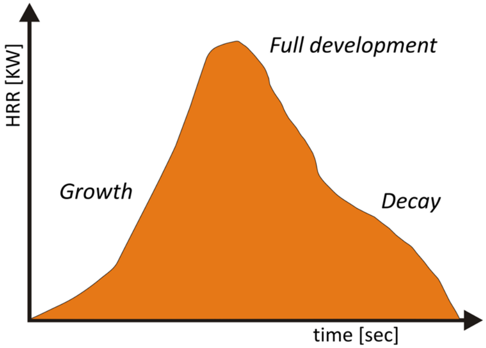
The combustion process is a sequence of chemical reactions between a fuel and an oxidant, accompanied by the production of heat, smoke and the conversion of chemical materials. The process can be specified by means of the Fire Triangle, which is composed of fuel, oxygen and a heat source. It is essential for a correct relationship among these three elements otherwise, combustion itself cannot take place (Harper, 2004).

Inside a *compartment* - i.e. a homogeneous and limited part of the building with respect to function, use destination and fire safety class - it is possible to identify four fire phases (La Malfa, 2009):

Ignition, a heat source acts on the fuel, and if sufficient thermal capacity is released, it warms it up to its ignition point. The thermal energy needed to attain the ignition temperature depends on size and the ratio between the mass and the surface exposed to the air.

- *Growth*, the fuel materials are heated and tend

Figure 1
The HRR curve over time during burning process.



to reach their ignition temperature. The spread of the fire produces: a reduction in visibility, increased toxic fumes, increment of the burning rate over time.

- *Development*, all combustible materials in the *compartment* are simultaneously involved in the burning process due to the irradiation caused by the products of combustion: the "flashover" phenomenon.
- *Decay*, the fire tends to slow down owing to the progressive reduction of combustible materials or oxygen and starts to be extinguished.

Codes do not involve an integrated approach nor do advanced CAD tools like building information modelling - BIM, but they do provide a list of documentations and prescriptions to be fulfilled, which are useful in the early design phases (Balaban et al., 2012):

- *Definition of project*, detailed description of building with particular reference to ventilation openings, fire and smoke *compartments*, structure and distribution of furniture and combustible materials;
- *Fire safety objectives* and indication of *performance requirements*, in relation to specific architectural goals and to requirements for which the analysis is applied (maximum gas temperature at human head height, visibility, air concentration of toxic substances);
- *Determination of fire scenarios*, schematizing events that may occur in relation to the characteristics of fire, the building and the occupants;
- *Method of contrast*, for the achievement of the safety objectives set (obstacles to combustion product propagation, smoke devices, fire extinguishing systems and fume extractors);

FIRE SAFETY PERFORMANCE APPROACH

Building codes are shifting from a *prescriptive-based* method towards a *performance-based* method due to the progress in fire safety technologies, including the development of an engineering approach (McGrattan et al., 2010; Hadjisophocleous and Benichou, 1999). The traditional *prescriptive* method uses a set of technical standards that are rigidly applied in a 'mechanical' way. The *performance* method allows the actual risks for specific activities to be evaluated step-by-step by means of careful analysis and simulation.

In Italy, the engineering approach to fire safety is regulated by laws, the most important of which (D.M., 2007) defines the procedural aspects and criteria for assessing the level of risk and consequently the mandatory design measures intended to contrast possible code violations.

Heat Release Rate Parameter

The *Heat Release Rate* - HRR - is the main parameter governing the fire phenomenon; it influences many other fire characteristics. Literally, the HRR indicates the heat released by the combustion of a material over time per unit surface area (Babrauskas, 1991).

The area under the curve (Figure 1) represents the energy released during all *phases*, while, for the purpose of fire safety, it is essential to evaluate the phase preceding the *flashovers*, because after this time conditions are created that are unsustainable for the human body.

For this reason, it is necessary to know the variation over time of the actual *fuel mass involved* which, in the *growth phase* of the fire, is expressed by the equation (1). It displays different curves pertaining to fire growth (Figure 2) depending on the time "t" by means of a quadratic function and on the constant "α" that takes into account different material types. The combustion speed can be: *slow*, $\alpha = 2.77$

$\times 10^{-3}$ KJ/s^3; *medium*, $\alpha = 11.11 \times 10^{-3}$ KJ/s^3; *fast*, $\alpha = 44.44 \times 10^{-3}$ KJ/s^3; *ultra-fast*, $\alpha = 177.77 \times 10^{-3}$ KJ/s^3 (La Malfa, 2009).

$$HRR = \alpha \times t^2 \qquad (1)$$

The curves do not grow indefinitely, but reach a peak and then begin to decrease, so the quadratic part refers only to the crescent monotonic curve. The decay phase, for common materials, accounts for 20÷30 % of the whole combustion process.

Curve peak values change according to the material being burnt. For example, plastic rubbish has a peak of 80 KW, while a car can reach 6000 KW.

As the HRR increases, also the temperature and the rate of temperature rise increase, thus accelerating fire development. In addition, increased HRR results in reduced oxygen concentration and increased production of gaseous and particulate matter; these are fundamental factors to be considered for fire safety.

Material Reaction Rate to Fire

For a given material, the reaction can produce a solid, denoted as *residue*, plus water vapour and/or fuel gas; for instance, the evaporation of water from a solid material is described by the reaction that converts liquid water-to-water vapour (McGrattan et al., 2010).

A pyrolyzing solid in a reaction produces a solid *residue*, *water vapour* and *fuel gas*, the sum of which has the same weight; this means that the mass of the reactant is conserved.

Another important parameter to consider is the *mass fraction* that can be burnt at time "t" (Figure 3, blue curve) of the normalized density of material, which decreases as the sample is slowly heated. The *reaction rate* (Figure 3, green curve) is the rate of change of the mass fraction at time "t"; where this curve peak is referred to as the *reference Temperature* "T_s", which is not the same as the ignition temperature, but is the most important parameter for defining the *reaction rate* of a material.

Equation (2) defines the *reaction rate* - "r" - at *reference Temperature* T_s [°C], of the -ith material undergoing its -jth reaction; $Y_{s,i}$ defines the ratio between the density of the -ith material component of the layer at temperature T_s, divided by the initial density of the layer.

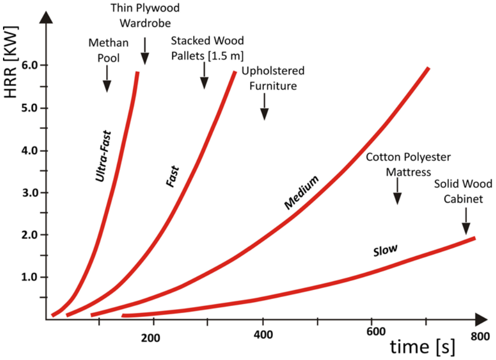


Figure 2
The HRR curves over time for different materials.

$$r_{ij} = A_{ij} \times Y_{s,i} \times \exp\left(-\frac{E_{ij}}{RT_s}\right) \qquad (2)$$

The model used is based on the FDS (Fire Dynamics Simulator) language, a simulation code for low-speed flows, focused on smoke, particle and heat transport by fire. This model provides the estimation of the fire's evolution, dividing the space into a large number of small contiguous elements where the thermodynamic state is calculated by solving the conservation equations of mass, energy, etc. (Ozel, 1998). methods and analysis of results, the field

This approach allows the problem to be solved by integrating a set of partial differential equations for the whole system, thus avoiding the explicit treatment of the boundary conditions. One of the

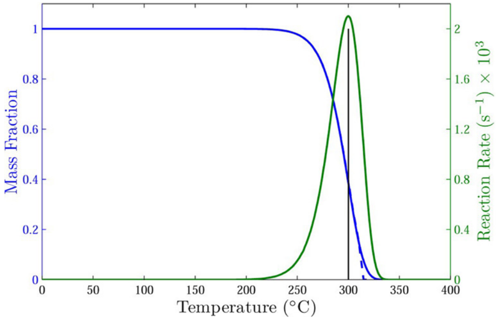
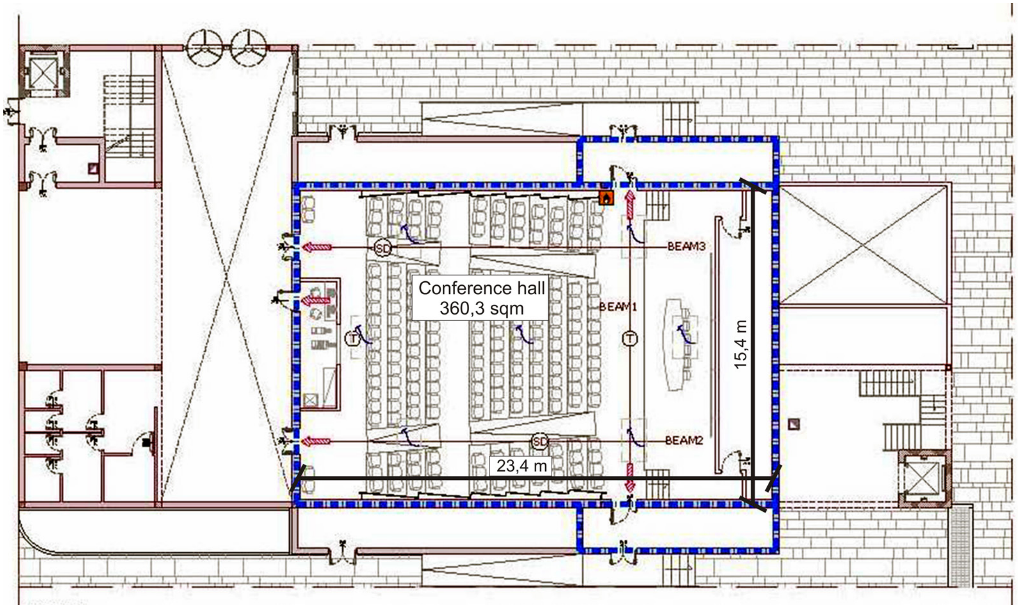


Figure 3
Reference Temperature. T_p= 300 °C ; r_p= 0.002 s^(-1); T= 5K/min ; v_s= 0.

Figure 4
Case study of a multi-purpose exhibition centre at Tivoli - the conference hall. The dashed blue lines define the compartment and the BEAM devices measure the total obscuration rate between two points.



main calculation problems is the actual choice of mesh: decreasing the size of the elements, a more realistic simulation is obtained, although this requires a longer computation time and greater hardware power.

The mathematical model used for solving the analysis of fire phenomenon and interface problems among contiguous space elements is the *phase field* model (Boettinger et al., 2002) that, by means of a specific and infinitesimal mesh, can correct dynamic interface problems.

MULTI-PURPOSE EXHIBITION CENTRE AT TIVOLI - CASE STUDY

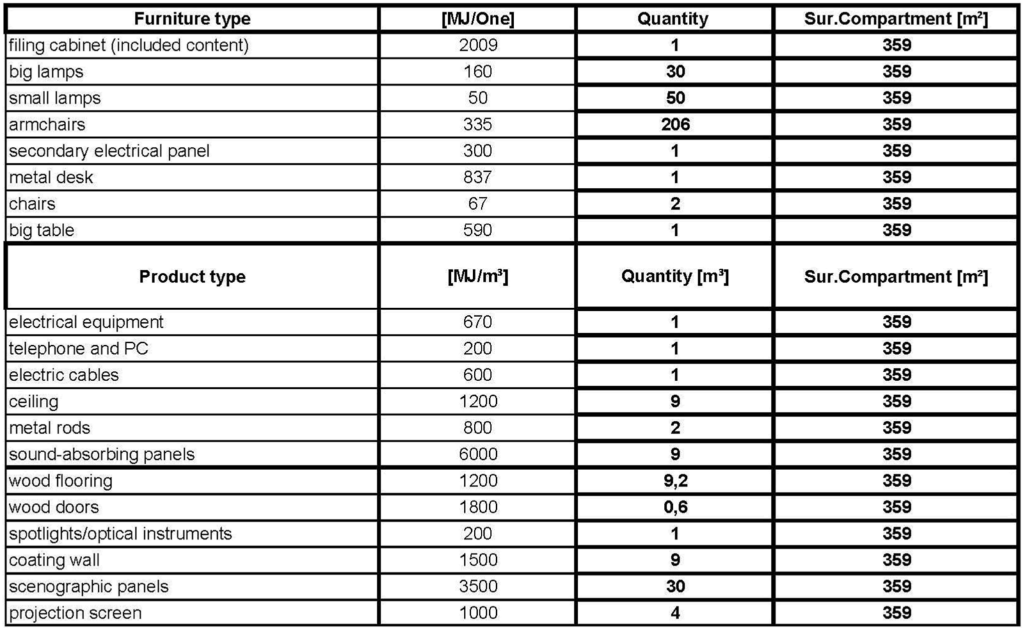
The case study was an experimental master's degree thesis of a project for a multi-purpose exhibition centre with a multi-storey underground parking station in Tivoli, near Rome; the simulation was focused on the *compartment* of the conference hall (Figure 4).

The fundamental value to be specified was, as previously mentioned, the *Heat Release Rate* - HRR. This was schematized with a *burner*, on which a *vent* was applied, which simulated a fire that released heat but also a specific quantity of *particles* and *gas*, based on input data. The levels of HRR developed from the case study are based on information derived from the experimental data and compared with the values identified in the technical literature for those specific activities.

In the case of a multi-purpose hall, the presence of scene panels is assumed (Table 1) which increases the total fire load.

A rapid decrease of the HRR was observed due to the action of the simulated sprinkler system (automatic opening), giving a value of the fire extinction coefficient. This was made possible only through the correct sizing of the sprinkler piping, by indicating the flow of the single sprinkler obtained from the product specifications and the UNI regulations (UNI EN 12845, 2005).

Some fire scenarios of NFPA 101 (Coté and Harrington, 2012) were determined in compliance with the law (D.M., 2007). Relevant critical scenarios representative of the actual conditions were produced



Furniture type	[MJ/One]	Quantity	Sur.Compartment [m²]
filing cabinet (included content)	2009	**1**	**359**
big lamps	160	**30**	**359**
small lamps	50	**50**	**359**
armchairs	335	**206**	**359**
secondary electrical panel	300	**1**	**359**
metal desk	837	**1**	**359**
chairs	67	**2**	**359**
big table	590	**1**	**359**
Product type	**[MJ/m³]**	**Quantity [m³]**	**Sur.Compartment [m²]**
electrical equipment	670	**1**	**359**
telephone and PC	200	**1**	**359**
electric cables	600	**1**	**359**
ceiling	1200	**9**	**359**
metal rods	800	**2**	**359**
sound-absorbing panels	6000	**9**	**359**
wood flooring	1200	**9,2**	**359**
wood doors	1800	**0,6**	**359**
spotlights/optical instruments	200	**1**	**359**
coating wall	1500	**9**	**359**
scenographic panels	3500	**30**	**359**
projection screen	1000	**4**	**359**

Table 1
Fire Load calculation in relation to the furniture or product type.

using: a preliminary check of regulations; expected performance levels; considering, for additional safety, the failure of the sprinkler system or devices for automatic door opening. It was also possible to simulate fire scenarios that are worse than the NFPA 101 code fire scenarios. Those could be the most severe fires ever recorded, or the average of the worst fires having occurred with some regularity. The fire scenarios were examined for a period of 10 minutes, an appropriate time for a preliminary investigation (Figure 5 and 6).

The choice of particulate *reaction rate* is one of the most critical aspects (Kittle, 1993): for example, in the pre-flashover phase, a modest amount of electrical equipment could spread smoke more dangerously than a common fire with greater reaction rate levels.

All the simulations verified the fire scenarios considered by analysing variations of: gas temperature at human head height and at construction element height (by temperature detectors - THCP); curve of heat release HRRPUA [KW/m^2] derived from the sum of the value of the initial burner plus any contribution of fuel elements; visibility in the room for the egress time (by rate dimming detectors - BEAM); fume, particle and heat flow trends in the *compartment*; sprinkler operation.

The main architectural problems were encountered both:

- outside the building, the relationship with the square (quality of urban space)
- inside the building, the layout of the conference hall within the overall shape of the building (quality of architectural composition).

As far as the first point is concerned, namely the urban environment, two aspects must be taken into consideration which heavily affect the architectural composition and the cost of the building: the time required for firemen to arrive from the nearest fire station and the building conformation, which is linked to the constraints imposed by the underground parking safety openings. In the case of the

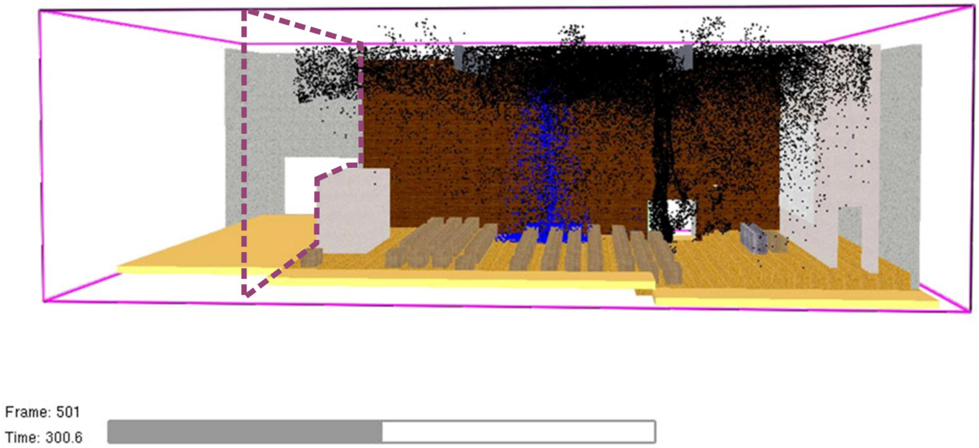


Figure 5
Particle diffusion showed in a longitudinal section of the multi-purpose conference hall study case 5 minutes after fire ignition.

first aspect, the most important features are the non-combustible nature of the materials used and/or the time needed for the bearing structure to resist until the fire fighters arrive. This aspect seems to be mainly dependent on the materials used and to exclude any reference to the 'form'. In actual fact the shape of the building, of its interior and the accesses to it constrain the possible manoeuvres of

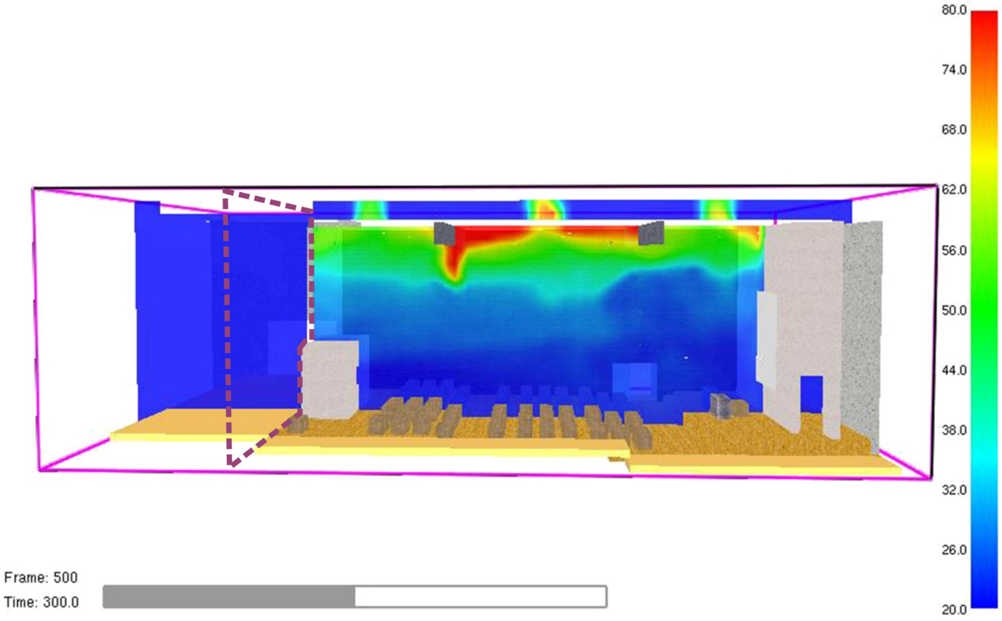


Figure 6
Gas temperature showed in a longitudinal section of the multi-purpose conference hall study case 5 minutes after fire ignition.

the fire fighting and rescue vehicles and the extinguishing of the fire. The second aspect, the shape of the building and of the surrounding area is directly affected by the large air wells required to make the underground parking levels comfortable and safe. It was observed that by simply applying the codes literally, these 'wells' heavily affected the restaurant area, unless the latter was shifted further north and thus could not be used in the winter. However, applying the model to an alternative proposal for the location of the 'wells' in such a way as to leave the positioning of the restaurant unchanged and simulating the fire process, it was possible to verify the safety.

As far as the second point is concerned, as for example the compartment of the multi-purpose hall, according to the code (UNI 9494-1, 2012), the smoke and heat exhaust openings must have a continuous surface as long as the corridor length at a height of over 1.2 meters, thus conditioning the compositional, formal and acoustical aspects. In addition, the façade would have to be constituted by solid and non-combusting materials with high temperature proofing. The simulation verified safety standards also with a less invasive action on architectural composition, thus allowing different materials and shape. The simulation computed that the required fresh air brought into the conference hall only through emergency doors was enough for people, for structural safety and for visibility even if the opening (doors and windows) size of the walls did not satisfy those codes. After an accurate simulation, glass façades were allowed as they would be shattered by the high temperature at the beginning of the fire process. This is dependent on the capacity of fire engineering simulation accurately to predict the fire status.

CONCLUSIONS AND FUTURE PROSPECTS

The simulation performed led to better use of the urban square (the prescriptive method imposed huge underground parking ventilation openings); more freedom in architectural composition (codes constrained doors and windows position and size); reduced risk to people; freedom in the use and choice of a larger number of materials, furniture and building components.

Moreover, if the traffic regulations governing the area outside the building were to change and cause a delay in the arrival of the fire fighting vehicles it would be possible to simulate the behaviour of the fire in the building to check whether in any case the safety of visitors and staff were guaranteed or whether any further action was necessary and the extent thereof. This simulation, extended to all the buildings affected by the change in traffic regulation, would entail at the town planning level a detailed estimate of the costs/benefits-safety ratio.

The main difficulty encountered in the use of the simulation model was due to the limited interface with other CAD programs as it exports only 3D (AutoCAD®, Blender®). The integration of this analytical model with BIM would be desirable, as has already been done with structural and thermal calculation programs. An integrated design could thus be totally exploited in the building process, thus facilitating collaboration and information exchange.

This study, which was developed in the form of an experimental master's degree thesis, should be included in an academic course. In Italy, although there are many post-graduate professional courses concerning the applications of fire safety, most academic students ignore fire safety problems, so they should be taught at least the main principles for fire safety and, secondly, those for high-performance buildings.

Nowadays, the buildings are often readapted through a change of use, resulting in fire load variation; besides the building codes are constantly changing, giving rise to maintenance and accommodation activities with additional costs not specified in the design process. Moreover, the relationship between the study of fire phenomena and architectural conformation becomes fundamental in historical buildings, where architectural restrictions and heritage preservation do not actually go hand in hand with fire safety needs. All these problems can be faced by means of the fire engineering simulation approach that allows performance evaluation during a building's lifetime.

Fire safety engineering should not be interpreted, in the narrow sense, as a tool allowing the prescribed regulations to be sidestepped, but as a system model that can analyse real cases in depth, afford more solutions to problems, achieve higher safety standards and a more accurate evaluation and analysis of the risk of fire, so as to reduce problems from the outset. For example, in Italy this approach, when adopted, has led to a new image of steel structures completely free of protective coatings (intumescent paintings or cement or stucco or aluminum and insulation panels), with evident savings in construction costs.

The performance-based method allows a preliminary evaluation during the design process, avoiding not only increased costs but also modifications that often distort the identity of the building.

The use of these tools during the various phases of new construction design or in rehabilitation projects regarding existing buildings or during a building's lifetime can allow designers and the competent authorities to collaboratively develop projects, ensuring enhanced security also at urban level. There are two possible future developments of these tools: a numerical one, through integration with other multi-physical tools (e.g. COMSOL®), or a semantic one using ontology tools and AI methodologies.

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