MATEC Web of Conferences **9**, 03002 (2013)
DOI: 10.1051/matecconf/20130903002

Computer-simulation study on fire behaviour in the ventilated cavity of ventilated façade systems

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Abstract. Fire spread through the façades is widely recognized as one of the fastest pathways of fire spreading in the buildings. Fire may spread through the façade in different ways depending on the type of façade system and on the elements and materials from which it is constructed. Ventilated façades are multilayer systems whose main feature is the creation of an air chamber of circulating air between the original building wall and the external cladding. The "*chimney effect*" in the air cavity is a mechanism that improves the façade's thermal behaviour and avoids the appearance of moisture from rain or condensation. However, in a event of fire, it may contribute to the quickest spreading of fire, representing a significant risk to the upper floors of a building. This study deals with some aspects of fire propagation through the ventilated cavity in ventilated façade systems. Also we review the provisions stipulated by the Spanish building code (Código Técnico de la Edificación, CTE) [1] to avoid fire spread outside the building.

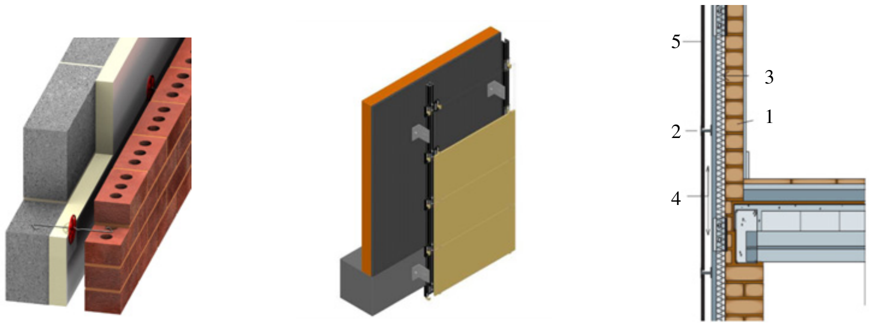
The results highlight the importance of the use of proper fire barriers to ensure the compartmentalization of the ventilated cavity, as well as the use of non-combustible thermal insulation materials, among others. In addition, based on the results, it might be considered that the measures stipulated by the CTE are insufficient to limit the risks associated with this kind of façades systems. The study has been performed using field models of computational fluid-dynamics. In particular, the Fire Dynamics Simulator (FDS) software has been used to numerically solve the mathematical integration models.

BACKGROUND

The ventilated façade system belongs to a group called *cladding systems* and is an updated version of that known as cavity wall. This method of construction was introduced in the Northwest of Europe during the 19th century and gained widespread use from 1920. Both systems base their performance on the air chamber of the cavity, and while the cavity wall system has been used only in brick walls, the ventilated façade has a vast variety of finishes.

Nowadays the trend in architecture is towards a growing usage of lightweight construction systems that are quick to install (drywall construction), versatile and have a high technical and aesthetic value. The ventilated façade has all these characteristics as well as providing a good performance from an acoustic and hygrothermal point of view.

In Spain and other Mediterranean countries, the use of ventilated façades over the last ten years has significantly increased as a result of the good performance of this kind of façade system. They are used in new buildings as well as in the refurbishment of façades.



(A) *(B)* *(C)*

Figure 1. Façade cavity systems (A) Cavity wall (B) ventilated façade (C) elements of ventilated façade.

The use of ventilated façades offers advantages such as:

Contributes to thermal comfort and energy saving: the fitting of insulation on the outside of walls and slabs eliminates thermal bridges in any part of the façade, thereby preventing the loss of heat to the exterior in winter and absorbing heat in summer.

Elimination of condensation on the inside of the façade wall: the pressure difference between the air in the cavity and outside leads to the creation of an airflow known as the "*chimney effect*", which eliminates humidity in wet conditions and prevents condensation.

However, in terms of fire safety, the chimney effect poses a risk, because the ventilated cavity may provide a pathway for the fire to spread quickly.

In general, the provisions of the Spanish building code (CTE) on external fire spread are perceived as insufficient to address risks associated to the fire spreading through the façades, taking into account the different types and design of the façade.

This study focuses on the CTE provisions regarding ventilated façades with the purpose of analyzing the risks which are not sufficiently covered.

Fire spread through the ventilated cavity

When there is a fire in a building, the façade may be one of the quickest spreading pathways. Some types of façades, as in the case of ventilated façade systems, pose a greater risk because of the characteristics of the elements that comprise them. The ventilated façade is a multilayer system consisting of the following elements (Fig. 1C):

1. Support: (wall, column, slab, etc) a resistant structural element which is part of the building and is responsible for transmitting forces to the structure of the building.
2. Substructure/ fixing system: a set of resistant elements responsible for transmitting forces received by the cladding to the support. Metal railing systems, usually aluminium uprights and cross members.
3. Insulation: Located on the exterior side of the supporting wall.
4. Air chamber: The cavity formed by the separation between the cladding and insulation (fixed to the building wall).
5. Cladding: The outer face of the façade, which be composed of different materials.

Several authors have highlighted the influence of the geometric factor of the façade in the development of a fire and its spread through the façade surface [2, 3]. In particular, it has an impact on the speed of propagation of fire, and the shape and trajectory of the fire plume.

The arrangement of the components of a multilayer façade, such as the ventilated façade, may be understood as part of its geometric development. Therefore, the ventilated cavity is an element that significantly influences the behaviour of fire.

In a ventilated façade, fire may spread along the following routes:

1. Through the window openings by the so-called "*leap frog*" effect.
2. Through the surface of the cladding, when the reaction of the material to fire contributes to the rate of fire spread, and
3. through the ventilated cavity, if adequate fire barriers are not employed; due to the chimney effect, this latter factor is considered the fastest propagation pathway [4].

In this study we focus only on this last case.

Once the fire is within the ventilated cavity, the hazards associated with the fire spreading through the cavity are as follows:

- **Thermal properties of insulation.** If a combustible material is used (which is often the case), fire intensity increases.
- **The substructure of the façade.** In this type of fire incident, the temperature within the fire envelope may achieve a local temperature in excess of 600 °C. Regardless of the external panel construction, if fire enters the cavity and comes into contact with the aluminium substructure, it may begin to lose its local strength and integrity as it is heated. Under prolonged fire exposure conditions, the railing system could melt, which may lead to localised system collapse.
- **Cavity shape and chimney effect.** As mentioned above, fire spread in ventilated façades occurs through the windows and the ventilated cavity. This may occur simultaneously.
  When flames are confined by the cavity, they will become elongated as they seek oxygen and fuel to support the combustion process. This process, together with the chimney effect, may lead to a flame extension five to ten times greater than of the fire plume spreading through the windows [4], regardless of the materials used as insulation. This may enable fire to spread quickly and unseen through the external cladding system, if appropriate fire barriers have not been provided.
- **Vulnerable areas.** Window and door frames may provide a direct entry route to the cavity. These are usually made of aluminium or PVC and lack fire barriers or seals.

Provisions of the CTE on ventilated façades

The Spanish building code CTE (DB SI) Fire Safety (Sects. 1 and 2) addresses the spread of fire in a very general way. It makes only a succinct reference to façade ventilated systems. In particular, it relates to two aspects:

- **Fire barriers,** under the following conditions:
  Barriers in cavities are required every 3 storeys or 10 m, in buildings higher than 18 m.
  Barriers in cavities are required every 3 storeys or 10 m, in buildings less than 18 m, except in cases in which insulation materials meet the classification of fire reaction B-s3,d2, i.e. it has a low level of combustibility. Otherwise, no fire barrier is required.
- **Combustibility of thermal insulation material**, under the following conditions:
  The insulation should meet the classification of fire reaction B-s3,d2 throughout the height of the entire building, in buildings higher than 18 m.
  The insulation should meet the classification of fire reaction B-s3,d2 until 3.50 m in public access areas. The rest of building does not have this requirement. The regulation does not provide details about these requirements.

Table 1. Computational domain.

Scenarios	Mesh size (m)	Number of cells	Cell size
Basic scenario	4.90 × 6.50 × 8.25	241,920	10 × 10 × 1
Double size scenario	4.90 × 6.70 × 18	599,760	10 × 10 × 10

OBJECTIVES

This study aims to assess fire behaviour and its propagation through the cavities of ventilated façades systems. In particular, we seek to assess the level of protection provided by the measures stipulated by the CTE. We focus our study on the following aspects:

A. Fire barriers in the ventilated cavity. Two different methods for partitioning the cavity are considered.
B. The influence of the use of combustible and non-combustible thermal insulation.
C. The influence of the size of the cavity and level of ventilation. Three variables are considered: low, medium and high ventilation.

METHODOLOGY

This research is conducted using field models of computational fluid-dynamics to evaluate some aspects of fire dynamics in the different cases studied, the conditions of which are explained below. In particular, the following software is used: The Fire Dynamics Simulator (FDS) to solve the models PyroSim for the graphical interface, and Smokeview to visualize the results. Computer-simulation is a useful tool that provides an approach to the problem of fires, taking into account different variables and scenarios. One of the great advantages of simulation is the possibility to study some aspects of the phenomenon of fire without incurring the high costs of laboratory tests. This does not mean that computer-simulation can replace the laboratory tests; however, it is a powerful tool for carrying out complementary studies, mainly as regards the physical behaviour of fire.

In this research a scenario representing a fire in a living room is considered. The fire starts on a couch in the ground floor of the scenario. To achieve this, an ignition source of 400 cm^2 is placed on the surface of the couch. This source is characterized by a burner with a heat release rate of 1000 kW/m^2. Once the fire reaches the stage of flashover, it spreads to the outside through the windows. The windows are disabled when a device (heat detector) reaches 300 °C. Moreover, the window frames are disabled when a device (heat detector) reaches 500 °C (Considering a failure in the aluminium window frames due to fire exposure) as a result fire enters to the cavity.

Fire growth occurs according to the calculation performed by the software. The FDS solves the equations governing the simulated system and provides graphical and numerical data for each scenario. The models show a simplified representation of the analyzed cases.

Eight cases are evaluated based on a common computational domain and a fire scenario. Table 2 describes the variables considered in each case under study.

The characteristics of the computational domain and the scenarios are described below.

Computational domain

Two computational domains are performed; one is the basic scenario and the other is double the size scenario. The basic scenario size is 6.50 m × 4.90 m × 8.25 m. Each cell has a uniform size (0.10 m × 0.10 m × 0.10 m). Table 1 shows the information about the two domains. Previously, two different computational domains are also performed for the same scenario to compare the evolution of fire: with cell size (0.20 m × 0.20 m × 0.20 m) and (0.10 m × 0.10 m × 0.10 m). The results were similar for both domains. The smaller mesh was chosen to all simulations.

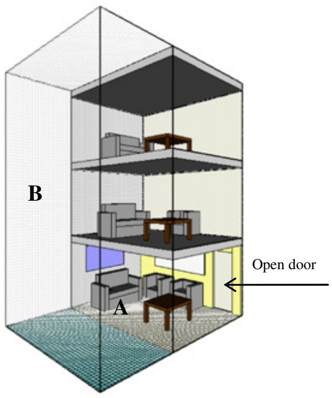


Figure 2. Computational domain – three-storey scenario.

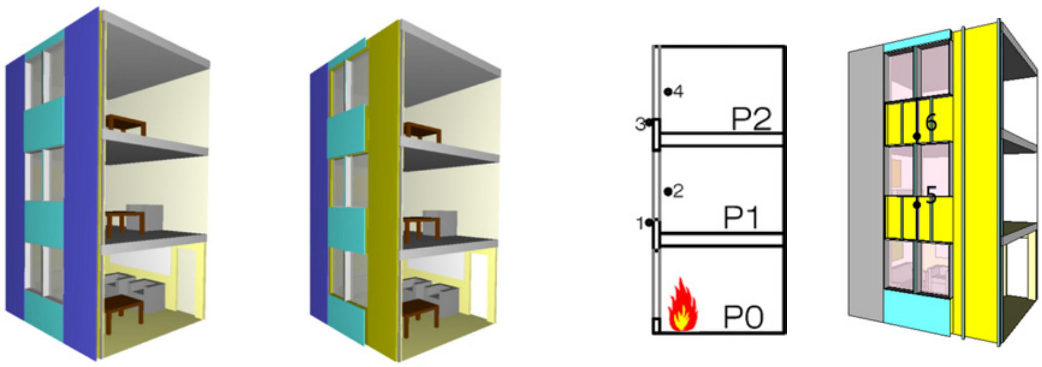


Figure 3. Geometric description of the scenarios and location of the thermocouples.

Table 2. Case studies.

		(A) Fire barriers		(B) Thermal insulation	
		FB	**WB**	**CI**	**NCI**
		Floor barriers	Window barriers	Combustible insulation	Non combustible insulation
(C) Cavity size and ventilation level	**LV** Low ventilation	**o**	**o**	**o**	**o**
	MV Medium ventilation			**o**	**o**
	HV High ventilation				**o**
	Double size scenario				**o**

The simulations parameters are follows: Temperature: 10 °C, Moisture: 60%, ventilation conditions 1.0 m/s (3.6 km/h), Simulation time: 900 seconds. There are two different areas to be considered in the domain (Fig. 2): (A) Enclosure (Living room) and (B) Open (external conditions).

Figure 4. Details of the ventilated cavity elements.

Geometric configuration and contents of the scenarios

The fire scenario consists of a three-storey living space of 4.00 m × 4.90 m. Each floor is 2.50 m high and is separated by concrete floors (non-combustible material). The façade cladding material is non-combustible. The scenario is representative of a typical living space with a fire load density

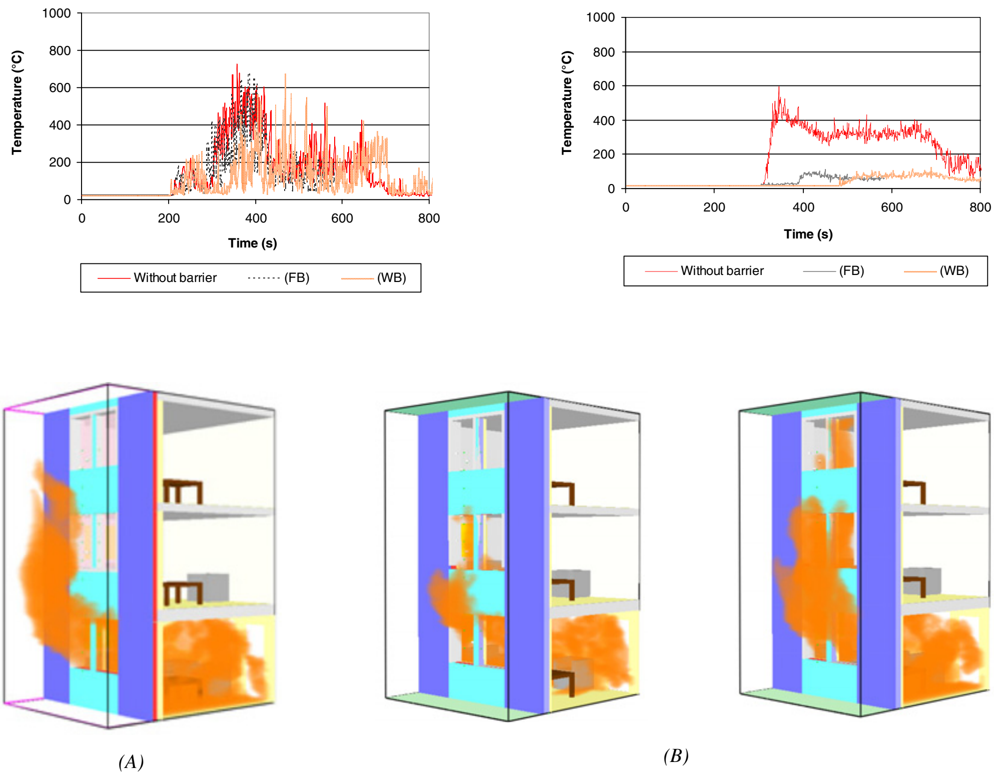


Figure 5. (Top) comparative of temperatures between a scenario without barrier and the two types of barriers studied, for thermocouples 1 (left) and 2 (right). (Bottom) graphics of fire spreading through the façade. (A) With barriers, at time of 300 s. (B) Without barriers, at 250 s and 300 s.

approximately of 600 MJ/m^2. The characterization of the materials that constitute the furniture is based on some parameters extracted from the database of Ref. [6].

Measurements devices

Data on the evolution of the temperatures are recorded through thermocouples located at the height of the parapet of the first floor, both inside and outside. Furthermore, thermocouples are placed inside the chamber to check the temperatures reached (Fig. 3).

In order to observe the distribution of temperatures in certain areas of the scenario, chromatic planes of two dimensions are used, as seen in Figures 6 and 7.

Ventilated cavity details

As indicated in the research objectives, in this study three aspects related to the ventilated cavity are explored. Table 2 and Figure 4 shows the information on each of them.

Two sizes of ventilated cavity are studied LV and MV (low and medium ventilation) according to the provisions of CTE DB HE Energy Savings (Appendix E). The third type of ventilation HV (high ventilation) incorporates a forced air flow.

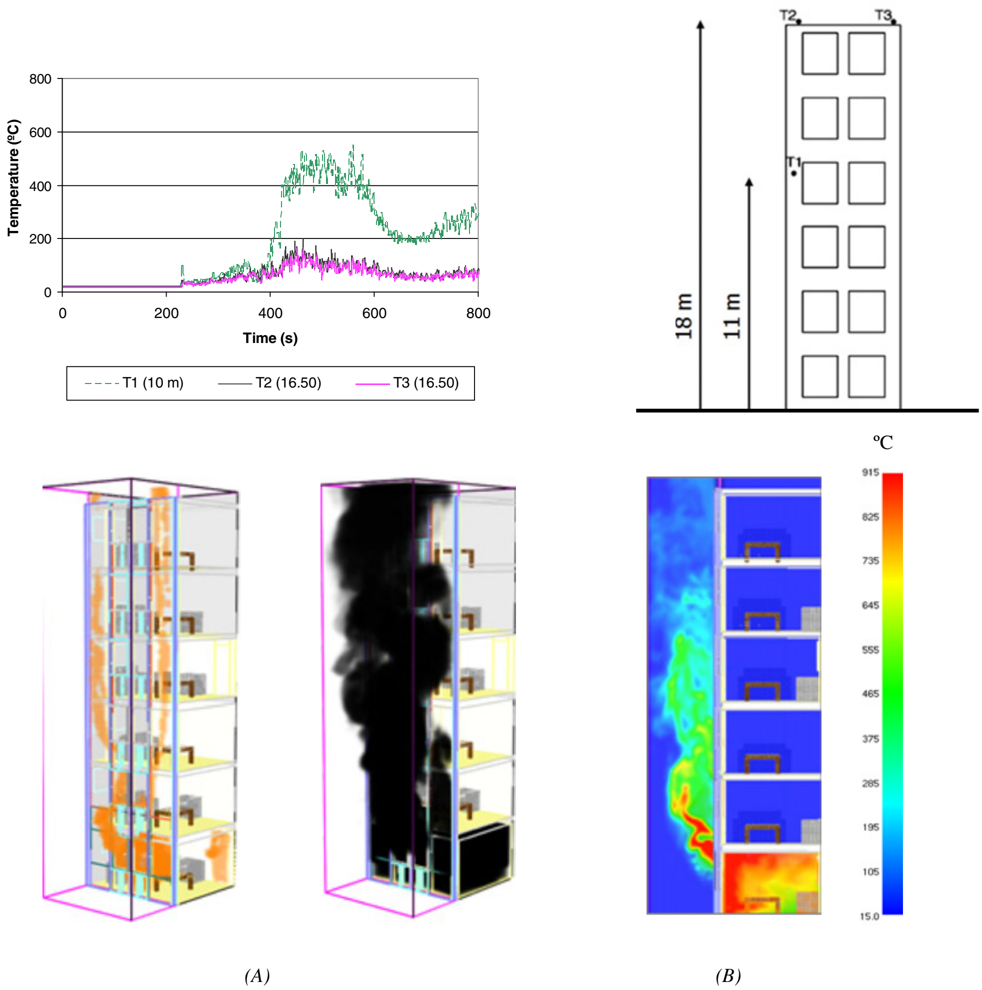


Figure 6. (Top) temperatures recorded by thermocouples located inside the cavity. (Bottom) (A) graphics of flames and smoke through the façade without fire barriers, at 450 s. (B) Temperature distribution for the same situation.

RESULTS

The results show the great influence of the ventilated cavity in fire spread through the façade, should adequate fire barriers not be employed.

Fire barriers

In all the cases studied, we observe that is very important to consider the use of fire barriers to prevent the entry and spread of flames into the cavity. It is also observed that fire spread through the cavity is much faster than through the windows. In addition, the probability of fire spread to the upper floors is greater.

The comparative of temperature evolution (Fig. 5 top) show peaks at slightly lower temperature on the surface of the façade when using barriers; indicating that the fire plume projected on the façade has a similar behavior in both cases. However, temperatures inside the enclosure are significantly lower when

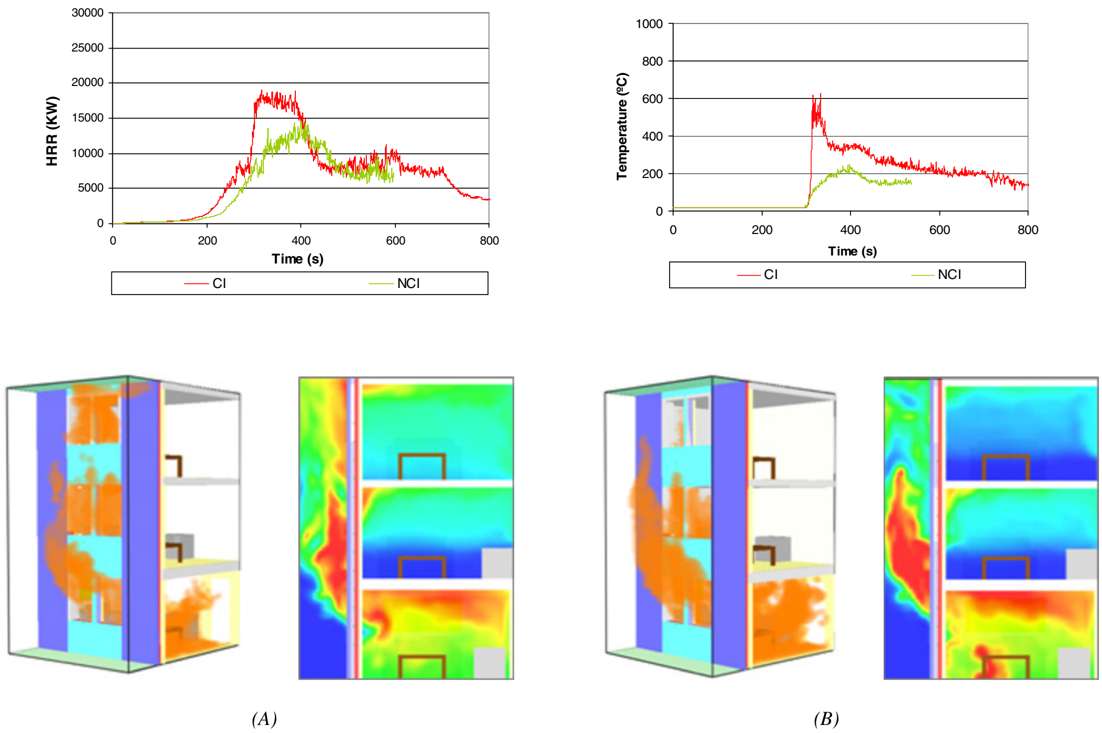


Figure 7. (Top) comparative of HRR and temperatures (thermocouples 4) between scenarios with combustible and non-combustible insulation. (Bottom) graphics of flame spread and temperature distribution, at 350 s. (A) Combustible insulation CI. (B) Non-combustible insulation NCI.

using barriers (FB) (WB). This shows that, preventing the passage of fire through the ventilated cavity decreases significantly the possibility of fire spreading to upper floors.

In general, it is observed that both partitioning methods are effective in preventing the passage of fire to the ventilated cavity. However, it should be considered that the barriers FB have the additional ability to limit the passage of flame through the camera, while the barriers WB only limit the input or output of fire through the window frames (or doors). This is an important aspect because the interior of the cavity may reach high temperatures. In the non-combustible insulation scenarios, temperature peaks near 800 °C were recorded, being of about 1000 °C in the scenarios with combustible insulation.

The double size scenario (18 meters) (height reference used by the CTE) which are performed without barriers, shows the ability that may have the fire and smoke to spread through the cavity, even if the insulation is non-combustible, as seen in Figure 6. This result highlights the importance of compartmentalize the ventilated cavity to prevent this type of spread.

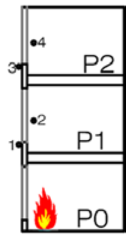
Because the study is conducted using computational techniques, it is not possible to obtain data on the fire resistance of the elements or on the degradation of materials exposed to flames, but rather their influence on fire dynamics. The potential effectiveness of a fire barrier design can only be fully assessed as a part of a series of large-scale tests.

Thermal insulation

It is observed that the combustibility characteristics of the thermal insulation material has a significant influence on the intensity and velocity of fire propagation through the cavity as seen in the comparative of HRR and temperatures in the curves of Figure 7 (top).

Table 3. Summary of temperature peaks.

LV				MV				HV	
CI		NCI		CI		NCI		NCI	
3	**4**	**3**	**4**	**3**	**4**	**3**	**4**	**3**	**4**
900 °C	600 °C	550 °C	250 °C	700 °C	750 °C	450 °C	500 °C	900 °C	400 °C
1	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
750 °C	600 °C	750 °C	400 °C	830 °C	570 °C	550 °C	500 °C	950 °C	500 °C



Once the fire is within the cavity the propagation through the ventilated cavity occurs quickly, regardless of used insulation material. However when this is a combustible material the spread of fire is much more intense and the probability of fire spread to the upper floors is increased (Fig. 7 thermocouple 4).

Cavity

Fire is a phenomenon sensitive to external factors. Ventilation is one of the factors that more affect fire behavior. The results obtained from the different temperature curves shown that the size of the cavity and the flow of ventilation affect the spread of fire through the ventilated cavity. It is observed that the larger the camera is, the higher possibility of the fire spreading to the upper floors.

According to the results on the scenario HV it may be considered that the ventilation contributes to the spread of fire through the cavity. The impact of ventilation may be more decisive than the size of the camera. Table 3 shows a summary of the temperature peaks reached in each case.

CONCLUSIONS

The ventilated cavity is a potential pathway for fire spreading in fire situations. For this reason the compartmentalization of the cavity on each floor of the building, by using appropriate barriers, is considered essential in order to prevent this type of propagation. The establishment of barriers every 3 floors or 10 meters, as is required by the Spanish building code (DB-SI Sect. 1.3), is not sufficient: it would be equivalent to protect a part of the building while the other part remains without protection.

The spread of fire through the ventilated cavity is due to the system configuration and the façade chimney effect that occurs within the cavity, regardless of the used thermal insulation material (whenever non-combustible). The provision of CTE (DB SI Sect. 2.4), in the sense that partitioning barriers are not required in buildings lower than 18 meters (in the conditions already explained), leaves a significant risk without covering. Therefore it deserves to be revised by legislation. It's worth to mention that a high percentage of residential buildings in Spain are lower than 18 meters.

It is important to use appropriate fire barriers which, at same time, allow the ventilated cavity to properly work in normal circumstances, without affecting the hygrothermal performance of the façade. The products market has evolved a lot in this area and offers interesting options based on intumescent materials.

Fire barriers arranged on the window frames are considered appropriate to prevent the passage of fire from one fire compartment to the ventilated cavity and vice versa. However, as they do not contain the passage of fire through the cavity, they are not effective in preventing the damage of the ventilated cavity substructure by the fire. Barriers crossing the entire façade are more effective for this purpose.

The use of combustible insulation materials significantly increases the spreading and the fire intensity and raises, therefore, the level of risk. We recommend the use of non-combustible insulation materials (reaction class A or B) along the whole façade.

It is important, in our opinion, to inform the professionals involved in building about the risks that remain unfilled by the regulations. The appropriate protective measures should be incorporated even if they are not required by the current regulations, because its fulfillment does not guarantee, in all the cases, an acceptable safety level.

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