MODELING URBAN FIRE SPREAD BASED ON SPECIFIC CHARACTERISTICS OF SUBSTANDARD HOUSING IN SPAIN

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ABSTRACT

Due to the increasing urbanization and development of denser cities, the risk of fire is becoming a significant issue. Different approaches can be found when trying to evaluate the risk of fire and several urban fire spread models have been proposed. However, these models present numerous vulnerabilities, like radiation exposure, direct flame contact, influence of wind, transport of firebrands, amongst others.

Nowadays, in Spain there are more than 1.5 million families living in substandard housing. The use of unstable stoves for cooking, lighting, and heating, unsafe electrical connections, along with an excess of combustible materials, contribute to a higher risk of fire. A realistic behaviour of the fire dynamics, with specific values of heat release rates and spread rates, in this type of substandard housing is needed when developing urban fire-spread models.

Real data is being recorded from marginal neighbourhoods in Madrid (Spain), with the aim to develop more accurate numerical simulations of the fire dynamics. These models are implemented in Fire Dynamics Simulator (FDS), which is a computational fluid dynamics (CFD) model of fire-driven fluid flow. These predictions are coupled with an urban fire spread model, assessing fire temperatures and heat evolution for this type of housing. Besides the influence of real-time wind is introduced to better evaluate how it influences fire spread between buildings.

INTRODUCTION

Fires cause more than 300,000 deaths per year and constitute one of the main causes of accidental injury globally. Besides, over 95% of the deaths and burn injuries occur in low- and middle-income countries, where death rates are nearly six times higher than in high-income countries [1].

Despite the costs of damage to houses, property, and livelihoods, they are rarely documented. In this regard, there is a lack of information recorded about the frequency, propagation, impact, and causes of urban fires. This is especially relevant in low-income houses, which are becoming more common due to the urban population growth. Substandard housing is usually concentrated in marginal neighbourhoods or densely-built urban areas, where fire easily propagates [2].

In order to characterize fire spread in cities, the behaviour of fire inside buildings should be coupled with its spread between them [3]. At a smaller scale, in a house, fire ignition and its development depends on many different factors, like the amount of flammable materials or fuel, ventilation conditions, and even on the social and cultural aspects of their occupants. Whereas at a higher scale, its spread is affected by the atmospheric conditions, wind, buildings geometry and configuration, etc. After flash-over in a room, flames and hot gases can be ejected out windows or doors of a building, which may also ignite proximate buildings by direct contact or by the emitted thermal radiation. Some other mechanisms can be also considered, like temperature rise due to wind-blown fire plumes, direct ignition from nearby burning vegetation, and firebrands [4], [5], [6].

There are many models that simulate fire spread in urban districts. The earliest one was empirically developed by Hamada, which expressed fire spread rate as a function of wind velocity and average building-to-building distance. Currently, so-called physics-based models include the different modes of fire spread, and couple models for compartment fires based on physical laws and empirical data [7].

Himoto and Tanaka [2] developed a model for an urban Japanese district, based on explicit representation of heat transfer using thermodynamics equations. Lee and Davidson [8] proposed a post-earthquake fire spread model which included the primary modes of urban fire spread: (1) evolution of fire within a room or roof; (2) room-to-room spread within a building through doorways to adjacent rooms, by burn-through to adjacent rooms or a room or roof above, or by leapfrogging through windows to a room above; and (3) building-to-building spread by flame impingement and radiation from window flames, radiation from room gas, radiation from roof flames, and branding.

In Shahaz and Benenson [3], some specific considerations were introduced, as in Mediterranean and Middle Eastern cities, most construction materials are non-flammable and flammable vegetation can be found between buildings,

Nowadays, in Spain there are more than 1.5 million families living in substandard housing. The main contribution of this paper is to drive the knowledge of fire dynamics and fire spread between this type of buildings with a higher risk of fire, supported by social, economic and cultural characteristics of their occupants.

NOMENCLATURE

A_o	[m^2]	Area of opening (window)
A_T	[m^2]	Total area of the compartment enclosing surfaces
D	[m]	Compartment width
H_o	[m]	Height of the opening (window)
L	[kg]	Total room fire load
$\dot{m}_r$	[kg/s]	Rate of fuel burning
$\dot{Q}$	[kW]	Heat Release Rate (HRR)
t	[s]	Time
T_r	[K]	Room temperature
W	[m]	Compartment depth

Special characters

α	[kWs^{-2}]	Growth factor

METHODOLOGY

The methodology here proposed follows the model proposed by Shahaz and Benenson [3], coupled with numerical simulations performed with Fire Dynamics Simulator (FDS), which is a computational fluid dynamics (CFD) model of fire-driven fluid flow. In addition, real data is being recorded by social workers at a particular neighbourhood in Madrid with a relevant number of substandard housing.

Substandard Housing characterization

A specific neighbourhood in Madrid, located in the urban core of the city, with diverse areas which correspond to different cultures due to immigration, has been chosen. Real data is being collected to characterize representative houses with respect to fire risk, as well as its relationship to cultural aspects.

Several aspects have been defined with the aim of precisely predict the dynamics of fire at the small scale. This type of housing generally consists of small houses with a clear excess of occupants that favours the accumulation of highly flammable materials (coaches, clothes, carpets, etc.). In addition, special attention will be paid to the type of kitchens, electrical connections, and particular habits that could enhance the risk of fire, like the use of candles.

Fire spread model

The model is based on the work of Shaham and Benenson [3], which starts with a novel algorithm of floor partition into rooms, apartments, corridors, and the allocation of windows and doors. Then, fire spread is evaluated by direct ignition, radiation, and fire brands. Therefore, after ignition, the evolution of temperatures inside a room is described as in Figure 1.

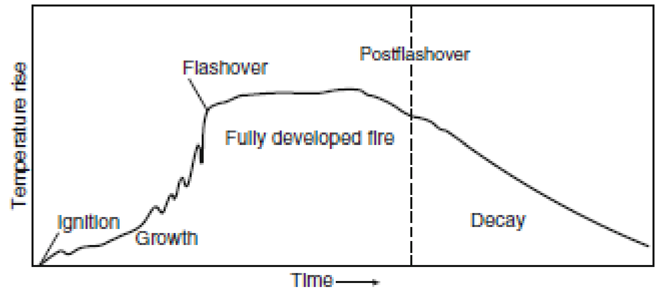

Figure 2 Temperature-time curve with fire phases **[9]**

When ignition occurs in a room or a compartment, the model first determines the amount of ventilation. In rooms with only one opening, the rate of fuel burning, assuming the fire is ventilation controlled, can be evaluated by equation (1):

$$\dot{m}_r = 0.18A_o(1 - e^{0.036\Omega})\sqrt{H_o(W/D)} \qquad (1)$$

where,

$$\Omega = \frac{(A_T - A_o)}{A_o\sqrt{H_o}}$$

The room temperature is evaluated as:

$$T_r = T_g + 6000(1 - e^{-0.1\eta})(1 - e^{-0.05\psi}) \qquad (2)$$

with,

$$\psi = \frac{L}{\sqrt{A_o(A_T - A_o)}}$$

However, when there is ample ventilation, which is considered when wind flows through the room at a speed above 5 m/s, because the room contains at least two openings, the rate of fuel burning is increased by a factor of 1.7. This factor is proposed in [3], due to the non-flammability characteristics of the walls.

Only average temperatures during the fully developed phase are calculated, since it is often assumed that spread between rooms occurs only in the fully developed. Inside a building, fire spreads through doors and by flames impinging from windows. In the former case, doors are considered to be highly flammable, regardless its opening condition. In the latter, flames could reach other windows and ignite other rooms immediately, although their development is highly dependent on the wind influence. In the same way, these impinging flames, or hot gas, can reach proximate buildings. Using radiation equations, and focusing on configuration factors, when the total radiation flux received from different sources exceeds the critical value of 12.5 kW/m^2, ignition is reached after 1, 7, 10, 25, or 30 min as a function of the values of the total flux of 30, 20, 17.5, 15, or 12.5 kW/m^2, respectively.

Numerical simulations

Numerical models in FDS version 6.7.1 [10] have been developed to study the fire behaviour in the representative houses, according the real features of the chosen neighbourhood. An evaluation of the values of the heat release rates (HRR) and how these develop inside the rooms are being evaluated.

Different models for the HRR, for domestic and public furniture, can be found in the database of the Combustion Behaviour of Upholstered Furniture (CBUF) project [11]. For some other commodities, exemplar data have been published in [10] and can be combined to the specific conditions of the representative houses. However, it is very common to use a simplified fire growth curve that represents the general types of combustible materials in the enclosure [9], for example, assuming the fire grows proportionately to the square of time (t^2):

$$\dot{Q}(t) = \alpha t^2 \tag{3}$$

with $\boldsymbol{\alpha}$ having values of 0.19, 0.047, 0.012, and 0.003 kWs^{-2}, respectively for ultrafast, fast, medium, and slow t^2 fires.

These numerical simulations mainly will help to understand the behaviour of fire under the influence of wind. Internal light wells are very narrow and windows are very close to each other. In addition, they contain plenty of clothe lines, which in the case of overcrowded houses, constitute a source of fire spread. Firstly, only steady-state wind analysis, without a fire, will be carried out to evaluate wind influence over the external features of the building. Some representative houses will be modelled, both the exterior and the interior, with the aim to analyse the indoor flows and obtain several fire scenarios to be tested. It will be relevant to search for the case with the highest air velocity inside the building. Even though the results may differ from the results obtained in the fire simulation, these scenarios will be chosen for the coupled analysis, i.e., with fire. The main difficulty of these numerical models will be the significant differences in scales. As can be observed in Figure 2, an extended domain will be required to solve wind with enough resolution, and a small mesh size will be needed to understand the dynamics of fire in the interior of the buildings [5].

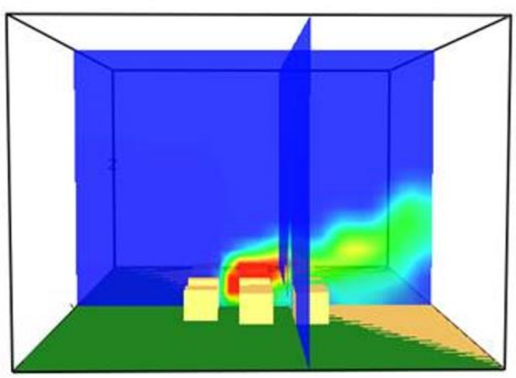

Figure 3 Three external boundary condition types

RESULTS

The neighbourhood called Tetuán, in the city centre of Madrid, is chosen for this first analysis. It is formed of blocks of buildings, where different cultures are present (Figure 3), [12], [13]. Many of these constructions are old, with only three or four floors, and many light wells are present between the buildings with complex configurations. Two buildings are shown in Figure 3, with their partition into different apartments.

Figure 3 Case study of two buildings and their partition

The fire spread model has been previously verified in [3] with a fuel load of occupied rooms of 16 kg/m^2. Here, as a starting point of the real study which is being performed, a sensitivity analysis of the fuel load is carried out in order to prove how the implementation of representative values according to the specific living conditions is crucial.

The building tested has an area of 137.1 m^2 and 5 floors, and has been divided into 2 different apartments with 5 rooms of similar size. Therefore, there is a total of 55 windows and also 55 doors. Different scenarios have been tested, with ignitions in the rooms. In Table 1, the total number of burnt down rooms and the room temperature after 60 minutes of simulation, are shown. In Figure 4, the evolution of fire spread, with time, within the building, can be also observed.

L [kg/m^2]	Burnt down rooms	T_r *[K]*
16	21	910.7
24	20	1028.6
32	13	1139.3
40	10	1213.9

Table 1 Sensitivity analysis of the fuel load for the case study

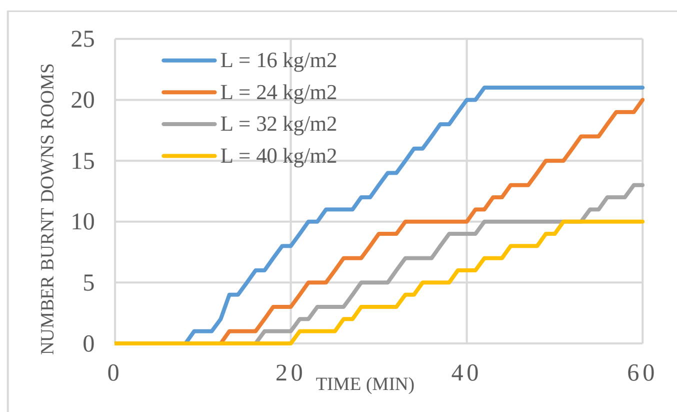

Figure 4 Evolution of the number of burnt down rooms

The fire on the room depends on the developed temperatures, but also on the duration of heating, which is a function of the fuel load. The accumulation of combustible material due to overcrowded houses increases the amount of fuel load, but also its distribution inside the compartments. As the fuel load increases, the room temperature also grows, but the number of rooms being burnt down decreases due to the slower initial growing phase of the fire. In this type of models, spread occurs only during the fully-developed phase, which is then delayed. However, due the distribution of the material and the elevated temperatures, spread between rooms could be generated during the growth phase. The numerical models of the representative houses will help to understand these spread mechanisms between the rooms and will adjust the fire spread model to the real data of this type of housing.

CONCLUSIONS

In this work, a methodology is proposed to improve the predictions of a physics-based model of fire spread in certain marginal neighbourhoods of Spain, where it is common to find substandard housing.

Due to the specific conditions of this type of housing, with a higher amount of fuel load, distributed along small rooms, a precise behaviour of the fire dynamics, with specific values of heat release rates and spread rates are required.

This methodology includes the collection of real data to better define certain representative houses, which will be modelled with Fire Dynamics Simulator (FDS) in order to understand the spread mechanisms between rooms. The results obtained, will also be tested with a detailed evaluation of the influence of wind on the building, and on its openings. The findings achieved will be coupled with the urban fire spread model, with the aim to obtain more accurate predictions.

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