The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

MODELING DIFFERENT MODES OF POST-EARTHQUAKE FIRE SPREAD

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ABSTRACT:

In this paper, a physics-based post-earthquake fire spread model that is under development is introduced. The model includes several key modules, representing 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. Each of these modes of spread is described in turn, including a discussion of how it has been modeled in the past, and the approach taken in the new simulation.

KEYWORDS: Fire, risk assessment, simulation

1. INTRODUCTION

For fifty years, post-earthquake fire spread models used an empirical approach based on the so-called Hamada equations, which assume that the built environment is comprised of equally-spaced, equal-size square urban city blocks of buildings, and that fire spreads in an elliptical shape (Lee et al. 2008). Recent efforts have begun moving to a physics-based approach that recognizes the different modes of fire spread and represents each separately, adapting models from the compartment fire literature based on physical laws and empirical data (Lee et al. 2008). The physics-based approach has several benefits. Cities are less homogeneous than assumed by Hamada, and while a fire typically has an elliptical shape initially, that does not last as it encounters different fuel loads, suppression efforts, and other fires. Physics-based models are more generally applicable across regions and times; are better grounded in theory so that more accurate estimates of fire spread can be expected; and provide results at a higher resolution. Since the factors contributing to spread are represented explicitly, they can easily be varied to gain insight into how fire spreads and into the effects of specific risk reduction strategies. In this paper, we introduce a new physics-based model we are developing. We describe the fire spread modes it includes, and for each, explain the key issues associated with it, how they have been modeled, and the approach we are using.

2. MODEL DESCRIPTION

2.1. Overview

The objective of the new fire spread model is to simulate the evolution of fires in an urban post-earthquake environment for use in estimating expected fire damage and losses, gaining insight into the relative importance of factors in the risk, and evaluating potential risk reduction strategies. The model takes as input building footprints and heights from remote sensing data to accurately capture the areas and relative orientations of buildings that are important for fire spread. Using GIS algorithms we developed for the purpose, we estimate the room configuration within each building footprint. Ignition and wind data are either input by the user or simulated. Detailed results, such as percentage of area burned in each building at each time *t*, and relative frequencies of the modes of spread are calculated, including randomness in the process. Active suppression activities are not included currently, but the model is designed to allow their future integration without changing its structure.

The model includes several modules, representing the primary modes of urban fire spread (Fig. 1): (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. These modes are described in turn in Sections 2.2 to 2.6. Convection is not included because although it can contribute to heating over short distances, it is not expected to be an important factor compared to radiation (e.g., Waterman 1969).

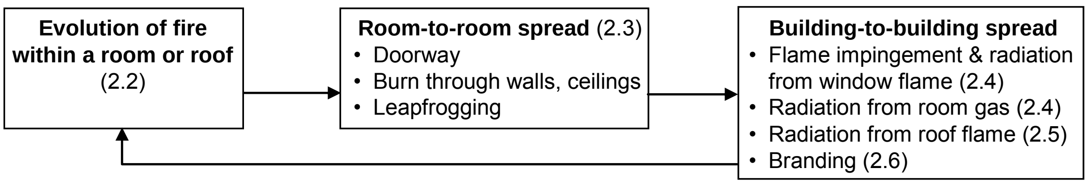

Figure 1. Modes of fire spread included in model (Section in which it is discussed)

A key difference between this new model and the few other recent physics-based post-earthquake fire models (summarized in Lee et al. 2008) is our room-based approach. While others have assumed a building, story, or 3m by 3m grid cell is the unit of analysis, we combine remote sensing data that accurately captures the building footprints and relative building orientations that are so critical to building-to-building fire spread, with GIS algorithms that allow automated estimation of reasonable room configurations so that room-based fire spread models can be employed while the method can still be applied to a large urban region. Other innovations relate to the module specifics, such as, modeling roof flames as pool fires and detailed estimation of the configuration factors that describe the proportion of emitted radiation received by neighboring buildings, rather than simplifying their calculation by assuming radiation is emitted from point source.

2.2. Evolution of a room or roof fire

There are three main approaches to modeling the evolution of fire within a room. Computational fluid dynamics models divide a room into many elemental volumes and solve fundamental equations governing the transfer of mass, momentum, and energy to estimate the evolution of fire within the room. More common are zone models, which divide a room into two zones—an upper hot gas layer and a lower cold gas layer—and solves conservation of mass, momentum, and energy for them. Finally, simplified relationships of temperature vs. time have been developed to represent the development of a fire within a room. For a post-earthquake fire spread model involving thousands of buildings, the temperature-time curve approach is appropriate for the level of data available, computational demands, and intended uses.

Compartment fires are often discussed in terms of three distinct phases: growth, fully-developed (or steady-state), and decay (Fig. 2). During the growth phase, the temperature rises quickly as the fire grows as a function of the fuel characteristics with little influence from the compartment. Flashover occurs when all combustible materials in the room suddenly ignite due to radiation from the hot gases in the room. While there is no precise, widely accepted definition of flashover, it is often taken to be the point at which a specified temperature is reached—500°C to 600°C are widely used (Walton and Thomas 2002), or a specified percentage of the fuel load has burned (e.g., Law 1978 suggests 30%). In the fully-developed phase, as temperatures reach 1000°C or higher, the fire is controlled either by the surface area of combustible materials (fuel-controlled) or the availability of oxygen through openings (ventilation-controlled, usually more severe), depending on the amount of combustible contents. Finally, the decay phase occurs as fuel is consumed and the heat release rate declines. Temperatures and heat flux during the growth and decay phases are small compared to the fully-developed phase, and are not typically considered to cause structural damage. The fully-developed phase, therefore, is often the focus of study.

The ASTM E119 "standard time-temperature curve" was introduced in 1917. After full-scale room burnout tests showed that real fires behave very differently from the standard curve, Inberg (1928) developed the equal area hypothesis to relate standard curve test results to real-life fire endurance. The standard curve still has many well-documented shortcomings, including that it does not account for the eventual decay of a fire or the effects of fire load density (amount of combustible material per unit floor area); surface area and arrangement of the combustible contents; size of ventilation openings; room dimensions; or thermal properties of the walls, ceiling, and floors. Nevertheless, the standard curve continues to be widely used as the definition of a "standard fire" to which building elements are exposed to determine their fire resistance ratings because it is considered to be conservative, has a proven safety record, and is simple to apply (Cooper and Steckler 1996). In the 1970s, curves were developed based on 16 full-scale room burnout experiments (Fang and Breese 1980). Using mathematical modeling to solve heat balance equations for the room under consideration, other temperature-time curves were developed by Kawagoe and Sekine (1963), Odeen (1970), Magnussen and Thelandersson (1970), Pettersson et al. (1976), and Babrauskas and Williamson (1978, 1979). These models are mostly based on cellulosic fuels (like wood), which may not be appropriate given modern synthetic materials, and on windows as the only type of room ventilation. They also often require lengthy computation and detailed data. Cooper and Steckler (1996), Lie (2002), Walton and Thomas (2002), and Drysdale (1998) review specific temperature-time curves.

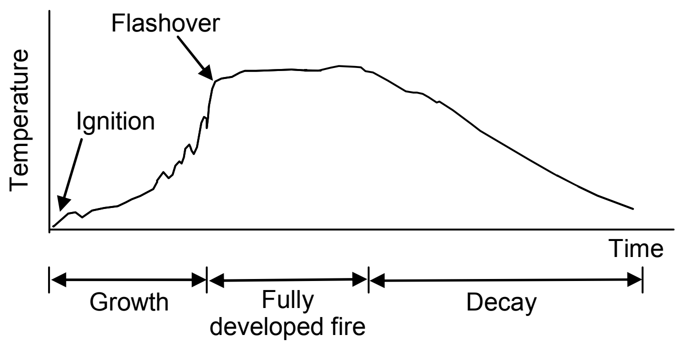

Figure 2. Fire phases (based on Walton and Thomas 2002)

Our new model is based on Law and O'Brien (1981) because it gives reasonable results; considers the key factors; requires as input only room dimensions, window area, and fire load, all of which we can estimate. Finally, Law and O'Brien (1981) include a method to estimate window flame geometry and radiation emitted by the room gas and window flame, ensuring that these modules are all consistent.

2.3. Room-to-room spread within a building

There are three main ways fire can spread from room to room within a building: (1) through doorways, (2) by burning through walls or ceilings, or (3) due to a flame ejected out the window igniting the room directly above it (i.e., leapfrogging) (Platt et al. 1994). The time until burn-through depends on the fire resistance of the barrier, existence of weaknesses in it (e.g., electrical services or earthquake damage), and the fire intensity. Leapfrogging depends on window flame geometry (see Section 2.4) and the layout of windows on the building wall. Some researchers have extended zone and CFD room fire models to consider the spread of smoke and fire spread, assuming room barriers remain in tact (e.g., Anderson et al. 1986). Himoto and Tanaka (2008) estimate the time until burn-through and area of the new opening created based on calculated heat flux in the burning room and the assumed fire resistance rating of barrier. Oleszkiewicz (1990) conducted full-scale experiments to examine spread from window flame to exterior cladding, which could then spread into the window of the room above.

We use a modified version of Platt et al.'s (1994) probabilistic model, randomly determining if open doors exist in each wall, randomly estimating a time until burn-through for each barrier based on occupancy type-dependent fire resistance ratings, and estimating leapfrogging based on window flame geometry (Section 2.4).

2.4. Building-to-building spread due to flame impingement and radiation from window flames and room gas

When a room with a window reaches flashover, a flame is ejected out the window and may curl back and contact the façade above the window. These window flames can cause fire to spread by leapfrogging (Section

2.3) or flame impingement on neighboring buildings, and will emit radiation. Hot gas ejected from the window also emits radiation. There are three key steps to modeling the effect of the window flame and room gas on neighboring buildings: (1) determine the window flame geometry and if any rooms are ignited by flame impingement, (2) estimate the configuration factor, which describes the relative positions of the radiator (window flame or room gas) and receiver, and (3) estimate the radiation received by the neighboring building due to the room gas and window flame.

The geometry of a window flame is typically described in terms of the height of the flame tip above the top of the window, the horizontal outward projection of flame from the exterior wall, and its width (Fig. 3). It depends on ventilation conditions (through draft or no through draft), window size and height-to-width ratio, and the presence of vertical or horizontal projections above or beside the window (Law and O'Brien 1981, Oleszkiewicz 1990). In the more common no draft condition, the flame emerges from the top 2/3 of the window, and air is drawn into the room from the bottom 1/3. In the through draft condition, the flame tends to emerge from the entire window area, and be projected outward more. Large windows tend to allow more fuel to be burned within the room, resulting in smaller external window flame heights. Tall, narrow windows tend to have taller flames, projected away from the façade more. If a window is narrow or has no wall above it, the outward projection is larger because in that case, more cool air is entrained in back of the flame, which projects it outward.

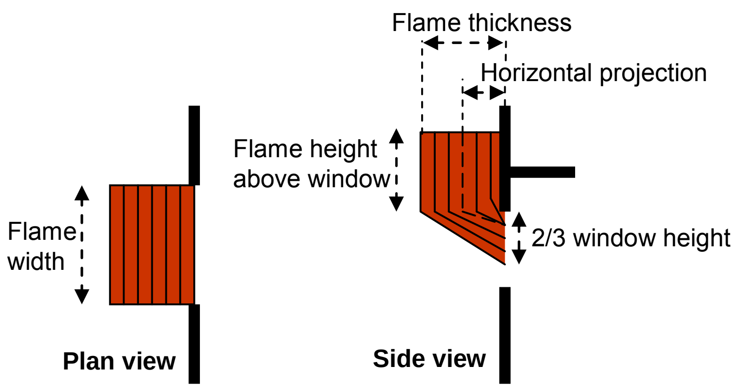

Figure 3. Assumed window flame geometry for no through draft conditions where there is a wall above the window and (window height)<1.25(window width) (from Law and O'Brian 1981 method)

Yokoi (1960) and Seigel (1969) performed experiments on fire spread from windows and developed equations to estimate window flame geometry and temperature. Thomas and Law (1974) reexamined earlier experimental work by Yokoi, Siegel, and others. Law (1978) and Law and O'Brien (1981) then included additional full-scale experimental results in developing a method to assess the fire safety of external building elements. Oleszkiewicz (1990) later modified the Law (1978) conservative assumption of constant flame thickness to instead assume a triangular flame shape that is thickest at the top of the window, decreasing as it rises until it has zero thickness at the building façade. Considering non-cellulosic fuels, Bullen and Thomas (1979) investigated the effect of the amount of unburned fuel leaving the room on the height of external flames. Sugawa et al. (1997) examined the effect of wind speed and direction on external flames. Klopovic and Turan (2001) present experimental results of plume characteristics and compare them to those predicted by previously developed models. Our new model estimates window flame geometry based on the Law and O'Brien (1981) method.

The radiation transferred to the neighboring building opposite the burning room is calculated as $I = \phi\varepsilon\sigma\left(T^4 - T_a^4\right)$, where ϕ is the configuration factor that determines, based on geometry, the fraction of the radiation emitted from the window flame and room gas that is actually received, ε is the radiator emissivity, σ is the Stefan-Boltzmann constant, and T and T_a are the radiator and ambient temperatures, respectively.

2.5. Building-to-building spread due to radiation from roof flame

When a roof ignites, a flame develops that behaves differently from a flame ejected from a room window. Since no models are available to represent this particular situation, roof flames can be treated as large, open pool fires, which have similar geometry, are similarly freely exposed to the atmosphere and wind, and for which models have been developed (Craig Beyler, Hughes Associates, personal communication; Woycheese et al. 1997). As with room gas and window flames, thermal radiation is the primary mechanism by which roof flames cause damage. Their effect on neighboring buildings depends on the fuel composition, size and shape of the pool (roof), duration of the fire, and proximity to and thermal characteristics of the neighboring buildings (Beyler 2002).

Three key steps are required to determine the effect of a roof fire on neighboring buildings. First, determine the burning rate and geometry of the flame. The flame is typically assumed to be a solid gray emitter with a regular shape, usually a vertical or tilted circular cylinder (Fig. 4). Its geometry is described by the flame base diameter, visible flame height, and flame tilt angle θ. Second, characterize the radiative properties of fire (i.e., average emissive power). The intensity of the thermal radiation emitted depends on the fuel type, fire size, flame temperature, and composition. Third, estimate the radiation received by neighboring buildings due to the roof flame. As with window flames, the radiation received is based on the relative positions of the flame and the target neighbor building and is described using configuration factors.

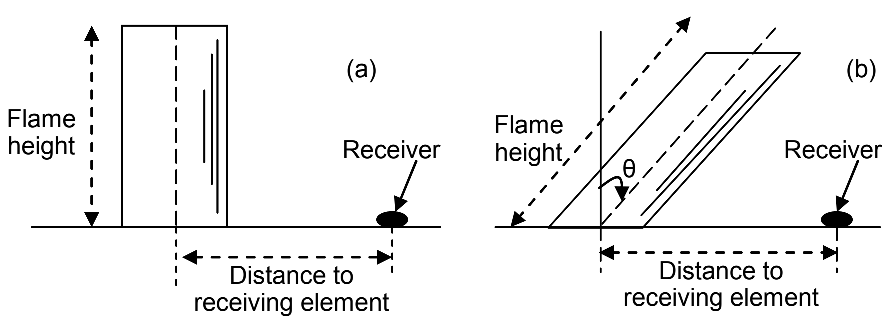

Figure 4. Assume pool flame geometry for (a) vertical and (b) tilted cylinders (from Beyler 2002)

Beyler (2002) presents and evaluates two screening and two detailed methods for determining the effect of pool fires on a target object. The Shokri and Beyler (1989) screening method is a simple correlation between radiant heat flux at ground level as a function of pool fire diameter and fire-target distance, and thus is only applicable for targets at the same level as the base of the pool fire. The point source screening model assumes the flame is a point source rather than a cylinder, which greatly simplifies the configuration factors, but it performs poorly at heat fluxes greater than 5 kW/m^2, and so is not a good option when the ignition of combustibles is of concern (Beyler 2002, Drysdale 1998). We use Mudan (1984) in our model because, unlike the Shokri and Beyler detailed (1989), it incorporates cylinder tilt due to wind. While burning rates are available for the hydrocarbons that these models were originally developed for, they are not available for roof fires. To estimate roof burning rates, therefore, we conduct additional analysis, considering the roof to be a room with the neutral plane at the ceiling height, assuming that air only flows in through the window and out through the roof.

2.6. Building-to-building spread due to branding

Branding or spotting is another important mechanism of building-to-building fire spread in post-earthquake fires. Firebrands (embers or small pieces of fuel) are entrained into the atmosphere, may be carried by winds over large distances, and when they land, may ignite the host fuel bed resulting in fire spread to an area far from the original fire. Branding can be divided into three main phases (Waterman 1969): Generation of firebrands from burning vegetation and structures; (2) transport through the atmosphere and brand combustion; and (3) possible ignition of new fires. Research has focused more on wildland fires than urban fires. While some lessons and models are transferable, there are important differences. The vegetation-generated brands in wildland fires tend to be spherical or cylindrical, coming from twigs, bark, cones, and needles; whereas structure-generated brands more common in urban post-earthquake fires tend to be disk-shaped, resulting from thin, flat roof shingles and building contents. Disk-shaped brands are lofted more easily and have a greater potential for spot fire propagation.

Research on the generation phase aims to determine how many brands will be released and when, and the size and mass distribution of the brands released. Brand generation depends on the fire area, fuel type, and wind, which creates internal pressure that increases brand generation. Some experimental studies have been conducted in which a real-scale object is burned, some or all of the resulting brands are collected in wet trays, and the brands are then dried and examined. Waterman (1969); Yoshioka et al. (2004); and Manzello et al. (2007, 2008) have conducted such studies for roof assemblies, a fire preventive wood house, and trees, respectively.

The transport of brands depends on time-dependent fire plume wind velocity fields, brand size and shape distributions, highly variable brand combustion rates, and terrain effects (Woycheese et al. 1999). Many brand transport models have been developed, focusing on determining brand propagation distances, and sometimes on the distributions of final brand size, mass, burning status (glowing, flaming, neither) as functions of heat release rate, wind velocity, air and brand properties. They include Tarifa et al. (1965); Lee et al. (1970); Albini (1983); Tse and Fernandez-Pello (1998); Woycheese et al. (1997, 1999); Himoto and Tanaka (2005); Huang et al. (2004); Sardoy et al. (2007); and Anthenien et al. (2006). The models typically combine three main submodels that describe the (1) fluid motion, (2) brand motion, and in some cases, (3) temporal mass change of the brands. The boundary layer of the atmosphere through which the brand is transported is a combination of the fire plume and wind velocity fields, and has been modeled in 2D or 3D using plume and wind models (e.g., Woycheese et al. 1999) and computational fluid dynamics simulations (e.g., Huang et al. 2004). Brand motion is typically determined using conservation of brand momentum equations, assuming two forces act on the brand—gravity and drag, which depends on the fluid motion. Some studies include a model of how the brand combusts and loses mass over time while being transported. This can affect the trajectory of the brand and the final mass when it lands, thus influencing its ability to ignite the host fuel bed. In fact, a brand may completely combust in the air posing no spotting risk. Brand combustion has been addressed using a burning spherical liquid fuel droplet model with the brand diameter following a regression rate (Woycheese et al. 1999) and using a more complex model of pyrolysis (Sardoy et al. 2007). Woycheese (2001) offers experimental data on the combustion of wood disk-shaped brands. Himoto and Tanaka (2005) develop results from a numerical simulation of the scattering of disk-shaped brands in a 3D turbulent boundary layer, ignoring brand combustion. Unlike other studies, they then fit a probabilistic model to the numerical model results, assuming a lognormal distribution of brand propagation in the downwind direction and a normal distribution in the crosswind direction.

If a brand lands on another building, there is then a chance it lands specifically on something combustible and actually ignites that combustible starting a new fire. Of the many places a brand could land (on the roof, in a pine needle-filled gutter, in an open window), some are more likely to ignite than others. Although it is extremely difficult to predict, the probability it lands inside where much more combustible materials are found may be increased when windows are open or have fallen out due to earthquake damage or nearby fire radiation. The probability of ignition can depend on the type of material it lands on, radiation from a nearby fire, and wind, which can affect convective cooling, move the brand, and provide oxygen to fuel a brand flame (Waterman and Takata 1969). Waterman and Takata (1969), Dowling (1994), Ellis (2000), and Manzello et al. (2006a, b) have conducted experiments to investigate the effect of various parameters on the probability of ignition upon brand deposition. The parameters investigated include brand size, number of brands, brand status (glowing or flaming), air flow velocity, moisture content of fuel bed, and fuel bed type (e.g., pine needles, shredded paper, cedar shingle crevices, mulch and cut grass, roofs, porches, indoor and outdoor fabrics, contents, and splintered wood).

We use empirical data, primarily from Waterman (1969), to estimate the number of brands generated by size, as a function of wind and fire area, and based on Yoshioka et al. (2004), assume they are released only during the fully-developed phase. We use the Himoto and Tanaka (2005) probabilistic model to estimate the transport of each brand due to its ease of implementation. If a brand lands on a neighboring building, an ignition probability is assumed as a function of brand size (based on empirical data from Waterman and Takata 1969 and others).

3. CONCLUSION

This paper introduces a new physics-based post-earthquake fire spread model. It describes the most important modes of fire spread, how each has been modeled in the past, and how it is modeled in the new simulation.

4. ACKNOWLEDGEMENTS

The authors gratefully acknowledge support for this research from the Earthquake Engineering Research Centers Program of the National Science Foundation under award number EEC-9701471.

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