Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 948

COMPARISON OF A NEW PHYSICS-BASED SIMULATION MODEL AND THE HAMADA EQUATIONS IN DETERMINING POST-EARTHQUAKE FIRE SPREAD

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ABSTRACT

This paper describes a comparison of the post-earthquake fire spread model implemented in HAZUS-MH, which is based on the Hamada model, and a new physics-based simulation model recently developed by the last two authors. The empirical Hamada model, the earliest and most widely used post-earthquake fire spread model, assumes buildings have equal-sized, equally-spaced square footprints and that fire spreads in an elliptical shape. It is simple to understand and apply, and produces reasonable estimates of fire spread. The new physics-based simulation model adapts and integrates models from the compartment fire literature to explicitly represent the primary modes of urban fire spread (e.g., branding, radiation from window flames). The models are compared in terms of their approaches, assumptions, and capabilities. We then describe empirical comparisons of the models for small case study areas under a variety of conditions (e.g., wind speeds, building separations, and number of ignitions).

Introduction

Under the right conditions, post-earthquake fires can dominate losses in an earthquake. Fires in the 1995 Kobe, Japan earthquake, for example, caused 500 deaths and damaged 6900 buildings (Chung et al. 1996). Since most cities have little recent historical experience with post-earthquake fires, computer models can be useful to help understand, estimate, reduce, and prepare for post-earthquake fire losses. The last two authors recently introduced a new physics-based post-earthquake fire spread simulation model (Lee and Davidson in press a, b). The model takes as input digitized footprints and other attributes of buildings in the study region. Ignition and wind data are either input by the user or simulated. Adapting and integrating models from the compartment fire literature, the new model explicitly represents the primary modes of urban fire spread (e.g., branding, radiation from window flames). Detailed results, such as percentage of area burned in each building at each time step, and relative frequencies of the modes of spread are calculated, including randomness in the process.

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In this paper, we compare this new model to the Hamada (1951) model which has been at least partially validated, has been widely used for decades, and is the standard of practice. Scawthorn et al. (1981) used a Hamada-based model to hindcast losses for three Japanese earthquakes. Scawthorn (1987) hindcasted losses for five U.S. earthquakes, and also compared the Hamada model against actual U.S. fire spread data. He concluded that the Hamada equations provide an approach that is relatively easy to understand and apply, and that produces “fair agreement” based on hindcasting losses for five U.S. earthquakes (Scawthorn 1987). Scawthorn et al. (2005) reports that “with the exception of spread by branding among wood buildings under high winds, using the Hamada equations agreed well with observation.” More recently, Himoto and Tanaka (2008) and Ohgai et al. (2004) compared their model results to those from the Hamada model as well. After briefly describing the Hamada and new models in turn, we compare the models in terms of their approaches, assumptions, and capabilities. We then describe empirical comparisons of the models for small case study areas under a variety of conditions (e.g., wind speeds, building separations, and number of ignitions).

Hamada Model

The Hamada (1951) model was the first post-earthquake fire spread model and it served as the basis for most subsequent efforts until about 2000 (Lee et al. 2008). Scawthorn et al. (1981) adopted the model, “conservatively using parameters for only a fully-involved fire.” That version of Hamada’s model, reprinted in Scawthorn et al. (2005) and used with a minor modification (see below) as the fire spread model in HAZUS-MH (FEMA 2006), is the version the authors’ new model is compared to. Since the Hamada equations are intended for estimating spread within a city block or built-up district, Scawthorn (1987) combined Hamada with an additional model that estimates the probability a fire spreads across a fire break (e.g., street).

The Hamada model assumes buildings have equal-sized, equally-spaced square footprints and that fire spreads in an elliptical shape (Fig. 1). It provides simple, empirically-based equations that can be used to estimate $K_d(t)$, $K_u(t)$, and $K_s(t)$, the distance a fire spreads in the downwind, upwind, and sideways directions, respectively, as a function of time since ignition. The K values are defined as simple deterministic functions of average building plan dimension a (m), average building separation d (m), unitless built-upness factor δ (a measure of density of

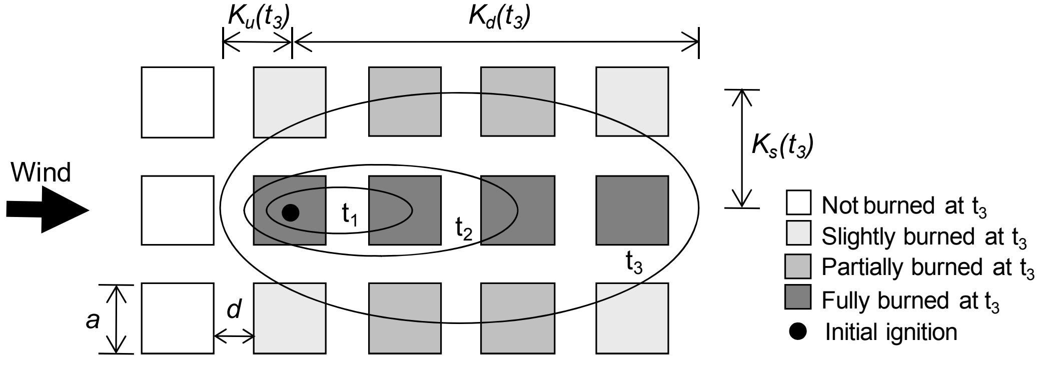

Figure 1. Hamada post-earthquake fire spread model (figure based on Scawthorn et al. 2005)

urban plan), percentage of buildings that are fire-resistant f_b, wind speed w (m/s), and several constants that are given. It is assumed then, that the fire spreads in the elliptical shape defined by those K values (Fig. 1), and that the number of low-rise buildings burned can be estimated using another simple function of the K values, a, and δ (Scawthorn et al. 2005). In the HAZUS-MH version, the K values are modified slightly so that the fire spread rates are equal in all directions as the wind speed approaches zero (FEMA 2006). We use those modified K' values in this analysis. The fire break model is a set of 6 curves showing probability a fire crosses a fire break vs. fire break width (m), one for each of three wind speed intensities (calm, light, and high), with and without suppression (Scawthorn 1987, Scawthorn et al. 2005).

New Model

Lee and Davidson (in press, a, b) describe the new model in detail. Its key features are briefly summarized here. The new model uses real building footprints and heights from remote sensing data so that it accurately captures the areas and relative orientations of buildings. Customized advanced geographic information system algorithms are then applied to estimate reasonable room configurations in each building, which enables direct use of room-based fire spread models from the compartment fire literature.

The model can be run in either a deterministic mode in which the user specifies ignition locations and times or a probabilistic mode in which a new ignition model using negative binomial regression simulates ignitions based on ground motions (Davidson 2009). The wind can also be considered in a deterministic mode in which the user specifies the wind speed and direction over time or in a probabilistic mode that randomly selects a wind time history from historical data for the study area. The model explicitly represents the primary modes of urban fire spread: (1) fire evolution within a room or roof; (2) room-to-room spread through doorways to adjacent rooms, by burnthrough to adjacent rooms or a room or roof above, or by leapfrogging to a room or roof above; (3) building-to-building spread by flame impingement from window flames; radiation from window flames, room gas and roof flame; and branding.

A room-specific temperature-vs.-time curve is used to estimate the evolution of fire within a room (Law and O'Brien 1981). When a burning room has flashed over, the fire in the room is considered to be able to spread to neighboring rooms. Room-to-room spread within a building is modeled probabilistically. The model randomly determines whether a wall has an open door, in which case fire spreads immediately, and estimates a random burnthrough time for each wall and ceiling based on building fire resistant ratings. It determines if leapfrogging occurs based on estimated window flame geometry. When a room has flashed over and a flame is ejected out the window, it may also ignite neighboring buildings by actually contacting the building or emitting radiation. Hot gas ejected out the window also emits radiation which may cause new ignitions. The method of modeling their effects is adapted from Law and O'Brien (1981): (1) estimate window flame geometry and if any rooms are ignited by flame impingement; (2) estimate the configuration factor which represents the fraction of emitted radiation received by neighboring buildings; and (3) check if the radiation received by room exceeds a threshold ignition value. When a roof ignites, a flame develops that behaves differently from a flame ejected from a window. Since there is no model to represent this situation, roof flames are treated as large, open pool fires that emit radiation as well. Configuration factors are introduced to estimate radiation received by neighboring buildings from the roof flame. The model adapts the Mudan (1984) method to capture the effect of roof flame radiations. Fire brands, another important mechanism of building-to-building fire spread in post-earthquake fires, are entrained into the atmosphere and may travel long distances. When they land, they may ignite combustible materials nearby. The model uses empirical data primarily from Waterman (1969) to determine the size and number of brands emitted as a function of wind speed and fire area. The Himoto and Tanaka (2008) probabilistic model is adapted to estimate the transport of each brand. An empirical ignition probability based on Waterman and Takata (1969) and other data is calculated to simulate if a brand ignites the host material when it lands.

Conceptual Comparison

While the models share the goal of estimating the spread of post-earthquake fires in urban areas, they are very different in their approaches (Table 1). The new model explicitly represents each of the primary modes of urban fire spread, using physics- and empirically-based models to simulate the spread of fire room-by-room within a building, and building-to-building within an urban area. The Hamada approach assumes fire spreads in an elliptical shape. One consequence of this difference, for example, is that branding can cause fire to jump in the new model but not

in Hamada. While the Hamada model is deterministic, the new model is probabilistic, including uncertainty in number and locations of ignitions (if run in probabilistic mode), wind speed and direction (if run in probabilistic mode), spread through open doors, time to burn through walls and ceilings, and brand size, propagation, and host ignition. The 2-dimensional Hamada model assumes the urban area is composed of equal-sized, equally-spaced square buildings; the new

Table 1. Conceptual comparison between the new model and the Hamada model.

Category	**New model**	**Hamada model**
Application	• City-sized area	• City-sized area
Modeling approach	• Physics-based simulation • Room-based	• Empirical equations • Building-based
Spread modes	• Several distinct spread modes	• Spreads in an elliptical shape
Randomness	• Probabilistic	• Deterministic
Dimension	• Considers building heights	• Building heights not represented
Required input	• Real building footprints • Building heights • Building fire resistant ratings or occupancy types • Ignition locations and times, or earthquake ground shaking • Wind speed, direction over time	• Equal-sized, equally spaced square buildings • Building fire resistant ratings • Ignition location • Constant wind speed, direction
Output	• Total area burned vs. time • Spatial distribution of spread • Spread modes	• Total area burned vs. time • Spatial distribution of spread
Insights into fire spread	• Can do sensitivity to see how different factors affect spread	• Not available

model uses building footprints and heights from remote sensing data to capture the true shapes, heights, and relative orientations of buildings. Unlike the Hamada model, which requires only a few estimated parameters to describe the square building dimensions and spacing (a, d, and δ), the new model requires this additional building footprint data as input. While Hamada is a quick calculation, the new model requires GIS preprocessing of the building footprints and running the fire spread simulation. Both models provide estimates of the total area burned vs. time and the spatial distribution of fire spread. In addition, the new model results can be disaggregated in many ways to estimate, for example, the relative importance of different modes of spread and the effect of different factors on the speed and location of spread. Finally, the Hamada equations have been partially validated by comparison with historical events (Lee et al. 2008).

Empirical Comparison

The new model and the Hamada model were compared empirically using sample study areas to help determine how well the results compare and under different circumstances. Table 2 summarizes the runs that were conducted and compared. In each case, the new model is run for 50 simulations assuming a minimum room wall length of 5 m, a constant wind from due North, and no fire-resistant buildings. The Hamada model can be divided into two key parts: (1) the assumption about building sizes and configurations and (2) the fire spread equations. Runs 1 to 11 adopt the Hamada assumption about building configurations (study area type A), so for those

Table 2. Summary of runs conducted

Run	**Study area***	**Number of buildings N**	**Average building separation d (m)**	**Average building footprint area, a^2 (m^2)**	**Built-upness factor δ**	**Number of ignitions n**	**Wind speed w (m/s)**
1	A	1763	1	144	0.86	1	3
2	A	1763	1	144	0.86	1	7
3	A	1763	1	144	0.86	1	10
4	A	1763	3	144	0.65	1	3
5	A	1763	3	144	0.65	1	7
6	A	1763	3	144	0.65	1	10
7	A	1763	6	144	0.45	1	3
8	A	1763	6	144	0.45	1	7
9	A	1763	6	144	0.45	1	10
10	A	1763	6	144	0.45	3	7
11	A	1763	6	144	0.45	5	7
12	B	65	--	975	0.63	3	7
13	A	64	9.3	973	0.63	3	7
14	C	107	--	153	0.45	3	7
15	A	110	5.8	151	0.45	3	7

* Study area of type A uses the Hamada assumption of equal-sized, equally spaced square building footprints. Study areas B and C are sample neighborhoods with real building footprints from remote sensing data. B is mostly single-family homes; C is mostly multi-family.

runs, the difference in results is due only to differences in the spread models, not the assumption about building footprint configurations. The results of Runs 12 to 15 suggest the effect of Hamada's building footprint configuration assumption. These two topics are discussed in turn.

Spread Model

Using Run 8 (Table 2) as an example, Fig. 2 compares the total building area burned vs. time for the Hamada and new model analyses. In 14 of the 50 new model simulations, the fire did not spread beyond the building that was initially ignited because, for example, the ceiling burn-through times sampled were relatively long and the window flame was not sufficiently tall, so the roof did not ignite and therefore, brands were not emitted. At the same time, the initial window flame and room gas radiation were insufficient to cause building-to-building spread by flame impingement or radiation. Across all runs, the average percentage of simulations with zero spread was 24%. Since the Hamada model is based on empirical spread data, we assume it does not consider the possibility that a fire will not spread to neighboring buildings at all, so we remove those simulations from the results before comparing them. The mean curve from the remaining 36 simulations is almost the same as the Hamada estimate (Fig. 2).

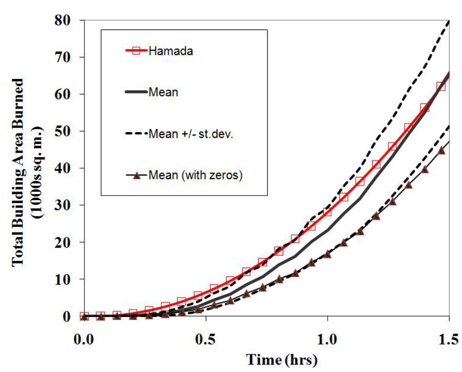

Figure 2. Total building area burned vs. time, for Run 8 with the Hamada model and the new model, mean +/- one standard deviation over only simulations that spread beyond the ignition building and over all 50 simulations.

Fig. 3 compares the spatial distributions of fire spread in Run 8 at 36 and 60 minutes. The ellipse represents the burned area estimated by the Hamada model and the shaded squares indicate the building footprints burned in the new model runs. The shape of the geographic area burned is quite similar for the two models, depending on how one defines the limit of spread in the new model, which includes uncertainty. A couple specific differences are worth noting. First, whereas the Hamada model estimates spread upwind about 30% as far as downwind, in the new model, the possibility of fire spread upwind is small, especially as the wind speed increases. In the new model, the branding propagation model used, based on Himoto and Tanaka (2008), does not allow brands to spread upwind. Further, for w>5 m/s, through draft conditions are assumed, prohibiting spread upwind due to room gas radiation, and window flame radiation, or flame impingement. This difference accounts for at least part of the relative underestimation of the new model vs. Hamada in many runs (see Fig. 5). Second, the Hamada model is two-dimensional. In the new model, the building height is considered as fire spread through each floor and the roof are modeled separately, and there is no mechanism by which fire can spread from the roof and upper floors downward to lower floors. In this example with single-story buildings, if a building's roof ignites, which is by far the predominant mode of new building ignition, the fire will not spread down to the first floor, and as a result only 50% of the total building floor area (first floor plus roof) will burn. To make a more direct comparison with Hamada, Fig. 3 shows the burned area as a percentage of the building footprint area rather than the total building floor area, which would include the first floor plus the roof (i.e., two times the footprint area).

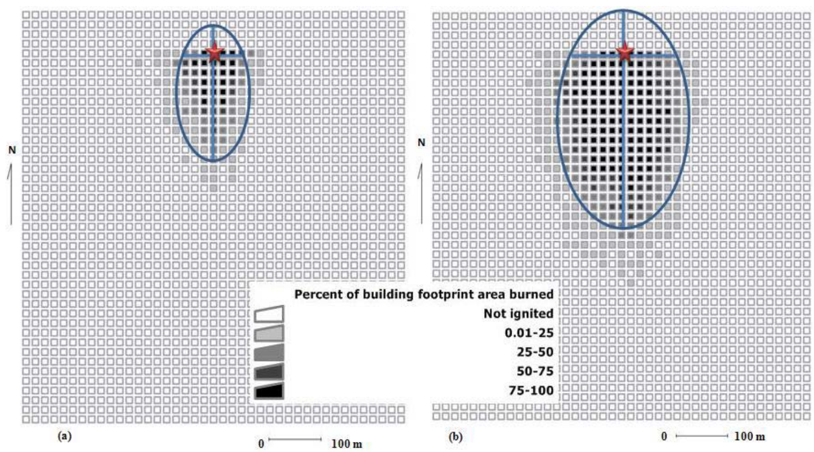

Figure 3. Spatial comparison of Run 8 results of the new model and the Hamada model (ellipses) at (a) 36 and (b) 60 minutes following ignition (star point), averaged over all simulations that spread beyond ignition building

Fig. 4 shows the relative frequency of modes of building-to-building and room-to-room spread for the new model. (Hamada does not offer this disaggregation.) It suggests that for Run 8, building-to-building spread is mostly by branding. An even closer look at the model results shows that for this Run, 93% of the spread to new buildings occurs through ignition of the roof (not a room). This is because, for this uniform study area with 6 m building separations and a 7 m/s wind, both of the modes by which a room in a new building could be ignited—flame impingement and radiation due to room flames and gas—are very unlikely. (Roof flame radiation can ignite rooms in neighboring buildings, but only if the neighboring building is taller, a situation which is does not exist in this example.) Since, as mentioned previously, fire does not spread down from a roof to lower floors, the new model results suggest almost exclusively roof-

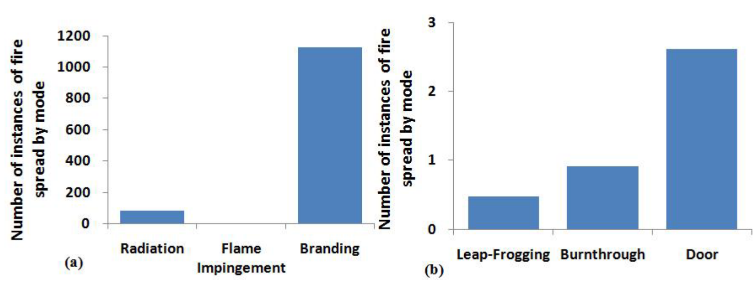

Figure 4. Spread by mode in Run 8: (a) building-to-building spread, (b) room-to-room spread, averaged over all simulations that spread beyond ignition building.

to-roof spread through the region, which is why there are so few instances of room-to-room spread recorded in Fig. 4b. Roof ignition can occur due to branding or roof flame radiation. In part because the model assumes a short time delay for ignition by radiation but not for ignition by branding, branding is the more frequent cause (Fig. 4a).

The previous results are just for one run. The comparison between models varies with study area configuration, wind speed, and number of ignitions. Fig. 5 shows a simple scalar comparison for all the runs, the building footprint area burned at 60 minutes after the earthquake. For all but one of the runs with the simplified Hamada study area (Study area A), the Hamada model estimates exceed the mean estimated by the new model, although in 7 out of 13 runs, it is within about +/- one standard deviation.

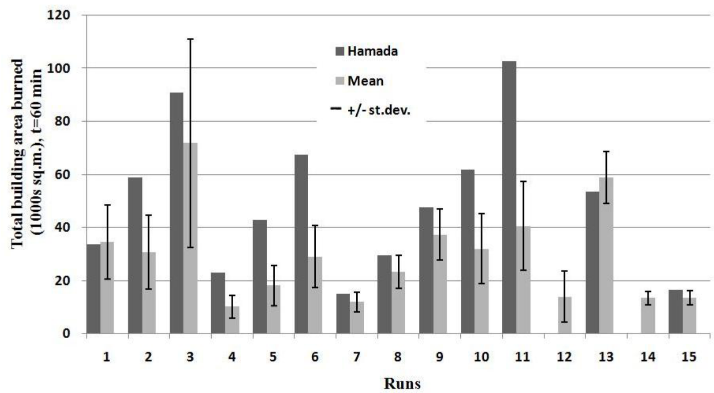

Figure 5. Building area burned at 60 minutes post-earthquake for all runs defined in Table 2. In each case, left column is Hamada model and right shows mean of new model averaged over all simulations that spread beyond ignition building, with errors bars for +/- one standard deviation.

Comparing selected runs, one can examine the effect of wind speed (or building separation or number of ignitions) with all else remaining equal. For example, comparing Runs 8, 10, and 11 suggests that more ignitions lead to more area burned. In general, for both the Hamada and new model results, increasing wind speed, reducing building separations, or increasing the number of ignitions all increase the total area burned, as expected. However, due to sampling variability, the effect of these parameters is not always apparent (or statistically significant) for the new model. Finally, although no strong generalizations are apparent, Fig. 5 suggests that the results of the Hamada and new models may match more closely when there is only one ignition (see Runs 10-11 vs. Run 9).

Building Footprint Assumption

To investigate the Hamada assumption that building footprints are equal-sized, equally spaced squares we obtained remote sensing data of real building footprints for two typical study areas in Los Angeles, one that is mostly multi-family buildings with 1 to 4 stories (Run 12) and one that is mostly one-story single-family homes (Run 14). For each case, we developed a Hamada study area with similar characteristics (Runs 13 and 15, respectively). Specifically, we defined the Hamada areas so they had the same average building area a^2, total number of buildings N, and built-upness δ. Fig. 6 shows the real study area and the Hamada simplification for Runs 12 and 13. The new simulation model was run for the real building footprints and the simplified Hamada footprints, and the ignitions were located in the same configuration, so that the only difference in results is due to the building configuration assumption. Run 12 with the real building areas burned more slowly and ultimately less than Run 13 (Fig. 5) because when fire reached the open areas in Run 12, it typically stopped, whereas there was no such natural fire break in Run 13. The results of Run 14, however, in which the buildings are more similar and evenly distributed, and therefore the assumption is more reasonable, are quite similar to those from its companion, Run 15 (Fig. 5). Spread by radiation was more common in Run 13 than Run 15 because it included buildings of different heights, so roof flame radiation could affect neighboring buildings. Note that N, a^2, δ, and area of the study region are related, and there are multiple ways to estimate their values for a single study area depending on the assumption one makes, and the results can be quite different. For example, one could also reasonably estimate a^2, N, and the average building separation d and calculate built-upness δ from those values. Using that approach for Study Area B (Run 12) results in δ=0.87 (vs. our estimate of 0.63).

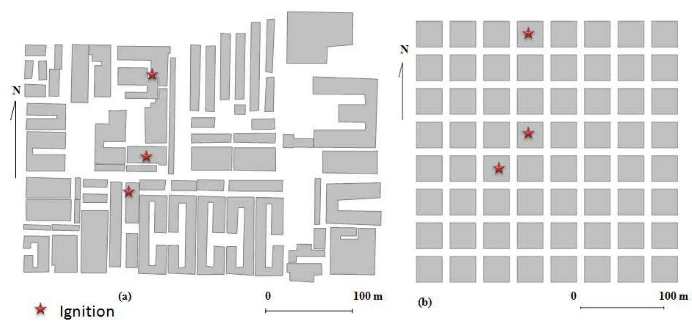

Figure 6. Case study of (a) real building footprints, Run 12, (b) similar Hamada area, Run 13.

Conclusions

The Hamada model, as described in Scawthorn et al. (2005) and applied in HAZUS-MH, was compared, conceptually and empirically, to a new physics-based post-earthquake fire spread model. The comparison depends, to some extent, on how the models are applied and interpreted. For example, the way in which the real building footprints are represented by equal-sized, equally-spaced square building footprints leaves some room for judgment. Since the new model provides a result with uncertainty, the closeness of the comparison also depends on how one considers that uncertainty. Nevertheless, the results suggest that overall the results are reasonably similar in character and magnitude. They estimate similar spread shapes, and similar total burned areas, although the Hamada model tends to predict burned areas on the high side of the range simulated by the new model. A few interesting issues arose from the comparison as well. While only two dimensions are represented explicitly in Hamada, three are in the new model, so the total floor area will be larger than the building footprint area. However, in the new model, fire cannot spread downward from the roof or upper floors to lower floors. In the new model, only limited upwind spread occurs, while in Hamada upwind spread can be considerable. In the new model, the transport of brands can cause fire to jump, while that is not possible in the Hamada model. Finally, the new model suggests that in some cases, the fire will not spread beyond the initial ignition building at all.

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