Fire Following Earthquake—Reviewing the State-of-the-Art of Modeling

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Models for estimating the effects of fire following earthquake (FFE) are reviewed, including comparisons of available ignition and spread/suppression models. While researchers have been modeling FFEs for more than 50 years, there has been a notable burst of research since 2000. In particular, borrowing from other fire modeling fields and taking advantage of improved computational power and data, there is a new trend towards physics-based rather than strictly empirical spread models; and towards employing different simulation techniques, such as cellular automata, rather than assuming fires spread in an elliptical shape. Past achievements include identification of the factors affecting FFE, documentation of historical events, and years of FFE model use by practitioners. Opportunities for future advances include continued development of physics-based spread models; better treatment of slope, water and transportation system functionality, and suppression by fire departments; and more validation and sensitivity analyses.
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INTRODUCTION

Fires often occur following earthquakes, sometimes developing into conflagrations that can be the dominant impact of an event. Fire following earthquake (FFE) can be extremely destructive because there may be many simultaneous ignitions at the same time that damaged water supply systems impair fire suppression capabilities, damaged communication networks hinder coordination, constricted and damaged roads restrict access, passive fire defenses are degraded (e.g., breached firewalls), and fire service personnel are injured or otherwise overwhelmed by the demand for their service. While FFEs were the dominant cause of the single largest earthquake-related losses in the USA and Japan in the twentieth century and a factor in more recent events such as the 1995 Kobe earthquake, in other earthquakes few fires have occurred, with minimal damage. This is due in part to FFE only being a significant concern in seismic regions with large wood building inventories, such as western North America, Japan, and New Zealand, but also simply to the large variability inherent in the FFE process. Despite this large uncertainty, however, and because FFEs are potentially so damaging, it is useful for fire departments, emergency planners, and the insurance industry to have models that esti-

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mate their potential frequency and severity. These models can be used to improve regional earthquake loss estimations and to evaluate possible post-earthquake fire risk reduction efforts.

This paper begins with a summary of earlier work on FFE and then reviews the literature on modeling the three main phases of the FFE process: ignition, spread, and suppression. Sources from five countries—the United States, Japan, China, New Zealand, and Germany—are examined, which is significant because recent work appears to be occurring in parallel, with incomplete communication among researchers. While modeling other types of fires—forest, wildland-urban interface (WUI), compartment/building, and non-earthquake-related urban—can offer many lessons relevant to FFE modeling, due to space limitations, this review only briefly mentions this other work as it relates to past FFE modeling. The following two sections review the literature related to ignition and spread/suppression modeling, respectively. In each case, models are compared according to their approaches, their theoretical and empirical foundations, the factors they consider, and other features. The final section discusses models that integrate ignition and spread/suppression.

To a significant degree, the data used to develop these models reflects differences in the regions for which the models were developed, making comparisons somewhat difficult. Nevertheless, although data differ by region, the statistical analysis and other treatment of that data can cut across regions. Additionally, the physics of fire spread is universal. In this way, comparisons are possible and of value, if differences are accounted for.

HISTORY OF FFE MODELING

Although the 1906 San Francisco and 1923 Tokyo earthquake-caused conflagrations were the impetus for various mitigation actions, including the construction of the world's largest high pressure water supply system in San Francisco, those disasters did not lead to development of analytical models. Urban firebombing was employed as a strategic weapon by both sides during World War 2. It resulted in major conflagrations in Europe (London, Hamburg, Dresden) and Japan (Tokyo, Nagoya, and other cities). These experiences and recognition of the fire setting potential of nuclear weapons led to significant research on urban fire spread during the 1950s and 1960s (Martin 2004). FFE was first addressed by Hamada in Japan soon after the 1948 Fukui earthquake and subsequent major conflagration (U.S. Army 1949). Hamada (1951) developed a set of equations for estimating urban fire spread as a function of fuel load, wind speed, and other factors. Other Japanese researchers carried on this work through to the 1970s (Horiuchi et al. 1974, Mizuno and Horiuchi 1976, Mizuno 1978), both compiling data and developing equations for estimating FFE ignition rates, and using scenario-based models to examine mitigation measures. Concurrently in the U.S., while Steinbrugge (1968) highlighted the FFE problem in the San Francisco Bay Area and collected data (Steinbrugge 1971), no FFE models were developed, although several researchers (e.g., Oppenheim 1984; Robert Reitherman, personal communication) collected data and began examining the problem. In the late 1970s and early 1980s, Scawthorn developed an integrated stochastic model of post-earthquake ignition, spread, and fire department response, which was first applied in Japan (Scawthorn et al. 1981) and then California (Scawthorn 1986). This approach has since formed the basis of insurance industry (Scawthorn 1987, Scawthorn and Khater 1992) and virtually all other modeling of FFE (FEMA 1999, Wellington Lifelines Group 2002). Integrated FFE models are now used by agencies such as the Federal Emergency Management Agency, Tokyo Fire Department, and the Japanese National Research Institute of Fire and Disaster, as well as practitioners and the insurance industry. Starting in the late 1990s, crossover began from the wildland fire field, which had made early and extensive use of GIS and physics-based fire spread models, and there is now a surge in attention to the FFE problem.

IGNITION MODELS

The purpose of an FFE ignition model is to estimate the number, locations, and/or times of ignitions after an earthquake. With the exceptions of Mohammadi et al. (1994) and Williamson and Groner (2000), which use event tree and fault tree approaches, respectively, all available post-earthquake ignition models are essentially regression models relating some measure of ignition frequency, y, to some measure of earthquake intensity, x. The 14 models listed in Table 1 are based on different data sets (Table 2) but generally approach the ignition rate estimation similarly, expressing ignitions per unit building area versus a measure of the intensity (e.g., million sq. ft. of building floor area vs. PGA, Figure 1a, or ignitions per building vs. building collapse ratio (BCR), Figure 1b). Most of the models provide similar estimates in the range of historical data but some have functional relations or other features that are problematic if extrapolated. To illustrate the difference between models, consider an urban area with 350 million sq. ft. of building floor area (i.e., about the size of San Francisco) subjected to a uniform PGA of 0.14 g. In that situation, Scawthorn et al. (2005) estimate the mean number of ignitions as 17.5, while Zhao et al. (2006) would estimate 28.6, clearly a major difference given the nonlinear nature of the FFE problem.

Several authors report an R^2 value to indicate goodness-of-fit (Table 1), but the details of the model fitting and any associated residual analyses are not provided. Since observations were available for the HAZUS and Zhao et al. (2006) models, we examined the residuals and found heteroscedasticity and non-normal behavior (a trait of seismic vulnerability models in general), suggesting a more in-depth exploration of the data is needed.

Most models randomly generate an ignition rate per unit area considering earthquake intensity as the only independent variable, generally at a fairly large degree of aggregation (e.g., section of a city). Ren and Xie (2004), however, also provide a method to estimate the ignition rate in particular buildings within each area unit, based on their relative estimated “fire risk.” Two models also estimate the time at which each post-earthquake ignition occurs. Li et al. (2001) assumes that ignitions follow a Poisson distribution in time as well as space; Zhao et al. (2006) assumes ignition times follow a Weibull distribution.

Sparseness of data and the variety of ignition sources have made it difficult to model the mechanisms of post-earthquake ignitions, with the result that most available ignition

Table 1. Comparison of ignition models: Model formulation

Model (year published)	Reference	Response variable, y	Covariate, x	Equation[a]	R^2	Num. ignitions predicted?; Estimate time to ignition?; Factors included besides x?
Kawasumi (1961)	Kobayashi (1985), Aoki (1990)	Rate of fire outbreaks in wooden buildings (%)	Rate of wooden collapsed buildings	$\ln y = 0.684 \ln x - 5.807$	0.885	n/a; no; none
Mizuno (1978)	Scawthorn et al. (1981)	Probability of fire occurrence per building	Probability of collapse given 5% damped response S_a	$y = 0.00289x^{0.575}$	0.724	n/a; no; none
	Kobayashi (1985)	Rate of fire outbreaks per household (%)	Rate of totally collapsed households (%)	$\ln y = a \ln x + b$ (figure shows linear function on log-log plot but equation not given)	0.769	n/a; no; none
	Aoki (1990)	Rate of fire outbreaks per household (%)	Rate of totally collapsed households (%)	$\ln(-\ln(1-y)) = 0.606 \ln(-\ln(1-x)) - 6.149$	0.882	n/a; no; none
Kobayashi (1984?)	Aoki (1990)	Num. fire outbreaks per 10,000 sq. m.	Building collapse ratio	(v1) $y = 0.00356x + 0.00031$ or (v2) $y = 0.00056 * \ln x + 0.00275$	0.756 or 0.751	n/a; no; none

Table 1. (cont.)

Model (year published)	Reference	Response variable, y	Covariate, x	Equation[a]	R^2	Num. ignitions predicted?; Estimate time to ignition?; Factors included besides x?
Scawthorn (1986)	Scawthorn (1986)	Ignitions per 1000 SFED	MMI	$y = ax + b$ (figure shows linear function, but equation not given)	n/a	Ignitions $\sim$ Poisson process($y(x)$); no; none
Li et al. (1992-2001)	Li et al. (2001)	Incidence of FFE	Area with moderate damage	n/a	n/a	Ignitions $\sim$ Poisson process(y); Time $\sim$ Poisson process; none
HAZUS (1999)	FEMA (1999)	Ignitions per million sq ft of building floor area	PGA	$y = -0.025 + 0.59x - 0.29x^2$	0.34	Ignitions $\sim$ Poisson process($y(x)$); no, but assumes 70% occur immediately after eq; none

Table 1. (cont.)

Model (year published)	Reference	Response variable, *y*	Covariate, *x*	Equation[a]	R^2	Num. ignitions predicted?; Estimate time to ignition?; Factors included besides *x*?
System Earthquake Risk Assessment (SERA) (1995-2003)	Scawthorn et al. (2005); Ostrom (2003)	Num. fire ignitions	n/a	n/a	n/a	n/a; n/a; n/a
TOSHO (1997, 2001)	TFD (1997, 2001)	Fire outbreaks by area (for Tokyo)	n/a	n/a	n/a	n/a; n/a; season, time of day, locations of fire based on presence of electrical equipment, chemicals, hazardous material, & industrial furnaces

Table 1. (cont.)

Model (year published)	Reference	Response variable, y	Covariate, x	Equation[a]	R^2	Num. ignitions predicted?; Estimate time to ignition?; Factors included besides x?
Utilities Regional Assessment of Mitigation Priorities (URAMP) (2002), by Scawthorn	Scawthorn et al. (2005), Seligson et al. (2003)	Num. ignitions per million sq ft	MMI or PGA, and occupancy type	Table 4–10 in Scawthorn et al. (2005) provides y as function of ground shaking and occupancy type	n/a	n/a; no; occupancy type, random placement of postulated ignitions, multiple ignitions to account for uncertainty
Cousins and Smith (2004)	Cousins and Smith (2004)	Mean num. ignitions per million sq m of floor area	MMI	$y=x-8.5$	n/a	Ignition rate (ignitions per million sq m) $\sim$Normal(y, 1); no; no
Ren and Xie (2004)	Ren and Xie (2004)	Fire sites per 100,000 sq m	PGA	$y=-0.11749+1.3453x-0.8476x^2$	n/a	Ignitions $=y$*(total building area); no; gas leaks

Table 1. (cont.)

Model (year published)	Reference	Response variable, y	Covariate, x	Equation[a]	R^2	Num. ignitions predicted?; Estimate time to ignition?; Factors included besides x?
Scawthorn et al. (2005)	Scawthorn et al. (2005)	Ignitions per 1,000 SFED	MMI	$y=0.015x^2-0.185x+0.61$	0.2	Ignitions ~ Poisson process($y(x)$); no; no
		Ignitions per million sq ft of building floor area	PGA	$y=0.028\exp(4.16x)$	0.2	
Zhao et al. (2006)	Zhao et al. (2006)	No. of outbreaks per 100,000 sq m building floor area	PGA	$y=0.0042+0.5985x$	n/a	Ignitions ~ Poisson process($y(x)$); Time ~ Weibull; none

[a] n/a = not applicable

Table 2. Comparison of ignition models: Data

Model (year published)	Range of ground shaking in data[a]	Ignitions considered in data	Country, number, and years of earthquakes included	Num. data points	Geographic analysis unit for data used to fit model
Kawasumi (1961)	n/a	n/a	1 Japanese eq, 1923	n/a	n/a
Mizuno (1978)	n/a	Those not extinguished immediately & that spread to surrounding buildings	12 Japanese eqs, 1923-1974	114	n/a
	n/a	n/a	12 Japanese eqs, 1923-1974	90	n/a
	n/a	n/a	12 Japanese eqs, 1923-1974	90	n/a
Kobayashi (1984?)	n/a	n/a	n/a	n/a	n/a
Scawthorn (1986)	MMI: V-1/2 to X	Those that develop into major structural fires requiring trained fire service personnel and equipment for suppression	10 US eqs, 1906-1984	13	City
Aoki (1990)	n/a	n/a	1 Japanese eq, 1923	n/a	n/a
Li et al. (1992-2001)	n/a	Those within 3 days of eq			n/a
HAZUS	PGA: 0.07 to 0.71, MMI: <VI to X	Only those requiring fire department response	10 US eqs, 1906-1989	30	City

Table 2. (cont.)

Model (year published)	Range of ground shaking in data[a]	Ignitions considered in data	Country, number, and years of earthquakes included	Num. data points	Geographic analysis unit for data used to fit model
SERA (1995-2003)	n/a	n/a	n/a		City
TOSHO (1997, 2001)	n/a	n/a	Causes of fires from previous earthquakes in Japan	n/a	Town, block, or 250 m× 250 m area
URAMP (2002)	*Based on Scawthorn and Khater 1992, but updated to include Northridge and other data*				
Cousins and Smith (2004)	MMI: VI to X-1/2	n/a	US eqs, 1906-1989 from HAZUS97+1931 Hawke's Bay, NZ	31?	n/a
Ren and Xie (2004)	n/a	n/a	China, US, Japan eqs, 1900-1996	n/a	n/a
Scawthorn et al. (2005)	n/a	Arson not included	California eqs, 1971-2005	59	n/a
Zhao et al. (2006)	PGA: 0.07 to 0.8, MMI: <VI to X-1/2	n/a	22 Chinese (5), US (10), Japanese (8) eqs, 20th cen.	65	City (District for ignition predictions)

[a] n/a=not available

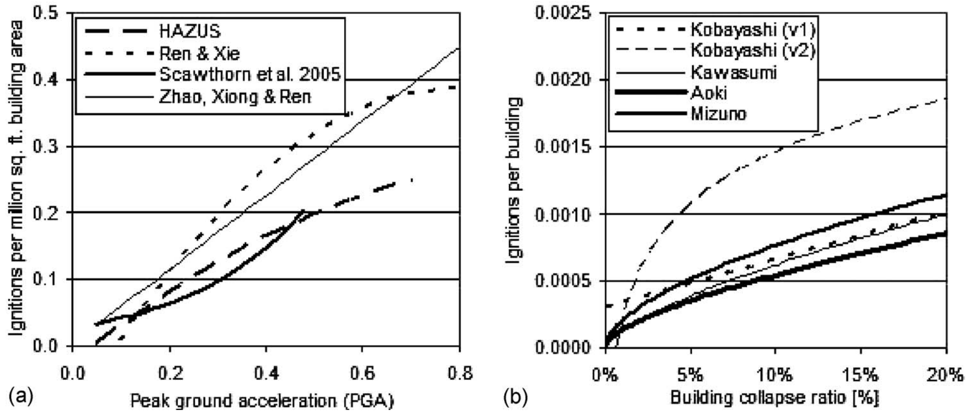

Figure 1. Comparison of (a) those ignition equations presented in terms of ignitions per million square feet of building area vs. PGA and (b) those presented in terms of ignitions per building vs. building collapse ratio. Mizuno is Scawthorn et al. (1981) version.

models are empirical and are only valid for situations representative of the data underlying the model. Table 2 summarizes each model's data although specifics are often lacking. For example, only a few sources specifically define which ignitions are considered (e.g., only those requiring fire department extinguishment or those that occurred within three days of the earthquake). Most sources do not specify the area unit considered or how it was used. If observations represent larger area units (e.g., cities), there will be fewer observations and fewer zero counts than if they represent smaller area units (e.g., neighborhood). Similarly, most sources do not specify how it was decided which cities (or other area units) to include in the data set. For example, was it only those that reported ignitions (therefore ignoring zero counts), or all cities with at least a specified level of ground shaking? What emerges from a review of existing models is that the data include a great deal of uncertainty, only some of which is captured in reported statistics. Errors in measurements of ground motion intensity; inaccurate and incomplete records, especially for older earthquakes; and inconsistencies between data from different earthquakes (e.g., what types of ignitions are included) should be considered when using any ignition model.

SPREAD/SUPPRESSION MODELS

Fire spread models are used to estimate, given the initial ignition locations, the geographic spread or status (e.g., burned or not, percentage burned) for each unit area (e.g., building, grid cell) as a function of time, with or without suppression measures. Available spread models are summarized based on their modeling approach (Table 3); model basis (Table 4); the factors they consider explicitly and suppression components (Table 5); and validation, sensitivity analysis, and application (Table 6). In cases where multiple versions of a model exist (e.g., Scawthorn et al. or Cousins et al.), they are summarized

Table 3. Comparison of spread/suppression models: Modeling approach

Model (year published)	Reference	Output quantity	Fire states[a]	Modeling technique & environment	Unit of analysis	Time step	Given ignitions, uncertainty is due to:
Hamada (1951, 1975)	Scawthorn et al. (2005), Himoto and Tanaka (2008)	Burned area	Fully, partially, barely, and not burned	Elliptical-shaped fire	Equal blocks of equally spaced structures	1 min.	None
Horiuchi (1974)	JAFSE (1984, 1985)			*Based on Hamada*			
Scawthorn et al. (1981)	Scawthorn (1986); Scawthorn et al. (1981, 2005)			*Based on Hamada*			
Murosaki (n/a)	JASFE (1984, 1985)			*Based on Hamada*			
Omori et al. (1990)	Matsuoka et al. (1997); Omori et al. (1990); JAFSE (1985, 1984)	Burnt out area	n/a	n/a	n/a	n/a	n/a
System Earthquake Risk Assessment (SERA) (1995-2003)	Scawthorn et al. (2005); Ostrom (2003)	Probability fire will spread	n/a	Simulation	n/a	1 min	n/a
TOSHO (1997, 2001)	TFD (1997, 2001)	Fire spread speed	n/a	Real-time simulation	Building	n/a	n/a

Table 3. (cont.)

Model (year published)	Reference	Output quantity	Fire states[a]	Modeling technique & environment	Unit of analysis	Time step	Given ignitions, uncertainty is due to:
HAZUS (1997)	FEMA (1999)	No. serious ignitions, total burned area, population and bldg exposure	Fully, partially, barely, and not burned	Simulation, GIS	n/a	user defined	None
Himoto/Tanaka (2000-2006)	Himoto and Tanaka (2000, 2002, 2008); Himoto et al. (in review)	Buildings not burning, burning,or burned at each time step	(Discrete states not defined.)	Simulation based on physical equations	Building	n/a	Spread by branding
URAMP (2002)	Scawthorn et al. (2005), Seligson et al. (2003)			*Based on Scawthorn*			

Table 3. (cont.)

Model (year published)	Reference	Output quantity	Fire states[a]	Modeling technique & environment	Unit of analysis	Time step	Given ignitions, uncertainty is due to:
Cousins et al. (dynamic) (2002-2006)	Cousins et al. (2002, 2003); Thomas et al. (2003, 2006), Heron et al. (2003)	At each time step, (1) state of each cell; (2) num., area, and value of buildings burned	(1) Recently ignited, (2) build-up state, (3) burning at max intensity, (4) burning down, (5) burnt out. Sparking and branding in 3, but not 2 or 4.	Cellular automata, GIS	3 m × 3 m grid cells	2.5 min.	Spread by branding
Cousins et al. (static burn zone) (2002-2006)	Cousins et al. (2002, 2003); Thomas et al. (2003, 2006), Heron et al. (2003), Cousins and Smith (2004)	Num., area, and value of buildings burned at each time step	Burned out or not	Static burn zones based on critical separation, GIS	Building	None	Random reduction in burn zonesize

Table 3. (cont.)

Model (year published)	Reference	Output quantity	Fire states[a]	Modeling technique & environment	Unit of analysis	Time step	Given ignitions, uncertainty is due to:
Iwami et al. (2004)	Iwami et al. (2004)	State of each building at each time step	Not ignited, flame rising only from opening, flame rising from opening & roof, whole building burning, burned out.	Simulation based on simplified physical relationships	Building	1 sec	n/a
Otake et al. (2003)	Otake et al. (2003)	Temperature	Not ignited, flame rising only from opening, flame rising from opening & roof, whole building burning, burned out	Computational fluid dynamics	Building	n/a	n/a

Table 3. (cont.)

Model (year published)	Reference	Output quantity	Fire states[a]	Modeling technique & environment	Unit of analysis	Time step	Given ignitions, uncertainty is due to:
ResQ Firesimulator (2004)	Nussle et al. (2004)	For each building, (1) % initial fuel burned, (2) temp. (3) energy	Discrete states not defined. (Could define based on % initial fuel burned)	Simulation, GIS	Buildings and 5 m × 5 m cells for air	n/a	n/a
Ohgai et al. (2004)	Ohgai et al. (2004)	Probability each cell is in each state	Unburnable, not burning yet, just catching fire but unable to spread, on fire and able to spread, extinguished, extinguished by fire fighting	Cellular automata	3 m × 3 m grid cells	1 min	Probability of spread to neighboring cells
Ren/Xie (2004)	Ren and Xie (2004)	Buildings that are burned	Not burning, burning, or burned out	Huygens' principle, GIS	Building	n/a	n/a

[a] n/a = not available

Table 4. Comparison of spread/suppression models: Modeling basis

Model (year published)	Type	Method to represent evolution of fire within a building[a]	Method to represent fire spread between buildings	Types of spread in physical models
Hamada (1951, 1975)	Empirical	n/a	Speed of spread in up-, down-, & cross-wind directions estimated as functions of wind speed, average building size & separation, % of fireproof buildings	n/a
Horiuchi (1974)			*Based on Hamada*	
Scawthorn et al. (1981)			*Based on Hamada*	
Murosaki (n/a)			*Based on Hamada*	
Omori et al. (1990)	Empirical	n/a	n/a	n/a
SERA (1995–2003)	n/a	n/a	n/a	n/a
TOSHO (1997, 2001)	Empirical	n/a	Speed of spread in wind direction as function of temperature, radiation, building collapse. Fire travels to closest building	n/a
HAZUS (1997)			*Based on Hamada*	
Himoto/Tanaka (2000–2006)	Physical	Zone model. Solve conservation eqs of mass, energy, & chemical species (CS) to get gas temp, density, CS' mass fraction at each time. Chance of adding openings by burn through	Ignite neighboring building if: incident heat flux >critical value (radiation), surface temperature of exterior wooden wall >critical value (convection), or firebrand at high energy state sufficient to ignite combustible lands on it (branding)	Radiation from gas or flame vented from opening, convection from downwind plume, branding
URAMP (2002)			*Based on Scawthorn* et al. (1981)	

Table 4. (cont.)

Model (year published)	Type	Method to represent evolution of fire within a building[a]	Method to represent fire spread between buildings	Types of spread in physical models
Cousins et al. (dynamic) (2002–2006)	Physical-empirical	Assume cell stays in state 2 for 7.5 min., state 3 for 15 min., and state 4 for 12.5 min.	Rules for each type of spread derived from simplified physics and historical experience. Based on distance from burning cells, num. neighboring burning cells, building height, wind direction and speed	Direct contact, radiation w/spontaneous ignition, radiation w/piloted ignition, branding
Cousins et al. (static) (2002–2006)	Empirical	n/a	Assume all buildings in a burn zone burn completely	n/a
Iwami et al. (2004)	Physical	Assumed heat generation vs. time curve for each building type	Ignite neighboring building if: flame touches it or temp $>$593 K. Temp rise of neighbor buildings is function of radiation heat flux from flame & convection.	Flame touch, radiation due to flame, convection
Otake et al. (2003–2004)	Physical	n/a	n/a	Plume, radiation, branding
ResQ Firesimulator (2004)	Physical	Assume specified % of initial fuel is transformed to energy in each time step.	Ignite neighbor. building if has enough fuel & temp. above ignition point. Temp. rise of neighbor buildings incremented due to sum of neighbor buildings' radiation, & temp. exchange with air. Temp. of air cells updated each time step due to air- and building-to-air temp. exchange, and convective heat loss. Wind shifts location of air cells.	Direct heat transport, radiation, convection
Ohgai et al. (2004)	Empirical (simplified)	Assume cell stays in state 3 for 2 min. and state 4 for 8 min.	Probability is function of structural type, wind speed and direction, and ability of burning cell to cause spreading	n/a

Table 4. (cont.)

Model (year published)	Type	Method to represent evolution of fire within a building[a]	Method to represent fire spread between buildings	Types of spread in physical models
Ren/Xie (2004)	Empirical	n/a	Fire prone area if distance between buildings >required fire stop distance. Huygens' principle to model fire spread process.	n/a

[a] n/a=not available

Table 5. Comparison of spread/suppression models: Factors considered and suppression by fire department

	FACTORS CONSIDERED EXPLICITLY[a]													SUPPRESSION BY FIRE DEPT.			
	Individual Buildings					Urban Plan				Environmental					Availability		
Model (year published)	Building categories considered	Damage state	Contents	Plan size/shape	Openings	Building height	Dist. b/t bldgs	Fire breaks	Vegetation	Wind speed & dir.	Air temperature	Slope	Humidity/ Rain	Suppression summary	Water supply	FD equip., crew	Transportation
Hamada (1951, 1975)	Fire-resistant wood., nonfire-resistant wood	N	N	S	N	N	S	N	N	D	N	N	N	None	n/a	n/a	n/a
Horiuchi (1974)													*Based on Hamada*				
Scawthorn et al. (1981)	Wood	N	N	S	N	N	D	S	N	D	N	N	N	Fire personnel response time (w/ transportation & water considerations) and time required to suppress fire approximated	S	S	S
Murosaki (n/a)													*Based on Hamada*				
Omori et al. (1990)	Wood	N	N	N	N	N	N	N	N	S	N	N	N	None	n/a	n/a	n/a
SERA (1995–2003)						Not Applicable								Detailed seismic vulnerability analysis of water supply system	D	U	N
TOSHO (1997, 2001)	97: Wood, fire resistive 01: incl. fire quasi-resistant	S	N	S	N	N	S	S	N	D	N	S	S	Real-time data regarding water level status availability but info not used in model	n/a	n/a	n/a
HAZUS (1997)						*Based on Hamada*											

Table 5. (cont.)

	FACTORS CONSIDERED EXPLICITLY[a]													SUPPRESSION BY FIRE DEPT.			
	Individual Buildings					Urban Plan				Environmental					Availability		
Model (year published)	Building categories considered	Damage state	Contents	Plan size/shape	Openings	Building height	Dist. b/t bldgs	Fire breaks	Vegetation	Wind speed & dir.	Air temperature	Slope	Humidity/ Rain	Suppression summary	Water supply	FD equip., crew	Transportation
Himoto/ Tanaka (2000–2006)	Wood, mortar plastered wood, fire resistant	N	D	D	D	D	D	D	N	D	D	N	N	None	n/a	n/a	n/a
URAMP (2002), by Scawthorn	Construction materials	n/a	N	U	N	N	n/a	n/a	U	U	N	N	N	Uses a water reliability factor between 0 (no water) and 1 (water avail.)	S	U	N
Cousins et al. (dynamic) (2002–2006)	Combustible wall cladding or not, combustible roof cladding or not	N	N	D	S	D	D	D	N	D	N	N	N	Adopted relationship between the number of fires the Fire Service may control and earthquake shaking intensity	N	N	N
Cousins et al. (static burn zone) (2002–2006)	Combustible cladding or not	N	N	D	N	N	D	D	D	N	N	N	N	None. (Except Cousins & Smith 2004 assumes num. fires that can be controlled as function of MMI)	n/a	n/a	n/a
Iwami et al. (2004)	Fireproof, covered wood, uncovered wood	N	D	D	D	D	D	D	N	D	D	N	N	None	n/a	n/a	n/a
Otake et al.(2003–2004)	NA	n/a	n/a	n/a	n/a	n/a	Y	n/a	n/a	Y	Y	n/a	n/a	None	n/a	n/a	n/a

Table 5. (cont.)

	FACTORS CONSIDERED EXPLICITLY[a]													SUPPRESSION BY FIRE DEPT.			
	Individual Buildings					Urban Plan				Environmental					Availability		
Model (year published)	Building categories considered	Damage state	Contents	Plan size/shape	Openings	Building height	Dist. b/t bldgs	Fire breaks	Vegetation	Wind speed & dir.	Air temperature	Slope	Humidity/ Rain	Suppression summary	Water supply	FD equip., crew	Transportation
ResQ Firesimulator (2004)	NA	N	S	D	N	N	D	D	N	D	S	N	N	For each bldg, track amt of water from fire brigades. Check enough water in brigade tank, close to fire, and max. rate of water spraying not exceeded. Water reduces heat energy of bldg.	S	N	N
Ohgai et al. (2004)	Wood, fire prev. wood, fireproof	N	N	D	N	N	D	D	N	S	N	N	N	Based on brigade response time, distance to adequate water source, time to required spray to extinction	S	N	S
Ren/Xie (2004)	Brick & wood; mixed structure; reinforced concrete; other material. Fireproof or not	N	N	D	N	n/a	U	D	N	S	S	N	S	None	n/a	n/a	n/a

[a] N=Not represented explicitly; S=in a Simplified way; D=in a Detailed way; U=Unclear; n/a=not available

Table 6. Comparison of spread/suppression models: Validation, sensitivity analysis, and application

Model (year published)	Validation[a]	Case study application(s)	Sensitivity analysis conducted?	Mitigation alternatives examined?	Used by
Hamada (1951, 1975)	n/a	n/a	n/a	n/a	n/a
Horiuchi (1974)	n/a	n/a	n/a	n/a	n/a
Scawthorn et al. (1981)	Compared estimates to 32 N. American data pts & found results were reasonable and conservative	US: Los Angeles, San Francisco, Vancouver, Seattle, Japan: Osaka	For key parameters	n/a	Insurance industry
Murosaki (n/a)	n/a	n/a	n/a	n/a	n/a
Omori et al. (1990)	Kobe earthquake	n/a	n/a	n/a	n/a
SERA (1995–2003)	Benchmark analysis using 1989 Loma Prieta eq—actual losses well under $1M, simulated losses were $0.3M	4 different earthquake scenarios (Hayward M7, M6, Calaveras M6.75, Concord M6.5)	n/a	water system seismic upgrades (5 ways)	EBMUD, San Diego Water Dept, BART Dist.
TOSHO (1997, 2001)	1923 Kanto & 1995 Kobe eqs, Sakata city fire	n/a	n/a	Yes	Tokyo, Kyoto & Kobe Fire Depts

Table 6. (cont.)

Model (year published)	Validation[a]	Case study application(s)	Sensitivity analysis conducted?	Mitigation alternatives examined?	Used by
HAZUS (1997)	n/a	All cities/states in U.S.	n/a	n/a	Federal Emergency Mgmt Agency
Himoto/Tanaka (2000–2006)	Compared to Hamada in terms of rate of spread for hypothetical urban area with 2,500 identically-configured, 2-story buildings, with 1 ignition	Sanmachi, Takayama, Japan (172 buildings); Sakata, Japan (?); Higashiyama, Kyoto, Japan (7,909 buildings)	No	Reinforcing walls, openings to prevent burn through	n/a
URAMP (2002), by Scawthorn	n/a	n/a	n/a	n/a	California Governor's Office of Emergency Response
Cousins et al. (dynamic) (2002–2006)	Compared to observed for 1931 Napier eq	75,800 buildings in Wellington City, New Zealand with 27 randomly located ignitions	Several key parameters/ assumptions	Qualitative discussion	n/a

Table 6. (cont.)

Model (year published)	Validation[a]	Case study application(s)	Sensitivity analysis conducted?	Mitigation alternatives examined?	Used by
Cousins et al. (static burn zone) (2002–2006)	Compared to observed for 1931 Napier eq	75,800 buildings in Wellington City with 1 to 100 randomly located ignitions; Napier/Hastings; Dunedin; Repeat of 1855 Wairarapa eq	To critical separation and number of ignitions	Qualitative discussion, additional firebreaks	n/a
Iwami et al. (2004)	n/a	239 buildings in unidentified area, 1 assumed ignition	No	Effects of increasing fireproof structures	Building Research Institute
Otake et al. (2003–2004)	n/a	Experimental data, Shirahama in Wakayama-ken (1998 fire)	n/a	n/a	n/a
ResQ Firesimulator (2004)	n/a	Kobe, Foligno, virtual city (733; 1,085; 1,269 buildings, respectively) for 300 time cycles	No	Preemptive extinguishing	n/a

Table 6. (cont.)

Model (year published)	Validation[a]	Case study application(s)	Sensitivity analysis conducted?	Mitigation alternatives examined?	Used by
Ohgai et al. (2004)	Compare to observed and Hamada model in terms of num. cells burned vs. time for Nagata district in Kobe eq	Futagawa district, Japan (400 m × 400 m) with 1 ignition for 180 min.	No	Increasing fireproof structures & firebreaks	Local/ community workshops
Ren/Xie (2004)	n/a	Shantou City, China (245 sq. km., 30,000 buildings)	No	No	n/a

[a] n/a = not available

in a single entry in the tables using the most recent information. If versions were significantly different (e.g., Cousins et al. static vs. dynamic models), then different entries were used.

MODELING APPROACH AND BASIS

Hamada (1951, 1975) provided the earliest post-earthquake fire spread model. It assumes that the built environment is comprised of equally-spaced, equal square urban blocks of buildings, and that fire spreads in an elliptical shape. It provides empirical equations defining the speed of spread in the upwind, downwind, and crosswind directions as functions of wind speed, average building size and separation, built-upness factor, and percentage of buildings that are wood-framed, fire-resistant (i.e., protected wood-framed) and "fireproof" (i.e., noncombustible). Until about 2000, subsequent spread models adapted Hamada's equations but kept the same basic approach and assumptions (Table 3). The Hamada equations provide an approach that is relatively easy to understand and apply, and that produces reasonable (although in some cases under-) estimations of fire spread (Scawthorn 1987). Nevertheless, cities are much less homogeneous than assumed, 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 (Scawthorn et al. 2005).

To address these issues and to take advantage of newly available computational power and data, recent efforts to improve FFE spread models have borrowed from modeling of compartment, forest, and wildland-urban interface (WUI) fires to incorporate different simulation techniques (e.g., cellular automata, agent-based simulation) and employ more directly the physics of fire spread (Tables 3 and 4). Physics-based models recognize the several modes of fire spread—radiation, convection, conduction, flame impingement, and branding—and derive models of each from basic physical laws and empirical data. Thermal radiation is the dominant mode of large-scale fire spread with its influence affecting buildings situated both within a relatively short distance by spontaneous ignition and a greater distance by piloted ignitions. Although less likely to cause fire spread, convection can be important because in combination with wind, it can shift the direction of fire spread (Nussle et al. 2004). Branding can spread fire great distances, doubling the apparent fire spread velocity (Scawthorn 1987). While important differences exist between post-earthquake, compartment, forest, and WUI fires (Table 7), there are lessons that can profitably be transferred among them, and until recently they have not been adequately explored.

The Himoto/Tanaka model treats a post-earthquake fire as a collection of individual compartment fires evolving under the thermal influence of neighboring building fires (Himoto and Tanaka 2008). Their method begins with the zone model approach commonly used for compartment fires. To determine fire evolution within a building, it involves simultaneously solving conservation equations of mass, energy and chemical species (oxygen and gasified fuel) to determine gas temperature, density, and mass fraction of chemical species at each time step. It also accounts for the possibility of burn through by adding openings. Fire spread to a neighboring building is determined to occur: (1) by radiation if the incident heat flux exceeds a critical value, (2) by convection if the surface

Table 7. Comparison of different fire types

Fire type	Ignitions	Fuel type	Scale
Fire following earthquake	Many simultaneous	Buildings that may be damaged and their contents	Regional
Forest	1 to a few	Vegetation	Regional
Compartment/Building	1	Building contents	Room, building
Wildland-urban interface	1	Vegetation and buildings	Regional

temperature of an exterior wooden wall exceeds a critical value, or (3) by branding if a brand at a sufficiently high energy state to ignite a combustible lands on it. The Himoto/Tanaka model requires detailed information about the geometric configuration and material in each building, but relatively few simplifications about the process of fire spread are made.

The Cousins et al. (2002), Iwami et al. (2004), and ResQ Firesimulator models use the physics of fire spread as a basis, but make simplifications in applying it to FFE modeling. The Cousins et al. approach simplifies the evolution of a fire within a building so that the progress from unburned to fully burned depends only on elapsed time (Cousins et al. 2002). Rules of fire spread are developed separately for each type of fire spread (e.g., radiation with piloted ignition, branding) based on simplifications of the physics of those modes and historical experience. For example, piloted ignition is assumed to be possible 7.5 to 22.5 min. after ignition, and to require at least 12.5 kW/m^2 of incident radiation. A table provides the estimated distance sparks can travel in each direction given different wind speeds.

In the Iwami et al. (2004) model, the evolution of fire is similarly based on elapsed time, but state transition times depend on assumed heat generation vs. time curves developed for each building type. The temperature of each building is estimated at each time step based on the estimated heat flux it receives due to radiation from flame and convection. A building is assumed to ignite if a flame touches it or if its temperature exceeds a critical temperature. The ResQ Firesimulator similarly simplifies physical laws to derive rules that address each mode of fire spread separately (Nussle et al. 2004). It has the unique feature of treating each building as a unit of analysis, but then modeling the air as a two-dimensional grid overlain on the buildings. The temperature of each air cell is tracked, and they are allowed to move with respect to the buildings to represent the existence of wind.

Earlier fire spread modeling was at a relatively large scale (e.g., city block, or neighborhood) and assumed that each fire would spread in the shape of an ellipse. More recent efforts are using much smaller scale simulation approaches, mostly borrowing from forest fire modeling (e.g., Muzy et al. 2005). The Cousins et al. (2002) and Ohgai et al.

(2004) models use cellular automata, in which the landscape is divided into equally-sized grid cells, each of which is in one of a few states (e.g., not burnable, burning, fully burned) at each time step. As time is incremented, the cells change state according to rules, which are based on the current states and other attributes (e.g., building density) of the cell and its neighboring cells. The ResQ Firesimulator (Nussle et al. 2004) is implemented in the RobocupRescue simulation environment, a GIS-based modular framework in which each building is considered to be an agent. The Himoto/Tanaka (2008) and Iwami et al. (2004) models represent each room or building as a unit of analysis and simulate fire spread by tracking temperatures and heat fluxes.

Since these more recent models have adopted geographic resolutions much smaller (e.g., building, 3m × 3m cell) than the previous generation of models (typically, city block), the finer resolution requires orders of magnitude more (and more detailed) data, but enables more direct application of physical laws and leads to more detailed results. In any case, the rules developed to model spread are scale-dependent, and more investigation into identifying the optimum modeling scale would be valuable.

Key benefits of the physics-based models are that they are more generally applicable across regions and times; can be used to simulate the effect of specific changes to building configurations, material properties, and location; and are better grounded in theory, so that more accurate estimates of fire spread can be expected. On the other hand, the physics-based approach requires detailed data and intensive computation, challenges currently addressed by making simplifying assumptions in applying the physical laws and representing the built environment. While the use of physics-based FFE spread models is only now emerging, as these models are more fully developed, validated, and applied, and as more data become available and computational power continues to improve, they will likely be more widely used.

FACTORS CONSIDERED

Many factors related to the characteristics of each building, the urban plan, and the environmental conditions over the duration of the fire together determine the way in which post-earthquake fires spread. To the extent that each can be represented explicitly in a spread model, their relative importance can be assessed and variability in the final results can be minimized. Table 5 summarizes the degree to which key factors are explicitly considered in each spread/suppression model. Values of N, S, D, U indicate that the factor is (N) not represented explicitly, is represented in a (S) simplified way, is represented in a (D) detailed way, or is represented but this review's authors are (U) unclear as to how, respectively. For example, while the Hamada model captures the distance between buildings in a simplified manner through the separation distance between blocks and a built-upness factor, the Himoto/Tanaka model uses actual building footprints so that it includes the actual distances between buildings. While almost all models account for the size and shapes of building plans, spaces between buildings, and wind speed and direction, few explicitly include the effect of slope, vegetation, or building damage state.

FIRE SUPPRESSION BY THE FIRE DEPARTMENT

Consideration of fire suppression measures taken by the fire department is vital to a useful FFE model, since it permits investigation of the relative benefits of a more robust water supply, investment in additional fire service assets, or other possible risk reduction efforts. Although much has been qualitatively written about the role of fire fighting activities in the early stages of fire (Sekizawa 1997, 2006), few models have quantitatively represented the effects of suppression explicitly (Table 5). Scawthorn (1987) provided perhaps the most detailed suppression representation, developing probabilities of crossing firebreaks of various widths, with and without fire suppression, based on data from U.S. and non-earthquake urban conflagrations, which were further elaborated by others and are presented in Scawthorn et al. (2005). In Ohgai et al. (2004), a burning cell is a candidate to be extinguished if the assumed time required for a fire brigade to arrive has passed and a water source is within a specified distance. The maximum number of cells a water source can extinguish is determined based on volume of water at the source, nozzle flow, hose range, and time required to extinguish a cell. Once extinguishment is initiated at a cell, it is considered "extinguished by fire fighting" after a specified time has passed. In the ResQ Firesimulator (Nussle et al. 2004), the model tracks the amount of water fire brigades have sprayed on each building. Making sure that the maximum rate of water spraying is not exceeded, water is sprayed on a burning building when the brigade tank has sufficient water and is close enough to the fire.

To varying degrees, existing models represent individual fire resources (e.g., engines, fire boats), location and amount of water available for fire suppression, amount of water needed to suppress a given fire, and time required for fire fighters to arrive at a fire and suppress it, but often in a somewhat idealized manner. For example, simulation modeling in Scawthorn (1987) explicitly included key decision variables (e.g., number of fire engines) but idealized their travel times by using an average speed, rather than explicitly modeling and accounting for transportation disruption due to transportation system and other damage, and post-earthquake congestion. Explicit integration of water supply and transportation system models, to examine impacts of their functionality in a detailed way on FFE has not yet been accomplished. Evaluation of the effectiveness of various mitigation actions, such as more fire engines, backup water supplies, or intumescent paint, is rare in the literature, although these have been examined in practice.

MODEL VALIDATION, SENSITIVITY, AND APPLICATION

The best way to validate FFE models would be to compare their estimates to observations from actual earthquakes. In practice, earthquakes are too few and idiosyncratic to provide a complete basis for validating FFE models. In addition to hindcasting, validation should proceed by: (a) confirming the logic connecting the several modules of an overall model (e.g., ignition, spread), then (b) demonstrating the validity of each module via theory, empirical data, or other approaches. In any case, one can try to establish that a model is reasonable by comparing its results to observed data, other models, or expert opinion (Table 6).

Scawthorn et al. (1981) hindcasted 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. Himoto and Tanaka (2008) and Ohgai et al. (2004) compare their model results to those from the Hamada model. The Ohgai et al. (2004) and Cousins/Thomas (Thomas et al. 2006) models are compared to observed fire spread for the 1995 Kobe, Japan and 1931 Napier, New Zealand earthquakes, respectively. Some of the models have been applied to hypothetical events in specified regions, demonstrating the availability of the required data and output the models provide (Table 6), although the more physics-based models appear to have focused on smaller applications.

Scawthorn et al. (1981) and more so Cousins et al. (2002) have reported the sensitivity of results to various input parameters and model assumptions. Such sensitivity analyses can be useful in estimating the uncertainty associated with model results, and in identifying the most influential parameters to focus on for data collection.

Finally, apart from studies reported by Nussle et al. (2004) and Himoto (personal communication), there has been limited use of models to evaluate the effectiveness of possible risk reduction strategies. Probably the most notable example is the modeling by O'Rourke, Scawthorn, and their colleagues, which demonstrated major vulnerabilities in San Francisco's Auxiliary and Portable Water Supply Systems and was then employed to develop major improvements to those systems (Scawthorn et al. 2006). The same reference documents analyses that led to the design and construction of an entirely new dedicated fire protection system, for Vancouver, B.C. Nussle et al. (2004) examine the effectiveness of preemptively wetting buildings to prevent their ignition, and Himoto (personal communication) reports the effect of reinforcing building walls and openings to prevent burn through. Recently, Toki and collaborators have demonstrated post-earthquake fire vulnerabilities to major cultural treasures in Kyoto, Japan, which has led to current construction of special fire protection systems there (K. Toki, personal communication).

INTEGRATED MODELS

The Scawthorn (1987), SERA, TOSHO (i.e., Tokyo Fire Department), HAZUS, URAMP, Cousins and Smith (2004), and Ren and Xie (2004) models offer ignition and spread/suppression models together in one package. Although they can easily be decoupled, integration of the two model types allows one to estimate fire damage for a specified earthquake (or distribution of ground shaking), so the model can be applied for any hypothetical future earthquake (as in Scawthorn et al. 2005). Such analyses can be useful for planning by fire departments, water supply agencies, city planners, and the insurance industry.

CONCLUDING REMARKS

Fire Following Earthquakes has accounted for the largest single earthquake-related losses in both the U.S. and Japan, and continue to be a source of potentially catastrophic risk. Modeling of FFE began with Hamada more than 50 years ago, and the 1970s and 1980s saw the main factors affecting FFEs identified and many historical and contemporary events increasingly better documented. In the 1980s and 1990s, several integrated

FFE models emerged that have been used by, for example, the Tokyo Fire Department, the Federal Emergency Management Agency, the insurance industry, and practitioners.

Opportunities to improve FFE modeling remain, as reflected in a notable increase in research in the field since about 2000. Data from recent earthquakes is being used to update empirical ignition models, and significant advances are emerging in urban fire spread modeling as researchers adapt ideas from other fire modeling arenas, and take advantage of improved computational power and data availability. The trend is towards spread models based on physical laws, often modified by historical experience, rather than strictly empirical models; and towards models that use different simulation techniques, such as cellular automata. Spread models will likely become more physics-based, making them more generally applicable and scientifically defensible. Important factors not yet included explicitly or needing better modeling are slope, vegetation, and building damage; the effects of suppression efforts by fire departments; and the functionality of water supply and transportation systems. Lastly, more effort should be made to open and verify existing models, and to improve our understanding of them via sensitivity and other analyses.

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REFERENCES

Aoki, Y., 1990. Stochastic theory on outbreaks of fire following earthquake: Theoretical analyses on stochastic spread of fire in urban area, Part 4, *J. Archit. Plann. Environ. Eng.* **412**, 52–60 [in Japanese].

Cousins, W., and Smith, W., 2004. Estimated losses due to post-earthquake fire in three New Zealand cities, in *Proceedings, New Zealand Society of Earthquake Engineering Conference*, paper 28.

Cousins, W., Thomas, G., Llyodd, D., Heron, D., and Mazzoni, S., 2002. *Estimating Risks from Fire Following Earthquake*, Research Report Number 27. New Zealand Fire Service Commission, Wellington. (Also available as a PDF at http://www.fire.org.nz/research/reports/reports/Report_27.htm)

Cousins, W., Thomas, G., Heron, D., Schmid, R., and Lukovic, B., 2003. Modeling the spread of post-earthquake fire, in *Proceedings, Pacific Conference on Earthquake Engineering*, Christchurch, NZ.

Federal Emergency Management Agency (FEMA), 1999. *HAZUS99 Technical Manual*. Developed by the Federal Emergency Management Agency through agreements with the National Institute of Building Sciences. Washington DC, 732 pp.

Hamada, M., 1951. *On Fire Spreading Velocity in Disasters*, Sagami Shobo, Tokyo [in Japanese].

——,1975. *Fire Resistant Construction*, Akira National Corporation [in Japanese].

Heron, D., Thomas, G., Cousins, J., Lukovic, B., and Schmid, R., 2003. *Modelling Fire-spread in and around Urban Centres, Research Report Number 44*, New Zealand Fire Service Commission, Wellington, NZ.

Himoto, K., and Tanaka, T., 2000. A preliminary model for urban fire spread, in *Proceedings, 15th Meeting of the UJNR Panel on Fire Research and Safety*, S. L. Bryner (editor), vol. 2, pp. 309–319.

——, 2002. A physically-based model for urban fire spread, in *Proceedings, 2nd Workshop of US-Japan Cooperative Research for Urban Earthquake Disaster Mitigation*, http://www.drs.dpri.kyoto-u.ac.jp/us-japan/cd-2/TakeyoshiTanaka.pdf

——, 2008. Development and validation of a physics-based urban fire spread model, *Fire Saf. J.* **43**, 477–494.

Himoto, K., Ikuyo, K., Akimoto, Y., Hokugo, A., and Tanaka, T., in review. A model for fire fighting activities of community residents considering physical impacts of fire suppression of water application, *Journal of the Japan Association for Fire Safety and Engineering*.

Horiuchi, S., Kobayashi, M., and Nakai, S., 1974. Study on the Emergency Escape in City Area, *Transactions of the Architectural Institute of Japan* **223**, 45–71 [in Japanese].

Iwami, T., Ohmiya, Y., Hayashi, Y., Kagiya K., Takahashi, W., and Naruse, T. N., 2004. Simulation of city fire, *Fire Science and Technology* **23**, 132–140.

Japan Association for Fire Safety and Engineering (JAFSE), 1984. *Fire Protection Handbook*, New edition, Kyouritsu Shuban Kabushiki Kaisha, Japan [in Japanese].

——, 1985. *Fire Protection Handbook*, 3rd edition, Kyouritsu Shuban Kabushiki Kaisha, Japan [in Japanese].

Kawasumi, H., 1961. *Examination of Earthquake-Fire Damage in Tokyo Metropolis*, Tokyo Fire Department.

Kobayashi, M., 1985. Urban post-earthquake fires in Japan, in *Proceedings, U. S.-Japan Workshop on Urban Earthquake Hazards Reduction*, Earthquake Engineering Research Institute 85-03, Palo Alto, CA, USA, pp. 121–133.

Li, J., Jiang, J., and Li, M., 2001. Hazard analysis system of urban post-earthquake fire based in GIS, *Acta Seismologica Sinica* **14**, 448–455.

Martin, S. B., 2004. Fire setting by nuclear explosion: A revisit and use in nonnuclear applications, *J. Fire Protect. Eng.* **14**, 283–297.

Matsuoka, H., Yasuno, K., Namba, Y., Omori, Y., and Nishitani, T., 1997. Fire Spread Speed and Prediction of the Southern Hyogo Prefecture Earthquake, *Summaries of Technical Papers of Annual Meetings of the Architectural Institute of Japan on Fire Safety, Off-shore Engineering and Architecture and Information Systems Technology*, A-2, 7–8.

Mizuno, H., 1978. On Outbreak of Fires in Earthquakes, Dissertation, Kyoto Univ., Kyoto [in Japanese].

Mizuno, H., and Horiuchi, S., 1976. Study on the prediction about the numbers of the outbreak of fires caused by the earthquakes, *Transactions of the Architectural Institute of Japan* **250**, 81–90 [in Japanese].

Mohammadi, J., Alyasin, S., and Bak, D., 1994. Risk analysis of post-earthquake fires, in *Proceedings, 5th U. S. National Conference on Earthquake Engineering*, vol. 4, Chicago, IL, pp. 679–688.

Muzy, A., Innocenti, E., Aiello, A., Santucci, J-F., and Wainer, G., 2005. Specification of discrete event models for fire spreading, *Simulation* **81**, 103–117.

Nussle, T., Kleiner, A., and Brenner, M., 2004. Approaching urban diasaster reality: The ResQ Firesimulator, www.science. uva.nl/~arnoud/research/roboresc/robocup2004/tdps-Rescue-Simulation-2004/01.PDF

Ohgai, A., Gohnai, Y., Ikaruga, S., Murakami, M., and Watanabe, K., 2004. Cellular Automata Modeling For Fire Spreading As a Tool to Aid Community-Based Planning for Disaster Mitigation in *Recent Advances in Design and Decision Support Systems in Architecture and Urban Planning*, J. Van Leeuwen and H. Timmermans (editors), Dordrecht, Kluwer Academic, pp. 193–209.

Omori, Y., Yasuno, K., and Namba, Y., 1990. Water supply planning for building fire in urban area, *in Proceedings of Japan Society of Civil Engineering* **425**, 145–153 [in Japanese].

Oppenheim, I. J., 1984. Modelling earthquake-induced fire loss, *Proceedings, Eighth World Conference on Earthquake Engineering*, vol. VII, San Francisco, pp. 777–784.

Ostrom, D., 2003. System Earthquake Risk Assessment (SERAII), in *Proceedings, Technical Council on Lifeline Engineering Research*, Long Beach, CA, pp. 587–596.

Otake, H., Huang, H., Ooka, Y., Kato, S., and Hayashi, Y., 2003. Simulation of flames and thermal plume in urban fire under windy condition, in *Proceedings, 17th Japan Society of Fluid Mechanics Symposium*, paper E.2-2 [in Japanese].

Ren, A., and Xie, X., 2004. The simulation of post-earthquake fire-prone area based on GIS. *J. Fire Sci.* **22**, 421–439.

Scawthorn, C., 1986. Simulation modeling of fire following earthquake, in *Proceedings, 3rd National Conference for Earthquake Engineering*, Charleston, SC, pp. 676–685.

——, 1987. *Fire Following Earthquake: Estimates of the Conflagration Risk to Insured Property in Greater Los Angeles and San Francisco*, All-Industry Research Advisory Council Report, Oak Brook, IL.

Scawthorn, C., Eidinger, J., and Schiff, A., 2005. *Fire Following Earthquake*, Technical Council on Lifeline Earthquake Engineering Monograph No 26, American Society of Civil Engineers.

Scawthorn, C., and Khater, M., 1992. *Fire Following Earthquake: Conflagration Potential in the Greater Los Angeles, San Francisco, Seattle and Memphis Areas*, EQE International, prepared for the National Disaster Coalition, San Francisco.

Scawthorn, C., O'Rourke, T., and Blackburn, F., 2006. The 1906 San Francisco earthquake and fire—Enduring lessons for fire protection and water supply, *Earthquake Spectra* **22**, S135–S158.

Scawthorn, C., Yamada, Y., and Iemura, H., 1981. A model for urban post-earthquake fire hazard. *Disasters* **5**, 125–132.

Seligson, H., Ballantyne, D., Huyck, C., Eguchi, R., Buckham, S., and Burtugno, E., 2003. URAMP (Utilities Regional Assessment of Regional Priorities)—A benefit-cost analysis tool for water, wastewater and drainage utilities: Methodology development, in *Proceedings, Technical Council on Lifeline Engineering Research*, Long Beach, CA, pp. 494–503.

Sekizawa, A., 1997. Post-Earthquake Fires and Firefighting Activities in the Early Stage in the 1995 Great Hanshin Earthquake, in *Proceedings, Thirteenth Meeting of the UJNR Panel on Fire Research and Safety*, vol. 2, pp. 289–302.

——, 2006. Simultaneous Post-Earthquake Fires and the Role of Firefighting Activity for Mitigating the Damage, in *Proceedings, The International Symposium on Management System for Disaster Prevention*, Invited Lecture.

Steinbrugge, K., 1968. *Earthquake Hazard in the San Francisco Bay Area: A Continuing Problem in Public Policy*, Institute of Governmental Studies, University of California, Berkeley, 80 pp.

——, 1971. *San Fernando Earthquake, February 9, 1971*, Pacific Fire Rating Bureau.

Thomas, G., Cousins, W., Lloydd, D., Heron, D., and Mazzoni, S., 2003. Post-earthquake fire spread between buildings, estimating the costing extent in Wellington, in *Proceedings, 7th Symposium of Fire Safety Science*, pp. 691–702.

Thomas, G., Schmid, R., Cousins, W., Heron D., and Lukovic, B., 2006. Post-earthquake fire spread between buildings—Correlation with 1931 Napier earthquake, in *Proceedings, New Zealand Society of Earthquake Engineering Conference*.

Tokyo Fire Department (TFD), 1997. *Analysis of the Causes/Spread of the Fires Caused by an Earthquake Directly below Tokyo*, Fire Prevention Deliberation Council Report, Tokyo Fire Department, Tokyo [in Japanese].

——, 2001. *Development and Use of the Method for the Evaluation of Local Preparedness for Earthquake Fires*, Fire Prevention Deliberation Council Report, Tokyo Fire Department, Tokyo [in Japanese].

U. S. Army, 1949. *The Fukui Earthquake, Hokuriku Region, Japan, 28 June 1948*, Office of the Engineer, General Headquarters, Far East Command, U. S. Army.

Wellington Lifelines Group, 2002. *Fire Following Earthquake: Identifying Key Issues for New Zealand*, Report on a Project Undertaken for the New Zealand Fire Service Contestable Research Fund, Wellington, 41 pp. (Also available as PDF at http://www.fire.org.nz/research/reports/reports/Report_38.pdf_)

Williamson, R., and Groner, N., 2000. *Ignition of Fires Following Earthquakes Associated with Natural Gas and Electric Distribution Systems*, Pacific Earthquake Engineering Research Center Report, University of California, Berkeley, CA.

Zhao, S., Xiong, L., and Ren, A., 2006. A spatial-temporal stochastic simulation of fire outbreaks following earthquake based on GIS, *J. Fire Sci.* **24**, 313–339.

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