

A Post-Earthquake Fire Spread Model considering Damage of Building Components due to Seismic Motion and Heating of Fire

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ABSTRACT

A physics-based model for post-earthquake fire spread was developed by modifying the prototype model previously proposed by the authors. In the new model, seismic motion and heating of fire are both considered as the causes of damage upon building components. The damage affects burning behavior of a fire involved building as well as behavior of building-to-building fire spread. For validation of the new model, simulation of fire spread which followed 1995 Kobe earthquake was conducted. Behavior of fire spread obtained by the numerical simulation was compared with the observed data. Reasonable agreement was obtained with regard to the number of burnt buildings.

KEYWORDS: post-earthquake fire, urban fire, fire spread, physics-based model, Kobe city.

NOMENCLATURE LISTING

b	length of cross section (m)	Greek	
f	strength (N/m ²)	σ	stress, force (N)
H	height (m)	θ	residual inclination angle (rad)
L	separation between walls (m)	φ	falling ratio of exterior material (-)
M	moment (Nm)	subscripts	
\dot{q}''	heat flux (kW/m ²)	B	bending
Q''	cumulative heat flux (kJ/m ²)	cr	critical
r	ratio (-)	D	opening
t	time (s)	H	transverse
v	maximum deflection (m)	0	reference
W	load (N)		
x	char depth (m)		
Z	section modulus (m ³)		

INTRODUCTION

Cities in Japan experienced numbers of urban fires involving thousands or even more buildings at a time. The risk of fire spread is especially high in densely-built urban areas where buildings are sited close together. Fire in such area may easily enlarge one from another once started. Despite several efforts implemented for the improvement of vulnerable city structure, substantial extent of the densely-built urban area still remains at risk. The risk became exposed in the 1995 Hyogo-ken Nanbu earthquake disaster. As many as 7,456 buildings were burnt due to fires started from multiple locations following the earthquake.

In order to evaluate the risk of fire spread, several attempts have been made in developing model for fire spread in urban area. Such a model was firstly proposed by Hamada [1], in which the rate of fire spread was formulated empirically as functions of macroscopic parameters of the target environment such as wind speed, representative scale of building, building-to-building separation, etc.. Similar attempt was concurrently made by Horiuchi [2]. His model evaluates the mitigation effect of fire spread by considering the component ratio of several building types. However, these early models were only applicable to homogeneous urban areas where buildings of similar burning property are uniformly aligned. In order to apply them to real urban area, Fujita [3] developed a computational algorithm by incorporating the effect of geometry of individual building and its spatial relations between other buildings. In contrast with the empirical approach adopted by the earlier models, a stochastic model was proposed by Itoigawa et al. [4]. The model explicitly predicts spotting ignition due to firebrand, instead of evaluating factors of building-to-building fire spread collectively. One of the difficulties on the empirical modeling of fire spread to obtain meaningful data for identification of model parameters. To overcome this, Tokyo Fire Department [5], in their research project, developed a formula for the rate of fire spread by using statistical data of ordinary fire incidents in their area of jurisdiction. Most of the existing fire spread models were developed on the empirical basis. While empirical model has advantage of simple computational procedure, its applicability on evaluating fire safety measures is limited since the cause-and-effect relationship of fire spread is black-boxed. Thus, by utilizing engineering technique on simulating fire behavior inside of a building, Himoto et al. [6] developed a physics-based model of fire spread by predicting burning behavior of individual buildings under the thermal influence of adjacent fire involved buildings.

Frequency of urban fire is not necessarily high. Even if a fire may start in densely-built urban area, it is ordinarily prevented from spreading owing to firefighting activity. However, urban fire may take place in one of the following cases, i.e., fire started in strong wind condition and fire started following earthquake. Even though they are equally termed as urban fire, features of fire spread are quite different. In the strong wind condition, burning of individual buildings tend to become intense due to abundant fresh air supply to fire involved buildings. In addition, discontinuous fire spread takes place by spotting of firebrands in the leeward. On the other hand, multiple outbreaks concurrently take place in the fire following earthquake. Some outbreaks enlarge in urban area consisting of structurally damaged buildings. Even though there are differences between fire in strong wind condition and fire following earthquake, most of existing models focused on features of the former. The effect of structural damage due to earthquake was not adequately considered in the existing models despite its measurable influence on the behavior of fire spread.

In this study, a model for post-earthquake fire spread was developed. Among several attempts made in the modeling of urban fire in the past, the new model is unique that it considers the damage of structural members caused both by seismic motion and heating of fire. As for the model validation, fire spread simulation was carried out within the city area of Kobe at the time of Hyogo-ken Nanbu earthquake in 1995. The result was compared with the observed behaviors of fire spread.

OUTLINE OF THE MODEL

Schematic of the new fire spread model is depicted in Fig.1. The model inherits framework of the prototype model previously proposed by the authors [6]. In the model, urban fire is assumed as a group of multiple fire involved buildings. The dynamics of fire spread in urban area is predicted by simulating fire behaviors of individual buildings under the influence of adjacent fire involved buildings. Behavior of fire inside a building is simulated based on the one layer zone model, assuming that occupied space of a floor is the control volume. As for the building-to-building fire spread, thermal radiation by window flame and compartment gas, thermal convection by wind-blown fire plume, and spotting of firebrands are considered as contributing factors.

Model for Burning Behavior of Fire-Involved Building – Two Modes of Combustion

One of the most important features of post-earthquake fire is that it takes place in the urban area with buildings of variety of structural damage levels. Burning behavior of a building will be affected by the structural damage which often reduces its fire resistance performance. Change in burning behavior becomes conspicuous if the interior space of the building vanishes after collapse. Thus, conditions of building in urban area are divided into two groups with respect combustion mode: “(I) building – not collapsed” with maintained interior space; and “(II) building – collapsed” with interior space vanished.

As for the “(I) buildings – not collapsed”, burning behavior is modeled based on the one layer zone concept, in which occupied space of a room inside the building is assumed as the control volume. The rate of heat release which dominates intensity of fire is evaluated based on the relation between the rate of flammable gas release and the rate of oxygen supply through openings. In the present model, burning behavior of “(I) buildings – not collapsed” is calculated following the algorithm adopted in the previous model [6].

As for the “(II) buildings – collapsed”, the one layer zone technique is inapplicable since the interior space which could be assumed as the control volume is vanished. It is more likely that combustibles stored inside the interior room or building components become exposed in sprawling manner after the collapse. Based on the fact that most of buildings in the densely-built urban area are wooden, burning of “(II) buildings – collapsed” is approximated to the burning of wood cribs in open space.

Model for Building-to-Building Fire Spread

Mechanism of fire spread itself is unaffected by the level of structural damage of buildings. Thus, procedure adopted in the prototype model is similarly used in order to simulate building-to-building fire spread [6]. The following are the basic mechanisms which are considered as contributing factors of building-to-building fire spread in the model: thermal radiation heat transfer from fire involved buildings assuming hot gas filled inside interior space and external flame ejected from window as heat sources; elevation of ambient temperature due to wind-blown fire plumes; and spotting of firebrands to the downwind of fire involved buildings.

Under the thermal influence of such phenomena, building-to-building fire spread takes place when either of the following conditions is met: incident heat flux upon combustible exceeds a critical value \dot{q}_{cr}'' ; and firebrands of high energy states fall upon combustibles. Although buildings of different level of structural damage share common causes of fire spread as listed above, burning behavior and associated mechanism of building-to-building heat transfer are inevitably controlled by the mode of combustion.

Structural Damage and Behavior of Fire

Another feature of post-earthquake fire is that structural damage of a building caused by seismic motion may be augmented by heating of fire. This may lead to the change in the behavior of fire itself. Relationships between the factors causing damage and its consequences are described in Fig. 2. If aftershock is neglected, seismic motion is exerted only once. However, heating of fire degrades building members continuously while the building is on fire.

The present model aims to predict fire spread within urban area damaged by earthquake. Thus, level of structural damage due to seismic motion for individual buildings is required as given condition of the simulation. By following one of the conventional manners, level of structural damage for entire building due to seismic motion is grouped into the following five categories [7]: (0) No damage; (1) Minor damage;

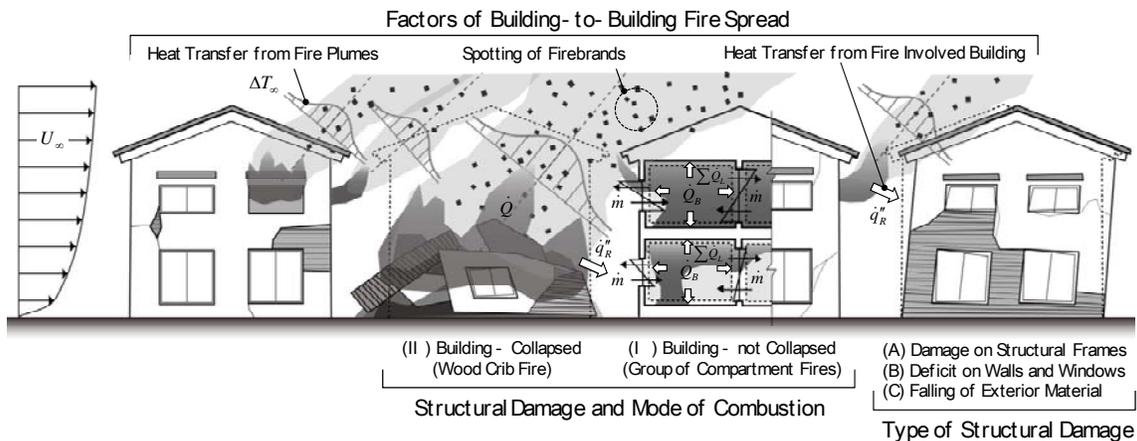


Fig.1. Schematic of the post-earthquake fire spread model.

(2) Moderate damage; (3) Major damage; and (4) Collapse. This classification represents structural soundness of building assessed by external appearance of the building, such as residual deformation of structural frame or unequal settling of groundwork. Thus, impact of the structural damage level upon fire behavior is not evident from this classification. It needs to be interpreted so that it could be reflected on the evaluation of fire behavior.

As mentioned above, computational procedure of fire behavior of a building is selected based on its mode of combustion. Although it is hardly possible to find rigorous equivalency, we defined the relationship between the structural damage level and the mode of combustion as shown in Fig. 3. It is assumed that internal space of a building is still maintained if its structural damage level is less than the rank (3) Major damage, even if it may be deformed to a certain extent. However, since “(I) buildings – not collapsed” covers such wide range of structural damage level, its effect upon fire behavior may not be evaluated properly if the one layer zone modeling is applied to all corresponding buildings indifferently. So, as for “(I) buildings – not collapsed”, structural damage and fire behavior is further associated each other by focusing on the following sectional damages in detail: (A) Damage on structural frames; (B) Deficit on walls and windows; and (C) Falling of exterior material.

Firstly, damage (A) corresponds to the damage by deformation of structural frame due to seismic motion, as well as its thinning by charring. Damage on structural frames leads to collapse of entire building which turns the mode of combustion from “(I) building – not collapsed” into “(II) building – collapsed”. In the present model, the magnitude of the damage due to seismic motion is represented by a parameter termed as ‘residual inclination angle of the column’, θ , and that due to heating of fire is represented by ‘charring depth of the column’, x . Occurrence of building collapse is judged by comparing bearing capacity of the column and size of the loading on it, former of which is dependent upon the two parameters θ and x .

Secondly, damage (B) corresponds to deficit of planar materials such as walls, doors, and windows. Dimension of the deficit is expressed by a parameter termed as ‘deficit ratio’. When the deficit ratio increases, supply of fresh air into fire involved room increases which may intensify combustion inside. The deficit on the planar material may also be a path of radiant heat transfer which allows ignition of combustibles stored inside of the room.

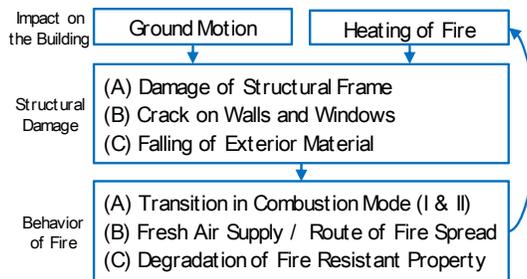


Fig. 2. Effect of structural damage on the behavior of fire.

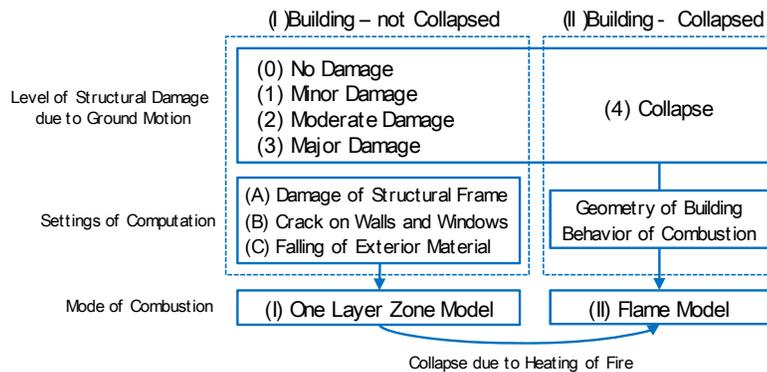


Fig. 3. Level of structural damage and the mode of combustion.

Thirdly, damage (C) corresponds to falling of exterior materials such as mortar plaster or ALC (autoclaved lightweight concrete) panel. Dimension of the damage is termed as ‘falling ratio’, φ . Once the exterior material falls, fire spread may easily take place as unprotected building members become exposed to heating from adjacent fire involved buildings.

Burning behavior of “(II) buildings – collapsed” is approximated to that of wood crib fire, which is determined by geometry of collapsed building including its porosity. Collapse of a building not only changes its mode of combustion, but also changes positional relationship between adjacent buildings which affects magnitude of heat transfer.

STRUCTURAL DAMAGE AND BEHAVIOR OF FIRE

Damage on Structural Frame

Damage level of structural frame is used as the criteria for judging collapse of a building, as well as transition of the mode of combustion from (I) to (II). Given the fact that internal space of a building is maintained by structural frame composed of multiple building members such as columns and beams, the fair approach for evaluating collapse of a building is to calculate transmission of force between these building members. However, in this model, damage of the structural frame is represented by that of a single column for simplicity. In other words, if loading onto the representative column exceeds its bearing capacity, collapse of the entire buildings takes place.

Damage level of structural frame due to seismic motion is represented by ‘residual inclination angle of the column’, θ . Structural damage level of building ranging from (0) No damage to (3) Major damage is empirically associated with the inclination angle θ as shown in Table 1. First, inclination angle θ of each building is given according to the structural damage level of the building due to seismic motion. The damage due to heating of fire following the earthquake is represented by ‘char depth of the column’, x

Table 1. Structural damage and mode of combustion.

Level of structural damage	Residual inclination angle θ (rad)	Mode of combustion
(0) No damage	0	I
(1) Minor damage	1/200	
(2) Moderate damage	1/100	
(3) Major damage	1/30	
(4) Collapse	-	II

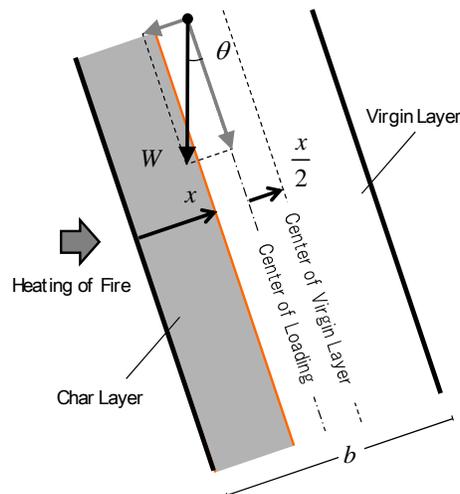


Fig. 4. Bending due to eccentric loading.

assuming that buildings in densely built environment are mostly wooden. Since char layer is fragile and cannot support loading, bearing capacity of the column gradually reduces as the charring progresses. Once the loading exceeds the bearing capacity, failure of the column takes place leading to entire collapse of the building. In the present model, failure of a column is predicted by considering bending of the column by eccentric loading and force in transverse direction of the column as follows,

$$\frac{\sigma_B}{f_B} + \frac{\sigma_H}{f_B} \geq 1 \quad (1)$$

where σ_B and σ_H are the bending stresses due to eccentric loading and transverse force respectively, and f_B is the bending strength of the column. Although behavior of charring is affected by exposure condition of peripheral surface of the column, it is assumed that section of the column is square shaped and that it receives heat only from one side.

If the char depth becomes x after a certain period of heating, loading position deviate from the center by $x/2$ as shown in Fig. 4. Deflection of the column becomes the maximum at the midsection of the column which is given by,

$$v = \frac{x}{2} \cdot \left(\frac{1}{\cos(kH/2)} - 1 \right) \quad (2)$$

where $k = \sqrt{W \cos \theta / EI}$ is the parameter, W is the vertical load, EI is the bending rigidity, H is the height of the column. Since the loading exerted in the longitudinal direction of the column becomes $W \cos \theta$, bending moment M_B is given by,

$$M_B = W \cos \theta \cdot \left(v + \frac{x}{2} \right) = W \cos \theta \cdot \frac{x}{2 \cos(kH/2)} \quad (3)$$

As for the bending in the transverse direction of the column, horizontal displacement of fixed column ends is considered. Magnitude of the moment at the column ends M_H is calculated by using the shear force $W \sin \theta$ as follows,

$$M_H = W \sin \theta \cdot \left(\frac{H}{2} \right) \quad (4)$$

Thus, stresses at the rim of the column σ_B and σ_H due to the moments M_B and M_H are respectively given by,

$$\sigma_B = \frac{M_B}{Z}, \text{ and } \sigma_H = \frac{M_H}{Z} \quad (5)$$

where $Z = b(b-x)^2/6$ is the section modulus, and b is the side length of the cross section.

Deficit of Walls and Windows

In the present model, deficit on the planar material such as walls and windows is assumed as a path through which heat and mass transfer freely occurs. The ratio of the deficit area over surface area of the planar material is termed as 'deficit ratio', which represents the damage level. Since ventilation and radiant heat transfer takes place through the deficit, magnitude of the deficit ratio affects behavior of fire involved building as well as building-to-building fire spread. Deficit of planar material could be produced either by

seismic motion or heating of fire. However, there is little information available as for the damage due to seismic motion. Thus, it is assumed that production and augmentation of deficit is caused predominantly by heating of fire.

Deficit of planar material due to heating of fire can be called as 'burn-through'. Its mechanism is diverse, e.g., degradation or melting of material, deformation at the attached surface of materials due to difference of thermal expansion ratio, etc. It is assumed that such change of condition can be evaluated as a function of cumulative heat flux received from heat sources regardless of its mechanism. In other words, start time for burn-through of a material t_{cr} satisfies following expression,

$$\int_0^{t_{cr}} \dot{q}'' dt = Q_{cr}'' \quad (6)$$

where \dot{q}'' is the incident heat flux, and Q_{cr}'' is the critical value of cumulative heat flux. With this expression, performance of materials against burn-through can be determined by the magnitude of Q_{cr}'' which may change with material type. However, Q_{cr}'' is a physical quantity which is not conveniently associated with the result of some test methods widely used for quantifying fire resistance performance of building members. Thus, the critical amount of cumulative heat flux Q_{cr}'' was transformed into the equivalent burn-through time t_{cr}^* defined as follows,

$$Q_{cr}'' = \int_0^{t_{cr}^*} \dot{q}_{standard}'' dt \quad (7)$$

where $\dot{q}_{standard}''$ is the incident heat flux to the material under the heating of ISO834 standard curve. In other words, fire resistance performance of a material with burn-through time of t_{cr}^* is equivalent to the performance of a material which does not produce any burn-through until t_{cr}^* when the standard heating was applied. Detail of computational procedure for the burn-through is described in the previous report [6]. Generally, position at which burn-through tends to be produced and rate of augmentation varies with material type. However, it is assumed that burn-through starts from the center of the planar material, enlarging to the direction perpendicular to the sides of the planar material at the rate proportional to the incident heat flux.

Falling of Exterior Material

In contrast with deficit, neither heat nor mass transfer takes place through falling part of the planar material. Effect of falling becomes apparent in the decrease of fire resistance performance and the increase of

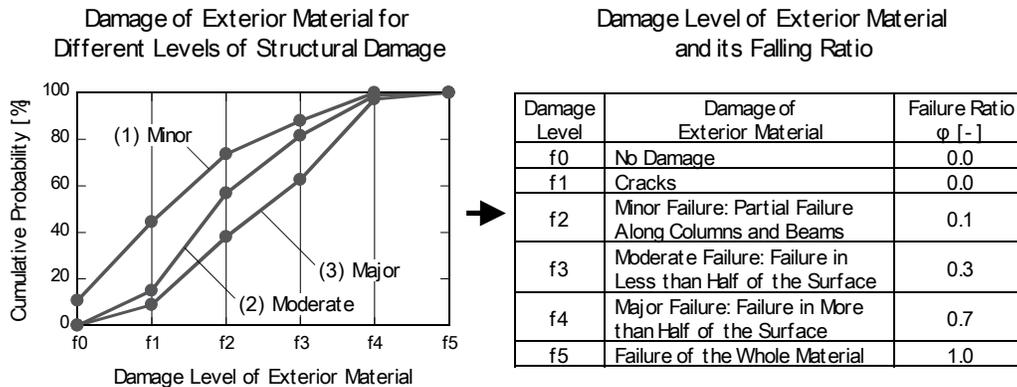


Fig. 5. Damage level of exterior material and falling ratio.

probability of ignition if the structural frame is composed of flammable construction material. Falling ratio φ is defined as the ratio of falling area over the surface area of planar material. With the falling ratio φ , critical amount of cumulative heat flux at which burn-through starts is expressed as follows,

$$Q''_{cr,\varphi} = \varphi \cdot Q''_{cr,A} + (1-\varphi) \cdot Q''_{cr,B} \quad (8)$$

where $Q''_{cr,A}$ and $Q''_{cr,B}$ are the critical amounts of cumulative heat flux for $\varphi = 1$ and $\varphi = 0$, respectively.

As for the evaluation of falling of exterior materials due to seismic motion, results of a survey in the 1995 Hyogo-ken Nanbu earthquake was employed in which damage level of structure (entire building) and that of exterior material (finish material) was associated [8]. Falling ratio φ was evaluated for the buildings which are rated either of the following categories of structural damage: (0) No damage; (1) Minor damage; (2) Moderate damage; and (3) Major damage. Procedure of the evaluation is described in Fig. 5. Since there is variation in the damage level of exterior material even if the structural damage level was in the same category, distribution of cumulative probability for the damage level of exterior wall is provided for respective structural damage level. Damage level of exterior material is grouped into six categories ranging from (f0) to (f5), with values of falling ratio φ taken from the report [8]. Note that falling of exterior material does progress due to heating of fire accompanying decrease in fire resistance performance of the planar material. Such change of condition was not incorporated in the present model explicitly, because the effect is implicitly incorporated within parameters such as critical amount of cumulative heat flux $Q''_{cr,\varphi}$ and the equivalent burn-through time t_{cr}^* .

VALIDATION OF THE MODEL

Hyogo-ken Nanbu earthquake took place at 5:46, 17 January 1995. Substantial damage was brought about to the city of Kobe due to seismic motion as well as fire spread. Number of occurrence of fires within 10 days following the earthquake was as many as 157, among which burnt area of 11 fires exceeded 10,000 m². Occurrence of such large scale fire spreads concentrated within the administrative district of Nagata and Suma wards. Table 2 shows outline of 17 fire spreads which took place in the two wards [9]. As for validation of the proposed model, simulation of fire spread in the two wards was carried out and the obtained results were compared with the observed data.

Simulation Condition

Data on the geometry of buildings in the target urban area was scanned from the city planning map of Kobe issued in 1990. Overall number of scanned buildings was 24,728. According to a long-time conventional classification system in Japan, buildings are grouped into 'general buildings' and 'sturdy buildings'. 'General buildings' mostly consist of buildings of traditional construction types of Japan such as wooden or earthen houses, whereas 'sturdy buildings' are relevant to steel-construction or reinforced concrete buildings. However, since the city planning map only provides peripheral shape of buildings, occupied space of the whole floor was assumed as the control volume of the governing equations of fire behavior.

As for the geometry of openings on exterior walls, ratio of the opening surface area over the wall surface area was given based on the results of field survey [10].

$$r_D = \begin{cases} 0.3(L/L_0) & (L \leq L_0) \\ 0.3 & (L > L_0) \end{cases} \quad (9)$$

where L is the separation between the concerning wall and the corresponding wall at its closest location, L_0 is the reference distance which was assumed as 5 m in this study.

As for the weather condition, record of wind velocity and its direction at the Kobe Marine Observatory was used as shown in Fig. 6. Average wind velocity at the site from 6:00 on 17th through 18:00 on 18th was 3.1 m/s. Although direction of the wind fluctuated from time to time, prevailing direction was from the north-east.

Damage level for individual building due to seismic motion is required as the initial condition of fire spread simulation. However, because damage level for every individual building was unidentifiable, the damage level was randomly distributed according to the proportion investigated for each administrative block [11]. The average proportion within the target urban area was: 20.1 % for (0) No damage; 27.7 % for (1) Minor damage; 20.8 % for Moderate damage; 31.4 % for (3) Major damage and (4) Collapse. Since proportions for (3) Major damage and (4) Collapse was given collectively in the survey report, it was equally divided into two in order to obtain the respective values.

Results and Discussion

Snapshots of simulated results at 5 and 10 h after the first seismic motion are shown in Fig. 7. Fires started from multiple locations rapidly spread to their surroundings engulfing widespread urban area. Buildings are still burning at several fire sites even at 10 h after the seismic motion. Range of damaged area varied substantially at different fire sites. This is attributed to the difference in the city structure of fire site and damage level of component buildings due to seismic motion. Range of eventual burnt area simulated by the

Table 2. Fire spread observed within the target urban area [9].

ID	Ward	Fire spreads	Date of outbreak	No. of bldg. burnt	Floor area of burnt bldg.
1	Nagata	Umegako fire	immediately after shaking (1995/1/17)	10	1,891 m ²
2		Sugahara-dori fire	immediately after shaking (1995/1/17)	751	54,900 m ²
3		Mikura-dori fire	immediately after shaking (1995/1/17)	225	22,397 m ²
4		Kawanishi-dori fire	immediately after shaking (1995/1/17)	11	3,630 m ²
5		Mifune-dori fire	a) immediately after shaking (1995/1/17) b) around 8:00 a.m. (1995/1/17) c) around noon (1995/1/17)	224	1,620 m ²
6		Higashi-Shiri-Ike-cho	immediately after shaking (1995/1/17)	41	3,344 m ²
7		Shin-Nagata-Minami fire	immediately after shaking (1995/1/17)	434	39,570 m ²
8		Wakamatsu-cho fire	a) immediately after shaking (1995/1/17) b) immediately after shaking (1995/1/17)	825	68,850 m ²
9		Nishidai-dori fire	immediately after shaking (1995/1/17)	419	34,407 m ²
10		Kubo-cho fire	around 7:00 a.m. (1995/1/17)	361	35,100 m ²
11		Mizukasa-dori fire	7:00 ~ 9:00 a.m. (1995/1/17)	1,164	106,241 m ²
12		Hiyoshi-cho fire	7:00 ~ 10:00 a.m. (1995/1/17)	52	3,072 m ²
13		Hosoda-cho fire	around 11:00 a.m. (1995/1/17)	5	4,063 m ²
14		Suma	Ohta-cho fire	immediately after shaking (1995/1/17)	7
15	Daikoku-cho fire		immediately after shaking (1995/1/17)	51	4,557 m ²
16	Ebisu-cho fire		6:30 ~ 7:00 a.m. (1995/1/17)	97	7,929 m ²
17	Chitose-cho fire		around 11:00 a.m. (1995/1/18)	3	1,592 m ²

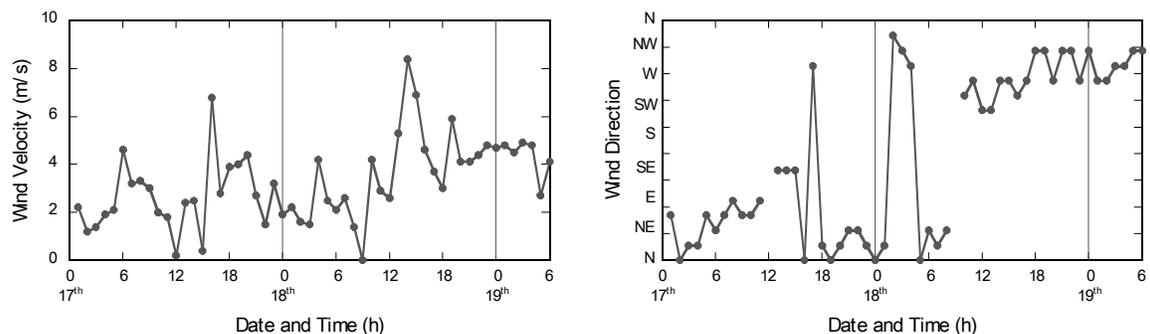


Fig. 6. Wind condition recorded at the Kobe Marine Observatory.

present model is compared with the observed range at the time of 1995 Hyogo-ken Nanbu earthquake in Fig. 8. Agreements between the simulated and observed burnt areas were inconsistent among the 17 fire sites, i.e., reasonable agreements were found for some of the fire sites, but certain discrepancies were also found for the other. However, note that this is the result when level of structural damage due to seismic motion was randomly distributed for individual building. Thus, the results might be changed under different distribution condition.

In order to exclude uncertainty effect of structural damage due to seismic motion, expected number of burnt buildings at each fire sites was evaluated through the Monte Carlo simulation. A total of 1,000 runs were duplicated after which the expected number of burnt buildings converged into a stable value. Obtained numbers of burnt buildings for the 17 fire sites were compared with the record in Fig. 9. Symbols and error bars in Fig. 9 indicate expected value and standard deviation, respectively. Agreements for most of the fire sites are reasonable except for that of Kubo-cho fire at which the number of burnt buildings was overestimated. One of the possible reasons for this is the disregard of firefighting activity in the fire spread simulation. Firefighting activity was conducted in the event of post-earthquake fires in Kobe city. Thus, it would not be unreasonable if number of burnt buildings was overestimated at different fire sites as well.

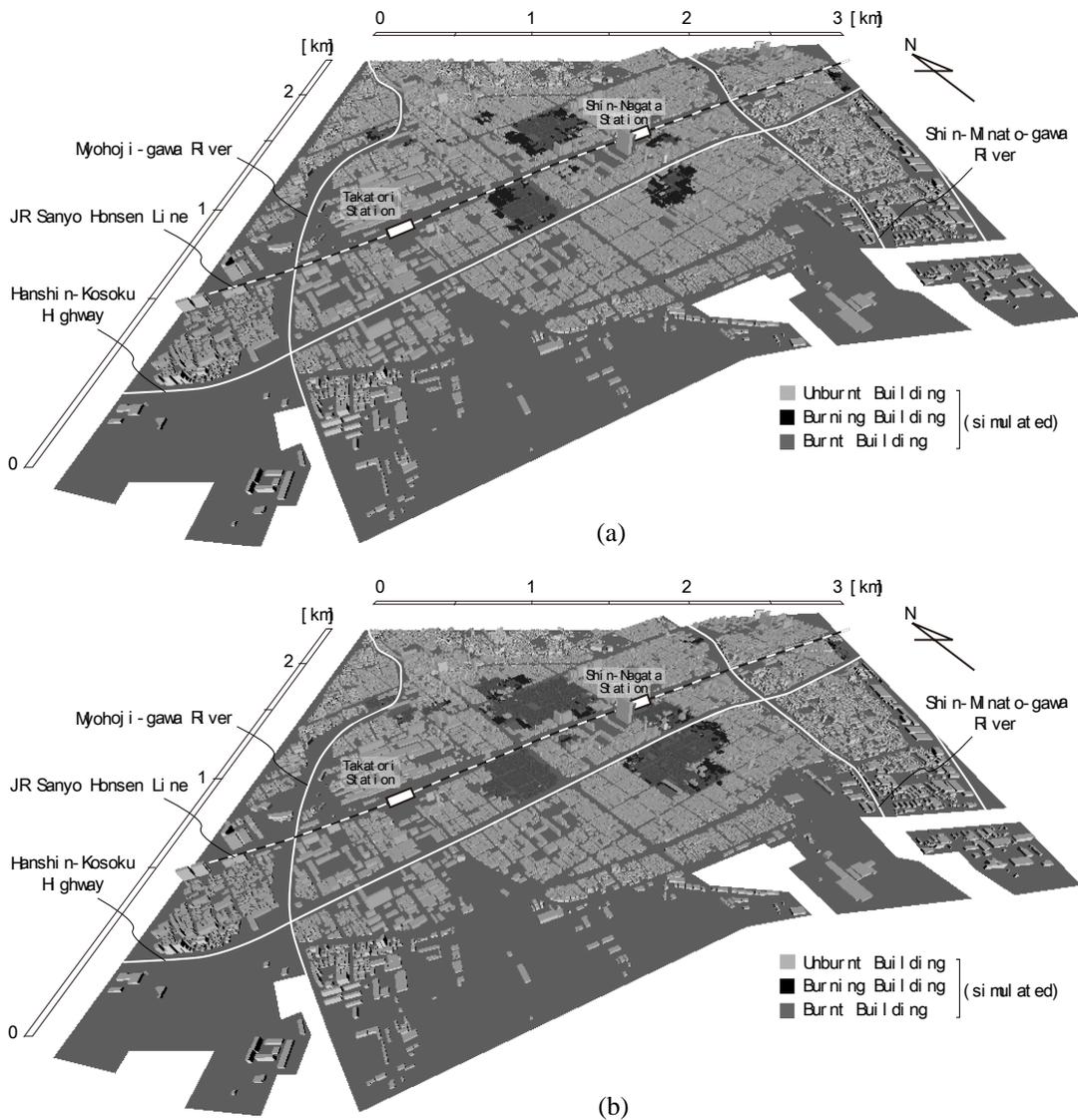


Fig. 7. Result of fire spread simulation – damage level randomly distributed for individual building: (a) 5 h after the first seismic motion; (b) 10 h after the first seismic motion.

However, Kubo-cho fire was the only case at which the damage was overestimated to an outstanding degree. As a matter of fact, firefighting activity was disrupted at most of fire sites due to fracture of water pipes. In addition, since outbreaks of fire took place at multiple locations shortly after the shaking, fire engines and fire pumps were deployed in a dispersed manner. Thus, firefighting activity was not necessarily conducted effectively at all the fire sites [9]. Presumably, discrepancy between the simulated and observed number of burnt buildings among the 17 fire sites implies the difference in effectiveness of firefighting activity. Accordingly, Kubo-cho fire is considered as the case at which fire spread was most effectively controlled by firefighting activity. The damage due to fire spread would have extended further if firefighting activity were not conducted.

CONCLUSIONS

In this paper, a post-earthquake fire spread model was developed considering the structural damage of buildings due to ground motion of the earthquake, as well as its progression due to heating of fire. In the

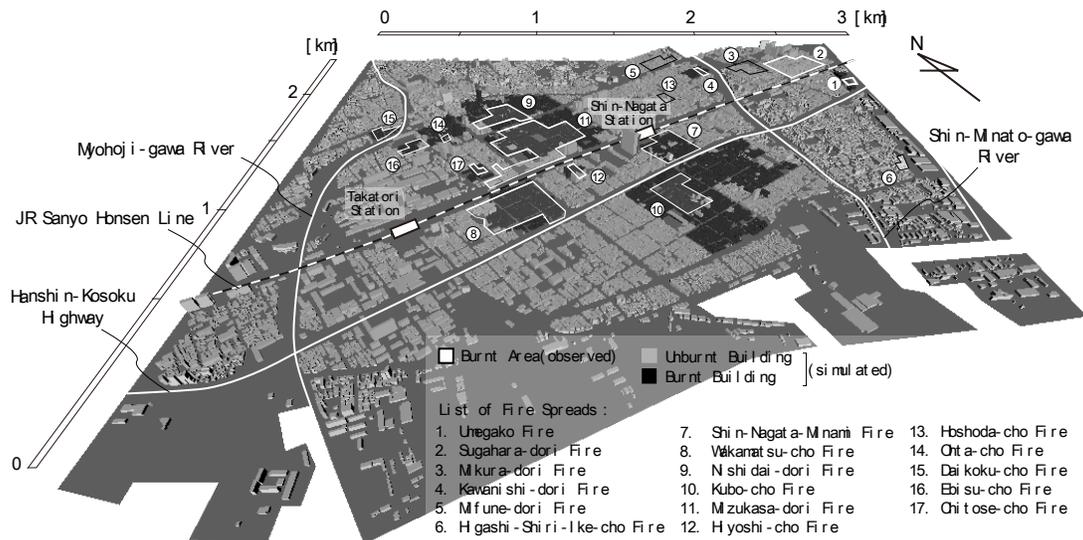


Fig. 8. Ranges of urban area eventually burnt in the fire spread simulation.

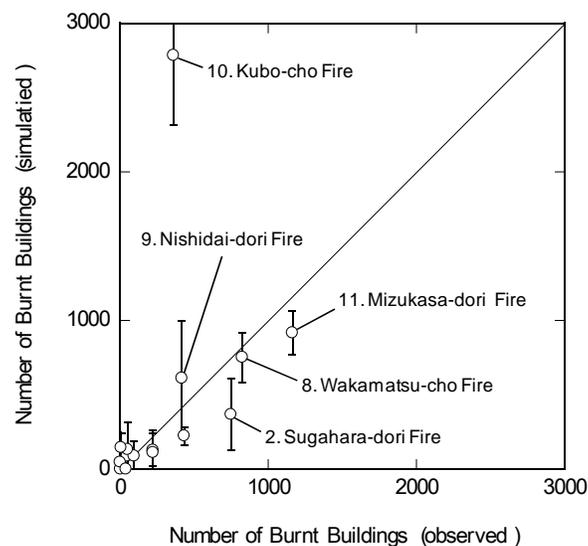


Fig. 9. Comparison of number of burnt buildings at the 17 fire sites.

model, structural damage of a building was grouped into the following types: (A) damage of structural frame such as columns and beams; (B) deficit on planar materials such as walls and openings; and (C) falling of exterior materials. Occurrence and augmentation of the damages and their resulting effect on fire behavior was modeled.

Numerical simulation of fire spread in the city area of Kobe at the time of 1995 Hyogo-ken Nanbu earthquake was carried out for the model validation. The target urban area consists of 24,728 buildings including 17 fire origins which extended to fires involving multiple buildings. Damage level of individual building due to seismic motion was randomly distributed according to the proportion provided by administrative city block. Thus, expected values on the number of burnt buildings in each fire spread were obtained through the Monte Carlo Simulation. The agreement between the observed and simulated data was reasonable except for that of Kubo-cho fire at which the number of burnt buildings was overestimated. The discrepancy could be attributed to the disregard of firefighting activity in the present simulation. Kubo-cho fire is considered as one of the few successful cases that the damage would be substantially extended if there were no firefighting activity.

As the future work, additional validation of the newly developed model will be necessary. Although reasonable agreement was obtained with regard to number of burnt buildings, simulated result still involves uncertainty due to restriction of information of urban area at the time of 1995 Hyogo-ken Nanbu earthquake. Comparison against the result of certain burn experiment conducted under more rigorous set-up condition will be effective. Validation of sub-models about damage of structural frame and deficit on planar materials will be another remaining issue.

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