

Estimating Areas Burned in Post-Earthquake Fires Using Nonflammable Area Ratios

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ABSTRACT

Earthquake fires are serious disasters for urban areas. The nonflammable area ratio can be employed as an index for examining the vulnerability of an urban area to post-earthquake fires and flame propagation. Existing studies show that the burned ratio of an area is extremely close to zero when its nonflammable area ratio is more than 70 percent. That is, the risk of flame propagation in that area is very small. Though the nonflammable area ratio is a useful parameter in assessing post-earthquake fire risk, it is unobtainable without detailed information on land use conditions. Except in some of large cities, the availability of such information is limited. This study develops a convenient method of estimating nonflammable area ratios that does not rely on this information and investigates the validity of this method using a numerical simulation. The numerical experiment shows that the proposed method is accurate enough to assess an area's post-earthquake fire and flame propagation risk.

INTRODUCTION

Large earthquakes that occur near urban areas often result in fires. Post-earthquake fires are one of the most serious urban disasters. The tragedy of the fires that resulted from the 1995 Kobe earthquake is still fresh in our memory. The fires caused by that earthquake resulted in the complete destruction of 6,982 buildings and the partial destruction of 388 buildings. The fires also accounted for 559 fatalities, almost 10 percent of the total number [1]. The fire destruction was localized in the densely populated residential areas of the city of Kobe, which had high concentrations of wooden houses. To reduce urban disasters, it is important to assess the post-earthquake fire risk.

The nonflammable area ratio can be used to assess urban vulnerability to post-earthquake fires and flame propagation. Previous studies show that the burned ratio of an area is extremely close to zero when its nonflammable area ratio is more than 70 percent. In other words, the risk of the flame propagation in such an area is very small.

Though the nonflammable area ratio is a significant parameter for assessing post-earthquake fire risk, it is not easy to obtain without detailed information on land use conditions. However, except in some large cities, the availability of such information is limited. This study develops a convenient method of estimating nonflammable area ratios without detailed land use information. A numerical simulation is then performed to investigate the validity of the proposed method.

RELATIONSHIP BETWEEN FIRE DISASTERS IN URBAN AREAS AND THE NONFLAMMABLE AREA

Nonflammability of Urban Area

The nonflammable area ratio is defined as follows;

$$\begin{aligned} (\text{Nonflammable Area Ratio}) &= \frac{(\text{Square Measure of Nonflammable Area})}{(\text{Total Square Measure of Area})} & (1) \\ (\text{Square Measure of Nonflammable Area}) &= (\text{Square Measure of Blank Space}) \\ &+ (\text{Building Area of Fire Protected Buildings}) \end{aligned}$$

Though the nonflammable area ratios of neighborhoods developed based on proper urban planning strategies are large, those of haphazardly structured and congested residential areas are small. The balanced development of greenbelts and wide streets is an effective way to increase the nonflammable area ratio. According to a previous study [2], the burned ratio of an area is extremely close to zero when its nonflammable area ratio is more than 70 percent. The relationship between the burned ratio and nonflammable area ratio is shown in Fig. 1 [2].

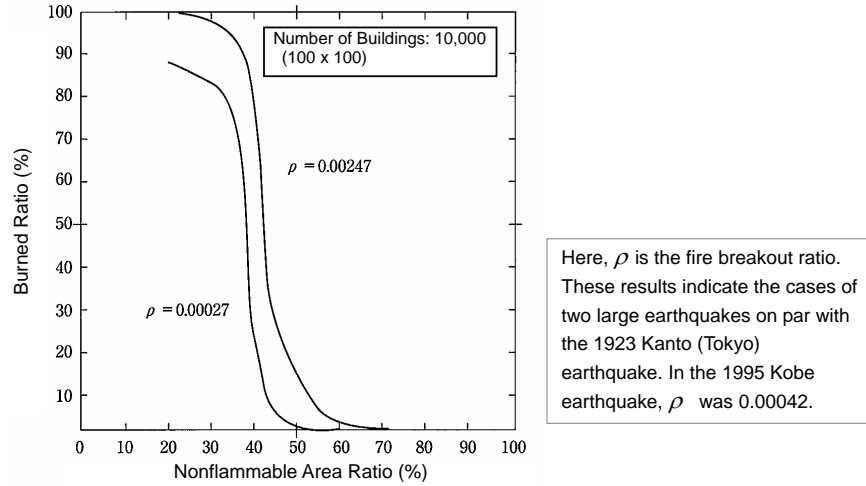


Fig.1 Relationship Between Burned Ratio and Nonflammable Area Ratio [2]

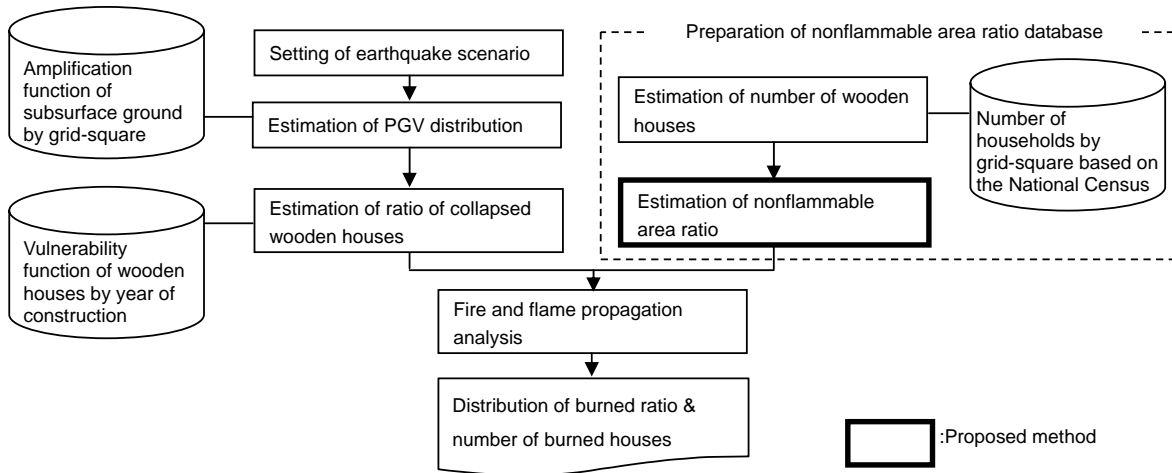


Fig. 2 Flow of Analysis

METHODOLOGY OF EARTHQUAKE FIRE SIMULATIONS IN URBAN AREAS

Flow of Numerical Simulation

The seismic microzoning method is generally employed to assess the vulnerability of urban areas. Grid-squares with sides of 250-500 meters in length are ordinarily used for conducting post-earthquake fire assessments. Fig. 2 shows the flow of analysis of post-earthquake fire and flame propagation. In this figure, the thick-bordered rectangle indicates the method proposed in this study.

Usually, the nonflammable area ratio of an area is obtained from an examination of detailed land use information. However, such information is not always readily available. In this study, the author proposes a convenient method of estimating the nonflammable area ratio from the number of wooden houses. Though this is a simple formula, it has enough accuracy to facilitate an assessment of post-earthquake fire risk.

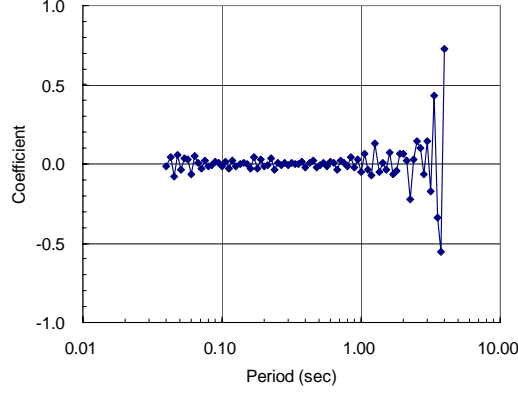


Fig. 3 Regression Coefficients of PGV Estimation

Estimation of PGV

Kurita et al. [3] proposed an estimation method of the JMA (Japan Meteorological Agency) instrumental seismic intensity using a regression formula with acceleration response spectra. In this study, the author applies this method to estimate the PGV distribution. The regression formula is shown in Eq. (2):

$$PGV = a_1 \cdot S_a(T_1) + a_2 \cdot S_a(T_2) + \dots + a_{81} \cdot S_a(T_{81}) \quad (2)$$

where, $S_a(T_i)$: acceleration response spectrum (damping ratio = 5%) of ground surface, T_i : period (s), PGV : peak ground velocity (cm/s), and a_i , ($i = 1, 2, \dots, 81$): coefficients of regression. A multiple regression analysis is performed to determine the coefficients using the 315 strong ground motion records observed in Japan and the USA. Fig. 3 shows the regression coefficients of Eq. (2).

Acceleration response spectra in Eq. (2) are obtained from Eq. (3).

$$S_a(T_i) = F[A(T_i), A_{\max}^{Base Layer}] \quad (3)$$

where, F : amplification function of subsurface ground, $A(T_i)$: acceleration response spectrum of base layer ($V_s \geq 300$ m/s), and $A_{\max}^{Base Layer}$: peak acceleration at base layer ($V_s \geq 300$ m/s). Here, the nonlinearity of shear modulus and damping ratio based on the stress-strain relation of each soil type is considered in the amplification function. A database of the amplification function of subsurface ground in the Tokyo metropolitan area has already been prepared [4].

$A(T_i)$ is provided from the attenuation relation of acceleration response spectrum. Eq. (4) shows the attenuation relation of acceleration response spectrum proposed by Annaka and Nozawa [5].

$$\begin{aligned} \log A(T) &= Cm(T) \cdot M_J + Ch(T) \cdot H + Cd(T) \cdot \log D + Co(T) \\ D &= R + 0.35 \exp(0.65M_J) \end{aligned} \quad (4)$$

where, T : period (s), $A(T)$: acceleration response spectrum of base layer ($V_s \geq 300$ m/s), M_J : magnitude of earthquake on JMA scale, H : depth of center of fault (km), R : shortest distance from fault (km), and $\{ Cm(T), Ch(T), Cd(T), Co(T) \}$: regression coefficients.

Vulnerability Function of Wooden Houses

Miyakoshi et al. [6] proposed the vulnerability function of wooden houses as follows:

$$P = \Phi \left[\frac{\ln PGV - \lambda}{\xi} \right] \quad (5)$$

Table 1. Parameters of the Vulnerability Function [6]

Year of construction	λ	ξ
- 1950	4.22	0.558
1951 - 1960	4.38	0.445
1961 - 1970	4.32	0.467
1971 - 1980	4.67	0.462
1981 -	5.12	0.552

where, P : damage ratio of wooden house, Φ : standard normal distribution function, PGV : peak ground velocity, and λ, ξ : coefficients. The coefficients in Eq. (5) are listed in Table 1. They were obtained from a regression analysis using the damage data from the 1995 Kobe earthquake ($M_J7.3$). The Japanese building code was revised in 1971 and 1981 to enhance structural performance. Thus, the year of construction has a significant effect on the damage estimation of wooden houses.

Fire and Flame Propagation Analysis

An existing methodology, which was used to conduct a post-earthquake fire analysis in Kanagawa Prefecture [7], was employed for the fire and flame propagation analysis performed in this study. The fire and flame propagation analysis is performed by examining the spread of fire between grid-squares on the ground. The rules of flame propagation between grid-squares are as follows: (1) Fire spreads to adjacent grid-squares whose nonflammable area ratios are less than 50 percent. (2) Fires automatically die down in grid-squares whose nonflammable area ratios are more than 70 percent. An image of the algorithm is shown in Fig. 4. The relationships between burned ratios and nonflammable area ratios are shown in Table 2. In Fig. 4, the target area is divided into nine micro-zones with different nonflammable area ratios. A fire breaks out in the center grid. At time step i , the flame propagation extends to the right as a solid arrow, since this is the only adjacent grid-square with a nonflammable area ratio of less than 50 percent. At the next time step, $i+1$, the fire spreads to the grid-square below that, following the arrow. The same process is repeated until flame propagation convergence is reached.

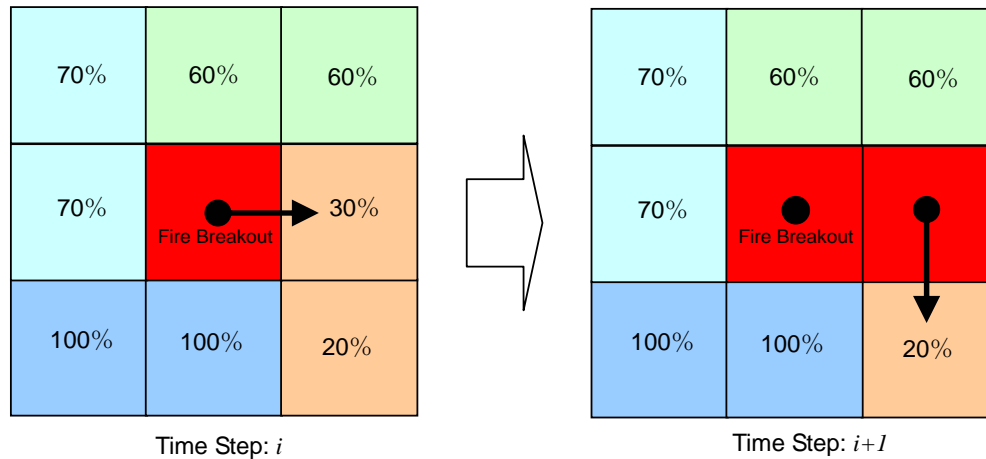


Fig. 4 Image of Flame Propagation

Table 2. Burned Ratio Within Grid-Square

Nonflammable Area Ratio	Burned Ratio
60% - 70%	25%
50% - 60%	50%
- 50%	100%

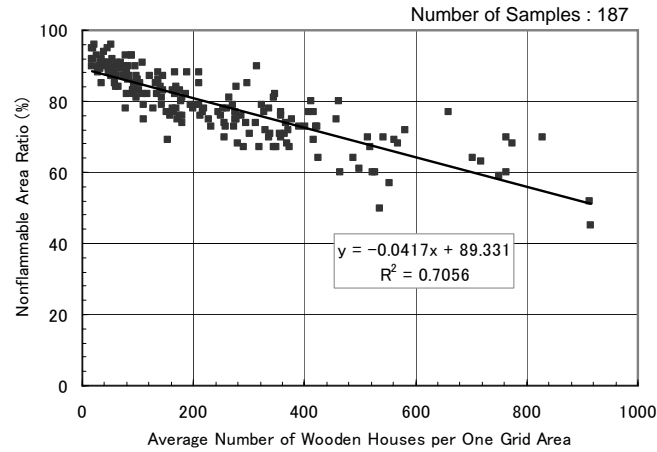


Fig. 5 Relationship Between Nonflammable Area Ratio and Average Number of Wooden Houses

The number of burned wooden houses in each grid-square can be obtained from following equation.

$$\begin{aligned} (\text{Number of Burned Wooden Houses}) = & (\text{Number of Wooden Houses Within Grid} - \text{Square}) \\ & \times (\text{Burned Ratio Within Grid} - \text{Square}) \end{aligned} \quad (6)$$

ESTIMATION OF NONFLAMMABLE AREA RATIOS

Relationship Between the Number of Wooden Houses and the Nonflammable Area Ratio

In general, the nonflammable area ratios of densely populated residential areas are small, while those of fire break areas are large. This study investigates the relationship between the nonflammable area ratios obtained from detailed land use information and the number of wooden houses in a given area.

Fig. 5 shows that there is a linear relationship between the nonflammable area ratio and the number of wooden houses in a given area. Both x - and y -axis datasets are comprised of municipalities in Tokyo, Kanagawa, Chiba and Saitama prefectures (total of 187 municipalities). The average numbers of wooden houses per grid-square (with sides of about 500 meters long) are used, since the square measures of municipalities differ from one another. “The 1998 Digital Data of Statistical Survey on Houses and Land” provided by the Statistical Information Institute for Consulting and Analysis in Tokyo provides the number of wooden houses by municipality. “The 1996 Detailed Numerical Information: Land Use Information by 10m Grid-Size” provided by the Japan Map Center provides land use information. Fig. 5 shows a negative correlation between the number of wooden houses and the nonflammable area ratio. The regression formula is obtained as follows:

$$y = -0.0417x + 89.331 \quad (7)$$

where, y is the nonflammable area ratio and x indicates the average number of wooden houses per grid-square. The regression formula is highly consistent with the original data since the contribution ratio (R^2) is large.

Validation of Estimation

To verify the validity of the proposed method, nonflammable area ratios by grid (with sides of about 500 meters long) in the Tokyo metropolitan area are estimated. Because the number of wooden houses in each grid is unknown, the author employed the method of estimation proposed by Hasegawa and Midorikawa [8], which uses the number of

households by grid-square provided by the National Census. A comparison of the estimated values and the exact values are shown in Fig. 6 in the form of a ratio. In this figure, the exact values are obtained from the above mentioned data from the “Land Use Information by 10m Grid-Size.” Since the geometric average is 0.95 and the logarithmic standard deviation is 0.07, the accuracy of the estimated values is high. The relationship in the figure suggests the following tendencies. The estimated values are large compared to the exact values in zones with small nonflammable area ratios, while the opposite tendency is observed in zones where those ratios are large. However, an estimation accuracy of around 50 percent in the nonflammable area ratio is important for the fire and flame propagation analysis. Consequently, estimation differences are small enough to provide an approximate analysis of post-earthquake fire and flame propagation.

Fig. 7 compares the exact and estimated distribution of nonflammable area ratios. Both distribution maps show a considerable level of consistency. Notably, both maps show the most widespread, highest risk area to be located in the western part of central Tokyo. The striped high risk areas in the northern part of the metropolitan area are also represented in the estimated result.

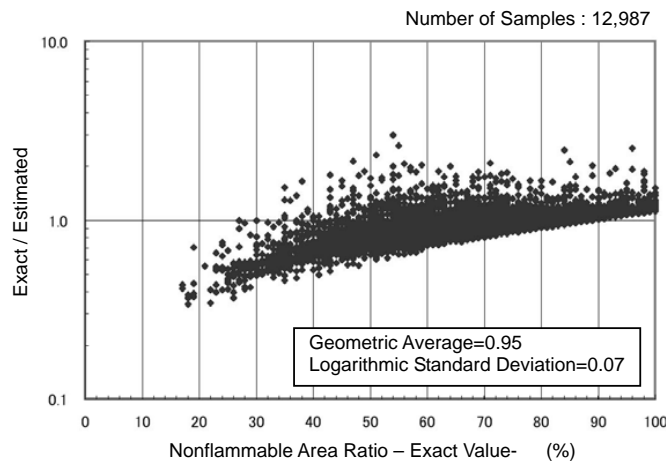
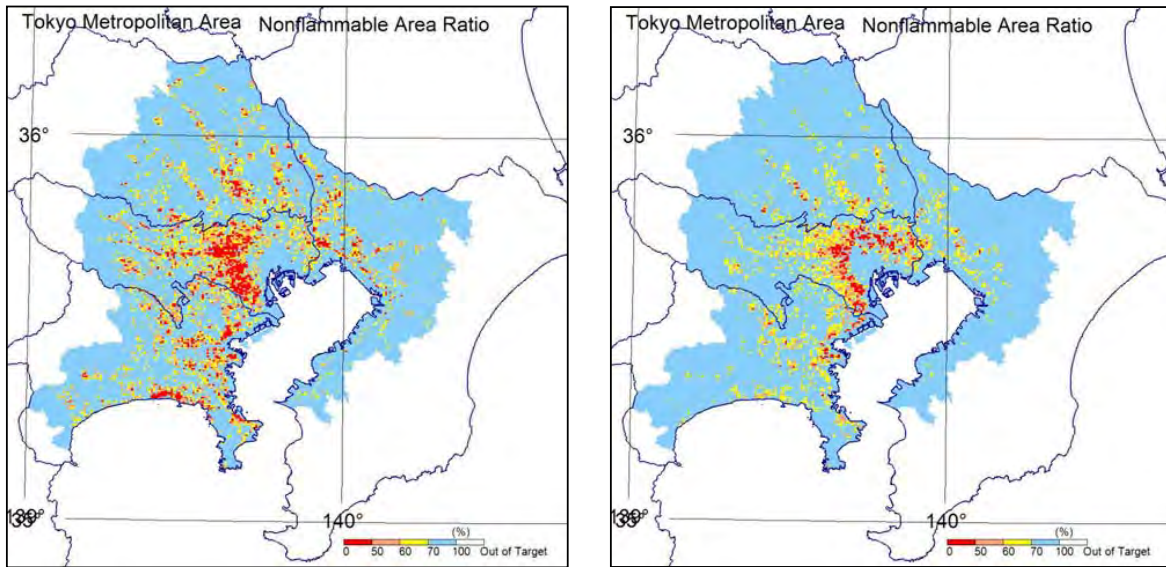


Fig.6 Accuracy of the Estimation of the Nonflammable Area Ratio (Exact Values / Estimated Values)



(1) Exact Value (2) Estimated Value

Fig. 7 Comparison of Exact and Estimated Nonflammable Area Ratios

NUMERICAL SIMULATION OF FIRE AND FLAME PROPAGATION

The numerical simulation of fire and flame propagation is performed using the estimated nonflammable area ratios derived above. The target area is the Tokyo metropolitan area. The hypothetical earthquake is a strong inland earthquake in central Tokyo (M_J7.2). Fig. 8 shows the distributions of PGV and housing damage. Strong ground motion and heavy building damage areas are localized in the western coastal belt of Tokyo Bay. The simulated results of collapsed wooden housing are employed for the fire breakout analysis. In the figures, rectangles drawn using solid and dotted lines indicate the fault model of the earthquake in this scenario. The fault inclines from south to north on the Philippine Sea Plate.

The results of the fire and flame propagation analysis are shown in Fig. 9. A ring-shaped fire destruction area is located in the center of the metropolitan area, an observation consistent with a densely populated residential area.

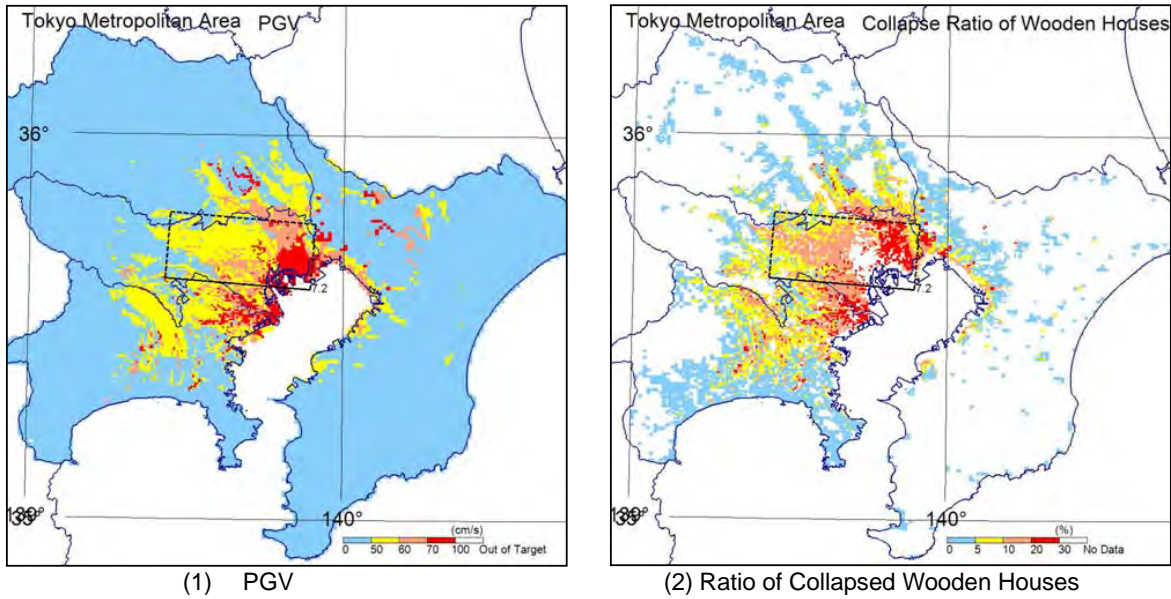


Fig. 8 Distribution of Ground Motion Intensities and Housing Damage

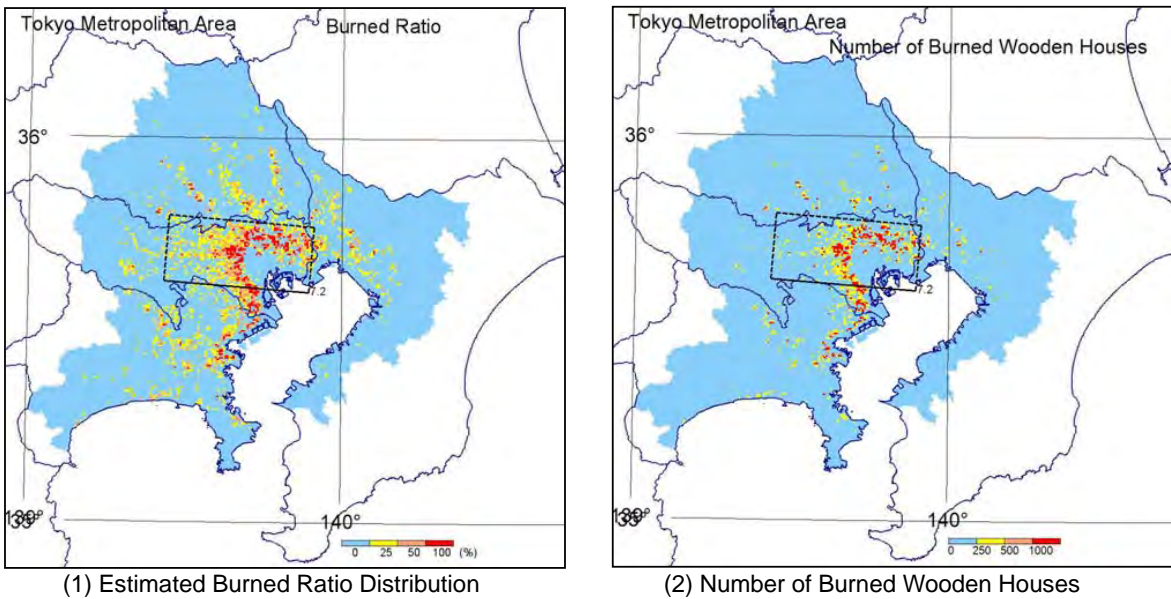


Fig. 9 Distribution of Results from Fire and Flame Propagation Analysis

A comparison of Figs. 7 to 9 indicates that the nonflammable area ratio has a greater impact on post-earthquake fires than ground motion intensity. Consequently, estimating the nonflammable area ratio in urban area is clearly important in assessing the post-earthquake fire risk.

CONCLUSIONS

The author investigated the relationship between the number of wooden houses and the nonflammable area ratio to develop a method of estimating the nonflammable area ratio in urban areas. A convenient and simple method of estimating the nonflammable area ratio has been proposed. A numerical simulation showed that the proposed method is accurate enough to be used in analyses of post-earthquake fire and flame propagation. It also confirmed that the nonflammable area ratio is a significant factor in assessing the post-earthquake fire risk of urban areas.

REFERENCES

1. Fire and Disaster Management Agency, Ministry of Internal Affairs and Communications, Government of Japan, *White Paper on Fire Management – 2000*, March 2000, pp. 32-35 (in Japanese).
2. Urban Disaster Prevention Office, City Bureau, Ministry of Construction, Government of Japan, *Urban Disaster Prevention: Practical Handbook*, Gyosei, Tokyo, September 1997, pp. 33-35 (in Japanese).
3. Kurita, T., Takahashi, S., Shimada, M. and Annaka, T., “Estimation of JMA Intensity Using Response Spectrum and Its Application to Inversion of Earthquake Fault,” *Journal of Applied Mechanics, Japan Society of Civil Engineers*, Vol. 3, pp. 547-557, August 2000 (in Japanese).
4. Kurita, T. and Suehiro, T., “Development of Earthquake Disaster Simulation System,” *Case Histories of Urban Geo-informatics, Edition 2004*, Asian Regional Technical Committee No.10 “Urban Geo-informatics” of the International Society of Soil Mechanics and Geotechnical Engineering, pp. 150-159, November 2004.
5. Annaka, T. and Nozawa, Y., “A Probabilistic Model for Seismic Hazard Estimation in the Kanto District,” *Proceedings of the Ninth World Conference on Earthquake Engineering*, Vol. II, pp. 107-112, August 1988.
6. Miyakoshi, J., Hayashi, Y. and Tamura, K., “Damage Ratio Function of Buildings Using Damage data of 1995 Hyogo-ken Nanbu Earthquake,” *Structural Safety and Reliability*, Balkema, pp. 349-354, 1998.
7. Committee for the Examination of Earthquake Damage Scenarios of Kanagawa Prefecture, *Report on Examination of Earthquake Damage Scenarios of Kanagawa Prefecture*, March 1999 (in Japanese).
8. Hasegawa, K. and Midorikawa, S., “Seismic Risk Mapping of Wooden House in Large Area using the Grid-square Statistics,” *Journal of Structural and Construction Engineering, Architectural Institute of Japan*, No. 497, July 1997, pp. 75-80 (in Japanese).