scientific reports

Check for updates

OPEN

Static analysis-based rapid fire-following earthquake risk assessment method using simple building and GIS information

Jaedo Kang[1,5], Taewook Kang[2,5], Kihak Lee[3], Hyewon Kim[4] & Jiuk Shin[2]✉

After the occurrences of large-scale earthquakes, secondary damage (e.g., fire following earthquake) can result in tremendous losses of life, properties, and buildings. To reduce these disaster risks, fire following earthquake assessment methods composed of ignition and fire-burned rate estimation models have been utilized. However, previous methods required for large amounts of building and GIS information, and complex modeling and analysis processes, leading to significant time consumption. This paper proposed a static analysis-based rapid fire following earthquake assessment method using simple information and implemented it in Pohang City, South Korea. Based on previous studies, the best-fit model for the ignition rate estimation was selected, and a cluster-based fire-burned rate estimation model was developed using simple building information (e.g., construction year, building occupancy, story, and total floor area) from the public building database (e.g., building registration data). For the fire-burned rate estimation model, fire-resistant structure types were defined using simple building information, and this was utilized to generate clusters of buildings at a regional level by comparing fire-spread distances for each fire-resistant structure type with adjacent distances among the buildings. This proposed method was applied to Pohang City, South Korea, and validated as follows: (1) the selected ignition rate model predicted similar ignition numbers to the actual reported number (actual number of ignitions = 4 vs. predicted number of ignitions = 3), and (2) the fire-burned rate model estimated fire-burned areas with a marginal difference compared to the fire spread simulation (fire-burned area using the proposed model = 13,703.6 m^2 vs. results of fire spread simulation = 16,800.0 m^2, with an error of approximately 18%).

In November 2017, a 5.4-magnitude earthquake hit Pohang, in South Korea, resulting in the first recorded fire following an earthquake in Korea; this was officially documented by the Ministry of Interior and Safety in its earthquake damage report[1]. This suggests that South Korea, which lacks a system for predicting and managing earthquake damage, faces the possibility of large-scale regional secondary damage from earthquakes, such as fire following earthquakes (FFEs) leading to the spread of fire. All abbreviations used in this paper are summarized in Table A. After an earthquake, the fires leading to the earthquake can get ignited simultaneously in multiple locations, resulting in greater losses of life, property, and buildings than through direct damage from the earthquake itself because immediate response and suppression of fires caused by earthquakes can be challenging due to obstacles created to firefighting. To address the FFE risk, the U.S. and Japan have developed methodologies for evaluating the same based on actual data related to fires caused by earthquakes in the past, and more detailed information of FFE risk assessment methodologies can be found in Lee et al.[2].

The FFE risk assessment methods proposed by previous studies are based on ignition rate and fire-burned rate (or fire-spread rate), and involve calculating a building's fire-burned rate, based on the probability and location of ignition caused by an earthquake. The ignition rate is the number of ignitions per unit building area after

[1]Division of Safety and Infrastructure Research, The Seoul Institute, Seoul 03909, South Korea. [2]Department of Architectural Engineering, Gyeongsang National University (GNU), Jinju-Daero, Jinju-si, Gyeongsangnam-do 52828, South Korea. [3]Department of Architectural Engineering, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 05006, South Korea. [4]Earthquake Hazards Reduction Center, National Disaster Management Research Institute, 365 Jongga-ro, Jung-gu, Ulsan, South Korea. [5]These authors contributed equally: Jaedo Kang and Taewook Kang. ✉email: jiukshin@gnu.ac.kr

an earthquake has occurred, and ignition rate estimation models have been developed by analyzing ignition and earthquake data. The HAZUS-MH earthquake model[3] from the Federal Emergency Management Agency (FEMA) utilizes peak ground acceleration (PGA) to estimate the number of ignitions per unit building area. The earthquake model used in Japan[4] estimates the ignition rate by considering factors, such as earthquake intensity, building occupancy, and season. The fire-burned rate is the number or area of buildings consumed/affected by fire. Methods for calculating the fire-burned rate include dynamic fire simulations, regression model-based static fire-spread analyses, and clustering techniques. Dynamic fire simulations include the method utilized in FEMA's HAZUS-HM earthquake model[5] and fire-spread simulation based on the Tokyo Fire Department (TFD) model; these two models calculate the fire-burned rate differently. The former is based on the Hamada model[6,7] and assesses completely burned structures using fire simulation. Fire-spread simulation[8] used in Tokyo, Japan, and takes into account factors, such as the fire-resistant structure type of buildings, wind speed, and burning velocity to calculate the fire-spread rate, which is used to estimate the extent of burned structures in the evaluation area. Static fire-spread analysis can calculate the fire-burned rate using unburned area ratio and covering volume fraction (CVF) associated with the density of buildings. Other methods[4,9–12] exist for calculating the fire-burned rate from wood building coverage ratio associated with the spread of fire. The methodology[13] applying clustering technique involves calculating the regional fire-burned rate using the clustering technique proposed by Kato et al.[14]. Clustering means forming groups of buildings by comparing the distance among neighboring buildings with the fire-spread distance determined from the fire-resistant structure type of the building. The existing methods (HAZUS-MH model in the U.S. and earthquake models in Japan) for FFE risk assessment have been validated with high accuracy because they utilize various information such as building information (e.g., occupancy, total floor area, story, etc.) and weather conditions (e.g., wind speed, wind direction, humidity, etc.) along with GIS-based step-by-step modeling and analysis processes. However, these methodologies require the prior acquisition of large amounts of data, and the modeling and analysis processes make the evaluation process complex and time-consuming. Owing to these limitations, a new methodology is needed to rapidly assess FFE risk using simple information.

This study proposed a FFE risk assessment methodology that can rapidly evaluate using simple building and geographic information system (GIS) information without complex modeling and interpretation processes. As a first step, the calculation methods for ignition rate and fire-burned rate utilized in the FFE risk assessment methods proposed by previous studies were analyzed. Then, a method was proposed to calculate the ignition rate determined from the earthquake intensity and fire-burned rate simulated using building information, such as year of construction, number of floors, building use, structural material, and total floor area. The FFE risk assessment method proposed in this study was implemented to Pohang, South Korea in 2017, shown in Fig. 1, and validated by comparing it with fire-spread dynamic simulation results.

Utilized SW: QGIS 3.28.3, URL: https://www.qgis.org

Fig. 1. Map of Pohang, South Korea (URL: https://www.qgis.org).

Previous FFE risk assessment methods

This section presents an analysis of the existing FFE risk assessment methods to propose a methodology for quickly evaluating FFE risk using simple information related to buildings, such as construction year, stories, building occupancy, structural material used, and total floor area. Furthermore, the process behind the proposed FFE risk assessment is explained.

The conventional FFE risk assessment methods are commonly based on calculating ignition and fire-burned rate. The ignition estimation models include regression analysis to estimate the ignition rate based on number of ignitions and earthquake intensity data[15–18], and the model to estimate the number of ignitions using earthquake and fire-related data (earthquake intensity, building occupancy, and season)[19]. The fire-burned rate estimation models include methods that use dynamic fire simulations[5,8], regression model-based static fire-spread analyses[4,10–14], and clustering techniques. Dynamic fire simulations involve calculating the number of fully burned structures using FEMA's HAZUS-MH earthquake model[5], which itself is based on the Hamada[6,7], and TFD models, which consider the fire-resistant structure type, wind speed, and burning velocity to calculate the fire-spread rate. This method estimates the burned area inside the evaluation region through fire-spread simulation[8]. Static fire-spread analysis methods involve calculating the fire-burned rates using the unburned area ratio–fire-burned rate function, wooden building coverage ratio–fire-burned rate function, and CVF–fire-burned rate function developed using actual FFE data, as well as a clustering method proposed by Kato et al.[14] to calculate fire-burned rate. Firstly, the unburned area ratio–fire-burned rate function assumes that areas with an unburned area ratio of 70% or more do not experience fire spread, and therefore the fire-burned rate in those areas is considered to be 0%. The wooden building coverage ratio–fire-burned rate function determines the fire-burned rate of a specific area based on the wooden building coverage ratio of that area. Areas with a wooden building coverage ratio above 40% are considered to have a high risk of fire, while those with a wooden building coverage ratio below 20% are considered to have a low risk of fire. However, the unburned area and wooden building coverage ratios cannot be applied to small-scale areas and have the drawback of not reflecting the effectiveness of buildings with high fire-resistant capabilities, such as quasi-fire-resistant and fire-resistant structures. To address these issues, the relationship between CVF and fire-burned rate was developed to evaluate the fire-burned rate. This methodology evaluates the distance between buildings as a buffer to mitigate the spread of fire, calculates the CVF, and determines the fire-burned rate of a building based on the average fire-burned rate derived from the CVF. The method of applying clustering techniques involves creating clusters, as proposed by Kato et al.[14] for the evaluation area and assessing the fire-burned rate for that area. Next, the fire-spread distance and proximity of buildings based on the fire-resistant structure type are used to create clusters, and the CVF and average fire-burned rate are calculated to determine the fire-burned rate of buildings at a regional level (or larger-scale).

Since the previous FFE risk assessment methods require complicated modeling and simulation processes with large amounts of data, they result in time-consuming tasks. To overcome the limitations and develop the rapid FFE method, this study investigated the characteristics and limitations of ignition rate and fire-burned rate estimation models proposed by previous researchers. This study examined the applicability of a new FFE risk assessment methodology using Korean public databases. The characteristics, limitations, and applicability of each model are summarized in Table 1. Based on the reviewed content, this study proposes the following FFE risk assessment methodology. An ignition rate model was proposed that calculates the number of ignitions by building area using cluster-based PGA in conjunction with FEMA's HAZUS-MH earthquake model[3] and the cluster method of Kato et al.[14]. Additionally, a fire-burned rate model was proposed based on simple information of buildings, such as construction year, stories, building use, structural materials, and total floor area, in conjunction with the cluster concept of Kato et al.[14]. The proposed FFE risk assessment method, whose steps are listed below, was applied to evaluate the regional FFE risk in Pohang City where the severe earthquake damage of buildings occurred in November 2017 in South Korea.

 i. Obtain building registration data for Pohang City and preprocess the raw data.
 ii. Classify the buildings based on their fire-resistant structure type, using the building registration data.
 iii. Estimate the fire-spread distance by fire-resistant structure type and create clusters by comparing GIS-based distances between the buildings.
 iv. Determine the number of ignitions using a model for calculating the ignition rate within the clusters.
 v. Apply a model to estimate the fire-burned rate within each cluster to calculate the number of burned buildings and burned area within that cluster.
 vi. Finally, evaluate the FFE risk at a regional level.

This assessment methodology does not require large amounts of data compared to existing FFE risk assessment methodologies because it evaluates FFE risk using simple building information. Additionally, since it does not involve step-by-step modeling and analysis processes, the evaluation process is straightforward and allows for rapid FFE risk assessment. This can contribute to making rapid decisions for responding to FFE risks.

Classification of buildings based on fire-resistant structure type

This section describes the classification process of the fire-resistant structures type of buildings in Pohang to generate fire-resistant characteristic-based clusters proposed by Kato et al.[14]. This involves grouping or clustering buildings with similar fire-resistant structure types and proximity distances based on the fire-spread distance. However, the building registration data in South Korea does not classify the buildings based on their fire-resistant structure types in its building-related databases. Hence, it is not possible to evaluate the fire-spread distance based on the fire-resistant structure type. This study developed a methodology to classify fire-resistant structure types

Existing FFE model	Key features	Limitations	Applicability
Earthquake Model in Japan[4]	Estimating ignitions rate considering climatic conditions (season, wind speed, wind direction, humidity, etc.), time of day, firefighting capacity, and building occupancy	Acquisition of large amounts of data related to actual earthquakes and fires is essential	Limited linkage between the data considered in this methodology and the databases established in Korea
FEMA's HAZUS-MH earthquake model[5]	Performing Fire simulations based on the Hamada model[6,7] The modeling process for buildings and urban areas is simple	The modeling and analysis processes require a significant amount of time Limited reflection of actual regional characteristics and low accuracy due to simplified modeling	Limited the rapid evaluation of FFE risk by the modeling and analysis processes
Fire spread simulation[8]	Predicting fire spread rate and fire spread range per grid unit based on Climatic conditions It can reflect characteristics very similar to actual regional characteristics and has high accuracy	The evaluation process is complex and time-consuming due to the modeling and analysis procedures	Limited the rapid evaluation of FFE risk by the modeling and analysis processes Can be used for validation purposes considering the ability to reflect actual regions and the aspect of accuracy
Static analysis evaluation method[4,9,11,12]	Calculating fire-burned rates using functions developed from actual FFE data Utilizing indicators related to fire spread or density	Not applicable to small-scale regions Limited ability to reflect the effects of buildings with high fire-resistance performance	Limited linkage with Korean buildings, which have a high number of fire-resistant performances
Static analysis evaluation method using CVF[10]	A proposed method to complement the weaknesses of the existing static analysis evaluation method By calculating the CVF according to the fire-resistant structure type, it is possible to reflect the effects of buildings with high fire-resistance performance	Limited evaluation for buildings not included in clusters	Can be connected with Korean databases based on the proposed method of classifying fire-resistant structure types Allows for rapid assessment compared to dynamic analysis
Static analysis evaluation method using cluster[13,14]	Calculating area-level fire-burned rates based on clusters formed within the assessment region		

Table 1. Summary of existing FFE models proposed by previous researchers.
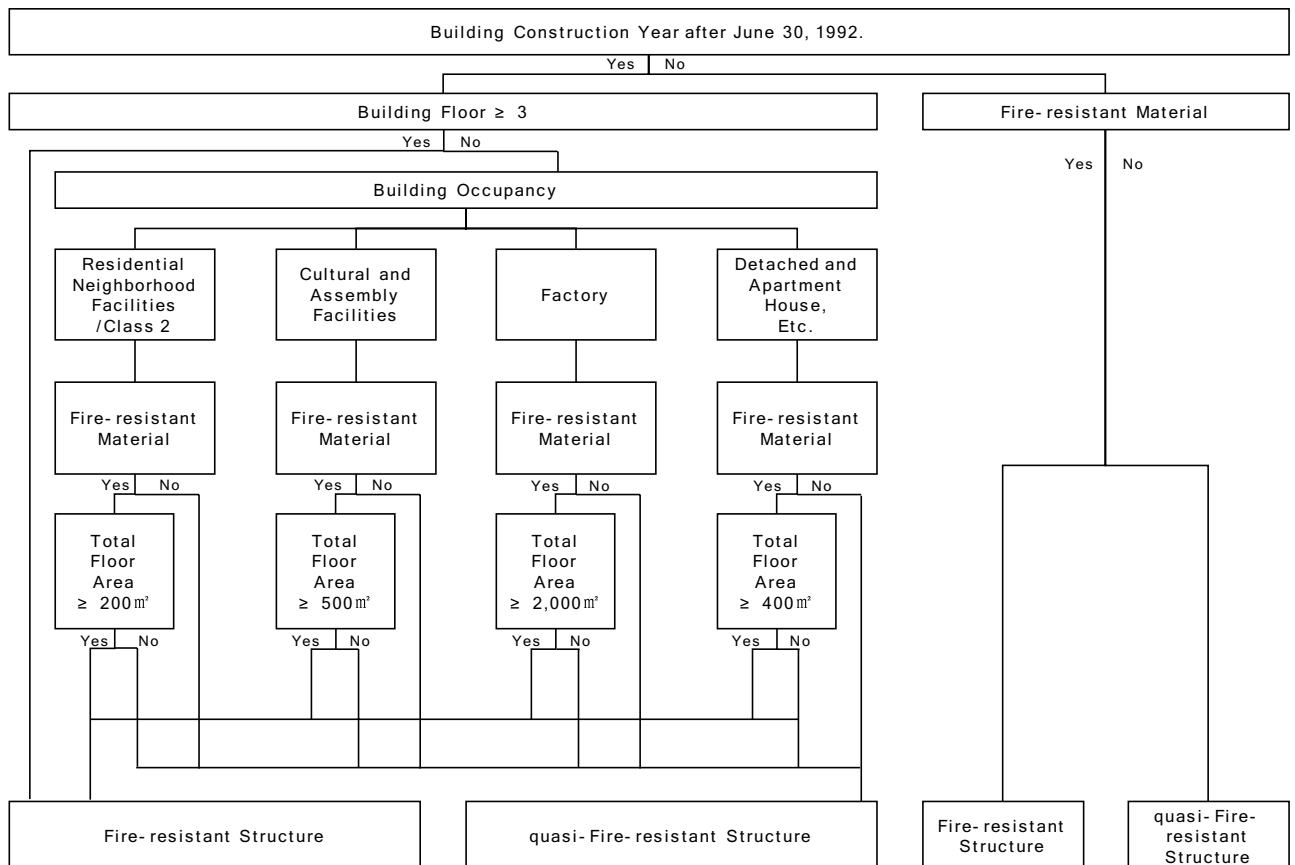
Fig. 2. The proposed method for classifying fire-resistant structure type of buildings using simple information.

of buildings using simple information based on the amendments in building laws, as shown in Fig. 2. On June 30, 1992, Article 56 'Fire-resistant Structures' of the Enforcement Decree of the Building Act in South Korea was amended for the first time. Using this date as the reference date, the classification methodology determines the fire-resistant structure type for buildings constructed before this date based on the structural materials used in the structural frames. For buildings constructed after the reference date, the classification is done by comparing the construction year, story, building occupancy, structural materials, and total floor area.

The aforementioned data for buildings in Pohang City were obtained. The analysis revealed that up to 50.6% of the necessary data were missing or incomplete, which could impact the assessment of fire spread in the FFE risk evaluation process, especially in determining the spread to adjacent structures; thus ensuring the completeness of data acquisition was essential and a backtracking algorithm was developed to trace the missing data elements in the building registration data, as shown in Fig. 3. This methodology has been developed by incorporating statistical results from public databases provided by the government related to buildings and land, and the characteristics of buildings. When applied to missing data, it can generate highly reliable information. To obtain complete data, the algorithm given in Fig. 3 was implemented to the building registration data of Pohang City. Among the data, the building coverage and floor area ratio, which had the highest missing rates of 50.6%, were reduced to 0% missing rate through the application of the data backtracking algorithm. Table 2 presents the backtracking results for the data considered for classifying the fire-resistant structure types of buildings. The resulting fire-resistant structure types of buildings in Pohang City included timber structures, fire-preventative timber structures, quasi-fire-resistant structures, and fire-resistant structures). The results are summarized in Table 3, which reveals that among 89,708 buildings in Pohang, the fire-resistant buildings comprised 12,688 timber structures and 19 fire-preventative timber structures. The quasi-fire-resistant structures comprised 64,730 buildings, representing the highest proportion, while the fire-resistant structures comprised 12,298 buildings. The classification results of regional fire-resistant structure types in Pohang City are presented in Table B of the Appendix.
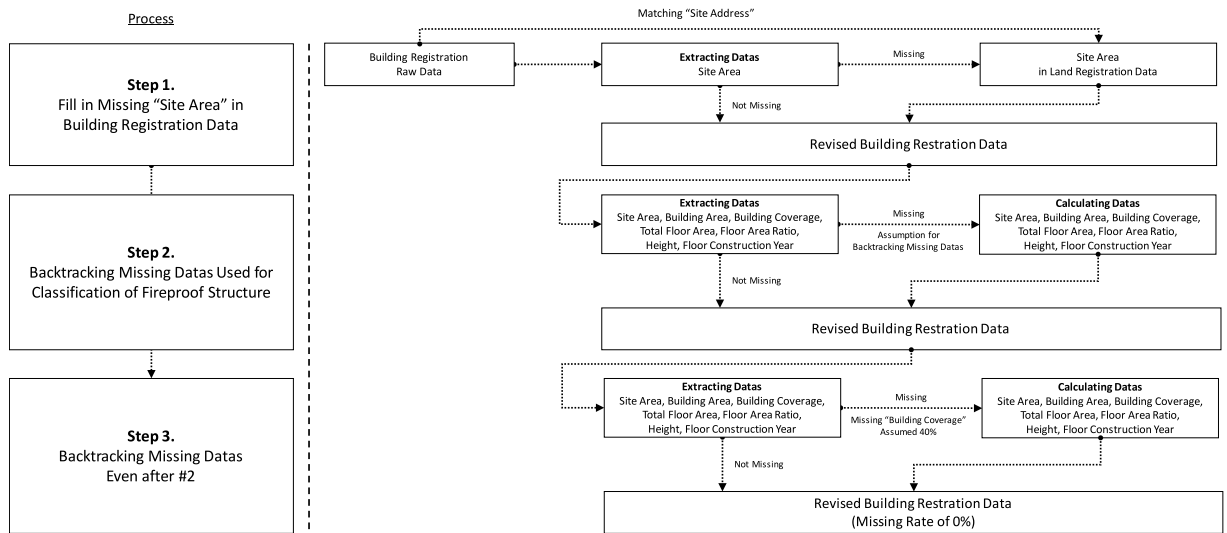

Fig. 3. Backtracking algorithm of building registration data.

List of building registration data	Result of backtracking building registration data in Pohang		
	Original	1st backtracking	2nd backtracking
	number of missing data (ratio)	Number of missing data (ratio)	Number of missing data (ratio)
Site area	43,469 (about 48.5%)	7,177 (about 8.0%)	3 (0.0%)
Building area	3,383 (about 3.8%)	379 (about 0.4%)	3 (0.0%)
Building coverage	45,364 (about 50.6%)	7,469 (About 8.3%)	0 (0.0%)
Total floor area	108 (about 0.1%)	87 (about 0.1%)	3 (0.0%)
Total floor area for calculation of floor area ratio	3,511 (about 3.9%)	359 (about 0.4%)	3 (0.0%)
Floor area ratio	45,367 (about 50.6%)	7,482 (about 8.3%)	3 (0.0%)
Height	44,367 (about 49.5%)	321 (about 0.4%)	0 (0.0%)
Floor	701 (about 0.8%)	397 (about 0.4%)	0 (0.0%)

Table 2. Result of backtracking of building registration data.

Fire-resistant structure type	Result of fire-resistant structure type for buildings in Pohang	
	Number of classified buildings	Rate (%)
Timber	12,688	14.14
Fire-preventative timber	19	0
Quasi-fire-resistant	64,730	72.13
Fire-resistant	12,298	13.71

Table 3. Results of classifying fire-resistant structure types of buildings in Pohang.

## Application of the FFE risk assessment method

This section describes the process of evaluating the regional FFE risk by implementing the proposed FFE risk assessment method to Pohang City. The fire-resistance type-based clusters generated through comparing between the fire-spread distance and adjacent building distance are used to calculate the ignition rate and fire-burned rate for assessing the regional-level FFE risk. The explanation of the technical terms used in this section is summarized in Table A of the Appendix.

Creation of clusters based on fire-resistant structure types

This section describes the process of creating clusters in Pohang City using fire-spread distance according to the classification of buildings considering their fire-resistant structure types, which was presented in Section "Classification of Buildings Based on Fire-resistant Structure Type".

The concept proposed by Kato et al.[14] involves grouping buildings with similar fire-resistant structure types based on comparing the fire-spread distance and adjacent distances according to the fire-resistant structure types, as shown in Fig. 4. When comparing the fire-spread distance (d_i) of buildings based on the adjacent distance (n_i) between them, and their fire-resistant structure types, the overlapping buildings form a single cluster. In this study, n_i was calculated based on the polygon shape data of buildings in the GIS. Furthermore, d_i was calculated using Eqs. (1)–(4), which are formulae based on the fire-resistant structure type of the building[6,20]:

$$\text{Timber structure}: d_i = 12 \times \left(\frac{a}{10}\right)^{0.442} [\text{m}], \tag{1}$$
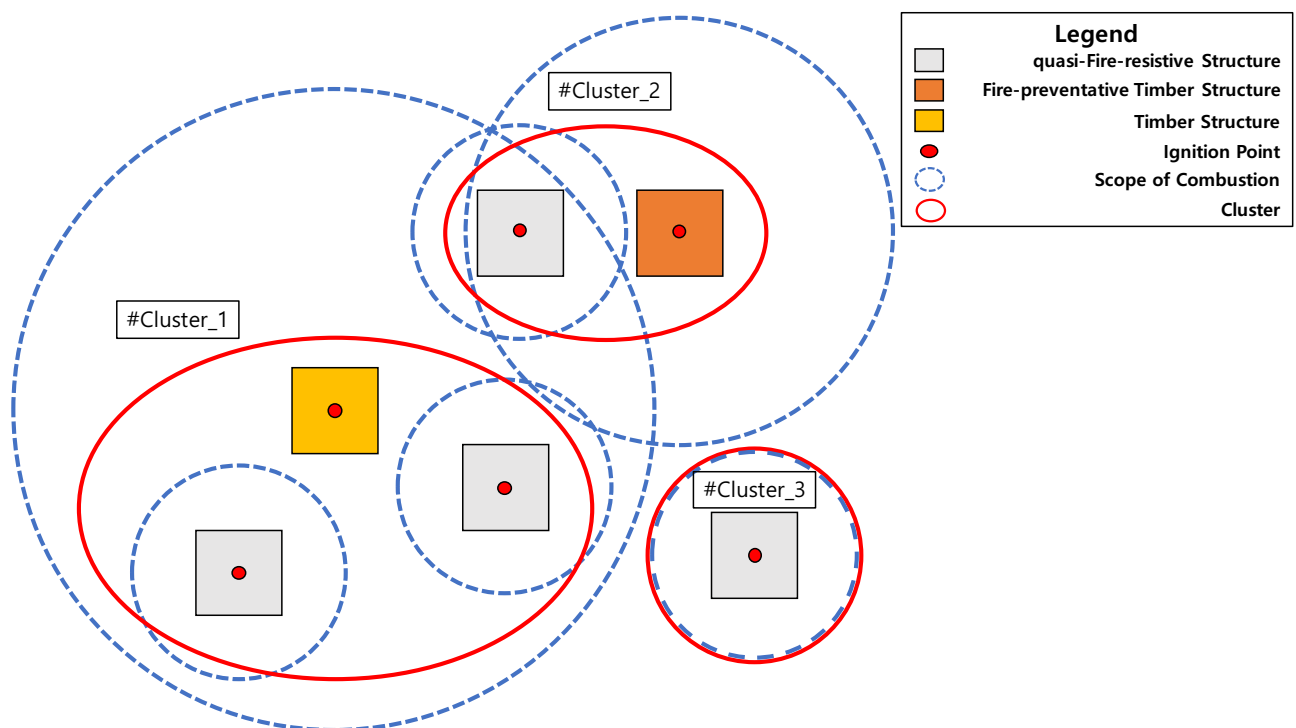
Fig. 4. Example of GIS information and fire-spread distance based on clusters.

$$\text{Fire-preventative timber structure}: d_i = 6 \times \left(\frac{a}{10}\right)^{0.332} [m], \tag{2}$$

$$\text{Quasi} - \text{fire} - \text{resistant structure}: d_i = 3 \times \left(\frac{a}{10}\right)^{0.181} [m], \tag{3}$$

$$\text{Fire} - \text{resistant structure}: d_i = 0 [m], \tag{4}$$

where, a is the length of one side of the building.

A total of 5,946 clusters were created by grouping buildings with similar fire-resistant characteristics based on the values of d_i calculated from Eqs. (1)–(4) and n_i calculated using GIS.

Calculation of number of regional ignitions

This section describes the process of calculating the number of regional-level ignitions using the ignition rate model, adopted in the FFE risk assessment method proposed in this study.

Ignition rate refers to an estimated number of ignitions per unit area of a building or per unit area after an earthquake has occurred. One model estimates the number of ignitions using regression with earthquake intensity data and other data related to earthquakes and fires[3]. The ignition rate model used in Japan[4] calculates the rate at which ignitions lead to fires by taking into account climatic conditions (e.g., season, wind speed, wind direction, and humidity), time, number of ignitions, first-fire-extinguishing rate, and firefighting force. Even though the ignition rate model, considering the aforementioned factors, results in high accuracy predictions, the use of the model is limited due to the lack of related data existing in Korea. Therefore, the prediction models based on earthquake intensity versus number of ignitions, proposed by other researchers[3,15–18,21] were considered in this study. To select the most suitable model from the above, the correlation of the proposed formula for the number of ignitions[3,16,18,21] was analyzed with 1,435 ignition data elements. Figure 5 depicts the correlation between the data and the number of ignitions as obtained from the formula. FEMA's HAZUS-MH model[5] had the highest R-squared (R^2) value of 0.425, while Ren and Xie's model[16] had the lowest mean square error (MSE) of 0.025. The ignition rate estimation models considered in this study were examined in Table 4. Despite the relatively high MSE of 0.093, it was determined that the model from FEMA's HAZUS-MH (2020) was appropriate because the ignition rate estimation model has the highest correlation ($R^2 = 0.425$) with the data among the considered models. The comparison of the correlation between the ignition rate estimation models considered in this study and the actual fire data is summarized in Table 4.

This study utilized the PGA of clusters generated in Pohang City to calculate the number of cluster-based ignitions using Eq. (5) to estimate the number of ignitions based on earthquake intensity:

$$\text{Ignition rate } = y(x) \times \frac{TFA \text{ by cluster } [ft^2]}{1,000,000}, \tag{5}$$
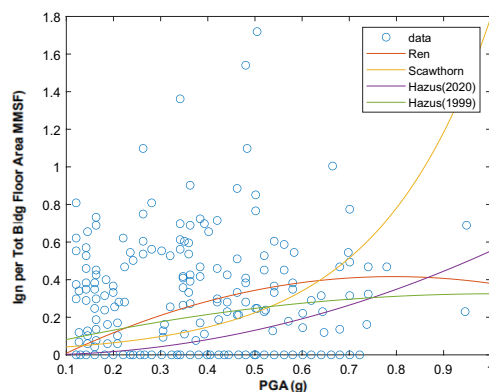
Fig. 5. Correlation between actual fire data and existing ignition rate estimation models.

Model	Formula	R^2	MSE
HAZUS-MH (1999)	$y = -0.025 + 0.59x - 0.29x^2$	0.207	0.049
HAZUS-MH (2020)	$y = -0.029444 - 0.581895x^2$	0.425	0.093
Ren and Xie (2004)	$y = -0.11749 + 1.3453x - 0.8476x^2$	0.212	0.025
Scawthron (2005)	$y = 0.028\exp(4.16x)$	0.398	0.046

Table 4. Summary of correlations with actual fire data of the ignition rate estimation models.

where, x = PGA and y = number of ignitions per total floor area of 1,000,000 ft^2. The results are summarized in Table 5.

For calculating the number of regional-level ignitions based on clusters, the buildings were classified into 29 administrative regions using the administrative codes of the buildings included in the clusters. The administrative code is defined as "dong," which is the unit that separates regions in South Korea, and it is used to represent the administrative districts of the South Korea. The number of regional-level ignitions was calculated by summing the number of ignitions for all the clusters in each region, and the results are summarized in Table 6. The number of regional-level ignitions ranged from 0.011 to 1.678, with a total of 2.786 (nearly 3) in Pohang city. A comparison between the numbers of ignition reported after an actual Pohang earthquake in 2017, which was four incidents[1], and the number as predicted by the model demonstrates a good agreement between the two results.

Calculation of regional CVF and average fire-burned rate

This section describes the process for calculating the cluster-based CVF and average fire-burned rate using the model proposed in this study for FFE risk assessment.

CVF is defined as the area excluding the fire area, as presented in Fig. 6. The fire area is defined as the area that includes the range of fire-spread distance, determined by the building area and fire-resistant structure type. The concept of CVF was developed in Japan to assess regional FFE risk, and represents the area excluding the fire-spread area per unit regional area, as shown in Eq. (6) [25]:

$$\text{CVF} = 1 - \frac{Buffer\ area}{Local\ area},\tag{6}$$

where the buffer area is calculated using Eq. (7) given below[25].

$$\begin{aligned}\text{Buffer Area} &= 3.293 \times \text{building coverage of timber structure} + 2.136\\ &\quad \times \text{building coverage of fire} - \text{preventative} - \text{timber structure}\\ &\quad + 1.340 \times \text{building coverage of quasi} - \text{fire} - \text{resistant structure}.\end{aligned}\tag{7}$$

In Japan, Eq. (7) is calculated to take into account the varying fire area based on the fire-resistant structure type of the building. Here, one issue with Eqs. (6) and (7) is that the area outside the cluster boundaries is not accounted for. Therefore, this study aimed to consider the area beyond the cluster boundaries as well, thus enlarging the peripheral land area. The newly proposed CVF equation is as follows:

$$\text{CVF} = 1 - \frac{Buffer\ area}{n \times cluster\ area},\tag{8}$$

where n is the peripheral land amplification coefficient.

To expand the area of the peripheral land, n was set to 1.1 in Eq. (8).

Subsequently, the average fire-burned rate used to calculate the fire-burned rate (total number of burned buildings and burned area) by regional FFE is defined as the rate at which buildings are lost to fire when ignition occurs in a cluster and is calculated using Eq. (9).

Cluster ID	Total floor area (m²)	PGA (g)	Average of number of ignitions
C0001	186	0.216	0.001
C0002	825	0.230	0.001
C0003	395	0.216	0.001
C0004	263	0.230	0.001
C0006	448	0.216	0.001
C0007	293	0.216	0.001
C0008	241	0.230	0.001
C0009	2,053	0.216	0.001
C0010	2,656	0.216	0.002
C0011	266	0.216	0.001
			. . .
C5946	160	0.216	0.001
C5947	163	0.216	0.001

Table 5. The number of ignitions by clusters in Pohang.

Region		Area (m²)	Total floor area (m²)	PGA (g)	Average of number of ignitions
South	A	19,560,000	3,073,939	0.245	1.678
	B	45,170,000	197,809	0.245	0.059
	C	3,440,000	56,640	0.245	0.030
	D	32,620,000	32,849	0.230	0.026
	E	4,940,000	21,405	0.216	0.011
	F	43,620,000	72,865	0.245	0.034
	G	1,860,000	31,813	0.245	0.015
	H	36,070,000	169,104	0.245	0.058
	I	70,500,000	145,511	0.245	0.072
	J	6,740,000	69,823	0.230	0.044
	K	100,270,000	114,852	0.245	0.044
	L	5,860,000	53,475	0.245	0.020
	M	1,940,000	25,861	0.230	0.014
	N	20,430,000	34,025	0.216	0.014
North	A	91,960,000	60,597	0.245	0.029
	B	52,390,000	24,986	0.245	0.011
	C	2,330,000	472,821	0.245	0.222
	D	1,380,000	39,360	0.245	0.015
	E	1,980,000	13,343	0.216	0.006
	F	59,400,000	53,674	0.245	0.028
	G	80,170,000	80,172	0.245	0.036
	H	11,180,000	105,111	0.245	0.041
	I	2,370,000	62,899	0.230	0.022
	J	3,950,000	83,668	0.245	0.033
	K	6,200,000	34,323	0.245	0.014
	L	1,860,000	103,941	0.230	0.047
	M	235,710,000	40,871	0.245	0.016
	N	78,200,000	70,215	0.230	0.030
	O	105,720,000	278,111	0.245	0.117

Table 6. Estimation of the number of regional-level ignitions in Pohang.
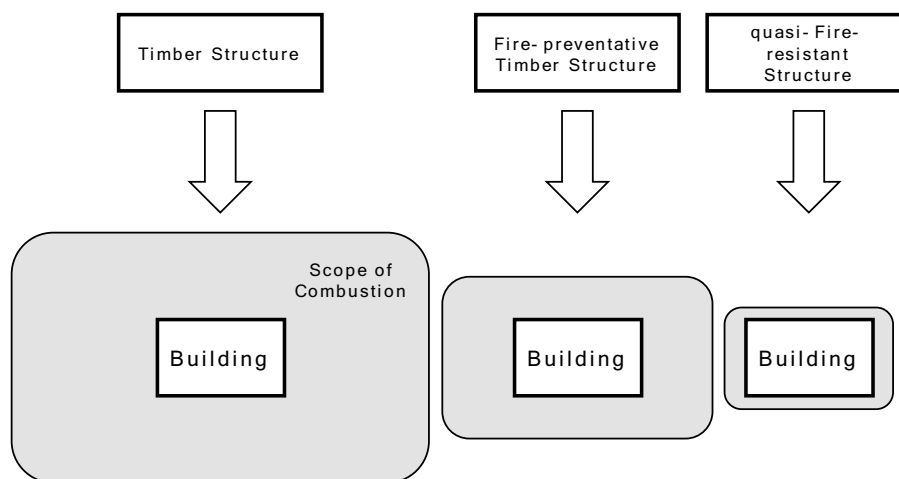
Fig. 6. Combustion range by fire-resistant structure type of buildings.

$$\text{Average fire} - \text{burned rate} = 1 - \exp\left(-\frac{0.01307}{CVF^{3.036}}\right), \qquad (9)$$

When the CVF of a cluster is less than or equal to 0.1 in Eq. (9), the average fire-burned rate of the cluster is approximately 1. The loss rate of buildings included in the cluster is 100%. When a cluster's CVF is more than 0.5, the cluster's average fire-burned rate is approximately 0.1, indicating a loss rate of approximately 10% for

Cluster ID	Number of buildings in cluster	CVF	Average of fire-burned rate
C0001	2	−0.169	0
C0002	2	0.380	0.219
C0003	2	0.897	0.018
C0004	3	0.691	0.039
C0006	1	0.934	0.016
C0007	3	0.593	0.062
C0008	3	0.674	0.042
C0009	3	0.545	0.079
C0010	4	0.793	0.026
C0011	2	0.990	0.013
			. . .
C5946	2	0.837	0.022
C5947	3	0.570	0.069

Table 7. The number of buildings, CVF and average of fire-burned rate by clusters.

the buildings in the cluster. Using Eqs. (8) and (9), the CVF and average fire-burned rate were calculated for 5,946 clusters in Pohang City. Table 7 summarizes the number of structures, CVF, and average fire-burned rate of clusters in Pohang City.

Assessment of regional-level FFE risk

This section describes the evaluation of regional-level FFE risk by utilizing the cluster unit average fire-burned rate explained in "Calculation of regional CVF and average fire-burned rate", which is used to determine the regional-level fire-burned rates (total number of burned buildings, total burned building area, and total burned floor area). Based on the regional-level fire-burned rates, the burned rates caused by FFE (number of burned buildings, burned building area, and burned floor area) were calculated to assess regional-level FFE risk.

The fire-burned rates used in the assessment of regional FFE risk refer to the number of burned structures or area caused by FFE. The fire-burned rates are calculated by multiplying the average fire-burned rate by the number of buildings, building area, and total floor area, respectively.

To calculate the fire-burned rate used in the regional FFE risk assessment, 29 areas were classified based on the administrative codes of the buildings included in the cluster. Then, the total number of burned buildings, burned building area, and total burned floor area were summed up at the regional level using Eqs. (10)–(12):

$$F_n = \sum FS_i \times n_i, \tag{10}$$

$$F_A = \sum FS_i \times A_i, \tag{11}$$

$$F_{TFA} = \sum FS_i \times TFA_i, \tag{12}$$

where, F_n is the total number of burned buildings in regional level; F_A is the total burned building area in regional level; F_{TFA} is the total burned floor area in regional level; i is an index for regional clusters ($i = 1, 2, 3, $ etc.); FS_i is the average fire-burned rate in regional cluster i; n_i is the number of buildings in regional cluster i; A_i is the total building area of regional cluster i; and TFA_i is the total floor area in regional cluster i.

Table 8 presents the information related to the local unit buildings in Pohang City, including the CVF and fire burned rates (total number of burned buildings, burned building area, and total burned floor area). The number of buildings, building area, and total floor area in Pohang City were estimated to be 61–1938, 7149–2,949,187 m², and 13,343–3,073,93 m², respectively. The results for the CVF and average fire-burned rate were calculated to be 0.311–0.808 and 0.046–0.321, respectively. The total number of burned buildings, burned building area, and total burned floor area were calculated using Eqs. (10)–(12) to be 4.03–598.86 buildings, 384.86–167,182.63 m², and 843.70–173,476.81 m², respectively. Subsequently, an analysis was conducted on the total number of burned buildings, burned building area, and total burned floor area in Pohang City, wherein it was found that Pohang City North C (N-C) had the highest total number of burned buildings at 598.86, while Pohang City North K (N-K) had the lowest at 4.03. In the case of burned building area and total burned floor area, Pohang City South A (S-A) had the highest values with 167,183 and 173,477 m², respectively, while Pohang City N-K had the lowest values with 384.86 and 843.70 m², respectively. The fire-burned rate of Pohang City N-C was expected to be the highest owing to its high regional number of structures (1,938) and average fire-burned rate (0.274). However, the actual fire-burned rate calculation showed that the burned building area and total burned floor area were highest in Pohang City S-A, wherein the factory areas account for approximately 82% of the total structures, resulting in a dense concentration of factories. Here, despite a low number of buildings (592) and an average fire-burned

Region		CVF	Average of fire-burned rate	Num of bldgs in region	Building area (m²)	Total floor area (m²)	Num of burned bldgs	Burned bldg area (m²)	Burned tot Flr area (m²)
South	A	0.453	0.049	592	2,949,187	3,073,939	26.11	167,182.63	173,476.81
	B	0.808	0.225	1,752	119,260	197,809	570.61	37,512.32	51,215.29
	C	0.545	0.118	188	26,418	56,640	24.98	2,917.05	5,617.74
	D	0.688	0.067	350	31,135	32,849	25.09	2,730.94	2,526.76
	E	0.543	0.168	114	11,972	21,405	23.19	2,322.40	3,576.20
	F	0.569	0.128	669	51,713	72,865	83.74	6,625.50	7,301.86
	G	0.528	0.135	159	15,899	31,813	20.68	1,609.65	2,573.80
	H	0.627	0.107	612	69,078	169,104	66.08	7,908.83	9,766.77
	I	0.627	0.121	1,140	94,660	145,511	145.10	13,635.78	19,905.14
	J	0.628	0.112	293	50,054	69,823	33.16	3,268.80	4,051.42
	K	0.545	0.130	1,515	113,680	114,852	212.05	15,883.64	15,731.82
	L	0.554	0.197	94	13,111	53,475	17.79	1,702.46	2,967.36
	M	0.557	0.129	121	13,020	25,861	14.32	1,548.22	4,007.92
	N	0.513	0.144	405	31,254	34,025	57.70	4,094.00	4,430.53
North	A	0.672	0.075	791	57,324	60,597	72.06	5,503.18	6,548.02
	B	0.703	0.056	385	24,690	24,986	30.16	2,158.14	2,150.68
	C	0.366	0.274	1,938	195,604	472,821	598.86	55,719.69	112,330.17
	D	0.533	0.150	142	14,238	39,360	23.55	1,903.12	3,438.59
	E	0.427	0.189	61	7149	13,343	10.84	1,288.00	1,800.40
	F	0.561	0.124	745	50,034	53,674	91.46	6,138.40	6,664.74
	G	0.615	0.080	1,149	78,572	80,172	112.00	7,050.20	7,222.78
	H	0.599	0.109	161	27,304	105,111	17.56	2,629.67	5,181.86
	I	0.525	0.168	165	27,777	62,899	28.18	2,188.83	3,752.08
	J	0.409	0.248	343	42,204	83,668	85.24	6,574.94	9,792.46
	K	0.794	0.046	77	12,226	34,323	4.03	384.86	843.70
	L	0.311	0.303	579	44,463	103,941	221.81	14,107.38	29,867.44
	M	0.694	0.057	609	38,745	40,871	32.20	2,348.45	2,581.74
	N	0.591	0.108	689	61,019	70,215	82.96	6,815.57	7,498.60
	O	0.588	0.107	2,570	204,573	278,112	282.32	22,497.75	27,781.06

Table 8. Result of calculation of the regional-level fire-burned rates in Pohang.

rate of 0.049, the burned building area and total burned floor area were the highest at 2,949,186 and 3,073,939 m², respectively. In the case of Pohang City N-K, the low number of buildings included in the cluster and average fire-burned rate, which were 77 and 0.045 respectively, resulted in the lowest fire-burned rates (number of burned buildings, burned building area, and total burned floor area).

The regional FFE risk was assessed by using the regional fire-burned rate (total number of burned buildings, burned building area, and total burned floor area), and ratio of buildings lost due to regional FFE (rate of total number of burned buildings and the rate of burned area). Therefore, this study included evaluation indicators and calculation formulae to assess area FFE risk. The rates of the total number of burned buildings, burned building area, and total burned floor area represent the rates of these variables due to regional FFE. These rates were calculated using Eqs. (13)–(15):

$$R_n = F_n/S, \tag{13}$$

$$R_A = F_A/S, \tag{14}$$

$$R_{TFA} = F_{TFA}/S, \tag{15}$$

where R_n is the rate of the number of burned buildings in regional level; R_A is the rate of burned building area in regional level; R_{TFA} is the rate of total burned floor area in regional level; S is the regional unit area.

Equations (13)–(15) were used to calculate the rates of the number of burned buildings, burned building area, and total burned floor area due to regional FFE. Table 9 summarizes the results of the regional fire-burned rates, and the corresponding numbers per unit regional area.

The rates of burned buildings, building area, and total floor area in Pohang City due to FFE were calculated to be 0.01–0.03%, 0.01–2.39%, and 0.01–4.82%, respectively. Subsequently, an analysis was conducted on the above rates by region. These were found to be highest in Pohang City N-C at 0.03%, 2.39%, and 4.82%, respectively, while, Pohang City North M (N-M) had the lowest value of 0.01% for all the three parameters. In Pohang City N-M, the fire-resistant structure type had the lowest rates at 1.12%, while the timber structure type had the
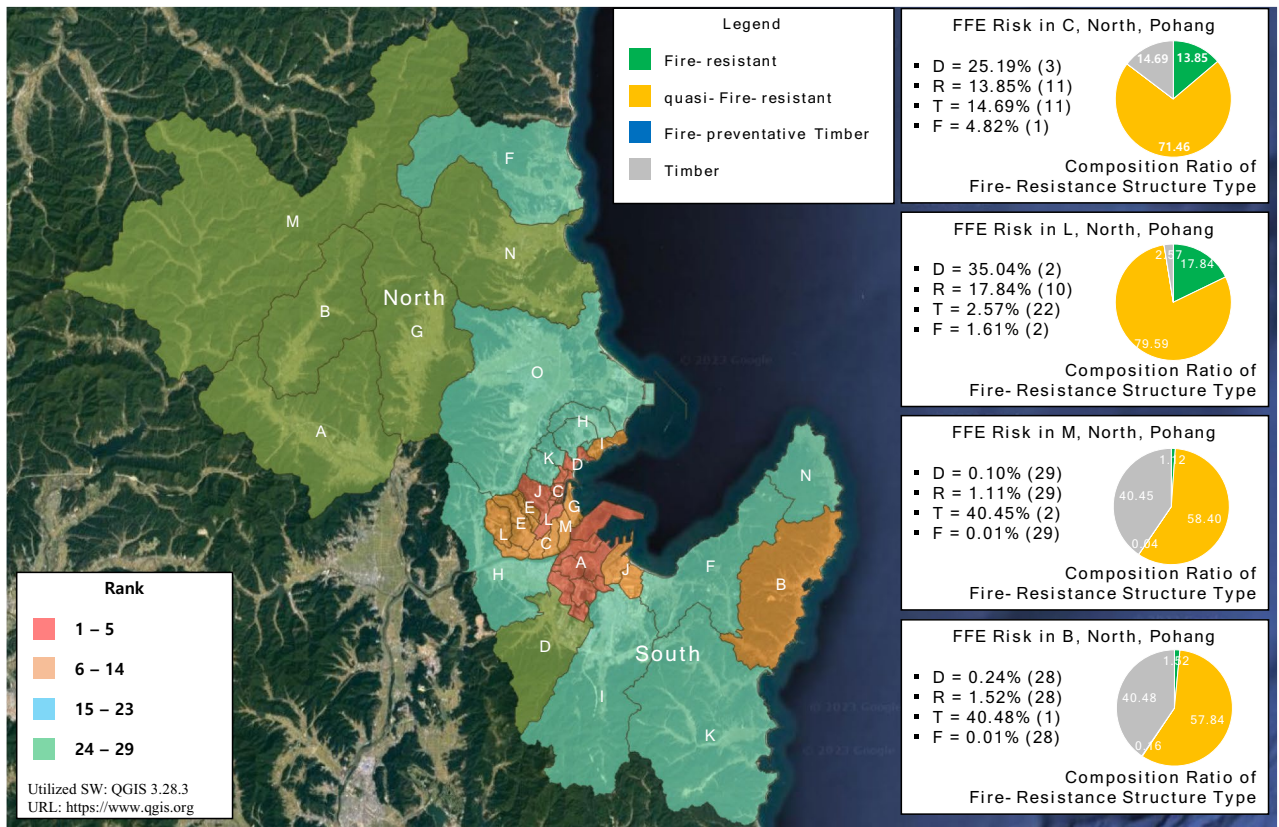
Region		Area (m²)	Num of burned bldgs	Burned bldg area (m²)	Burned tot Flr area (m²)	Rate of the num of burned bldgs (%)	Rate of the burned bldg area (%)	Rate of the burned tot Flr area (%)
South	A	19,560,000	26.11	167,182.63	173,476.81	0.01	0.86	0.89
	B	45,170,000	570.61	37,512.32	51,215.29	0.01	0.08	0.11
	C	3,440,000	24.98	2,917.05	5,617.74	0.01	0.09	0.16
	D	32,620,000	25.09	2,730.94	2,526.76	0.01	0.01	0.01
	E	4,940,000	23.19	2,322.40	3,576.20	0.01	0.05	0.07
	F	43,620,000	83.74	6,625.50	7,301.86	0.01	0.02	0.02
	G	1,860,000	20.68	1,609.65	2,573.80	0.01	0.09	0.14
	H	36,070,000	66.08	7,908.83	9,766.77	0.01	0.02	0.03
	I	70,500,000	145.10	13,635.78	19,905.14	0.01	0.02	0.03
	J	6,740,000	33.16	3,268.80	4,051.42	0.01	0.05	0.06
	K	100,270,000	212.05	15,883.64	15,731.82	0.01	0.02	0.02
	L	5,860,000	17.79	1,702.46	2,967.36	0.01	0.03	0.05
	M	1,940,000	14.32	1,548.22	4,007.92	0.01	0.08	0.21
	N	20,430,000	57.70	4,094.00	4,430.53	0.01	0.02	0.02
North	A	91,960,000	72.06	5,503.18	6,548.02	0.01	0.01	0.01
	B	52,390,000	30.16	2,158.14	2,150.68	0.01	0.01	0.01
	C	2,330,000	598.86	55,719.69	112,330.17	0.03	2.39	4.82
	D	1,380,000	23.55	1,903.12	3,438.59	0.01	0.14	0.25
	E	1,980,000	10.84	1,288.00	1,800.40	0.01	0.07	0.09
	F	59,400,000	91.46	6,138.40	6,664.74	0.01	0.01	0.01
	G	80,170,000	112.00	7,050.20	7,222.78	0.01	0.01	0.01
	H	11,180,000	17.56	2,629.67	5,181.86	0.01	0.02	0.05
	I	2,370,000	28.18	2,188.83	3,752.08	0.01	0.09	0.16
	J	3,950,000	85.24	6,574.94	9,792.46	0.01	0.17	0.25
	K	6,200,000	4.03	384.86	843.70	0.01	0.01	0.01
	L	1,860,000	221.81	14,107.38	29,867.44	0.01	0.76	1.61
	M	235,710,000	32.20	2,348.45	2,581.74	0.01	0.01	0.01
	N	78,200,000	82.96	6,815.57	7,498.60	0.01	0.01	0.01
	O	105,720,000	282.32	22,497.75	27,781.06	0.01	0.02	0.03

Table 9. Result of calculation of the rates of regional-level burned building lost due to FFE in Pohang.

highest proportion at 40.45%, indicating that the risk level due to fire is expected to be the highest for timber structures. However, the actual FFE risk assessment results were rated as the lowest. The rate of fire-resistant structures in Pohang City N-C was found to be 13.85% higher than in Pohang City N-M. Furthermore, the low rate of timber structures at 14.49% indicates an expected low FFE risk. However, it was rated the highest in the actual evaluation results. To ascertain the causes of these results, data related to the regional FFE risk assessment results were analyzed, and it was found that FFE risk is associated with the density of buildings at the regional level and proportion of fire-resistant structure types.

To understand the relationship between the FFE risk, building density, and proportion of fire-resistant structure types, the regional FFE risk assessment results were analyzed along with building density and the trend of fire-resistant structure types. In Pohang City N-M and North B (N-B), the proportion of fire-resistant structures in the local building units was lowest at 1.12% and 1.52%, respectively, and the timber structures were expected to have the highest FFE risk at 40.45% and 40.48%, respectively. However, the actual FFE risk was evaluated as the lowest due to the lowest density of such buildings at 0.10% and 0.24%, respectively (In the case of Pohang City N-B, the FFE risk was calculated at 0.01% for the number of burned buildings, building area, and total floor area). In comparison to Pohang City N-M and N-B, Pohang City N-C and North L (N-L) exhibited higher proportions of fire-resistant structures at 13.85% and 17.84% respectively, and lower ratios of timber structures at 14.69% and 2.57% respectively, indicating a lower risk of FFE, as expected. However, the density of buildings at the local level was highest at 25.19% and 35.04% respectively, resulting in the highest evaluated FFE risk (in the case of Pohang City N-L, the rates of burned buildings, building area, and total floor area as FFE were calculated as 0.01%, 0.76%, and 1.61%, respectively).

Figure 7 shows the results of applying the proposed FFE evaluation methodology to Pohang and evaluating the density of buildings, proportion of fire-resistant structure types, and risk assessment due to FFE for the four locations mentioned earlier (Pohang City N-C, N-L, N-M, and N-B). Furthermore, in areas with similar building density, the FFE risk was determined by the proportion of fire-resistant structure types in buildings. Detailed information regarding the density of buildings at the regional level, proportion of fire-resistant structure types, and their relation to the FFE risk are presented in Table C of the Appendix. Based on the analysis of the evaluation of the regional FFE risk, it was confirmed that the FFE risk was influenced by the density of buildings at the

12

FFE Risk in C, North, Pohang
- D = 25.19% (3)
- R = 13.85% (11)
- T = 14.69% (11)
- F = 4.82% (1)

Composition Ratio of Fire- Resistance Structure Type

FFE Risk in L, North, Pohang
- D = 35.04% (2)
- R = 17.84% (10)
- T = 2.57% (22)
- F = 1.61% (2)

Composition Ratio of Fire- Resistance Structure Type

FFE Risk in M, North, Pohang
- D = 0.10% (29)
- R = 1.11% (29)
- T = 40.45% (2)
- F = 0.01% (29)

Composition Ratio of Fire- Resistance Structure Type

FFE Risk in B, North, Pohang
- D = 0.24% (28)
- R = 1.52% (28)
- T = 40.48% (1)
- F = 0.01% (28)

Composition Ratio of Fire- Resistance Structure Type

* D: Density; R: Composition Ratio of Fire-resistant Structures; T: Composition Ratio of Timber Structures; F: Rate of the Burned Total Floor Area; and Number in (): Regional-level Rank in Pohang

Fig. 7. Result of regional-level fire following earthquake risk assessment in Pohang (URL: https://www.qgis.org). *D* density, *R* composition ratio of fire-resistant structures, *T* composition ratio of timber structures, *F* rate of the burned total floor area, *number in* () regional-level rank in Pohang.

regional level and proportion of fire-resistant structure types in a complex manner. Additionally, this approach allows users to understand the relationship between building characteristics and FFE risk and to determine the regional risk ranks from FFE. By utilizing the FFE assessment methodology proposed in this study, it is possible to develop preemptive measures for FFE risk, such as allocating additional firefighting resources to high-risk areas or determining priority response orders for regions to reduce casualties. This is expected to contribute to rapid and rational decision-making in policy formulation or urban planning.

Fire-spread simulation

This section describes the validation of the proposed simple information-based FFE risk assessment method, by conducting fire-spread simulations, as shown in Fig. 8, in an actual area Pohang City North O (N-O), where an earthquake occurred. This process also includes comparing with the FFE risk assessment results of Pohang City N-O presented in "Assessment of regional-level FFE risk".

The fire-spread simulation[8] calculates the burned area of a target region based on the fire-spread speed in terms of grid units of a certain size that the target region is divided into. The fire-spread rate is calculated taking into account the fire-resistant structure type of the building, wind speed, and burning velocity. This methodology involves a preliminary building modeling process for the target area and utilizes grid-based building information,
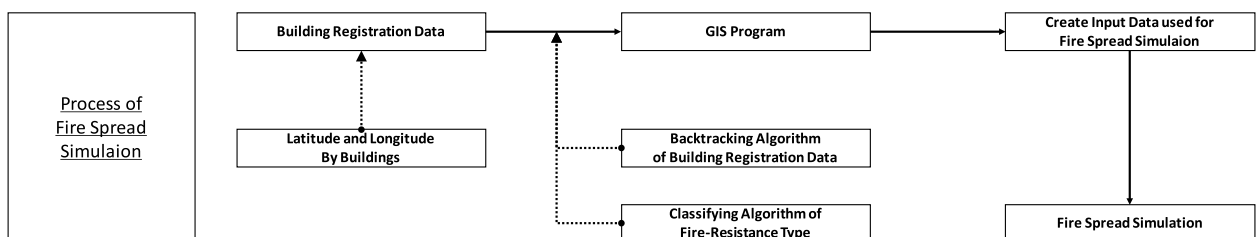
Fig. 8. Process of fire-spread simulation.

Utilized SW: QGIS 3.28.3, URL: https://www.qgis.org

(a)   (b)
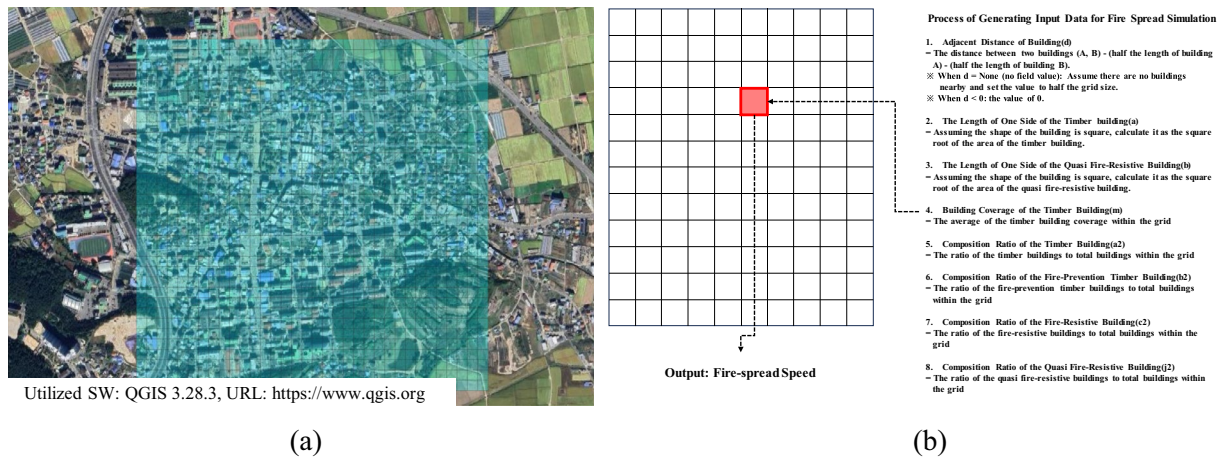
Fig. 9. Grid and input data for calculating fire-spread speed; (**a**) created grid in target region, (**b**) process of generating input data for calculating fire-spread speed (url: https://www.qgis.org).

thereby accurately representing the characteristics of the actual target area and achieving high accuracy in the results. However, the process of modeling the target area is time-consuming. Additionally, if the building density in the target area is low or the building information is missing, fire spread to adjacent buildings does not occur. Therefore, in this study, fire spread simulation was conducted for the N-O in Pohang City, where an actual earthquake had occurred. Considering that higher building density facilitates fire spread, the simulation was limited to the most densely populated urban area within the N-O in Pohang City. To calculate the fire-spread rate in grid units for the target region, it was divided into grids of a uniform size as shown in Fig. 9a. Next, as shown in Fig. 9b, a GIS program was used to generate GIS-based input data for the fire-spread rate by creating simulation input data for the fire spread. These data included proximity distance between the buildings, the length of one side of the timber structure buildings), and the length of one side of quasi-fire-resistant structure buildings. The generated input data for the fire-spread simulation, including the coordinates of the target region and fire-spread rate, are summarized in Table 10.

The fire-spread speed over time was calculated using the GIS-based input data, adjacent distance between the buildings, and length of one side of the timber structure, and Eq. (16)[8]:

$$V(t) = \frac{V_f}{1 + \left\{1.3 - 0.3 exp(-0.3t)\right\}\left(\frac{V_f}{V_0}\right)exp\left\{-\left(\frac{0.5 V_f}{V_f - V_0}\right)t\right\}}, \tag{16}$$

where, V_0 is the initial burning velocity and V_f is the final burning velocity.

The initial and final burning velocities used in Eq. (16) were calculated using Eqs. (17) and (18), respectively[9]:

Grid size (m)	Set coordinate		Number of created cell	Result of created input data for simulation	
	X	Y		List of input data	Number of creation
20	Min 410,893 Max 411,893	Min 291,914 Max 292,914	2,601	Adjacent distance between the buildings (d)	2,601
				One side length of buildings of timber structure (a)	196
				One side length of buildings of quasi-fire-resistant Structure (b)	0
				Building coverage of buildings of timber structure (m)	196
				Composition ratio of buildings of timber structure (a2)	946
				Composition ratio of buildings of fire-preventative timber (b2)	946
				Composition ratio of buildings of fire-resistant (c2)	946
				Composition ratio of buildings of quasi-fire-resistant (j2)	946

Table 10. Result of created the input data of fire spread simulation. *When create input data, The set coordinate system is EPSG:5174.

$$V_0 = \delta \times g(h)\left(1 - c'\right), \tag{17}$$

$$V_f = \frac{V_u + exp\{-50(k - 0.14)\}V_t}{1 + exp\{-50(k - 0.14)\}}, \tag{18}$$

where, δ is the burning velocity.

The burning velocity used in Eq. (18) was calculated using Eq. (19)[9]:

$$\delta = \frac{\frac{\left\{\gamma(U)\left[a\left(a'^{V_w}+b'^{V_j}\right)+b''_j V_j\right]+(a+2.6)d'V_c\right\}}{(a'+b'+c'+j')} + \frac{\gamma(u)\left[d(a'+b')\{(a'+b')V_{nn}+j'V_{nj}\}+2(d-1.3)(a'+b')d'V_{nc}+(d-2.6)d'^2 V_{cc}\right]}{(a'+b'+c'+j)^2}}{\frac{(a+d)(a'+b'+d')+(b+d)j'}{(a'+b'+c'+j')}}, \tag{19}$$

where, a and b are the length of building; d is the adjacent distance of buildings; a', b', c', d' and j' are the area ratios of the building; V_w, V_c, V_m and V_j are the burning velocities of the building; and V_{nn}, V_{nc}, V_{cc} and V_{nj} are the burning velocities between the buildings.

Fire-spread simulations were conducted based on the grid unit fire-spread speed, calculated using Eqs. (16)–(19), and the results are presented in Fig. 10. The simulation revealed that the burned area of the target location was 16,800 m². The burned rates, which are the ratio of the burned area to the area of the target region or regional unit, were 1.65% and 0.02% for the fire-spread simulation target region and the regional-level, respectively. The fire-burned rate was calculated using Eqs. (20) and (21):

$$R_{sim} = \text{BA}/S_{sim}, \tag{20}$$

$$R_{reg} = \text{BA}/S_{reg}, \tag{21}$$

where, R_{sim} is the burned rate per the area of target region; R_{reg} is the burned rate per the area of administrative region; BA is the burned area derived through fire-spread simulation; S_{sim} is the area of target region set for fire-spread simulation; and S_{reg} is the area of administrative region.

In this study, S_{sim} and S_{reg} were set to 1,020,100 m² and 105,720,000 m², which are the area of the simulation target area and the area of Pohang City N-O, respectively. To validate the proposed FFE risk assessment method, the results for Pohang City N-O, calculated as per the process explained in "Assessment of regional-level FFE

Utilized SW: QGIS 3.28.3, URL: https://www.qgis.org

(a)

Utilized SW: QGIS 3.28.3, URL: https://www.qgis.org

(b)
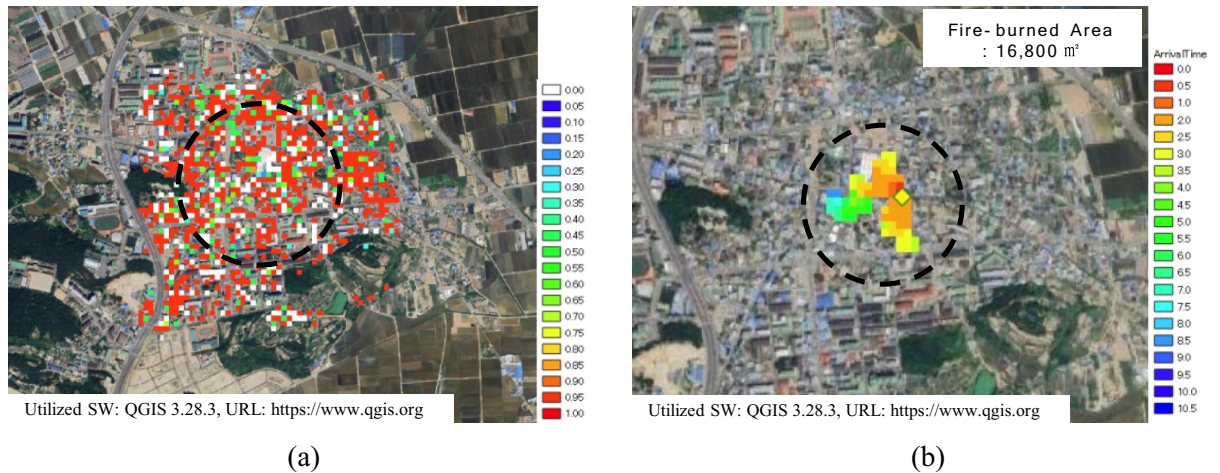
Fig. 10. Result of fire-spread simulation, (**a**) composition ratio of quasi-fire-resistant structures, (**b**) fire-burned area in target region (url: https://www.qgis.org).

Region	Area (m²)	Results of FFE risk assessment				Error between results of each model (%)
		The proposed FFE risk assessment method		Fire spread simulation		
		Fire-burned area (m²)	Fire-burned rate (%)	Fire-burned area (m²)	Fire-burned rate (%)	
O, North, Pohang	Target region for simulation	1,020,100				
		13,703.6	1.34	16,800.0	1.65	18.43
	Region area	105,720,000				
			0.01		0.02	18.24

Table 11. Comparison results between the proposed FFE risk assessment methodology and fire spread simulation.

risk" were extracted for the selected area. The ratio of fire-burned area in the extracted region was compared with that from the fire-spread simulation and presented in Table 11. The proposed FFE risk assessment method resulted in a burned area of 13,703.6 m^2 in the target region. The ratios of the fire-burned area computed from the proposed method to the target region area and the Pohang City N-O area are 1.34% and 0.01%, respectively. The differences of the fire-burned area between the fire-spread simulation and the proposed FFE assessment method for the target region and the Pohang City N-O were 18.43% and 18.24%, respectively. The variations between the proposed method and fire spread simulation were due to the differences in the main variables considered by each analysis method, which affected the fire-burned area. The results of the proposed method were governed by the characteristics and number of clusters, which were determined by the fire-resistant types and the adjacent distance between buildings. However, the results of the fire spread simulation highly depended on the building densities in the target region. The difference between the results obtained by applying the proposed FFE risk assessment method and fire-spread simulation is marginal. However, the FFE risk assessment methodology proposed in this study has only been validated in the N-O in Pohang City, where an actual earthquake occurred. To utilize this methodology for disaster preparedness in policy-making and urban planning, it is essential to apply and validate it in other regions and large cities beyond the N-O in Pohang City.

Conclusions

In this study, a new FFE risk assessment method was proposed to overcome the limitations of the existing methods and validate its feasibility. The ignition rate and fire-burned rate models of the FFE risk assessment methods proposed by previous studies were thoroughly analyzed. Based on the findings, a simple information-based FFE risk assessment method was proposed and applied to Pohang City, where an earthquake had occurred, to evaluate its regional FFE risk. Furthermore, the proposed method was validated by comparing it with the results of a fire-spread simulation. The key findings of this paper are as follows.

(1) The FFE risk assessment methods proposed by previous studies require large amounts of information (e.g., actual data related to the building, earthquake, fire and weather conditions) and complex modeling methodologies (e.g., FEMA's HAZUS-MH earthquake model and TFD model-based fire spread simulation). In contrast, the proposed method allows for rapid evaluation using simple information (e.g., PGA, construction year, story, building occupancy, structural material, and total floor area) based on clusters. Additionally, this methodology can contribute to developing rapid and rational preparedness strategies for FFE risks in the context of policy-making and urban planning.

(2) The public database established in South Korea does not differentiate the fire-resistant structure type of buildings. Therefore, a method for classifying the fire-resistant structure type of buildings was proposed based on simple information of building and the Building Act in South Korea. The proposed method enabled the classification of the building's fire-resistant structure types from construction year, story, building occupancy, structural material, and total floor area. Using this method, the fire-resistant structure types of buildings located in Pohang City were simply classified.

(3) To validate the proposed FFE risk assessment method, the number of regional-level ignitions was evaluated in Pohang, South Korea. Using the provided ignition rate estimation model, the evaluation of the number of regional ignitions yielded approximately three incidents (2.786 incidents). This agreed well with the actual reported number of ignitions (four incidents)[1] in the actual Pohang earthquake.

(4) Using the fire-burned rate estimation model proposed in this study, the regional FFE risk in Pohang City was evaluated. The areas with the highest building density, Pohang City N-C and N-L (25.19% and 35.04%, respectively) showed the highest risk levels (rates of the burned total floor area are 4.82% and 1.61%, respectively), while the regions with the lowest building density, Pohang City N-M and N-B (0.10% and 0.24%, respectively), were rated as having the lowest risk levels (rates of the burned total floor area are 0.01% in both regions). In regions with similar building densities (e.g., S-B and S-F in Pohang city, densities are 0.94% and 0.87%, respectively), a higher ratio of timber structures (25.80% and 23.02%, respectively) tended to be associated with a higher level of risk assessment (rates of the burned total floor area are 0.11% and 0.02%, respectively). The evaluation of regional FFE risk revealed that the FFE risk was influenced by the density of buildings and type of fire-resistant structure in a complex manner. This indicates that FFE risk can be varied depending on building characteristics. Utilizing the methodology proposed in this study, it can contribute to the development of rapid and rational disaster preparedness strategies, such as allocating additional firefighting resources to high-risk areas or determining priority response orders.

(5) The FFE risk assessment method developed in this study was validated by conducting fire-spread simulations on Pohang City N-O from which the fire-burned area and fire-burned rate of the target region were calculated. The results obtained through the proposed FFE risk assessment method (total burned floor area, burned rate compared to the area of the target region, and burned rate compared to the area of Pohang City N-O were 13,703.6 m^2, 1.34%, and 0.01%, respectively) were compared with the results from the fire-spread simulation (with the corresponding results being 16,800 m^2, 1.65%, and 0.01%, respectively). It was confirmed that the discrepancy between the two was not significant. The fire-burned rate compared to the area of the target region and fire-burned rate compared to the area of Pohang City N-O showed differences of 18.43% and 18.24%, respectively. Thus, the FFE risk assessment method proposed in this study yielded results similar to those from the fire-spread simulation.

(6) Based on a series of research processes, it was confirmed that the FFE risk assessment methodology proposed in this study allows for rapid evaluation compared to existing FFE assessment methodologies and produces reliable results for the N-O in Pohang City, where an actual earthquake occurred. However, the primary purpose of this study is to propose a methodology that can rapidly evaluate FFE risk using simple

information. To utilize this methodology for disaster preparedness, it is essential to ensure the reliability of the data used in the evaluation process and to further demonstrate the methodology on various regions.

Data availability

References

1. Ministry of the Interior and Safety, MOIS. *Pohang Earthquake White Paper*. 158–159 (2018).
2. Lee, *et al.* Fire following earthquake—Reviewing the state-of-the-art of modeling. *Earthq. Spectra* **24**(4), 933–967 (2008).
3. Federal Emergency Management Agency (FEMA). *Hazus Earthquake Model Technical Manual, Hazus 4.2 SP3*. 9-1–9-8 (Federal Emergency Management Agency, 2020).
4. Cabinet Office. *Regarding Damage Estimation Methods Related to an Earthquake Directly Hitting the Tokyo Metropolitan Area* (首都直下地震に係る被害想定手法について), *Japan* (2022).
5. Federal Emergency Management Agency (FEMA). *Hazus Earthquake Model Technical Manual, Hazus 4.2 SP3*. 9-1–9-11 (Federal Emergency Management Agency, 2020).
6. Hamada, M. *On Fire Spreading Velocity in Disasters, Sagami Shobo, Tokyo* (in Japanese) (1951)
7. Hamada, M. *Fire Resistant Construction, Akira National Corporation* (in Japanese) (1975)
8. Tokyo Fire Department (TFD). Development of disaster prevention evaluation and countermeasure technology in urban development, disaster prevention and urban development general professional committee (まちづくりにおける防災評価•対策技術の開発, 防災まちづくり総プロ全体委員会).155–280 (Tokyo Fire Department, 2005).
9. Cabinet Office. Guidelines for local governments regarding the designation of "areas where efforts should be made to eliminate dangers such as the occurrence and spread of electrical fires during earthquakes, etc.(地震時等の電気火災の発生•延焼等の危険解消に取り組むべき地域」の指定に関する地方自治体向けガイドライン), Japan (2018).
10. Ministry of Land, Infrastructure, Transport and Tourism, MLIT. Development of disaster prevention evaluation and countermeasure technology in town development (disaster prevention town development general professional) report (まちづくりにおける防災評価対策技術の開発(防災まちづくり総プロ)報告書), Ministry of Land, Infrastructure, Transport and Tourism, MLIT, Japan. 11–36 (2005).
11. Himoto, K. & Tanaka, T. A preliminary model for urban fire spread. In *Proceedings, 15th Meeting of The United States-Japan Cooperative Program in Natural Resources* (UJNR) *Panel on Fire Research and Safety* (Bryner, S. L. ed.). Vol. 2. 309–319 (National Institute of Standards and Technology, 2000).
12. Himoto, K. & Tanaka, T. A physically based model for urban fire spread. In *Proceedings, 2nd Workshop of US-Japan Cooperative Research for Urban Earthquake Disaster Mitigation, Fire Safety Science.* Vol. 7. 129–140 (2003).
13. Kato, T. *et al.* Integrated earthquake fire risk evaluation based on single building fire probability applicable to all map scales. *J. Nat. Dis. Sci.* **28**(2), 61–72. https://doi.org/10.2328/jnds.28.61 (2006).
14. General Insurance Rating Organization of Japan (GIROJ). Development of earthquake fire spread risk assessment method considering urban area characteristics (市街地特性を考慮した地震火災の延焼危険評価手法の開発), General Insurance Rating Organization of Japan (GIROJ), Japan (2005).
15. Zhao, S., Xiong, L. & Ren, A. A spatial-temporal stochastic simulation of fire out-breaks following earthquake based on GIS. *J. Fire Sci.* **24**, 313–339 (2006).
16. Ren, A. & Xie, X. The simulation of post-earthquake fire-prone area based on GIS. *J. Fire Sci.* **22**, 421–439 (2004).
17. Scawthorn, C. *Simulation modeling of fire following earthquake. In Proceedings, 3rd National Conference for Earthquake Engineering* 676–685 (Charleston, 1986).
18. Scawthorn, C. *Fire Following Earthquake* 104–112 (American Society of Civil Engineering, 2005).
19. Kawasmi, H. *Examination of Earth-quake-Fire Damage in Tokyo Metropolis.* (Tokyo Fire Department, 1961).
20. Tokyo Fire Department (TFD). Development of disaster prevention evaluation and countermeasure technology in urban development, disaster prevention and urban development general professional committee (まちづくりにおける防災評価•対策技術の開発, 防災まちづくり総プロ全体委員会). 15–18 (Tokyo Fire Department, 2007).
21. Federal Emergency Management Agency (FEMA). *HAZUS®99 Technical Manual. Developed by the Federal Emergency Management Agency Through Agreements with the National Institute of Building Sciences. Washington DC.* 1–732 (1999).

Acknowledgements

Author contributions

Conceptualization, J.S. and H.K.; investigation, T.K., J.S. and H.K.; data curation, T.K. and J.K.; illustration of figures, T.K. and J.K.; data analysis, T.K. and K.L.; data simulation, T.K. and H.K.; writing—original draft preparation, J.K., T.K. and J.S.; and writing—review and editing, K.L. and J.S.;

Competing interests

The authors declare no competing interests.

Additional information