13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2240

DEVELOPMENT OF SEISMIC RISK ASSESSMENT METHOD REFLECTING BUILDING DAMAGE LEVELS
-FRAGILITY FUNCTIONS FOR COMPLETE COLLAPSE OF WOODEN BUILDINGS-

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SUMMARY

To protect human lives from earthquake disaster is essential for disaster management. In the case of the 1995 Hyogo-ken Nanbu Earthquake, especially, the completely collapsed building without survival space was a major killer. Therefore, it is an important issue to reveal how many buildings are facing such a risk and how to deal with it. However, there was not enough data to clarify t---he factors of occurrence of completely collapsed buildings. Although many organizations investigated the building damage after the Hyogo-ken Nanbu Earthquake and classified such as "major damage" and "moderate damage", these categorized data definitions did not reflect the different types of building damage patterns.

In this paper, a seismic risk assessment method using fragility functions reflecting damage levels of buildings focused on the completely collapsed damage, was developed. Firstly, building damage patterns were classified using more than 14,000 photographs linked to a GIS database, which was archiving the digital data on the disaster process at the Hyogo-ken Nanbu Earthquake. The completely collapsed buildings were also detected in this classification. Secondly, the relationship among the building damage patterns and the intensity of seismic ground motion, and building characteristics such as the building construction year were analyzed. Finally, a set of the fragility functions with consideration of the building characteristics was developed based on the above analysis. The distribution of completely collapsed buildings due to the Hyogo-ken Nanbu Earthquake was also reconstituted using the fragility functions. It will be a useful tool for first aid to help locate the possible search and rescue area given by a shaking intensity distribution.

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INTRODUCTION

"To save life" is the top priority of countermeasures on disaster reduction. To mitigate human damage at the time of an earthquake, the fact that among 5,500 fatalities, more than 80% were reported to be caused by collapse of buildings in the 1995 Hyogo-ken Nanbu Earthquake should be paid attention. As reported by Lu *et al.* [1], in the case of Nishinomiya City, Hyogo prefecture, 84.6% of the fatalities was caused by the building damage patterns of “complete collapse” with loss for survival space (see **Figure 1**).

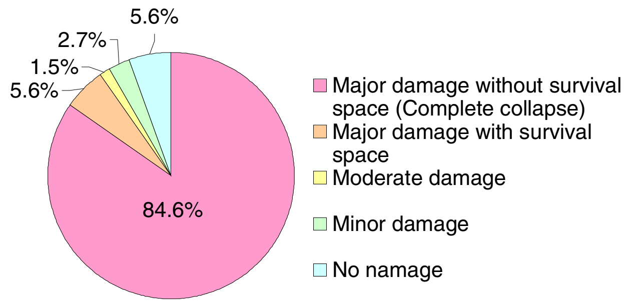


Figure 1: Percentage of human casualties by building damage level (Lu *et al.* [1])

To mitigate human casualties, first of all, occurrence of such complete collapse of buildings has to be prevented. Additionally, an establishment of countermeasures for rapidly life saving activities in case such a disaster happens should be prepared beforehand. In order to implement such two-staged measures, it is an important issue for us to clarify the occurrence mechanism of complete collapse of buildings and evaluate the area and buildings facing such a high risk accurately beforehand.

Fragility functions are one of effective tool for evaluation of building damage occurrence. There are several studies on the formulation of fragility functions; most of them are statistical fragility functions obtained from actual earthquake damage survey result. However, few damage surveys used for the base were performed focusing on complete collapse. The reason was that building damage survey results used to obtain such fragility functions after an earthquake did not include "complete collapse" in their classification categories of damage level, and “complete collapse” was classified into categories such as "major damage" or "moderate damage".

Maki *et al.* [2] performed analysis on building damage status for those buildings evaluated as "major damage" in the Hyogo-ken Nanbu Earthquake, and clarified that "major damage" covered a variety of damage patterns ranging from completely ruined to debris to seemingly slight damage. Lu and Miyano [3] pointed out that there was little significant correlation in the relationship between human casualties and indices of building damage extent such as the number of major damaged buildings and the ratio of major damage. As a factor of such phenomenon, it is indicated that the definition of "major damage" was not clear as described above.

Therefore, not only for the estimation of human casualties, but for other estimations such as the volume of debris, the number of buildings to be demolished and the number of refugees, a damage evaluation based on specific damage levels rather than indices such as "major damage/moderate damage" will be needed to promote countermeasures on disaster reduction in the future.

This paper aims to develop a method that accurately estimates and evaluates building damage beforehand to establish countermeasures to mitigate building damage which was a main factor of human casualties. For this purpose, building damage levels are classified using photos of damaged buildings taken at the time of the earthquake disaster. Especially, complete collapse of wooden buildings that caused most of fatalities during the Hyogo-ken Nanbu Earthquake are focused on, and the relationship among the occurrence of complete collapse, intensity of seismic ground motion and building attributes, such as year of construction, is analyzed to reveal the occurrence mechanism. From the result, fragility functions to estimate the occurrence of complete collapse is also formulated. Finally, the applicability of the formulated fragility functions is verified.

IDENTIFICATION OF COMPLETELY COLLAPSED BUILDINGS

In this chapter, completely collapsed buildings in the 1995 Hyogo-ken Nanbu Earthquake are identified from photos of building damage. The features of completely collapsed building damage patterns and their spatial distribution are also investigated.

Nishinomiya Built Environment Database

Earthquake Disaster Mitigation Research Center, National Research Institute for Earth Science and Disaster Prevention (EDM/NIED) are now developing a GIS database on the Hyogo-ken Nanbu Earthquake "Nishinomiya Built Environment Database (further referred to as Nishinomiya BEDB)" targeting Nishinomiya City, Hyogo prefecture (Lu *et al.* [4], Kohiyama *et al.* [5]). **Figure 2** shows the location of Nishinomiya City. In this area, the Architectural Institute of Japan (AIJ) and City Planning Institute of Japan (CPIJ) [6] (further referred to as AIJ & CPIJ) conducted building survey for mainly academic interest. The result of survey was recorded by BRI [7]. The distribution of major damage rate obtained from investigation by AIJ&CPIJ is also shown in **Figure 2**. Nishinomiya City covers an area that suffered relatively slight damage and the area that suffered considerable damage with JMA seismic intensity 7.0 at the time of the Hyogo-ken Nanbu Earthquake.

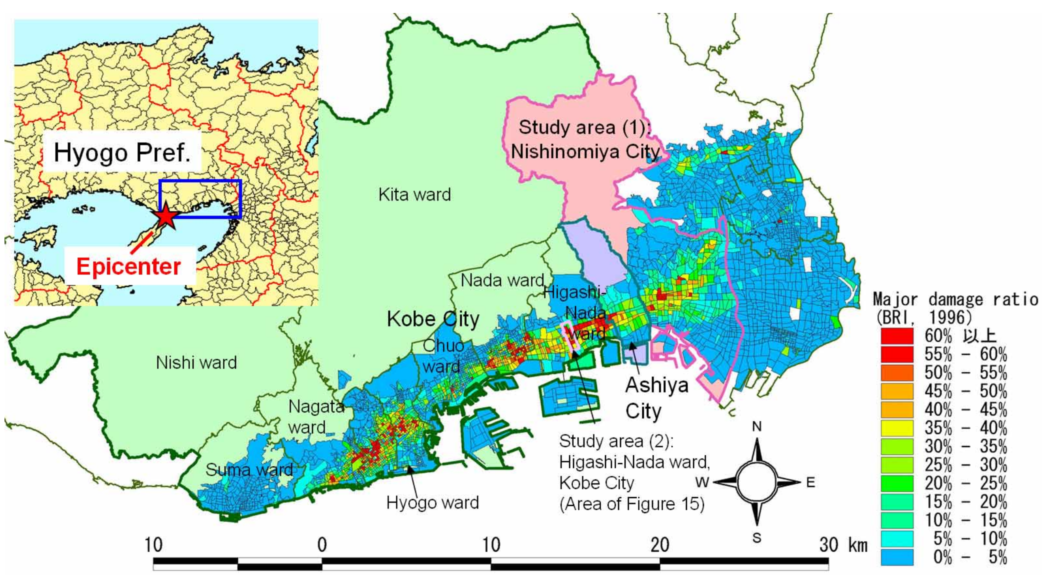


Figure 2: Target area of the Nishinomiya Built Environment Database

Figure 3 shows general configuration of Nishinomiya BEDB. In the database, there are 96,176 buildings. The data such as building attributes, human casualties, building damage survey results, photos of building damage are linked to each building. Among this data, building information data was provided by Nishinomiya City, and detailed information such as use type, structure type, number of stories, year of construction, building area, and floor area is linked. As damage image data, it contains 11,426 photos, which were taken at the time of the survey by AIJ & CPIJ, and records the locations and directions of taking point for each photo with an arrow mark. These photos cover 26,075 buildings. **Figure 4** shows an example of such photo data viewed on a GIS screen.

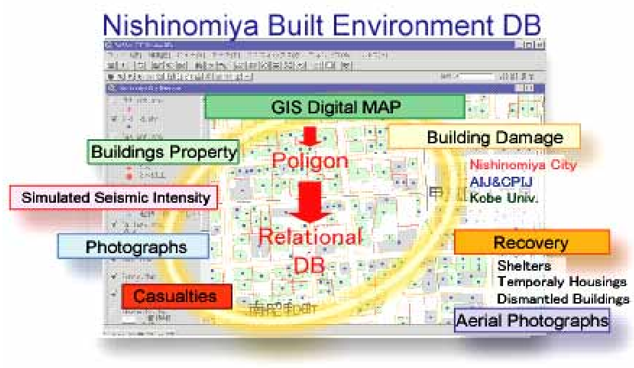


Figure 3: Configuration of Nishinomiya BEDB

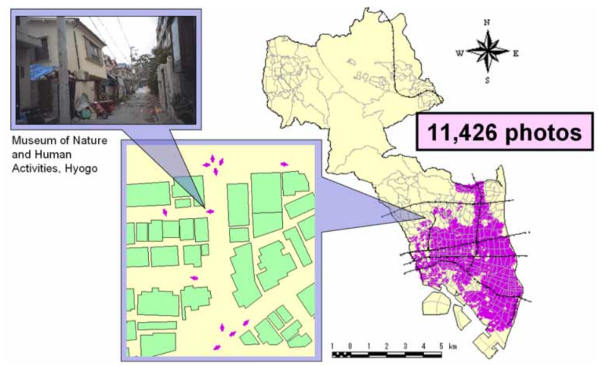


Figure 4: Photo Taking Points in the database

Identification Method of Completely Collapsed Building

For the Hyogo-ken Nanbu Earthquake, even though many damage surveys on building were performed by various agencies. However, there were few surveys that focused on completely collapsed buildings, and data on its occurrence mechanism was insufficient. Therefore, completely collapsed buildings in Nishinomiya City were identified using Nishinomiya BEDB by the former research (Horie *et al.* [8]). The complete collapses among 26,075 buildings recorded in photos of damaged buildings in the database were detected using three-stage method: 1) damage classification based on damage pattern chart proposed by Okada and Takai [9], 2) damage interpretation with aerial photograph, and 3) local interview survey to confirm damage. For the identification, completely collapsed buildings were defined as damage grade D5 or higher in damage pattern chart by Okada and Takai as shown in **Figure 5**. However, for patterns of Ud5+ and Ud5- with the complete collapse of the second story, detailed classifications were set based on lost volume of interior space. As the result, Pd5+ and Pd5- were defined newly.

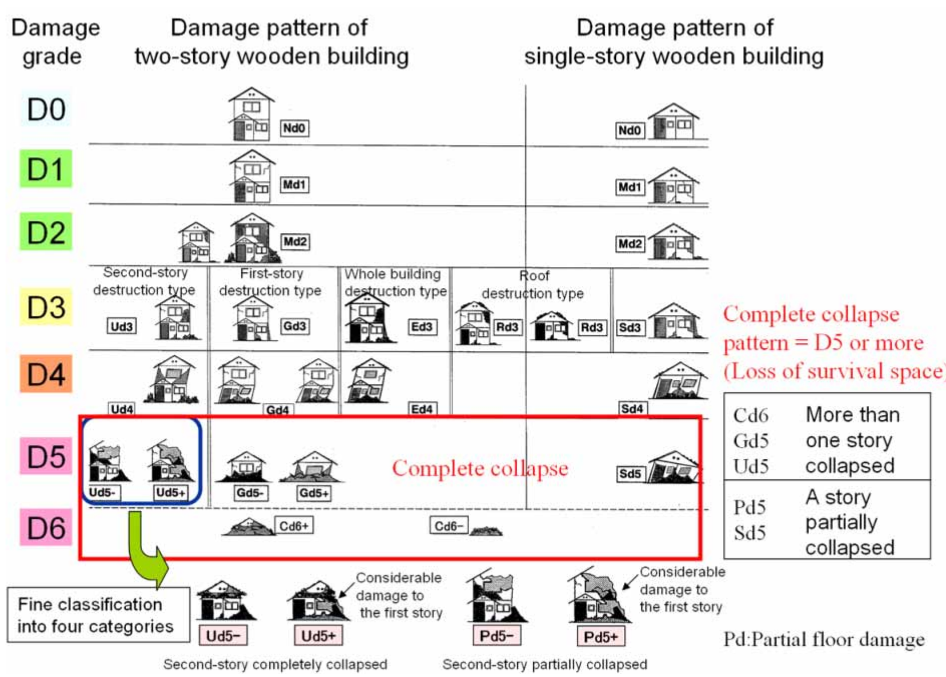


Figure 5: Building damage pattern chart for wooden buildings (Source: Okada and Takai [9])

Damage Patterns and Spatial Distribution of Completely Collapsed Buildings

As a result of the damage pattern classifications, among buildings recorded in photos in Nishinomiya City, 1,114 buildings were identified as the completely collapses. **Figure 6** shows details of the completely collapsed patterns. Pattern (Gd5) where the first floor of a two-story building completely collapsed represents the largest portion, the next was pattern (Cd6) with all stories completely collapsed. When these two are added up, it covers 89.1% of overall complete collapse.

Figure 7 shows the distribution of completely collapsed buildings and distribution of Peak Ground Velocity (PGV) obtained as an estimation result. The estimation of seismic ground motion distribution was performed by Kohiyama *et al.*[5] using Nishinomiya BEDB. As an overall trend, the completely collapsed buildings spread in an area with a large PGV, while complete collapse of wooden buildings occurred in an area with comparatively smaller seismic intensity. It was also revealed that the complete collapse of wooden buildings spread in a wider area compared with non-wooden buildings.

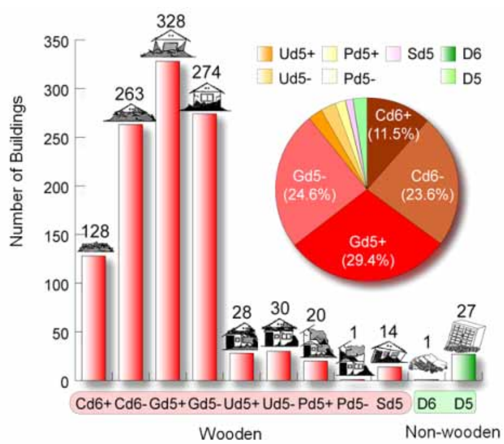


Figure 6: Identification result

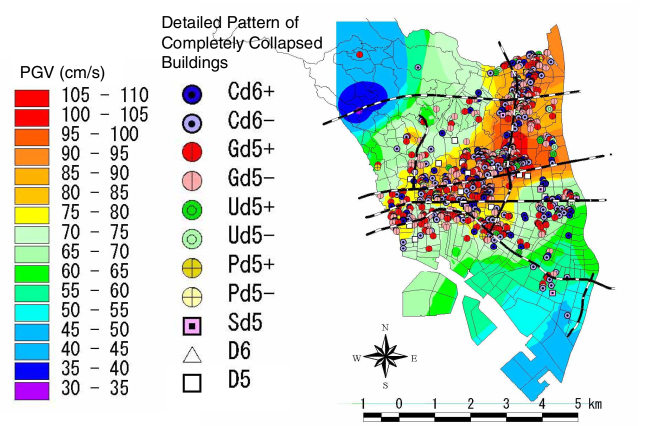


Figure 7: Distribution of completely collapsed buildings

INDICES OF SEISMIC MOTION INTENSITY TO FORMULATE FRAGILITY FUNCTIONS

In this chapter, the relationship between characteristics of seismic ground motion and complete collapse damage is analyzed to set an appropriate index of seismic ground motion intensity for formulation of fragility functions.

Data Set

As a result of complete collapse identification using damage photos, 97% of completely collapsed buildings in Nishinomiya City turned out to be wooden buildings. Therefore, the wooden buildings were focused on, and a data set was established to analyze the factors of occurrence of complete collapse. **Figure 8** shows the making flow of the data set. At first, 96,176 buildings in Nishinomiya BEDB were linked with seismic ground motion data by matching based on spatial analysis. The estimation of seismic ground motion distribution was made by interpolation. Therefore, as shown in **Figure 9**, an area surrounded by borehole points with higher reliability of analysis results was selected as analysis target area. Among 75,240 buildings in the target area, 32,825 wooden buildings with building attribute information were selected as analysis target buildings. From the data, 11,908 buildings with photo data were extracted as sample data. However, it is possible that they tended to take photos of building with significant damage or photogenic buildings. Horie *et al.* [8] confirmed that sample data extracted were not biased in terms of building attributes and building damage by means of chi-square test. **Table 1** shows outline of extracted data.

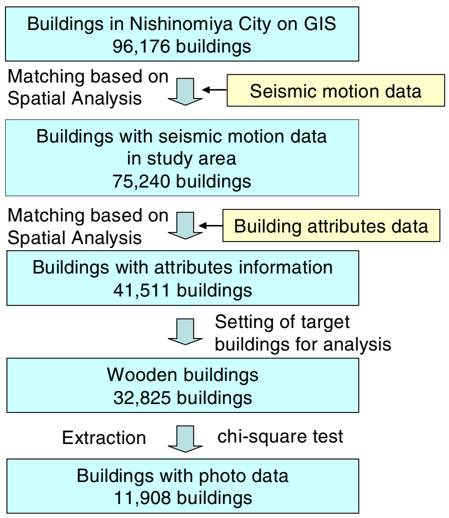


Figure 8: Making flow of data set for Analysis

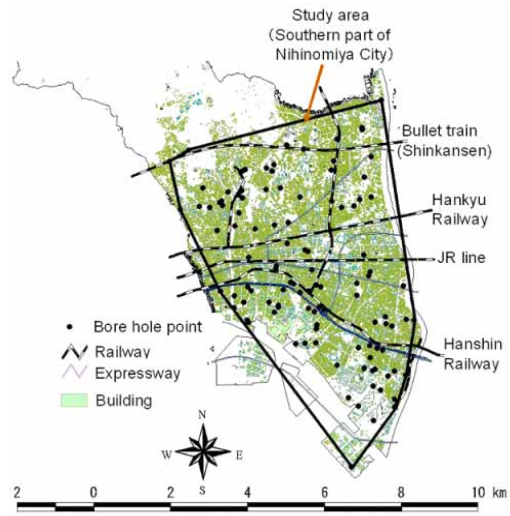


Figure 9: Study area for analysis

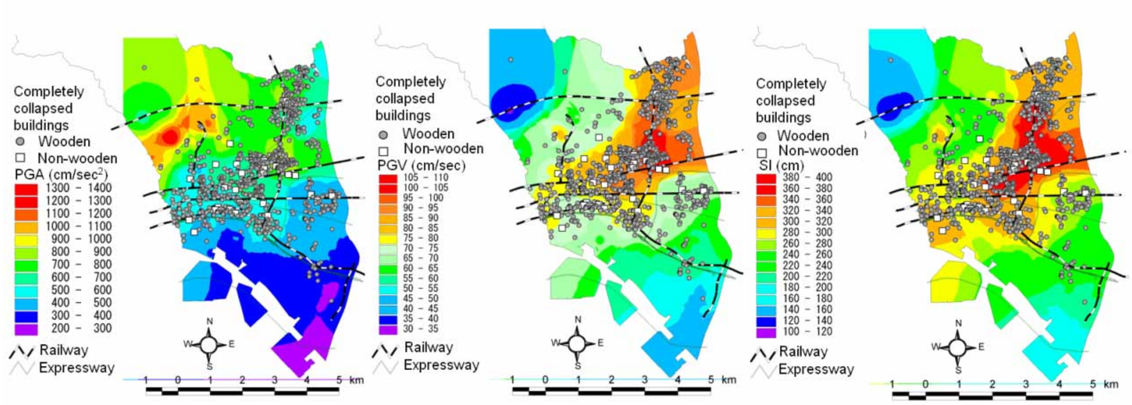
Table 1: Characteristics of data for analysis

Group of buiilding use type	Number of buildings	Average age of building (year)	Building size			Damage Assessment by Nishinomiya City
			Average number of stories	Average floor space (m2)	Average area ratio	Ratio of major damage (%)
Detached house	10645	26.6	2.0	71.6	1.8	35.0
Apartment house	802	26.9	2.0	158.0	1.9	53.9
Row house	181	37.6	1.8	159.9	1.7	41.4
Farmhouse	80	68.2	1.5	216.7	1.2	83.8
Building for commerce or industrial business	95	33.8	1.9	188.6	1.8	32.6
Others	105	35.3	1.5	291.7	1.4	12.4
Total	11908	27.2	2.0	82.6	1.8	36.5

Relationships between Indices of Seismic Motion Intensity and Complete Collapse Damage

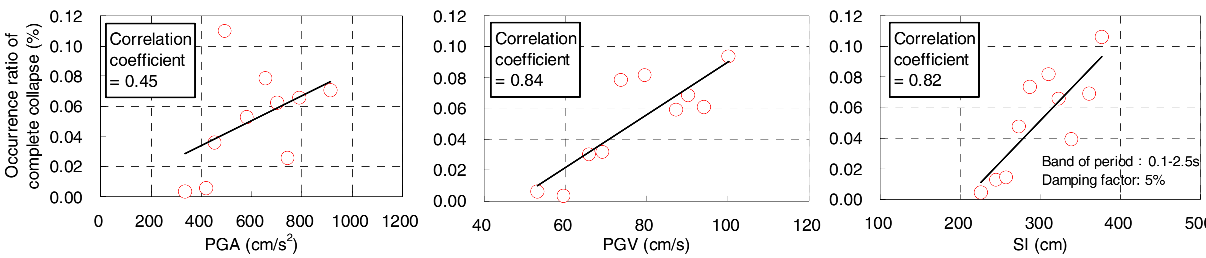
As indices to represent seismic motion intensity to formulate fragility functions, indices such as PGA (Peak Ground Acceleration), PGV, and SI (Spectrum Intensity) are usually used. **Figure 10** shows distributions of PGA, PGV and SI and distributions of complete collapse buildings. SI was obtained by integrating the velocity response spectrum in a band of period of 0.1 to 2.5 sec. The dumping factor was 5%. It was found that many complete collapses occurred in an area with a larger PGV and SI. PGA values were larger in northern mountainous area. However, the area with many complete collapses was different. To analyze the relationship in detail, the relationship between indices and ratio of complete collapse for 11,890 buildings were examined, excluding buildings that were not clear whether they had suffered complete collapse or not, out of 11,908 wooden buildings extracted as data set. **Figure 11** shows the relationship between each index of seismic ground motion intensity and the ratio of complete collapse. The each index value that represents each class is the mean value of buildings included in the class, and the ratio of complete collapse was obtained by dividing the number of completely collapsed buildings of each class by the total number of buildings. It was clarified that the correlation coefficient of PGV, SI and ratio of complete collapse in **Figure 11** correlated well. Therefore, it is possible to evaluate the occurrence of complete collapse using these indices.

With the above result in this study, since PGV features a higher correlation than PGA and it can be calculated more easily than SI, PGV was adopted as the appropriate index to formulate fragility functions.



(a) PGA(cm/s2) (b) PGV(cm/s) (c) SI(cm)

Figure 10: Distributions of indices of seismic intensity and completely collapsed buildings



(a) PGA(cm/s2) (b) PGV(cm/s) (c) SI(cm)

Figure 11: Relationship between indices of seismic intensity and occurrence ratio of completely collapsed buildings

CLASSIFICATION BASED ON CONSTRUCTION YEAR OF BUILDING

It is effective to create fragility functions that take seismic performance of a building into consideration. In the case of wooden buildings, it is desirable to use indices that directly evaluate seismic performance such as wall ratio and results of seismic diagnosis. For this purpose, however, detailed investigation inside of building is required. Additionally, it is quite difficult to obtain sufficient data for completely collapsed buildings since the completely collapsed buildings was already dismantled. In this chapter, relationship between the complete collapse damage and building information possessed by local government such as construction year and roof type is analyzed. The classification of buildings based on construction year is also established to formulate fragility functions with consideration of the above analysis.

Relationship between Complete Collapse Damage and Building Attributes of Wooden Buildings

The relationship between complete collapse damage and building information owned by local government were investigated by Horie *et al.* [8]. Results of the relationships between various building attributes and the ratio of complete collapse of building are summarized in **Table 2**. As a result, the following conclusions were obtained:

1) The older the year of the construction, the higher the ratio of complete collapse.
2) Ratio of complete collapse of buildings with tiled roof was higher than other types of roof materials.
3) Two-storied buildings tend to have higher occurrence ratio of complete collapse than single-story building.
4) The wider the building area, the higher the occurrence ratio of complete collapse.

5) Ratio of complete collapse of apartment house and farm house was higher than those of detached house, row house (terraced house), house used for commerce or industrial business and other houses (temples, attached house, warehouse, etc.).
6) Shape of building constituted one factor that caused complete collapse.
7) In the case of a two-story detached house, building attributes influenced damage patterns: first floor of a two-story building completely collapsed type, second floor of a two-story building completely collapsed type and all stories completely collapsed type.

In the above results, the construction year of a building had significant influence on occurrence of complete collapse; this can be used as a general index that represents seismic performance. In further discussion to formulate fragility functions, the relationship between the complete collapse damage and construction age of building are examined to set appropriate construction period segments.

Table 2: Occurrence ratio of complete collapse of wooden building consideration of building use type, structure type, roof type and building stories

Number of stories	Buiilding use type / Structure type (Roof type)	Detached house %	(Buildings)	Apartment house %	(Buildings)	Row house %	(Buildings)	Farm house %	(Buildings)	Building for commerce or industrial business %	(Buildings)	Others %	(Buildings)	Total %	(Buildings)
1	Conventional construction method (Tiled roof)	**4.0**	(29)	**7.1**	(1)	**0.0**	(0)	**25.6**	(10)	**0.0**	(0)	**0.0**	(0)	**4.9**	(40)
	Conventional construction method (Roof other than tile)	**1.7**	(1)	**-**		**0.0**	(0)	**-**		**0.0**	(0)	**4.3**	(2)	**2.5**	(3)
	Prefabricated house	**0.0**	(0)	**-**		**-**		**-**		**-**		**-**		**0.0**	(0)
	Subtotal	**3.9**	(30)	**7.1**	(1)	**0.0**	(0)	**25.6**	(10)	**0.0**	(0)	**3.8**	(2)	**4.6**	(43)
2	Conventional construction method (Tiled roof)	**5.1**	(399)	**14.7**	(97)	**7.0**	(8)	**23.1**	(9)	**17.9**	(7)	**0.0**	(0)	**5.9**	(520)
	Conventional construction method (Roof other than tile)	**0.7**	(9)	**11.3**	(12)	**0.0**	(0)	**-**		**2.9**	(1)	**12.5**	(5)	**1.7**	(27)
	Prefabricated house	**0.0**	(0)	**0.0**	(0)	**0.0**	(0)	**-**		**-**		**-**		**0.0**	(0)
	Subtotal	**4.3**	(408)	**14.0**	(109)	**5.6**	(8)	**23.1**	(9)	**11.0**	(8)	**9.8**	(5)	**5.2**	(547)
3 or more	Conventional construction method (Tiled roof)	**0.9**	(2)	**0.0**	(0)	**-**		**-**		**0.0**	(0)	**-**		**0.9**	(2)
	Conventional construction method (Roof other than tile)	**0.0**	(0)	**0.0**	(0)	**-**		**-**		**0.0**	(0)	**0.0**	(0)	**0.0**	(0)
	Prefabricated house	**0.0**	(0)	**-**		**-**		**-**		**-**		**-**		**0.0**	(0)
	Subtotal	**0.4**	(2)	**0.0**	(0)		(0)		(0)	**0.0**	(0)	**0.0**	(0)	**0.4**	(2)
Total		**4.1**	(440)	**13.8**	(110)	**4.4**	(8)	**24.4**	(19)	**8.4**	(8)	**6.7**	(7)	**5.0**	(592)

* Figures in parenthesis shows the number of completely collapsed buildings.

Complete Collapse Damage and Building Construction Years

Figure 12 shows the relationship between the ratio of complete collapse and the year of construction. The number of buildings differs considerably depending on the construction year, and the occurrence ratio of complete collapse fluctuated widely every year. Therefore, moving average line in five years including two years before and after construction is also plotted in **Figure 12**. As already discussed, the older the year of construction, the occurrence ratio of complete collapse tends to became higher. It gradually lowers from around 1960. **Figure 12** shows years of revision of the building law. Maki and Hayashi [10] analyzed the relationship between the year of construction and damage from the viewpoint of effectiveness of the building law. They pointed out that in the case of wooden buildings, the influence of the revision of building law was small and the damage rate gradually lowers. Their findings were in agreement with the trend of the above result.

From 1940 to 1960, the occurrence ratio of complete collapse was less rather; they were smaller than that of later years. **Figure 12** shows the number of buildings, use ratio of tiles for roofs and transition of the portion of buildings higher than two-story. Years from 1940 to 1960 were in special construction situation being a period during the war or a period after the war. The number of buildings during the period is rather small, with lower use of tiles for roofs, less two-story buildings and this resulted in relatively more single-story buildings. The influence of such a situation might be a factor in this trend. In this way, the factors other than building law that influenced the seismic performance of building must be considered.

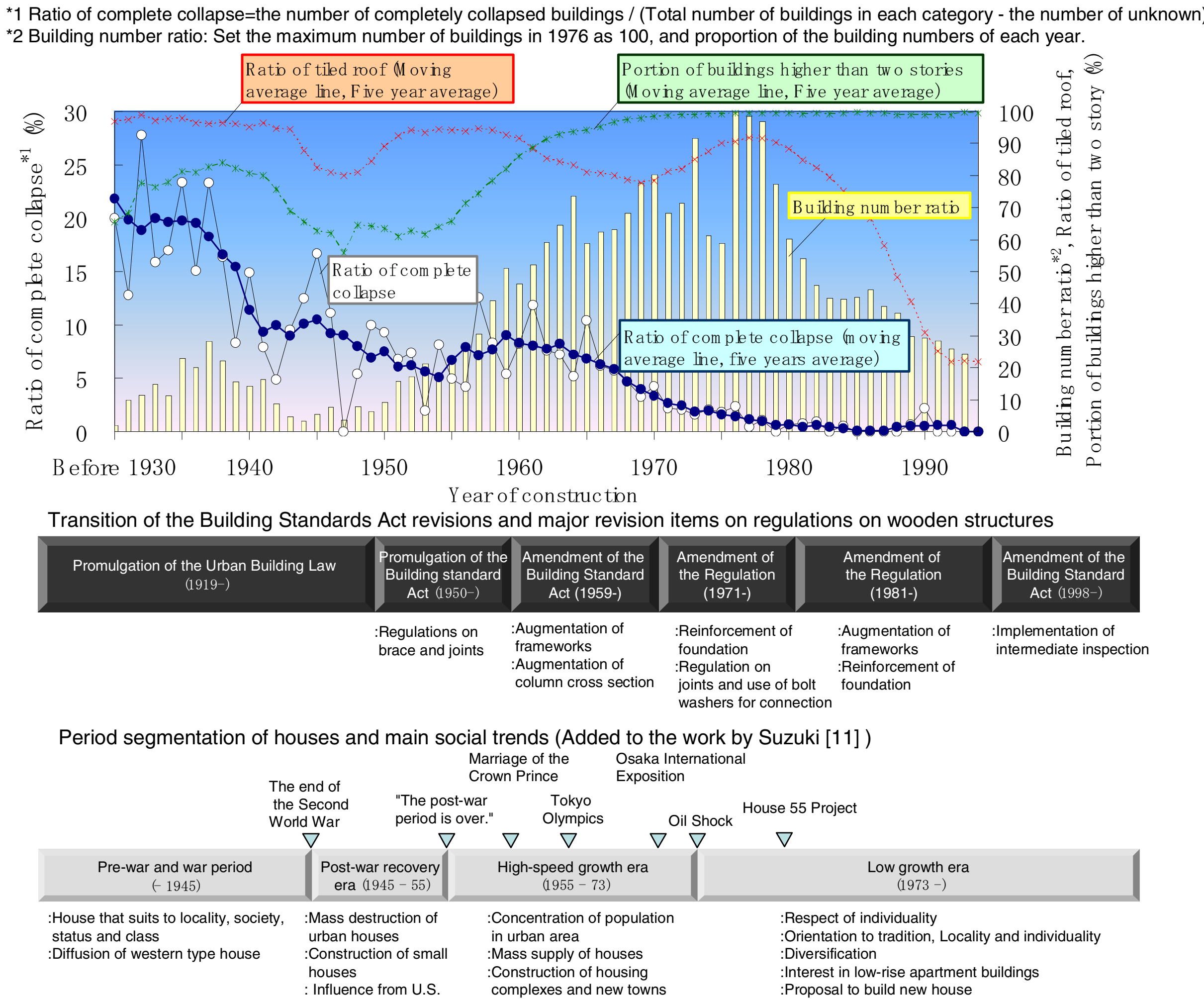


Figure 12: Relationship between construction year and occurrence ratio of complete collapsed

Classification of Construction Year

Suzuki [11] classified factors of change of house into three categories: 1) External influences (change of social situation, development of technology and contact with foreign culture), 2) Intrinsic demands (change of family configuration, change of requirement for housing and change of awareness regarding housing) and 3) Force of plans (artificial changes such as laws and regulations). Suzuki also classified transformation processes of houses after the Second World War into following three periods;

1) Post-war recovery era (1945 to 1955)
2) High-speed growth era (1955 to 1973)
3) Low growth era (since 1973)

Therefore, the above classifications were adopted basically to set the construction year period. The revisions of the building law were also considered to be a factor that influences transformation of houses with regard to seismic performance of building. As a result, seven categories of construction periods were set as shown in **Table 3**.

Table 3: Classification based on building construction year

Classification of the construction year	Items taken into consideration for setting
-1945	Pre-war and war period.
1946-1955	Post-war recovery era. The Building Standards Act was promulgated in 1950. However the numbers of buildings that fall in this period are too few to classify.
1956-1960	Earlier period of high-speed growth era. With the marriage of the Crown Prince in 1959, TV diffused at explosive pace and changed the role of mass media radically. With diffusion of TVs, the supply of unified information across the country was promoted and it is assumed that the notion regarding housing was influenced significantly. We also took the revision of The Building Standards Act in 1959 into consideration*.
1961-1964	Middle period of high-speed growth era. Tokyo Olympics in 1964 as a national project promoted significant urban infrastructure development and caused a rush of construction.
1965-1971	Later period of high-speed growth era. Until the period shifted to low-growth period with the oil shock, with Osaka International Exposition in 1970 in Kansai area, influence of economic growth rippled across the country. For segmentation, we took revision of The Building Standards Act in 1971 into consideration.
1972-1981	Earlier period of low-growth era. We took the revision of The Building Standards Act in 1981 into consideration. From 1980, promoted by both the Ministry of Construction and the Ministry of International Trade and Industry "House 55 Project" that aimed at the supply of high quality houses at reasonable prices was initiated.
1982-1994	Later period of low-growth era.

* Revision in 1959 was enforced from 23rd December. 1960 was its transition period and we set 1960 as a separating border.

DEVELOPMENT OF FRAGILITY FUNCTIONS CONSIDERING CONSTRUCTION PERIOD TO EVALUATE COMPLETE COLLAPSE

Method of formulation

As an assumption, the probability of occurrence of damage larger than D with certain seismic motion intensity can be expressed by lognormal distribution using cumulative probability distribution function of standard normal distribution. The fragility functions were formulated using following formula (1).

$$P_D(x) = \Phi\{(\ln(x) - \lambda)/\zeta\} \tag{1}$$

$P_D(x)$: Probability of occurrence of fragility function larger than D

(x) : Seismic motion intensity

$\Phi(x)$: Cumulative probability distribution function

λ : Mean value obtained by least squares method using probability paper

ζ : Standard deviation obtained by least squares method using probability paper

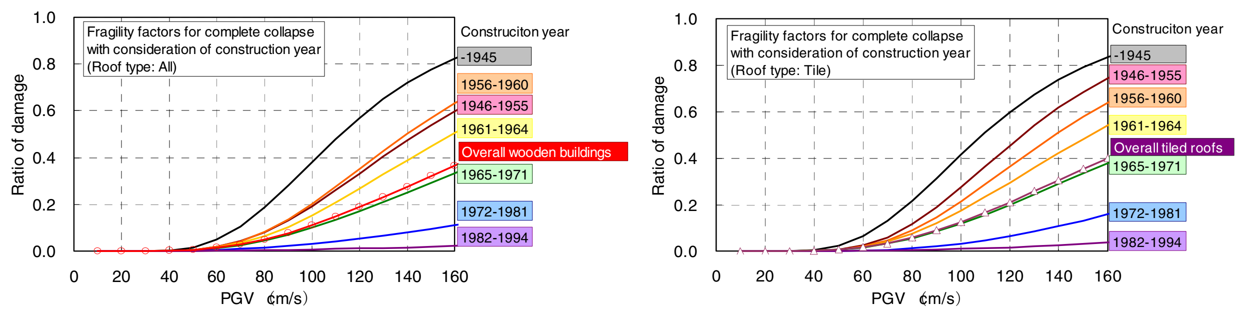
To formulate fragility functions, buildings were sorted according to the PGV, and unified with a certain unit. The number of buildings was included in each class to be equal in principle. PGV value that represent each class, mean value of buildings included in the class. Ratio of complete collapse is obtained by dividing the number of building of complete collapse for each class by the total number of buildings.

Fragility Functions Considering Construction Period

Fragility functions for complete collapse of wooden buildings with consideration of construction year were formulated. **Table 4** shows list of regression coefficient for each period. Coefficient of determination R^2 was low in new period after 1965. It is due to low occurrence of complete collapse in new buildings. **Figure 13(a)** shows fragility functions of for each formulated construction segment. With **Figure 13(a)**, the older the year of construction, the occurrence ratio of complete collapse grows higher. The relation between post-war recovery era (1946-1955) and the earlier period of high-speed growth era (1956-1960) looks reversed. The reason is that for buildings built during post-war years of recovery, apparent seismic performance had improved due to the influence of building attributes as pointed out before.

Fragility Functions with Consideration of Building Attributes other than the Year of Construction

As shown in **Figure 13(a)**, the relationship between post-war recovery era and the earlier period of high-speed growth era was reversed. The fragility functions taking roof type into consideration that was assumed to be the factor of this phenomenon were formulated. **Figure 13(b)** shows the fragility functions of tiled roof houses by building construction year. **Table 4** shows list of regression coefficient. When compared with **Figure 13(a)**, for all construction year segments, fragility functions of tiled roof showed higher damage occurrence rate than any other roof types. The relationship in post-war recovery era and in the earlier period of high-speed growth era is in the order of year. From this fact, the reduced use of tiled roof during post-war recovery era contributed to lower ratio of complete collapse occurrence for the period. The fragility functions by the number of stories and the purpose of building were also formulated. **Table 4** shows a list of regression coefficient.



(a) Roof type: all

(b) Roof type: Tile

Figure 13: Fragility functions for complete collapse of wooden building with consideration of building construction year

Table 4: Regression coefficient of fragility functions for complete collapse of wooden building

Structure type	Use	Number of stories	Roof type	Year of construction	Number of data	PGV (cm/s) λ	ζ	R^2
Wooden	All	All	All	All	11866	5.26	0.54	0.815
				-1945	1306	4.72	0.38	0.879
				1946-1955	604	4.97	0.42	0.668
				1956-1960	913	4.94	0.40	0.747
				1961-1964	1167	5.07	0.45	0.681
				1965-1971	2233	5.31	0.55	0.607
				1972-1981	3623	5.97	0.74	0.618
				1982-1994	2020	7.36	1.14	0.634
			Tile	All	9782	5.21	0.53	0.829
				-1945	1259	4.69	0.39	0.880
				1946-1955	545	4.83	0.37	0.785
				1956-1960	859	4.93	0.41	0.743
				1961-1964	990	5.03	0.45	0.678
				1965-1971	1776	5.24	0.54	0.620
				1972-1981	3228	5.62	0.54	0.673
				1982-1994	1125	6.52	0.81	0.797
		Two-storied	All	All	10325	5.23	0.52	0.784
			Tile	All	8744	5.18	0.51	0.802
	Detached house	All			10455	5.30	0.53	0.790
	Apartment house	All			789	4.91	0.51	0.745
Non-wooden	All				3608	6.12	0.69	0.580

SEISMIC RISK ASSESSMENT USING FRAGILITY FUNCTIONS OF COMPLETELY COLLAPSED BUILDINGS

In this chapter, spatial distribution of completely collapsed buildings in the Hyogo-ken Nanbu Earthquake is estimated using the formulated fragility functions. The estimated distribution is also compared the results with actual occurrences of completely collapsed buildings to verify the applicability of formulated fragility functions.

Application of fragility functions to Nishinomiya City

Firstly, the fragility functions are applied to Nishinomiya City. The Target area is the same as shown in **Figure 9**.

Estimation Method of Completely Collapsed Building

An estimate was performed according to procedures listed below. With procedure 1 and procedure 2, the complete collapse occurrence rate for each block unit is obtained as spatial distribution. Procedure 3 to procedure 5 is steps to estimate the complete collapse occurrence for each building.

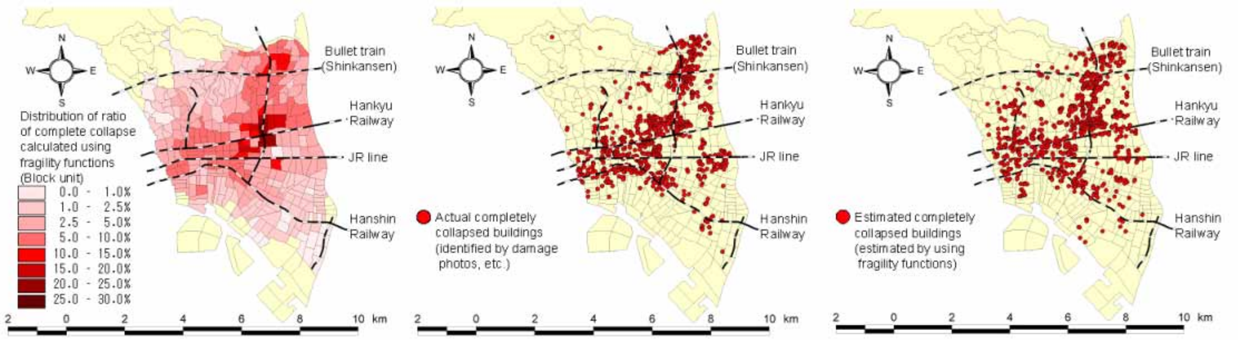
1) From PGV data input for each building, the probability of complete collapse occurrence is calculated for each building using fragility functions that corresponded to the year of construction.
2) By each block, the mean value of complete collapse occurrence probability for 1) is calculated.
3) By block unit, aggregate the probability of complete collapse occurrence of each construction period segment.
4) Multiply the occurrence ratio of complete collapse in each construction period, the number of buildings of each construction period in the block, to estimate the number of completely collapsed buildings in the block.
5) Assume the building with the highest complete collapse occurrence probability calculated for each respective building, in construction period segment in the block to be building with high risk of relatively complete collapse occurrence. The buildings are estimated from the building to buildings obtained by 4) are those with complete collapse occurrence.

Spatial Distribution of Occurrence Ratio of Complete Collapse

Figure 14(a) shows calculated distribution of occurrence ratio of completely collapsed wooden buildings by each block unit. **Figure 14(b)** shows building distribution of actual complete collapse identified using data such as damage photos. When **Figure 14(a)** and **Figure 14(b)** are compared in areas of each block unit calculated to be with a high probability of complete collapse risk, actually many complete collapses occurred. As to spatial distribution of complete collapse, it accurately estimated actual complete collapse occurrence area.

Estimation of Complete Collapse Building Distribution

From the above examination result, the validity of estimation of spatial distribution and the number of completely collapsed buildings as overall damage volume using fragility functions were confirmed. Here, the estimate accuracy of each building is evaluated. **Figure 14(c)** shows estimation result. When **Figure 14(b)** and **Figure 14(c)** are compared, estimate results spread in the area where actually many complete collapses were confirmed. In an area with rather smaller seismic intensity, it accurately estimated occurrences of complete collapse. However, in some cases, occurrence location for each building was different. Complete collapse fragility functions used to obtain the factors were those that took only year of construction period into consideration. However, in reality, even though the construction was old, there were many buildings that had sufficient seismic performance and were not subject to damage.



(a) Simulated distribution (Unit: block)　(b) Actual Distribution (Unit: buildings)　(c) Simulated Distribution (Unit: buildings)

Figure 14: Distribution of the completely collapsed buildings at Nishinomiya City

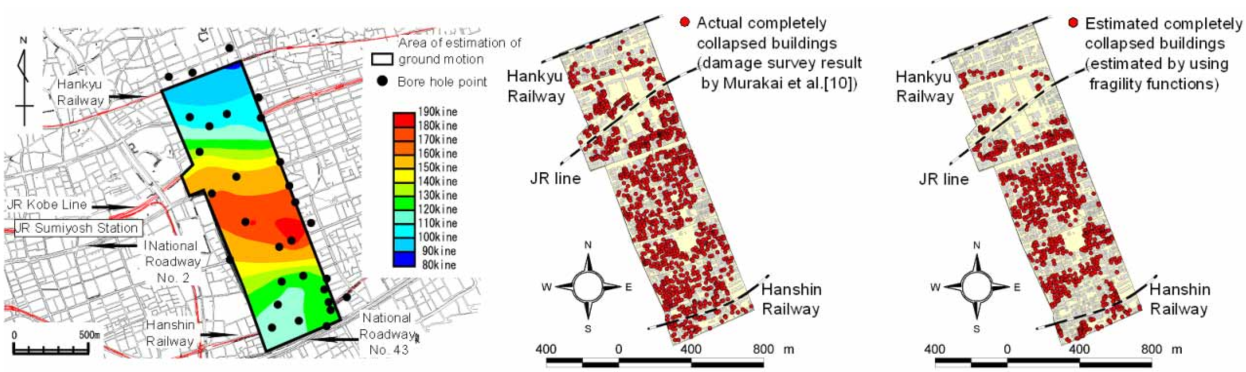
Application of fragility functions to Higashi-Nada ward, Kobe City

Used Data

In the previous chapter, the fragility functions for complete collapse formulated were applied by using data of Nishinomiya City to Nishinomiya City, and its validity were confirmed. The validity is needed to examine whether the function is also applicable to other areas. However, as discussed previously, there were few surveys that focused on completely collapsed buildings, and the areas were limited. Therefore, the fragility functions were applied to western part of Higashi-Nada ward, Kobe City, shown in **Figure 2**. where a damage survey was made by Murakami *et al*. [12]. **Figure 15(a)** shows the detail of the study area. For seismic ground motion data, the result of the distribution estimation performed by Okimura *et al*. [13] was used for the area. **Figure 15(a)** also shows calculated distribution of PGV.

Estimation of Completely Collapsed Buildings

Figure 15(b) shows distribution of completely collapsed buildings obtained by interpreting aggregation chart of survey results by Murakami *et al*. [12]. **Figure 15(c)** shows completely collapsed buildings estimated by the same method as in the previous chapter. When **Figure 15(b)** and **Figure 15(c)** were compared, the calculation result corresponds to an area where complete collapse occurred with that of a rather smaller seismic intensity and area where completely collapsed buildings were concentrated. However, as with the previous chapter, occurrence locations of respective buildings were different.



(a) Estimated seismic ground motion (Unit: block)　(b) Actual Distribution (Unit: buildings)　(c) Simulated Distribution (Unit: buildings)

Figure 15: Result of application of fragility functions for completely collapsed buildings to Higashi-Nada ward, Kobe City

CONCLUSIONS

In this paper, the building damage level was classified using photos taken at the time of the Hyogo-ken Nanbu Earthquake in 1995 and damage pattern charts. Then, the complete collapse of wooden buildings were focused on to clarify the reality of occurrence. The relationship among complete collapse occurrences, intensity of seismic ground motion and building attributes such as year of construction was analyzed. Based on these analysis results, the fragility functions were formulated. The applicability of fragility functions were also verified on Nishinomiya City, Hyogo prefecture and Nada ward, Kobe City, Hyogo prefecture. As a result, as to estimation of spatial distribution, sufficiently accurate result was obtained.

As to the estimates for respective buildings, even though this represented a complete collapse occurrence area and density fairly well, precise occurrence location could not be estimated. The major cause was that the fragility functions applied only took the year of construction of the building into consideration. Therefore, some extent of improvement of accuracy can be expected by using fragility functions for roof types and for number of stories, shown in **Table 4**.

However, with estimation accuracy verified in this study, when the damage estimation map of respective building shown in **Figure 14(c)** and **Figure 15(c)** is used as a reference for simulation to enhance countermeasures to be taken immediately after the disaster, the volume of information obtained from **Figure 14(c)** and **Figure 15(c)** is much larger when compared with those shown in **Figure 14(a)**, the spatial damage distribution assessment map. So it will be more useful for the formulation of a more concrete disaster reduction mitigation plan. An important issue learned from the Hyogo-ken Nanbu Earthquake is that for large-scale seismic damage with low frequency, our capacity to cope with disaster should be enhanced by means of preliminary simulations. Fragility functions formulated by this study allow easy building risk assessment. It will serve as a most effective tool to develop strategy: for example, where to dispatch limited resources of lifesaving units effectively immediately after a disaster. In future, the feasibility of whether the estimation accuracy obtained in this study can actually be used in a preliminary simulation to enhance the capacity of the administration to cope with such damage will be investigated in the "Search & Rescue Game" being developed by Kikkawa *et al.* [14].

To mitigate human casualties, it is essential to prevent the occurrence of damage such as complete collapse. And it is essential to promote seismic diagnosis of buildings and seismic retrofitting of existing buildings. The needs of inhabitants are to know whether their houses are secure against earthquake; if not, they want obtain information such as how they can make them secure, with how much cost, and what methods of reinforcement, and to which extent safety is warranted? There is an earthquake hazard map (risk assessment map) as an incentive to promote seismic diagnosis, seismic retrofitting, and, as a means of disclosure for inhabitants, Kobe City is now developing the Kobe City Earthquake Hazard Map to commemorate the decade after the Hyogo-ken Nanbu Earthquake. The result of this study will be reflected in the hazard map. The effectiveness of hazard map will be also examined.

For this purpose, the occurrence mechanism of complete collapse will be analyzed based on dynamical model to further improve accuracy of damage estimation aiming at development of seismic risk assessment methods applicable to other areas and other seismic damage.

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