FRAGILITY CURVES FOR BUILDINGS IN JAPAN BASED ON DAMAGE SURVEYS AFTER THE 1995 KOBE EARTHQUAKE

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SUMMARY

The 1995 Kobe Earthquake caused unprecedented damage in the Hanshin-Awaji area. Several coordinated damage surveys were conducted by groups of researches and engineers after the earthquake. Using these ample data of building damage due to the earthquake, the authors tried to develop fragility curves for damage assessment. First, an analysis of building damage due to the Kobe Earthquake was conducted using the building damage data surveyed by Nishinomiya City Government for the purpose of property tax reduction. Fragility curves for buildings in Japan which considered the structural type and construction period were created using the building damage data provided by Nishinomiya City and estimated ground motion indices. Note that the ground motion indices were estimated based on another building damage survey data in the Hanshin area compiled by the Building Research Institute and the recorded motions. Since of the quality and quantity of the data used, improved accuracy is expected for the obtained fragility curves compared with existing ones.

INTRODUCTION

The Hyogoken-Nanbu (Kobe) Earthquake directly struck the densely populated Kobe and its neighboring cities in the early morning of January 17, 1995 and caused huge losses to infrastructures and private properties. A large amount of data obtained in this earthquake should properly be analyzed for estimating and mitigating damage due to future seismic events. In order to evaluate the building damage in this area due to the Kobe Earthquake, it is important to estimate the distribution of earthquake ground motion. In the earthquake, scores of strong ground motion records were obtained in the heavily damaged area by several organizations. However, since they are still not enough in number for estimating the detailed spatial distribution of ground motion during the event, it is necessary to estimate the distribution using other data sources. The estimation of the distribution of earthquake ground motion in the affected area due to the Kobe Earthquake has been conducted by several researches. Midorikawa and Fujimoto [1996] estimated the distribution of the peak ground velocity (PGV) in Kobe and its neighboring cities using the overturning ratio of tombstones. Miyakoshi et al. [1998] estimated the distribution of PGV in the damaged area using the damage ratio of buildings in the district level. The present authors [Yamaguchi and Yamazaki, 1999] also

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estimated the distribution of the peak ground acceleration (PGA), PGV, the spectrum intensity (SI), and the instrumental JMA (Japan Meteorological Agency) intensity using the building damage data compiled by the Building Research Institute [BRI, 1996], the Ministry of Construction.

The data digitized by BRI are the results of the damage survey conducted by a group comprising members of the Architectural Institute of Japan (AIJ), the City Planning Institute of Japan (CPIJ) and Hyogo Prefectural Government [AIJ & CPIJ, 1995]. Although the BRI data are very useful, the inventory of buildings (structural type, construction period, etc.) is not associated with the data. Thus the estimated strong ground motion distribution might be affected, especially by the construction period of buildings in each district. Also the distribution was not estimated in some areas without enough number of buildings. Hence, in developing fragility curves considering detailed building information, it is desirable to re-estimate strong motion distribution using other building damage data containing inventory. For removing the influence from the distribution, the present authors created fragility curves for wood-frame buildings considering construction period using the building damage data surveyed by Nishinomiya City Government for the purpose of property tax reduction. Using these fragility curves, we re-estimated the distribution of strong motion indices in Nishinomiya City, based on the method as Murao and Yamazaki [1999a]

In the present paper, using the re-estimated strong ground motion distribution and the damage survey data by Nishinomiya City Government, fragility curves considering detailed building information are developed.

OVERVIEW OF BUILDING DAMAGE IN NISHINOMIYA CITY

Nishinomiya City is located in approximately 40km northeast of the epicenter of the Kobe Earthquake. A belt of intensity 7 in the JMA scale ran across the southern part of the city. The number of victims of the earthquake in Nishinomiya City was 1,114 dead and 6,386 injured. The death toll and the affected houses ranked second among the cities in the affected area [Nishinomiya City Government, 1996].

Table 1 shows the number of buildings in Nishinomiya City with respect to the structural type and construction period for three damage levels: heavy, moderate, and insignificant or no damage. This damage classification was used in reducing the property tax for the damaged buildings in proportion to damage degree: heavy (exemption of the property tax in the year of 1995), moderate (50% reduction), and others (10% reduction). Note that this damage classification is different from that of the BRI data [Murao and Yamazaki, 1999b]. The following items of inventory such as “district block”, “structural type”, “construction period”, “number of stories”, “roof type”, “use” and “spatial coordinate” are also provided together with the damage classification for each building.

Table 1: Number of buildings in each damage level with respect to the structural type and construction period due to the damage survey by Nishinomiya City

Structural					Total
Wood-Frame (W					14,016
					9,585
					16,323
					15,996
					12,072
					67,992
Wooden-Prefabri					1,571
Reinforced Conc					3,200
					3,413
					4,385
					10,998
Steel-Frame (S)					5,311
Light-gauge steel					4,481
Others		664	598	4,646	5,908
Total		24,807	17,381	54,073	96,261

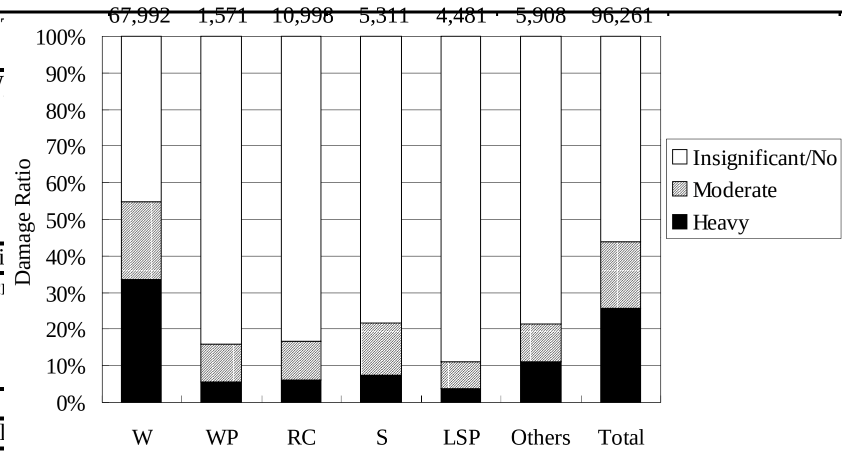


Figure 1: Damage ratio of buildings in Nishinomiya City for each structural type

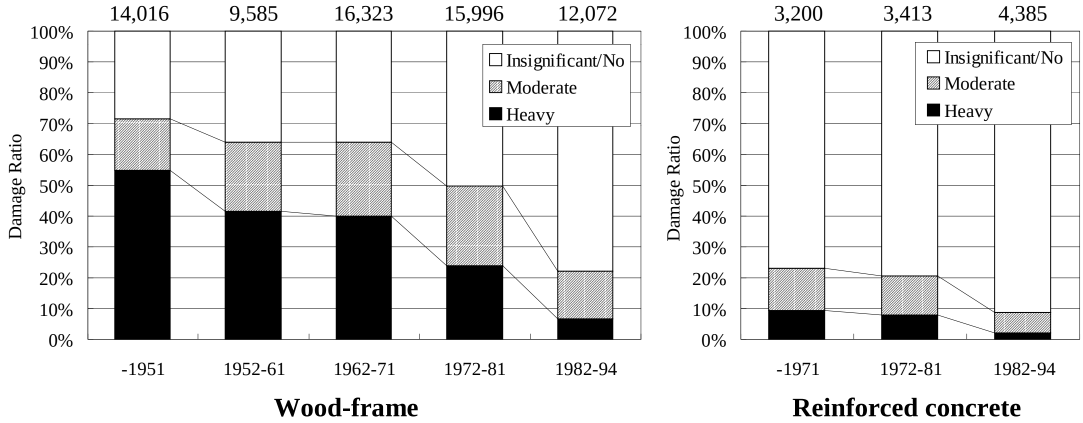


Figure 2: Damage ratio of wood-frame and reinforced concrete buildings in Nishinomiya City with respect to the construction period

The type of structures is classified into five categories: wood-frame (W), wooden-prefabricated (WP), reinforced concrete (RC), steel-frame (S), light-gauge steel-prefabricated (LSP). The others contain steel-frame reinforced concrete (SRC), light-gauge steel-frame, brick, concrete block, and steel prefabricated. In Nishinomiya City, wood-frame buildings accounted for approximate 50% and reinforced concrete buildings about 10% in number. Since the number of buildings was large enough for wood-frame and reinforced concrete buildings, they were further classified by the construction period. For reinforced concrete buildings, three construction periods were considered taking into account the revisions of the seismic design code of the building construction standard act in 1971 and 1981. Construction period for wood-frame buildings was divided into five periods (approximate by every 10 years) in similar way to reinforced concrete buildings for easy comparison.

Figures 1 and 2 show the damage ratio of buildings in Nishinomiya City with respect to the structural type and construction period. These figures indicate that the damage ratio for wood-frame buildings is largest among all the structural type, and that the damage ratio for old buildings is larger than that for new buildings for the most structural types.

FRAGILITY CURVES OF BUILDINGS

The fragility curves of buildings in Japan were constructed using the relationship between the damage ratio of buildings in each block level of Nishinomiya City and the estimated strong ground motion indices. Figure 3 shows the estimated strong motion distribution (PGV) in Nishinomiya City. The damage ratios of buildings were calculated for each block (coinciding with the address system in Japan containing a few hundreds buildings). However, after classifying the buildings within a block using the category in Table 1, the number of buildings in each block with the same category becomes small. Hence the several blocks having a certain range of the estimated strong motion indices were synthesized when calculating the damage ratios. In selecting the blocks to combine the damage data, the blocks were rearranged based on the value of the estimated ground motion indices and they were combined to a larger group to obtain reliable damage statistics. The number of combined blocks and the approximate number of buildings per combined block after the grouping are shown Table 2. In synthesizing blocks, the strong motion indices for each district were calculated as the weighted mean of the number of buildings.

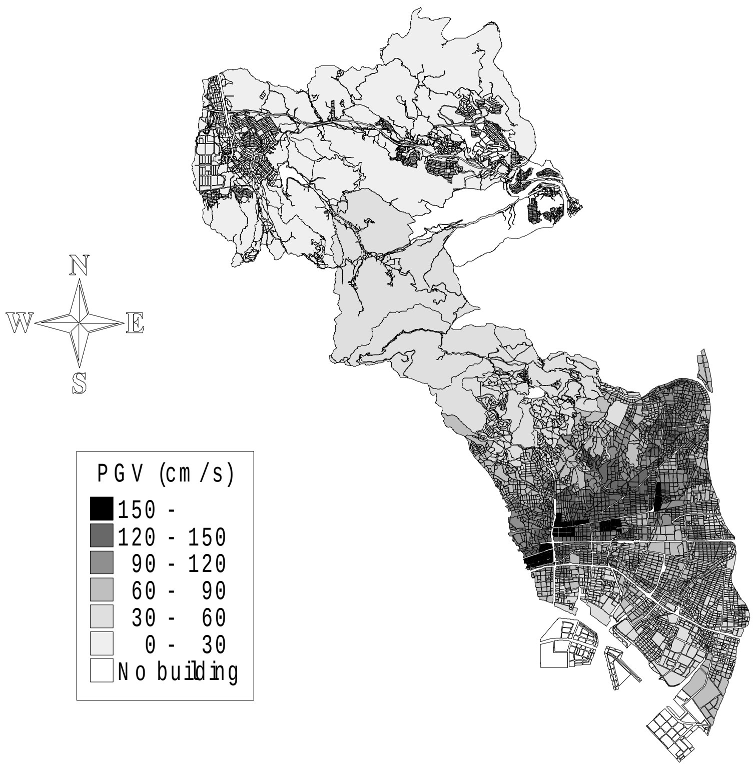


Figure 3: Distribution of estimated PGV in Nishinomiya City

For a strong motion index x (PGA, PGV and SI), the cumulative probability $P_R(x)$ of the occurrence of damage equal or higher than rank R is assumed to be log-normal as follows:

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

in which Φ is the standard normal distribution and λ and ζ are the mean and the standard deviation of ln x. The two parameters of the distributions, λ and ζ, were determined by the least square method on probability paper. Similarly, for the JMA intensity I, a normal distribution is assumed as

$$P_R(I) = \Phi((I - \lambda)/\zeta) \tag{2}$$

Table 2: The number of combined blocks and the number of buildings per each block for each structural type

Structural Type	Construction Period	Number of Combined Blocks	Number of Buildings in a Combined Block
Wood-Frame	average	30	2,250
	-1951	30	460
	1952-61	30	310
	1962-71	30	540
	1972-81	30	530
	1982-94	30	390
Wooden-Prefabricated		10	150
Reinforced Concrete	average	20	530
	-1971	20	155
	1972-81	20	165
	1982-94	20	200
Steel-Frame		10	480
Light-Gauge Steel-Prefabricated		10	400

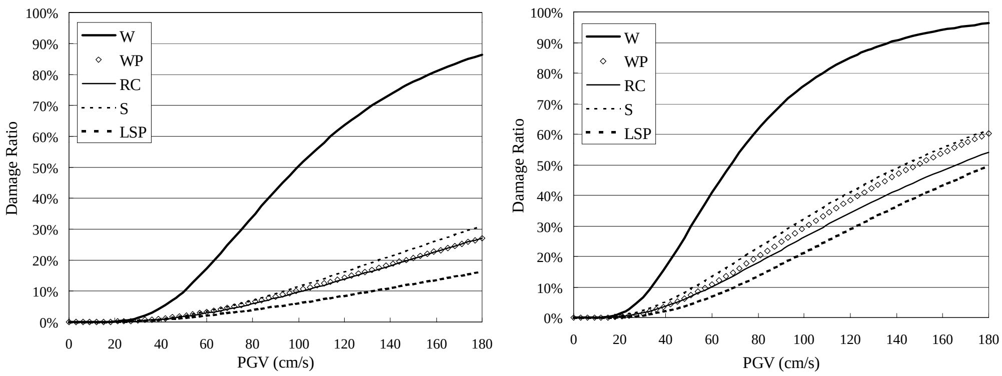
Table 3: Parameters of fragility curves for each structural type (Heavy damage)

Structural Type	Consrtruction Period	PGA (cm/s^2)			PGV (cm/s)			SI (cm/s)			JMA Intensity		
		ƒ E	ƒ A	r	ƒ E	ƒ A	r	ƒ E	ƒ A	r	ƒ E	ƒ A	r
W	average	6.76	0.613	0.992	4.60	0.538	0.992	4.77	0.568	0.992	6.35	0.500	0.981
	-1951	6.38	0.571	0.988	4.27	0.501	0.988	4.42	0.529	0.988	6.05	0.477	0.988
	1952-61	6.62	0.585	0.977	4.48	0.525	0.978	4.64	0.554	0.978	6.25	0.600	0.939
	1962-71	6.67	0.561	0.985	4.52	0.493	0.985	4.69	0.520	0.985	6.29	0.468	0.986
	1972-81	6.93	0.547	0.972	4.75	0.480	0.973	4.93	0.507	0.972	6.51	0.455	0.974
	1982-94	7.58	0.682	0.924	5.32	0.599	0.923	5.53	0.632	0.924	7.06	0.574	0.917
WP		8.05	1.01	0.940	5.74	0.891	0.938	5.97	0.939	0.939	7.49	0.880	0.921
RC	average	8.03	0.970	0.932	5.71	0.849	0.931	5.94	0.898	0.931	7.35	0.750	0.904
	-1971	7.75	0.907	0.936	5.46	0.789	0.940	5.68	0.833	0.940	7.22	0.798	0.912
	1972-81	7.94	0.996	0.898	5.64	0.876	0.898	5.86	0.925	0.898	7.36	0.847	0.895
	1982-94	10.5	1.97	0.590	7.89	1.73	0.589	8.24	1.83	0.589	9.56	1.68	0.576
S		7.90	0.939	0.980	5.60	0.824	0.980	5.83	0.870	0.980	7.32	0.781	0.980
LSP		8.61	1.20	0.930	6.23	1.05	0.932	6.49	1.11	0.931	7.88	0.984	0.940

Table 4: Parameters of fragility curves for each structural type (Heavy + Moderate damage)

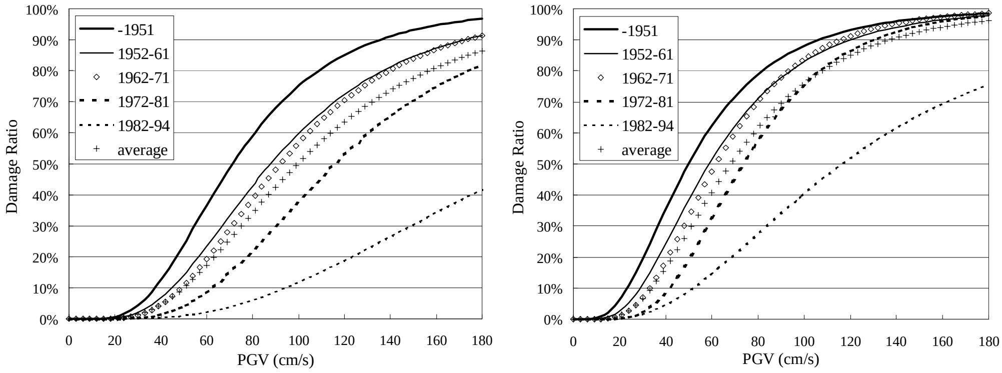
Structural Type	Consrtruction Period	PGA (cm/s^2)			PGV (cm/s)			SI (cm/s)			JMA Intensity		
		ƒ E	ƒ A	r	ƒ E	ƒ A	r	ƒ E	ƒ A	r	ƒ E	ƒ A	r
W	average	6.33	0.622	0.992	4.22	0.546	0.992	4.37	0.576	0.992	6.00	0.503	0.991
	-1951	5.97	0.673	0.978	3.91	0.591	0.978	4.04	0.624	0.978	5.71	0.562	0.978
	1952-61	6.18	0.616	0.972	4.08	0.555	0.970	4.22	0.585	0.971	5.79	0.640	0.923
	1962-71	6.22	0.557	0.983	4.12	0.489	0.983	4.27	0.516	0.983	5.92	0.465	0.984
	1972-81	6.41	0.508	0.978	4.30	0.446	0.978	4.45	0.471	0.978	6.08	0.422	0.981
	1982-94	6.94	0.718	0.983	4.76	0.629	0.983	4.94	0.665	0.983	6.52	0.595	0.982
WP		7.47	0.839	0.985	5.00	0.737	0.985	5.20	0.778	0.985	6.74	0.698	0.985
RC	average	7.34	0.912	0.942	5.11	0.798	0.942	5.31	0.844	0.942	6.83	0.723	0.911
	-1971	7.19	0.947	0.921	4.97	0.825	0.923	5.16	0.871	0.923	6.72	0.821	0.895
	1972-81	7.29	1.01	0.888	5.06	0.887	0.887	5.26	0.936	0.887	6.82	0.859	0.877
	1982-94	8.05	1.18	0.798	5.73	1.04	0.797	5.97	1.10	0.798	7.45	0.989	0.792
S		7.18	0.894	0.970	4.97	0.784	0.969	5.16	0.828	0.970	6.72	0.744	0.969
LSP		7.45	0.852	0.951	5.20	0.747	0.951	5.41	0.789	0.951	6.93	0.705	0.952

Table 3 and 4 summarize the results of the regression for heavy damage and equal or larger than moderate damage for each strong motion index. Figure 4 shows the fragility curves for the five structural types. In each figure, wood-frame (W) buildings show the smallest seismic capacity and light-gauge steel prefabricated (LSP) buildings show the largest seismic capacity. Clear difference of seismic resistance between conventional wood-frame buildings and wooden-prefabricated (WP) buildings is observed, and hence, different fragility curves for these two should be considered in earthquake damage assessments. The fragility curves for wooden-prefabricated, reinforced concrete (RC) and steel-frame (S) buildings look very similar. This tendency is consistent with that of actual damage data of Nishinomiya City [Yamaguchi et al., 1998].



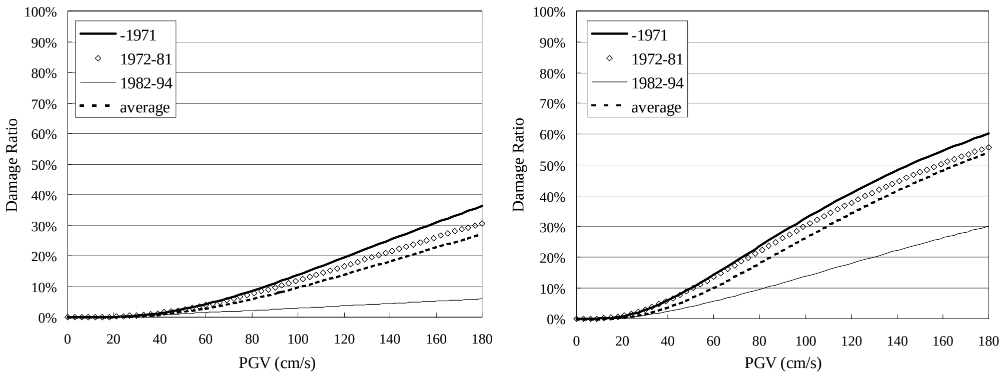
(a) Heavy damage **(b) Heavy + Moderate damage**

Figure 4: Fragility curves with respect to PGV for different structural types



(a) Heavy damage **(b) Heavy + Moderate damage**

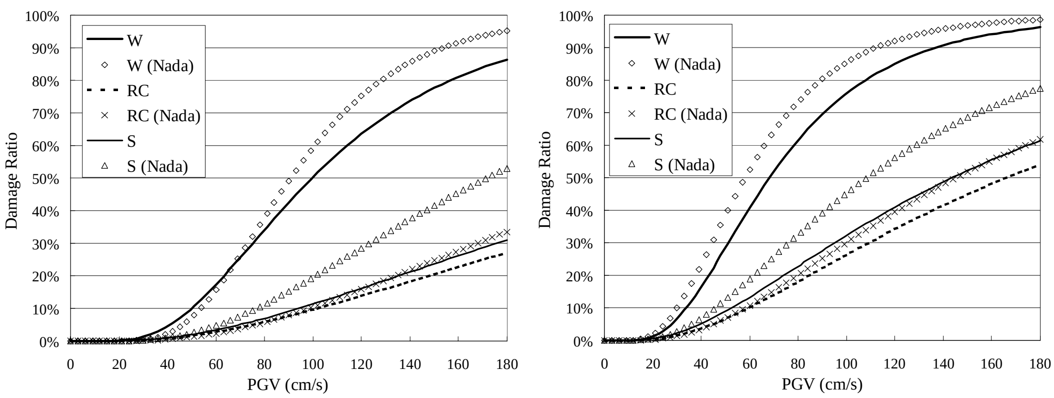
Figure 5: Fragility curves of wood-frame buildings with respect to PGV for different construction periods



(a) Heavy damage **(b) Heavy + Moderate damage**

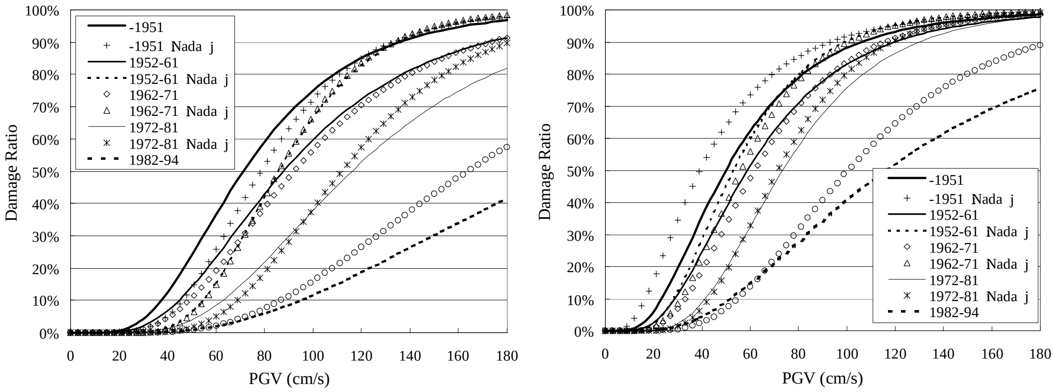
Figure 6: Fragility curves of reinforced concrete buildings with respect to PGV for different construction periods

Figure 5 and 6 show the fragility curves of wood-frame and reinforced concrete buildings for different construction periods. It is clearly seen in the figures that, in general, the older buildings are more vulnerable than the newer buildings. Aging of buildings may be mostly responsible for this observation, especially for wood-frame buildings. However, the fragility curves of wood-frame buildings for 1952-61 and 1962-71 are quite alike. For the figures of reinforced concrete buildings, although the fragility curves for buildings equal or before 1971 are very similar to those for 1972-81, the fragility curves for 1982-94 show much lower damage probability than the other construction periods. The revision of the seismic design code in 1981 might affect the reduction of building damage.



(a) Heavy damage **(b) Heavy + Moderate damage**

Figure 7: Comparison of obtained fragility curves with those for Nada Ward (different structural types)



(a) Heavy damage **(b) Heavy + Moderate damage**

Figure 8: Comparison of obtained fragility curves with those for Nada Ward (wood-frame with different construction periods)

COMPARISION WITH OTHER RESEARCH RESULTS

Similar studies using the results of damage surveys by other local governments are also found. Murao and Yamazaki [2000] constructed the fragility curves with respect to PGV considering the structural type and construction period using the damage survey data for Nada Ward conducted by Kobe City. The estimated PGV distribution used was obtained in the same manner as the present study. Figure 7 compares the fragility curves for wood-frame, reinforced concrete and steel-frame buildings by Murao and Yamazaki [2000] and by the authors. It is seen in the figure that, for all the structural types, Murao's curves show higher damage probability than ours. Figure 8 compares the fragility curves of wood-frame buildings for the different construction periods by the two studies. Except for the curve of the heavy damage ratio for equal or before 1951, Murao's curves show higher damage probability than ours. The difference in the two sets of fragility curves may be resulted from the difference of the building damage survey data used (Nishinomiya City and Nada Ward) and the difference in the damage classification of the two surveys [Murao and Yamazaki, 1999b]. Another possible reason is the difference in the estimated PGV. Although the PGVs were estimated by the same approach in these two studies, the estimated PGV was distributed in a wider range in Nishinomiya City than in Nada Ward, especially in a small PGV range. A further research to develop "standard" fragility curves to be used for damage assessments is necessary considering the statistical results for other cities as well as Nishinomiya and Nada, and the results of numerical simulation for building fragility.

CONCLUSIONS

In order to improve the accuracy of fragility curves for buildings in Japan, it is important to include the building damage data from the 1995 Kobe Earthquake. In this paper, the fragility curves for buildings in Japan considering detailed characteristics of buildings were constructed based on the damage survey data of Nishinomiya City Government developed for the purpose of property tax reduction. The fragility curves considering the structural type and construction period were developed using the damage data and the estimated distribution of strong motion indices obtained from the recorded strong motion and another building damage survey covering all the Hanshin area. It was identified that each fragility curve reflected actual situation of building damage: the fragility curves for wood-frame buildings show higher damage probability than other structural types and the fragility curves for the old buildings show higher damage probability than those for the new buildings. Compared with a similar study for Nada Ward, Kobe City, some difference, were observed in the empirical fragility curves although general tendency was very similar. The accuracy of the proposed fragility curves can further be improved by introducing building damage data of neighboring cities and the result of analytical studies.

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