Vulnerability Functions for Japanese Buildings based on Damage Data due to the 1995 Kobe Earthquake

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Introduction

More than hundred thousand buildings were severely damaged and about one hundred and fifty thousand buildings were moderately damaged due to the Hyogoken-Nanbu (Kobe) Earthquake on January 17, 1995 (National Land Agency, 1997). 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 the affected area by the Kobe Earthquake, the strong motion distribution is required. However, since the number of recorded motions was not large enough to estimate the detailed spatial distribution of ground motion (JMA, 1997), the strong motion distribution is necessary to be estimated using other data sources.

To estimate the strong motion distribution, the results of the building damage survey by the group of the Architectural Institute of Japan (AIJ), the City Planning Institute of Japan (CPIJ) and Hyogo Prefectural Government (AIJ & CPIJ, 1995) may be most useful since the survey was conducted for the entire affected area using the unified damage classification. The data obtained by this survey were digitized on a geographic information system (GIS) by the Building Research Institute, Ministry of Construction (BRI, 1996). Miyakoshi et al. (1998) estimated the distribution of the peak ground velocity (PGV) by comparing the BRI data and the PGV obtained from a two-dimensional response analysis. More recently, Yamaguchi and Yamazaki (1999) also estimated the distribution of the peak ground acceleration (PGA), PGV, spectrum intensity (SI), and the instrumental JMA intensity (Shabestari and Yamazaki, 1998) using the BRI's building damage data and the strong motion indices calculated from the records.

Note that, although the BRI data are very useful, the inventory of buildings (type of structure, construction period, etc.) was not associated with the data. Only the use of buildings (residential, commercial/office, or industrial) and story classification (one or two-storied, or higher than that) were given since the survey by the AIJ & CPIJ group was conducted visually from the outside of buildings. To construct the building vulnerability functions to be used for damage assessments, however, building damage data associated by inventory are necessary. In this view point, the results of building damage survey conducted by local governments are highly useful although the damage classification was different from that of the AIJ & CPIJ and it was even not the same among the local governments in the affected area (Murao and Yamazaki, 1999).

The present authors have collected the building damage data surveyed by local governments and performed basic analyses on damage (Murao and Yamazaki, 1997; Yamaguchi et al., 1998; Sugiura and Yamazaki, 1998). Combining the damage survey data by Kobe City with the estimated ground motion distribution by Yamaguchi and Yamazaki (1999), this paper aims to construct the vulnerability functions (fragility curves) for Japanese buildings that consider the structural type and construction period.

Figure 1 shows the flowchart for the development of the (empirical) vulnerability functions. First, vulnerability functions (I) were created by using the 17 recorded ground motion indices and the BRI damage data for one or two-storied residential buildings. Employing these vulnerability functions (I) to all the district blocks (corresponding to the postal address) in the stricken area, the distributions of PGA, PGV, SI and JMA intensity (I) were estimated (Yamaguchi and Yamazaki, 1999). Using these estimated ground motion distributions and the building damage data for Nada Ward surveyed by Kobe City, the vulnerability functions (II) considering structural type and construction period are developed in this paper. Employing the vulnerability functions (II) to each district block of Nada Ward, the distribution of PGV is further refined. Using the updated strong motion distribution (II), further refined vulnerability functions (III) are finally obtained.

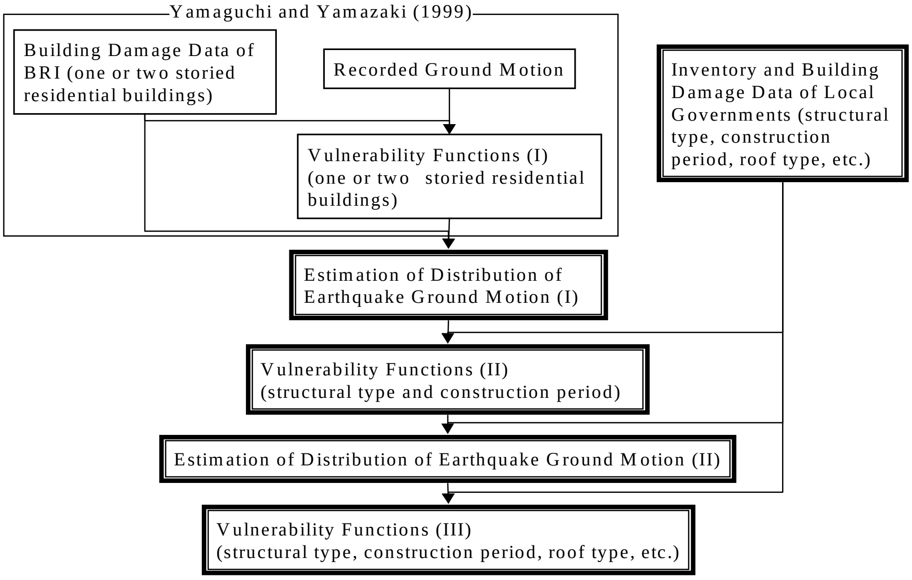


Figure 1. Flowchart for the development of vulnerability functions based on the damage data due to the Kobe Earthquake

Overview of Building Damage in Nada Ward

Nada Ward is one of the nine wards in Kobe City having population of approximately 125,000 in 1994. While the northern part of the ward suffered only slight damage, a large number of buildings were seriously damaged or collapsed in the southern part due to strong shaking. Some buildings were burnt down due to fires and some buildings near the coast were suffered from displacements associated with liquefaction. As a whole, about thirteen thousand buildings were heavily damaged, about six thousand buildings were moderately damaged, and 924 people were killed in Nada Ward by the earthquake (Kobe City, 1996).

Table 1 shows the number of buildings in Nada Ward with respect to the structural type and the period of construction (wood-frame only) for three damage levels: heavy (H), moderate (M), and slight/no damage (N). This damage classification was used for the purpose of property tax reduction for the damaged buildings in the fiscal year of 1995. Note that the damage classification is different from that of the BRI data (Murao and Yamazaki, 1999). The following information such as “district block”, “structural type”, “construction period”, “roof type”, and “use” is associated with each building as well as the damage classification.

The type of structures is classified into four categories: wood-frame (W), reinforced concrete (RC), steel-frame (S), and light gauge steel frame (LS). In Nada Ward, wood-frame buildings were about three-quarters of all buildings. Since the number of buildings was large enough for wood-frame buildings, they were further classified into five construction periods.

Figures 2 and 3 show the damage ratio of buildings in Nada Ward with respect to the structural type and construction period (for wood-frame). The figures indicate that: 1) the damage ratio for wood-frame buildings is largest among all the structural types; 2) the damage ratio for old buildings is larger than that for new buildings for the most structural types.

Table 1. Summary of building damage in Nada Ward due to the Kobe Earthquake

Type of Buildings		Heavy	Moderate	No/Slight	Total
Wood-frame (W)	-1951	5,032	1,636	1,138	7,806
	1952-61	2,897	936	992	4,825
	1962-71	2,588	928	1,126	4,642
	1972-81	1,006	764	1,218	2,988
	1982-94	384	542	1,523	2,449
	Subtotal	11,907	4,806	5,997	22,710
Rainforced Concrete (RC)		354	532	2,928	3,814
Steel (S)		532	462	1,179	2,173
Light Gauge Steel (LS)		272	164	865	1,301
Others		133	89	324	546
Total		13,198	6,053	11,293	30,544

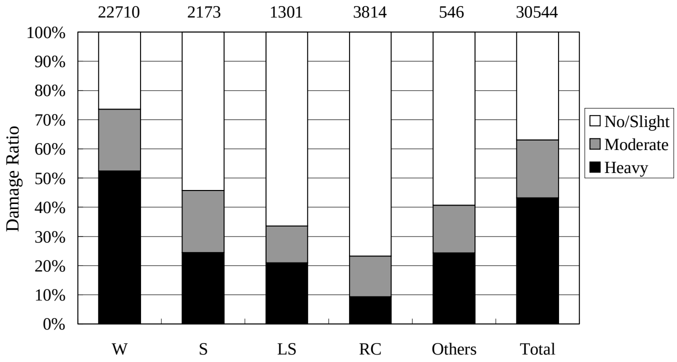


Figure 2. Damage ratio of buildings in Nada Ward for different structural types

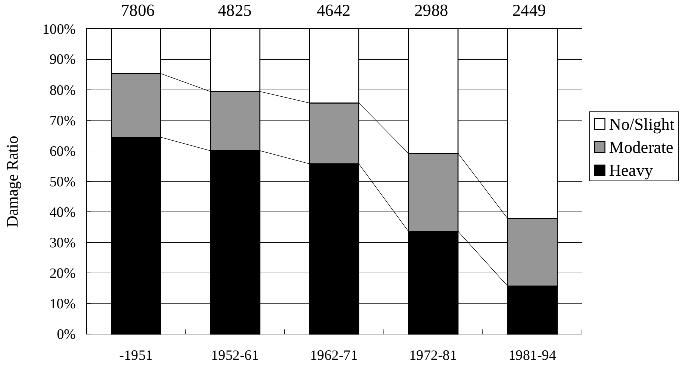


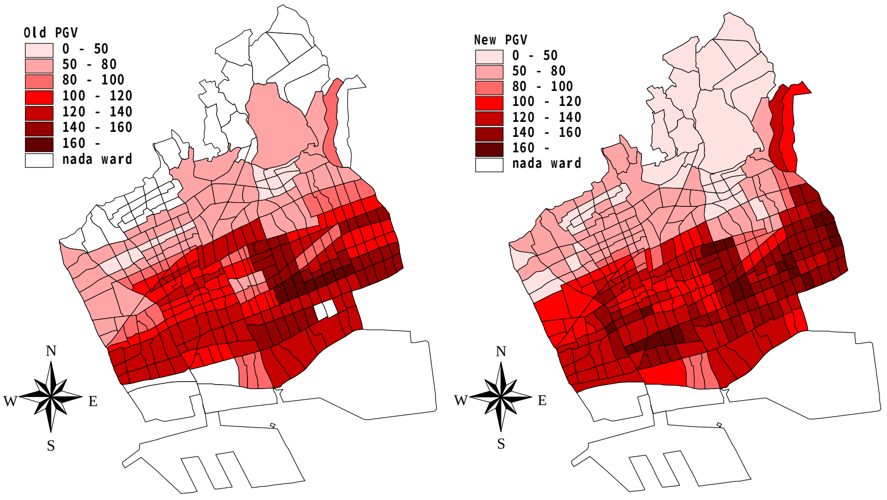
Figure 3. Damage ratio of wood-frame buildings classified by construction period

Re-estimation of Ground Motion Distribution in Nada Ward

The distribution of PGV in Nada Ward estimated by Yamaguchi and Yamazaki (1999) is shown in Figure 4 (a). The seaside area where liquefaction occurred and the mountain area with small number of buildings were excluded from the area to study since, for these areas, the estimation of strong motion indices was difficult from the building damage. In some blocks in Figure 4 (a), PGV was not determined because a block consists of a large park with almost no residential buildings or blocks were outside of the investigation by the AIJ & CPIJ group.

Since the building damage data used for the development of Figure 4 (a) do not include detailed building information, such as the construction year, the estimated PGV may be affected by the characteristics of buildings in each block. Hence, it is desirable to correct this bias using another damage data associated with the detailed building information.

First, (interim) vulnerability functions of wood-frame buildings were constructed using the damage ratio of buildings in each block level of Nada Ward and the estimated PGV distribution shown in Figure 4 (a). The damage ratios of buildings were first calculated for each block (containing about scores to a few hundred 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 neighboring blocks having a certain range of the estimated strong motion indices were synthesized when calculating the damage ratios.



(a) (b)

Figure 4. Comparison of (a) estimated PGV by Yamaguchi and Yamazaki (1999) and (b) re-estimated PGV from the interim vulnerability functions (II) in Nada Ward, Kobe City due to the 1995 Kobe Earthquake

In selecting the neighboring blocks to combine damage data, the extent of damage and the subsurface soil condition of the blocks were considered. For each construction period of wood-frame buildings, 20 combined blocks were used with the approximate number of buildings in each block as: 360 buildings for period -1951, 220 buildings for period 1952-61, 200 buildings for period 1962-71, 120 buildings for period 1972-81, and 100 buildings for period 1982-94. Such regional grouping was adopted to obtain reliable damage statistics that correspond to the estimated PGV.

For a strong motion index x, 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:

$$P_R\,(PGV) = \Phi\,((ln\ PGV - \lambda)/\zeta\,) \qquad (1)$$

In which Φ is the standard normal distribution and λ and ζ are the mean and the standard deviation of $ln\ PGV$. The two parameters of the distributions, λ and ζ, were determined by the least square method on lognormal probability paper.

Vulnerability Functions

Figure 5 shows the interim vulnerability functions for wood-frame buildings in Nada Ward for different construction periods based on the building survey data of Kobe City.

As demonstrated in Figure 5, the interim vulnerability functions for wood-frame buildings are dependent on the period of construction. However, no such information was available for the building damage data of BRI. Hence, in estimating the distribution of PGV from the BRI data, we implicitly assumed that the construction periods of one or two-storied residential buildings had similar distribution in all the studied area. But this assumption is obviously not true. Some districts consist of old buildings and some others consist of new buildings.

Considering these issues, the distribution of PGV was re-estimated using the interim vulnerability functions shown in Figure 5. From the damage ratio of buildings for one construction period in a block, one PGV value in the block can be estimated. Using the five interim vulnerability functions corresponding to the different construction periods, the five PGV values are obtained. Similarly, the two damage levels (heavy, heavy + moderate) give two PGV values for a block. These estimated PGV values were averaged for the re-evaluation of PGV. Figure 4 (b) shows the distribution of re-evaluated PGV.

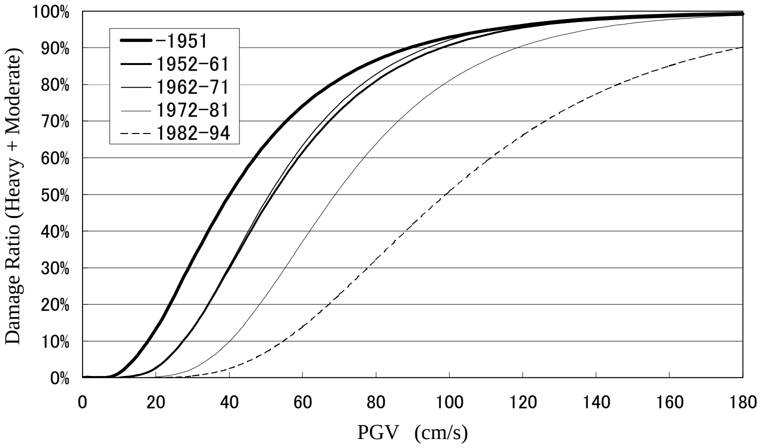


Figure 5. Interim vulnerability functions of wood-frame buildings with respect to PGV for different construction periods

Vulnerability Functions of Buildings

In the similar manner, the vulnerability functions for all of the buildings based on the re-estimated PGV were constructed with regard to structural types and construction periods. Table 2 summarizes the results of the regression analysis. With regard to R_h and R_m in Table 2, the square of correlation coefficients (R^2) for wood-frame building are largest. This fact can be explained by 1) the PGV was re-estimated from the mean value of damage ratio for wooden buildings; and 2) the number of wood-frame buildings is largest among structural type, thus they gave the most stable statistics. R^2 values for other type of structures are lower than those for wood-frame buildings. But they are, in general, very high.

Table 2. Parameters of vulnerability functions for Japanese buildings

		Heavy (R_h)			Heavy + Moderate (R_m)		
		λ	ξ	R^2	λ	ξ	R^2
Wood-flame (W)	-1951	4.36	0.41	0.96	3.66	0.67	0.88
	1952-61	4.44	0.35	0.98	3.97	0.49	0.95
	1962-71	4.45	0.34	0.98	4.02	0.46	0.97
	1972-81	4.73	0.38	0.97	4.25	0.39	0.98
	1982-1994	5.12	0.50	0.88	4.61	0.47	0.97
	All	4.51	0.41	0.98	4.07	0.51	0.98
Rainforced Concrete (RC)	-1971	5.12	0.65	0.95	4.72	0.69	0.93
	1972-81	5.33	0.58	0.94	4.85	0.61	0.84
	1982-94	6.00	0.79	0.90	5.33	0.79	0.92
	All	5.50	0.71	0.97	4.99	0.72	0.92
Steel (S)	-1971	4.64	0.62	0.72	4.25	0.71	0.79
	1972-81	4.97	0.49	0.94	4.49	0.55	0.80
	1982-94	5.64	0.73	0.89	5.01	0.73	0.82
	All	5.14	0.63	0.75	4.69	0.67	0.69
Light Gauge Steel (LS)	-1971	4.70	0.55	0.93	4.41	0.50	0.91
	1972-81	5.82	0.97	0.73	4.95	0.86	0.78
	1982-94	6.19	1.10	0.86	5.28	0.87	0.85
	All	5.03	0.56	0.94	4.73	0.60	0.97

Figure 6 shows the vulnerability functions for the four structural types. In each figure, wood-frame buildings show the smallest seismic capacity and RC structures show the largest seismic capacity. The functions for steel-frame and light-gauge steel-frame structures look very similar.

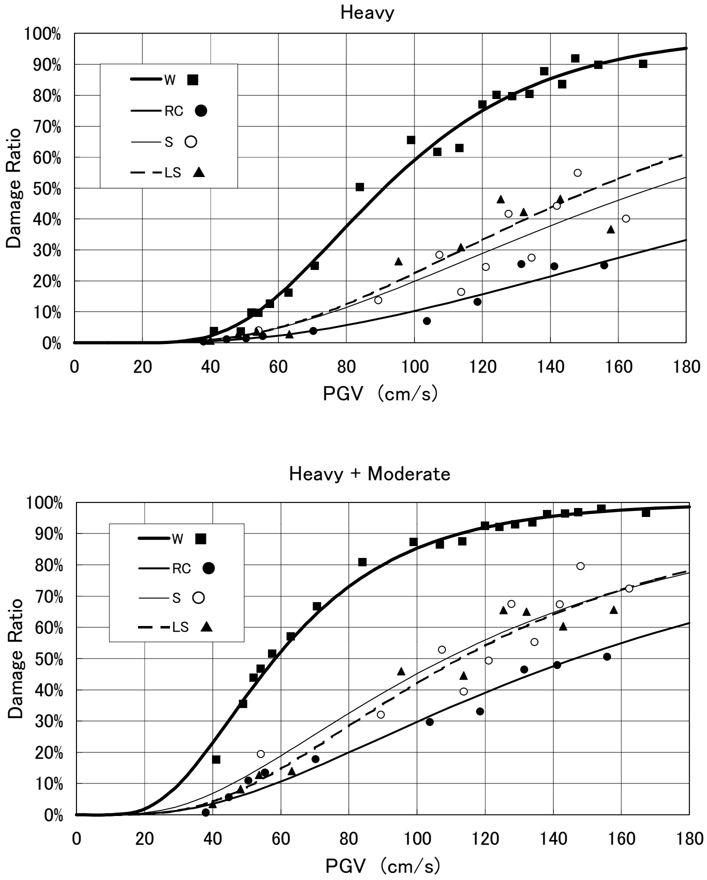


Figure 6. Vulnerability functions with respect to PGV for different structural types

Figures 7 and 8 show the vulnerability functions for reinforced concrete and steel buildings with different construction periods. It is clearly seen in the figures that the older buildings are more vulnerable than the newer buildings. For these engineered structures (S and RC), the revision of the seismic design code in each construction period may have a significant effect for the improvement of seismic resistance. However, for other structural types, especially for wood-frame buildings, it is concluded that the aging of buildings is mostly responsible for this observation, based on the plot of building damage ratios year by year (of construction).

The vulnerability functions developed here may be further improved by introducing the damage data from neighboring cities in the 1995 Kobe Earthquake (e.g. Yamaguchi and Yamazaki, 2000) and the results of numerical simulation for building damage.

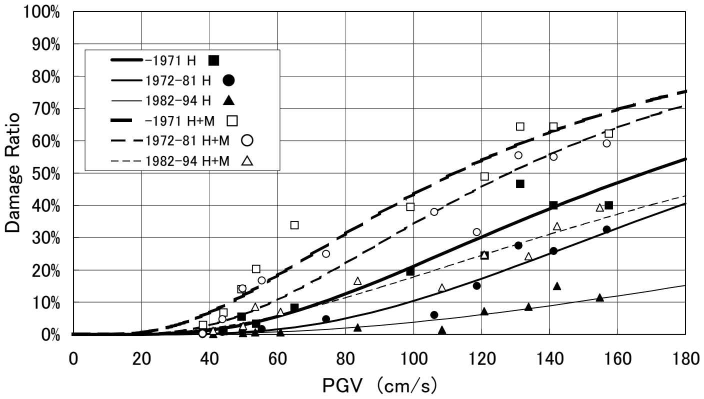


Figure 7. Vulnerability functions for RC buildings

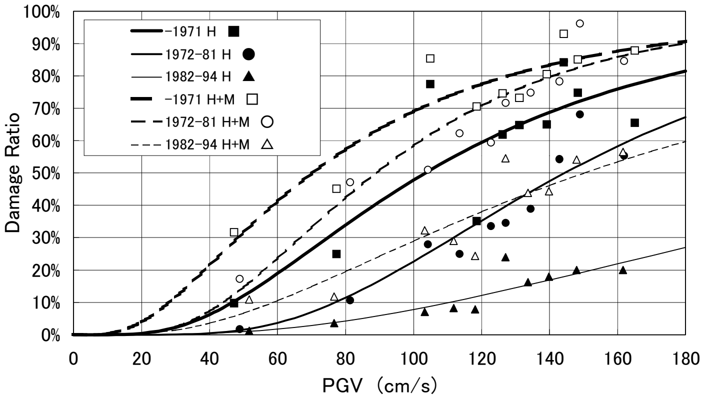


Figure 8. Vulnerability functions for steel buildings

Conclusions

The 1995 Hyogoken-Nanbu (Kobe) Earthquake caused unprecedented damage in Kobe and its surrounding area. A number of building damage surveys were carried out for different purposes. The results of these surveys contain highly valuable information on building fragility and ground motion estimation. In this paper, the building damage data for Nada Ward of Kobe surveyed by Kobe City Government were employed to construct vulnerability functions that consider the structural type and construction period. The resultant vulnerability functions show that the structural type and construction period are important parameters to determine the occurrence probability of damage.

In developing the empirical vulnerability functions, the distribution of strong motion indices estimated using the recorded ground motion and other building damage survey data were used. Since the estimated PGV was affected by the inventory characteristics of each district block, the PGV distribution was re-evaluated using the obtained vulnerability functions that consider the construction period of wood-frame buildings. Using the re-evaluated PGV distribution, refined vulnerability functions considering more detailed characteristics of buildings were developed. The final vulnerability functions may be useful for damage assessments and early damage estimation systems in Japan.

Acknowledgement

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References

Architectural Institute of Japan and City Planning Institute of Japan (1995). Report of Emergency Damage Survey of the 1995 Hyogoken-Nanbu Earthquake.

Building Research Institute (1996). Final Report of Damage Survey of the 1995 Hyogoken-Nanbu Earthquake (in Japanese).

Japan Meteorological Agency (1997). “Report on the Hyogo-ken-Nanbu Earthquake,” Technical Report of JMA, No. 119, 1995 (in Japanese).

Kobe City (1996). Statistical Year Book 1996 (in Japanese).

Miyakoshi, J., Hayashi, Y., Tamura, K., and Fukuwa, N. (1998). “Damage Ratio Functions of Building using Damage Data of the 1995 Hyogo-Ken Nanbu Earthquake,” Proceedings of the 7th International Conference on the Structural Safety and Reliability, Vol. 1, 349-354.

Murao, O., and Yamazaki, F., (1997). “Analysis on Building Damage in Nada Ward due to the Hyogoken-Nanbu Earthquake,” Proceedings of the 24th JSCE Earthquake Engineering Symposium, Vol. 2, 1261-1264 (in Japanese).

Murao, O., and Yamazaki, F. (1999). “Comparison of Building Damage Evaluation by Local Governments after the 1995 Hyogoken-Nanbu Earthquake,” Journal of Architecture, Planning and Environmental Engineering, 515, 187-194 (in Japanese).

National Land Agency (1997). White Paper for Disaster Prevention 1997 (in Japanese).

Shabestari, K. T. and Yamazaki, F. (1998) “Attenuation Relation of JMA Seismic Intensity Based on JMA-87-Type Accelerometer Records,” Bulletin of Earthquake Resistant Structure Research Center, No. 31, 13-21, Institute of Industrial Science, University of Tokyo.

Sugiura, M., and Yamazaki, F. (1998). “Fragility Curves for Buildings based on Damage Data in Takarazuka due to the Hyogoken-Nanbu Earthquake,” Proceedings of the 10th Japan Earthquake Engineering Symposium, Vol. 2, 3385-3390 (in Japanese).

Yamaguchi, N., Yamazaki, F., and Wakamatsu, K. (1998). “Analysis of Building Damage in Nishinomiya City due to the Hyogoken-Nanbu Earthquake,” Proceedings of the 6th U. S. National Conference on Earthquake Engineering, Seattle, USA, 11p, CD-ROM.

Yamaguchi, N., and Yamazaki, F, (1999). “Estimation of Strong Motion in the 1995 Hyogoken-Nanbu Earthquake based on Building Damage Data,” Proceedings of the Asian-Pacific Symposium on Structural Reliability and its Applications, Taipei, Taiwan, 478-489.

Yamaguchi, N., and Yamazaki, F, (2000). “Fragility Curves for Buildings in Japan Based on Damage Surveys after the 1995 Kobe Earthquake,” Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand.