13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 727

DAMAGE INDEX FUNCTIONS OF WOODEN BUILDINGS AND REINFORCED BUILDINGS FOR SEISMIC RISK MANAGEMENT

Shigeyuki OKADA[1] and Nobuo TAKAI[2]

SUMMARY

This paper discusses the Damage Index Function available to minute damage estimation of each individual building. The derived functions for the structural types of wood frame and reinforced concrete are expressed the three-dimensional nomogram of seismic input motions, load-carrying capacity of individual building, and damage index representing the estimated damage degree of building. We can apply the 3D nomogram to utilize for various kinds of seismic risk management.

INTRODUCTION

Recently, a demand for seismic damage evaluation, which is the basis of risk management for reducing earthquake hazards, has been accelerating into the elaborating from rough estimation of regional damage in municipal units to minute damage estimation of each individual building. The functions necessary for evaluating the regional damages have been studied and proposed by many researchers as Damage Ratio Functions; however, we have not still reached the common understanding upon damage degree of individual building that is called Damage Index Function. This paper discusses Damage Index Function and proposed the method for deducing the functions with structural parameter of the load-carrying capacity for buildings.

DAMAGE RATE FUNCTION AND DAMAGE INDEX FUNCTION

Definition of Damage Rate Function

Damage Rate and Damage Index discussed in this paper are terminology used frequently not in the field of structural analysis and design for engineered building but in the field of urban disaster protection planning conducted by local authorities. Damage Rate Function, which is a sort of vulnerability function describing the percentage of elements damaged in the area, is available for roughly estimating the number of damages to regional elements at risk, especially building, at the level of administrative pre-countermeasures. The function is generally described with the following cumulative normal distribution function.

$$V(s) = \frac{1}{\sqrt{2\pi}\sigma}\int_0^s e^{-\frac{(s'-s_0)^2}{2\sigma^2}} \cdot ds' \qquad (1)$$

[1] Associate Professor, Graduate School of Engineering, Hokkaido University, Dr. Eng.
[2] Research Associate, Graduate School of Engineering, Hokkaido University, M. Eng.

where, $V(s)$ means damage rate in damaged area, and s means seismic input motion severity such as seismic intensity and peak ground velocity. Figure 1(1) illustrates a simplified expression of the function.

Many researchers, for example Murao and Yamazaki [1], Hayashi et al. [2], developed such functions of wood frame dwellings and reinforced concrete buildings by means of a lot of data concerning the percentage of building damage in Kobe areas in the 1995 Hanshin-Awaji earthquake (Kobe earthquake), Japan.

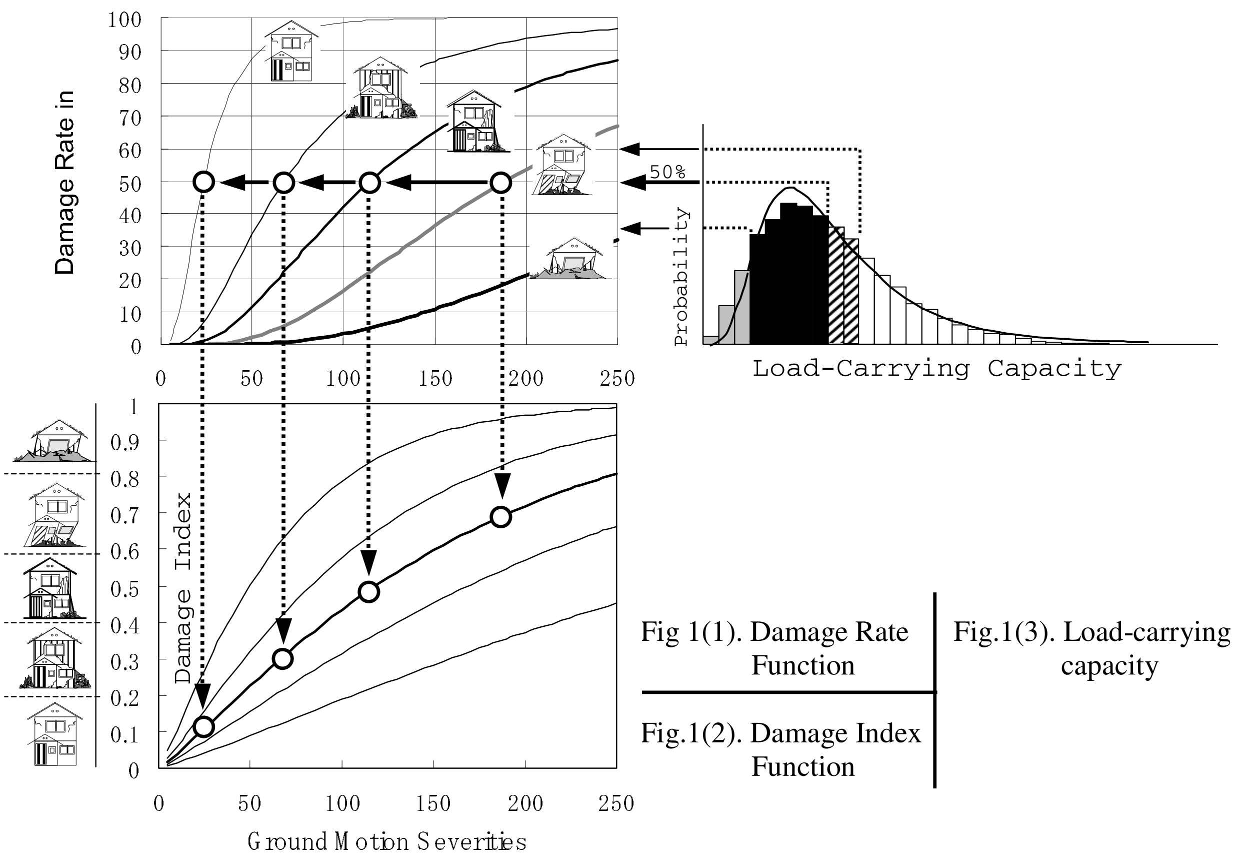

Figure 1. Relations among the Damage Index Function, the Damage Rate Function and the histogram of load-carrying capacity of buildings.

Definition of Damage Index Function

On the other hand, Damage Index Function can express the seismic structural damage state of individual building. The term "Damage Index" has not strictly defined in the research field of earthquake engineering. A few researchers proposed various kinds of Damage Index Functions from the original standpoint. For example, Park et al. [3] proposed the function as a linear combination of the maximum deformation and the hysteretic energy. Okada and Takai [4] gave the numerical scale of damage degree defining from 0 (No damage) to 1.0 (total collapse) with some visualized damage patterns of buildings so as to help field investigators to classify building damaged without a gross error. Figure 2 shows the Damage Index scale comparing with diagrammatized damage pattern in each damage scale. We define the Damage Index Function estimating the damage state of individual building in terms of our damage index scale as a result of experiencing earthquake ground motion of a certain severity.

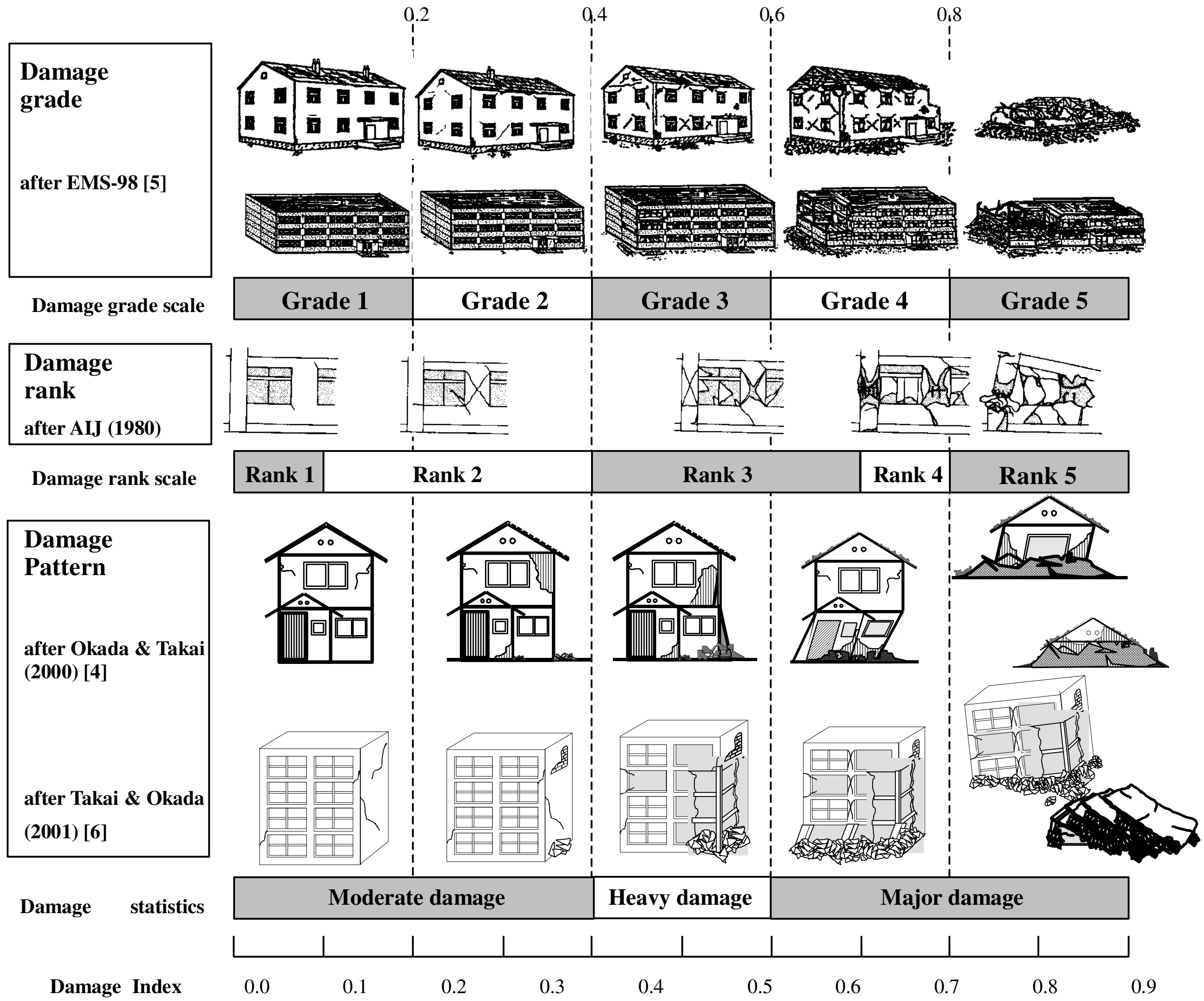

Figure 2. Comparison among various damage scales (retouched Okada and Takai [4]).

In order to directly derive the Damage Index Function from observed data on damaged buildings, we must obtain a large amount of data that consist of a three-kind set of input seismic motion severity, load-carrying capacity value and damage index of each individual building in damaged areas. Load-carrying capacity means seismic safety of building. It can be estimated by combination of capacity value in each element of building; for example, basement and resisting wall, conforming the checking standard for seismic proof structure in Japan. However, a complete set of material seldom exists even in earthquake–prone countries as Japan. It is only the data on damage rate in the area and the rough distribution of load-carrying capacity in the area that we can manage to obtain. Therefore, from the standpoint of the arithmetic deterministic approach we try to arrange the relationship between load-carrying capacity and damage rate function, which shows the damage ratio in the area, and to statistically estimate the Damage Index Function by use of that relation.

The Damage Index Function is a function capable of calculating the damage state (i.e. Damage Index) of individual building under a certain ground motion severity represented by the seismic intensity or peak ground velocity. The score of Damage Index is equivalent to a sort of probabilistic valuable distributing concentratedly and non-symmetrically around an interval of ground motion severity. A familiar probability function satisfying the above conditions is the following cumulative probability distribution with the Weibull density function:

$$F(s) = 1 - e^{-\frac{s^m}{s_0}} = 1 - e^{-\left(\frac{s}{\eta}\right)^m} \qquad (2)$$

where, *F(s)* means damage index, *s* is a index of ground motion severity, *m* and η are parameters of the Weibull distribution. Figure 1(2) illustrates a simplified expression of the function. As shown in Figure 1, the Damage Index Function and the Damage Rate Function can be linked each other by mediating the probability of exceedance on the distribution of load-carrying capacity for buildings.

Definition of the distribution of load-carrying capacity in Japan

The seismic performance index is used commonly in Japan as an index representing load-carrying capacity for buildings. The index is frequently abbreviated to $Is_{\text{-WF}}$ for wood frame building and to $Is_{\text{-RC}}$ for reinforced concrete building. The engineering experts for seismic diagnosis are responsible for controlling the seismic performance index of individual building by referring the checking standard for seismic proof structure. The higher the value of indices is, the safer the building is seismically. For example, the index for wood frame building, $Is_{\text{-WF}}$, means risky in the range of 0.0 to 0.7, nearly risky in the range of 0.7 to 1.0, nearly safe in the range of 1.0 to 1.5, and safe over 1.5. Nakano and Okada [7] showed that the frequency distribution of the indices in an arbitrary area can be described by the logarithmic normal distribution, as follows:

$$P(y) = \frac{1}{\sqrt{2\pi}\sigma \cdot y} \cdot e^{-\frac{(ln(y) - y_0)^2}{2\sigma^2}} \qquad (3)$$

where, *P(y)* means relative frequency distribution, *y* means the seismic performance index, y_0 and σ are the average value and the standard deviation of the logarithmic normal distribution, respectively. The simplified expression of this distribution is illustrated in Figure 1(3).

METHOD OF CALCULATING THE DAMAGE INDEX FUNCTION

We can obtain the Damage Index Function both for wood frame and RC constructions by the following procedures.

Procedure 1: Transferring the Damage Rate Function (Fig.1 (1)) to the Damage Index Function (Fig.1 (2))

First, we must arrange the relation between damage rate and seismic motion severity for both types of wood frame and RC constructions. Second, directing our attention to a damage rate of the Damage Rate Function, for example 50% in Fig.1 (1), we read the ground motion severities from the above relation, the severities which affect every damage indices such as the state of partial damage corresponding to Damage Index (abbreviated to D.I.)=0.2, heavy damage corresponding to D.I.=0.5, pancake collapse corresponding to D.I.=0.9. Third, the Damage Index Function, that is Fig.1 (2), can be obtained by curve-fitting the Weibull distribution to the data created as a pair of damage index and ground motion severity.

Procedure 2: Making the distribution of seismic performance index (Fig.1 (3))
We are required to collect the data on seismic performance index throughout Japan and to fit the logarithmic normal distribution to the data for the purpose of obtaining Fig.1 (3).

Procedure 3: Linking between the Damage Index Function and the seismic performance index
Transferring the logarithmic normal distribution function obtained by Procedure 2 to the cumulative distribution, we calculate the seismic performance index corresponding to a given probability of exceedance, for example 50% in Fig.1 by use of the cumulative distribution on seismic performance index. By following the deterministic approach that all of the structures not satisfied with load-carrying capacity against a given ground motion severity are destroyed, we can consider the damage rate in an area to be as the probability of exceedance of seismic performance index. That is, the parameter of Damage Index Function in Fig.1 (2) can be specified in terms of seismic performance index.

USED DATA

Wood frame building
The dataset needed for the Procedure 1 mentioned above is Damage Rate Function. We adopt the functions proposed by Okada and Takai [4] as the Damage Rate Function for wood frame building, because the proposed functions are available for all of damage indices specified as 0.1 (D1: slight damage in the MSK scale), 0.3 (D2: moderate damage in the MSK scale), 0.5 (D3: heavy damage in the MSK scale), 0.7 (D4: very heavy damage in the MSK scale), and 0.9 (D5: Destruction in the MSK scale). The functions are shown in Figure 3 and the parameters of the cumulative normal distribution functions for Okada and Takai's damage rate function are listed in Table 1. By calculating the inverse function of this damage rate function, we can obtain the ground motion severities, that is, seismic intensity and peak ground velocity, affecting the damage degree from D1 to D5 in the MSK scale at arbitrary damage rates (1, 10, 20, 30, 40, 50, 60, 70, 80, 90, 99% in this study) . The Damage Index Functions can be obtained by fitting the Weibull distribution function written in Eq.(2) to the above dataset which relates between ground motion severity and damage index. The derived functions are depicted in Figure 4.

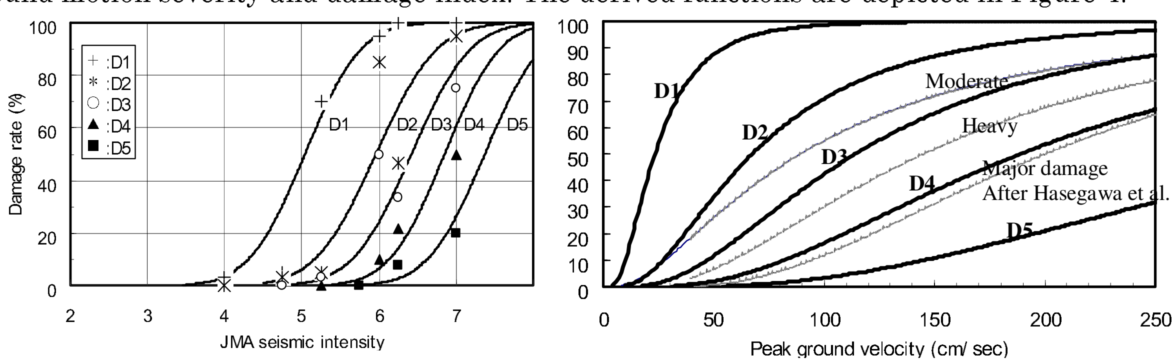

Figure 3. Proposed Damage Rate Functions (after Okada and Takai [4]). Left: Damage rate vs. JMA intensity. Right: Damage rate vs. Peak ground velocity.

Table 1 Parameters of Proposed Damage Rate Functions (after Okada and Takai [4])

	For JMA intensity		For peak ground velocity	
	Average	Stand. Dev.	Average	Stand. Dev.
Damage Index D5	7.37	0.582	5.07	0.582
Over Damage Index D4	6.85	0.565	4.55	0.565
Over Damage Index D3	6.42	0.600	4.12	0.600
Over Damage Index D2	5.96	0.621	3.66	0.621
Over Damage Index D1	5.04	0.574	2.74	0.574

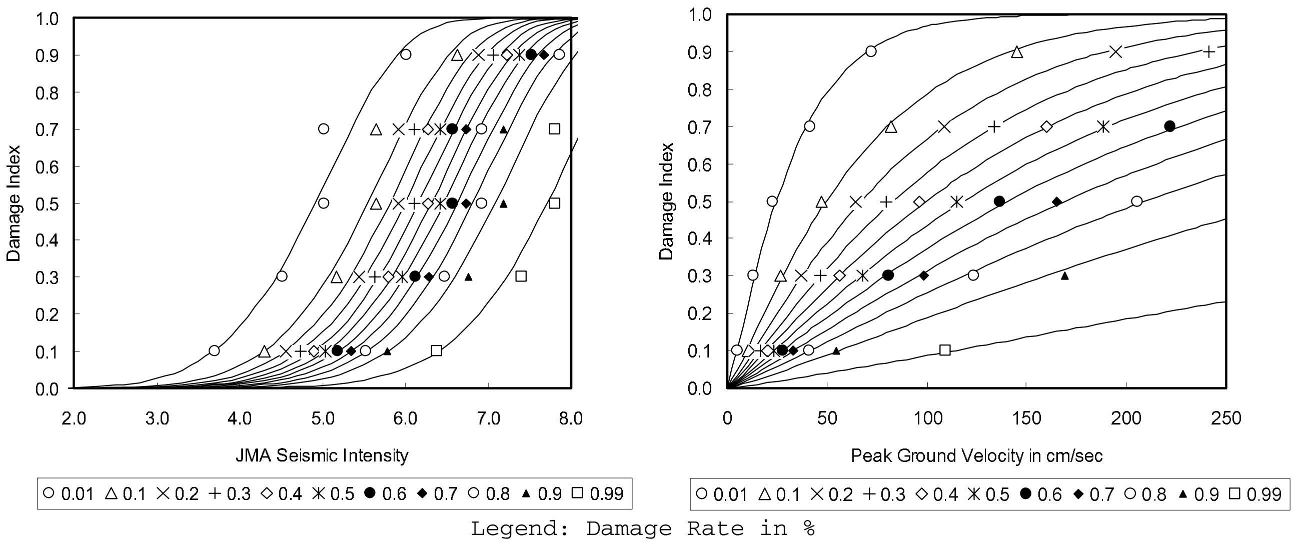

Figure 4. Obtained Damage Index Functions by curve-fitted with the Weibull distribution. Left: Damage Index vs. JMA intensity. Right: Damage Index vs. Peak ground velocity.

On the other hand, the histogram of load-carrying capacity of Japanese wood frame buildings shown in Fig.1 (3) has been examined by the Japan Wooden Housing Earthquake-Proof Reinforcing Businesses Cooperative (abbreviated to the Mokutaikyo). From December of 1998, they have been surveying the load-carrying capacity of buildings throughout Japan by following the seismic capacity evaluation standardized by the Ministry of Land, Infrastructure and Transport, Japan. We used the 9,360 data that they finished compiling. Figure 5 shows the histogram of load-carrying capacity and the appropriate curve defined in Eq. (3). Using this fitted curve, we can relate between seismic ground severity and load-carrying capacity of building under the assumption that the ratio of area less than a given load-carrying capacity to the total area in Fig.1 (3) corresponds to the damage rate of the region.

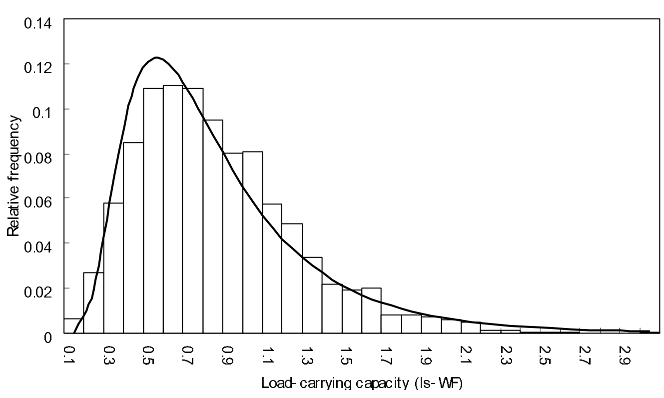

Figure 5. Frequency distribution of load-carrying capacity of wood frame buildings in Japan.

Reinforced Concrete building

For the purpose of making the Damage Index Functions for reinforced concrete building, we used the Damage Rate Function proposed by Hayashi et al. [2] for RC buildings. Hayashi et al. estimated the functions on Rank 2 (minor damage), Rank 3 (moderate damage), and Rank 4 (heavy damage) in the Damage Rank Scale of AIJ (referring to Fig.2) using the data on damage to RC buildings in the 1995 Kobe Earthquake. Their Damage Rate Functions for RC building are shown in Figure 6. Carrying out the Procedures 1 and 2 in this method, we can obtain the Damage Index Functions on RC buildings with the histogram of load-carrying capacity for RC that was examined by Nakano and Okada [7] (shown in Figure 7) as the result of following the same calculation as the case of wood frame building.

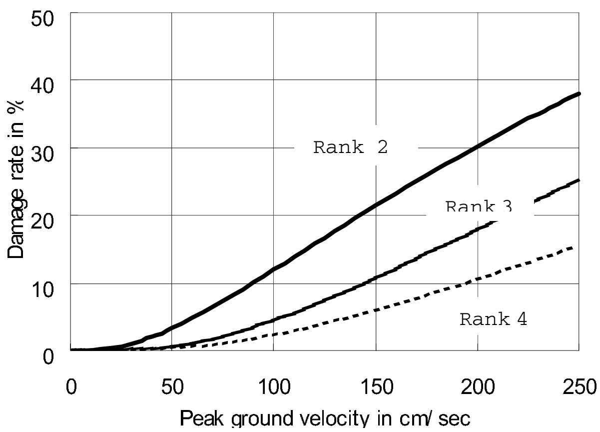

Figure 6. Damage Rate Functions for RC building (after Hayashi et al. [2]).

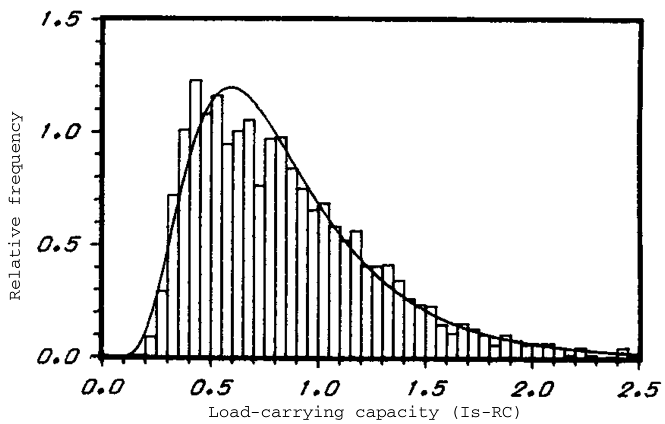

Figure 7. Frequency distribution of load-carrying capacity of RC building (after Nakano and Okada [7]).

3D DESCRIPTION OF THE DERIVED FUNCTIONS

A group of derived functions is expressed on the three-dimensional plane of which axes are seismic ground motion severity, damage Index and load-carrying capacity respectively as shown in Figures 8 and 9. These figures indicate that the damage is occurred even in the low seismic intensity with lowering load-carrying capacity of building. By projecting this three-dimensional function on the two-dimensional plane, it is possible to offer for the disaster-preventing utilization like the followings.

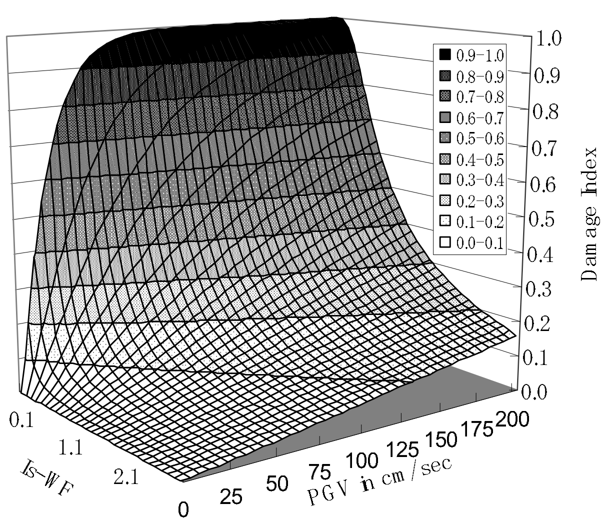

Figure 8. Derived Damage Index Function for wood frame building in the case of considering peak ground velocity as input motion.

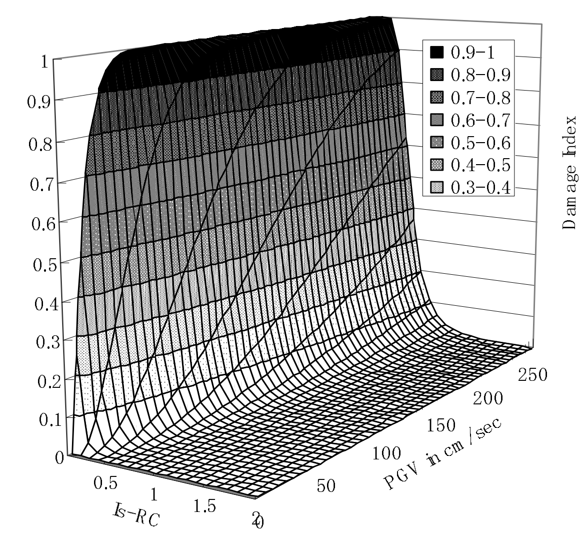

Figure 9. Derived Damage Index Function for RC building in the case of considering peak ground velocity as input motion.

APPLICATIONS

Seismic Risk Estimation

Projecting the derived 3D functions on the plane of load-carrying capacity and seismic input motion severity, we can obtain the graph for estimating the assumable damage index. Figures 10 and 11 show the examples for wood frame and RC buildings, respectively. Using these graphs and the seismic hazard map in regions, we can evaluate the damage state of individual building kept with a load-carrying capacity. From Figure 10, the damage index of wood frame building, of which load-carrying capacity is 0.7 corresponding to the average of wooden houses in Japan, can be judged with 0.5 (D3 expressed in Fig.10) when the peak ground velocity in the region is 100 cm/sec. That is Due Diligence Investigation.

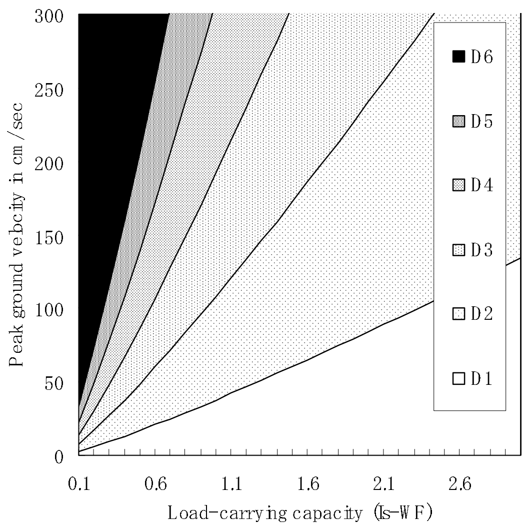

Figure 10. Graph for estimating the damage index of wood frame building.

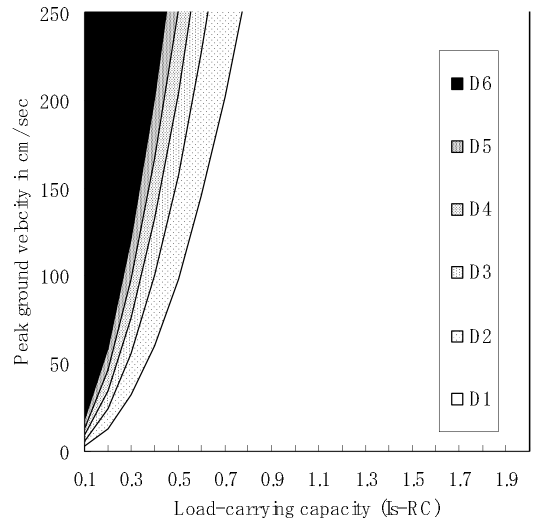

Figure 11. Graph for estimating the damage index of RC building.

Seismic Capacity of Building Estimation

Projecting the derived 3D functions on the plane that is constituted by the axes of seismic input motion severity and damage index, we can obtain Figures 12 and 13 for estimating the assumable load-carrying capacity of building. Using these graphs we can estimate the seismic strength of buildings in those days when a hazardous earthquake occurred, and we can estimate

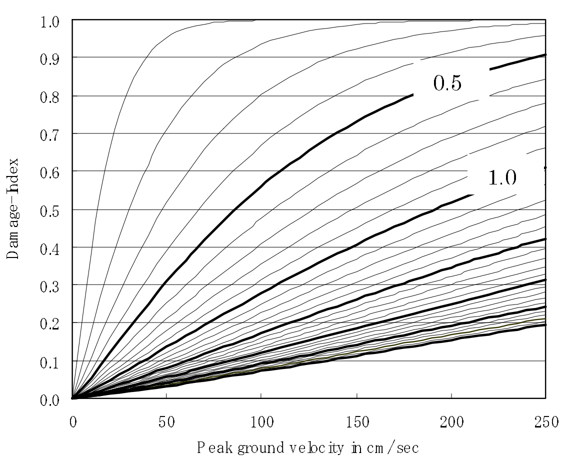

Figure 12. Graph for estimating the load-carrying capacity of wood frame building.

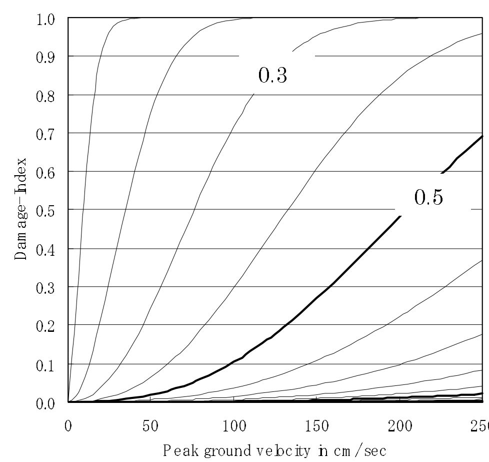

Figure 13. Graph for estimating the load-carrying capacity of RC building.

how degree of seismic capacity of buildings is necessary so as not to be damaged in the target region. For example, it is proven that load-carrying capacity over 0.4 must be ensured, since the structural damage is not generated (D.I.<0.4) for wood frame building in peak ground velocity of 50 cm/sec.

Seismic Input Motion Severity Estimation

Projecting the derived 3D functions on the plane of load-carrying capacity and damage index, we can obtain Figures 14 and 15 for estimating the assumable seismic input motion severity. Using these graphs, we can estimated the hazard maps of the past earthquakes, for example, seismic intensity distribution map and peak ground velocity distribution map, in terms of the damage rate in the regions. In addition, the graph indicates that a wooden building with load-carrying capacity of 0.6 that is the average of this type in Japan is structurally damaged by seismic motion of the peak ground velocity over 200 cm/sec, and the risk probability can be calculated from the relation between the durable period of wooden house and the return period of seismic hazard in this region.

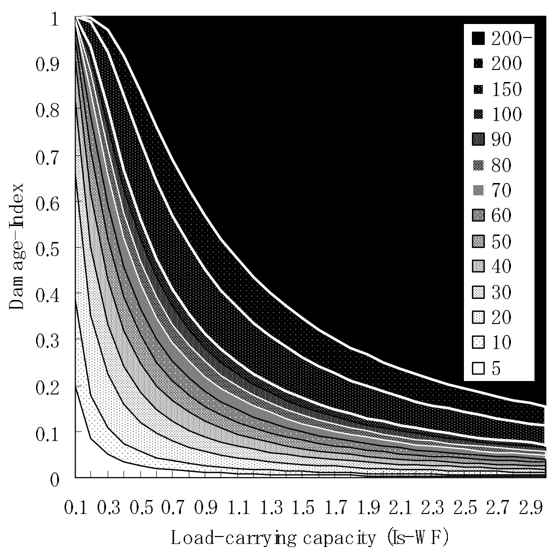

Figure 14. Graph for estimating the peak ground velocity that affects wood frame building.

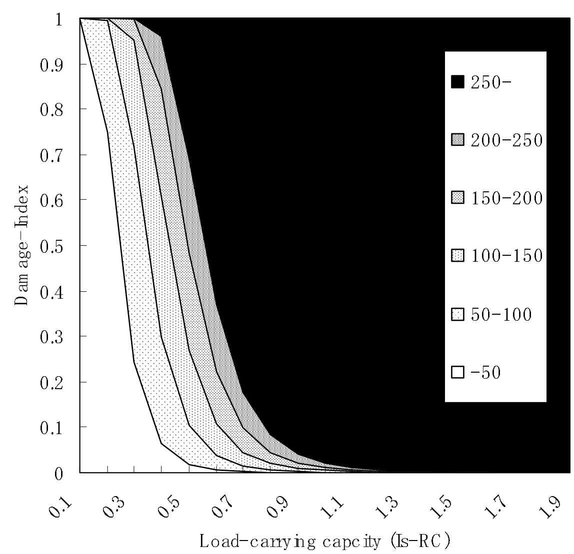

Figure 15. Graph for estimating the peak ground velocity that affects RC building.

CONCLUSIONS

In this paper we discussed the relation among the Damage Rate describing the percentile of damages in a region, the load-carrying capacity of building, and the Damage Index Functions specifying damage state of individual building, and proposed the three-dimensional description of the above relation. Through this analysis we could give the common understanding on damage index function. We can apply the 3D nomogram to utilize for various types of seismic risk management; for example, damage evaluation of individual building for an assumed earthquake, estimation of the standardized strength of buildings in regions not for generating damages, and stochastic estimation of return period on regional input motions that give rise to devastating damages to buildings. In this paper, we proposed the related functions for Japanese buildings. However, we can obtain the same functions capable of applying in other countries by following the above method.

ACKNOWLEDGEMENT

We are sincerely grateful to the Mokutaikyo Cooperative for providing the data on load-carrying capacity of wooden houses in Japan.

REFERENCES

1. Murao O. and Yamazaki F. “Development 0f fragility curves for buildings based on damage survey data of a local government after the 1995 Hyogoken-Nanbu Earthquake.” Journal of Structural and Construction Engineering, AIJ, 2000; 527, 189-196 (in Japanese with English abstract).
2. Hayashi Y., Miyakoshi J., Tasai A., and Ohno Y. ”Seismic performance of RC buildings during Hyogo-Ken Nanbu Earthquake.” Journal of Structural and Construction Engineering, AIJ, 2000; 528, 135-142 (in Japanese with English abstract).
3. Park Y. J., Ang A. H.-S., and Wen Y. K. “Seismic damage analysis of reinforced concrete buildings.” Journal of Structural Engineering, 1985; 111, 740-757.
4. Okada S. and Takai N. “Classifications of structural types and damage patterns of buildings for earthquake field investigation.” Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zeeland. Paper no.705, 2000
5. Grunthal G. “European Macroseismic Scale 1998.”, Cahiers du Centre Europeen de Geodynamique et de Seismologie, 1998; 15, 1-99.
6. Takai N. and Okada S. “Classifications of damage patterns of reinforced concrete buildings for earthquake field investigation.” Journal of Structural and Construction Engineering, AIJ, 2001; 549, 67-74 (in Japanese with English abstract).
7. Nakano Y. and Okada T. “Reliability analysis on seismic capacity of existing reinforced concrete buildings in Japan” Journal of Structural and Construction Engineering, AIJ, 1989; 406, 37-43 (in Japanese with English abstract).