13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 130

VULNERABILITY FUNCTIONS FOR WOODEN HOUSES IN JAPAN BASED ON SEISMIC DIAGNOSIS DATA

Masayuki KOHIYAMA[1] and Fumio YAMAZAKI[2]

SUMMARY

The regional difference of seismic capacity of wooden houses in Japan is revealed based on the seismic diagnosis data. The new vulnerability functions of wooden houses, which use the results of seismic diagnosis and an acceleration response spectrum, are proposed. They employ a probability density function of seismic performance indices of wooden houses, which are separated into an index of the resistance force and other indices regarding the degradation of resistance force. The input seismic motion is evaluated based on an acceleration response spectrum and natural periods determined by the indices of resistance force. The application results to the 1995 Hyogo-ken Nanbu earthquake are compared with the damage statistics at the five sites, which have seismic records. Though the proposed vulnerability functions are not based on the damage statistics, the estimated damage ratios coincide fairly well with the actual damage surveyed by local governments.

INTRODUCTION

The real-time systems of earthquake disaster mitigation have been developed in some countries, which estimate buildings damage based on distribution of earthquake motions in the aftermath of a large event. The systems use fragility curves or vulnerability functions, which describe the relationship between seismic input motion and probability of buildings damage occurrence. In Japan, the national and local governments have introduced disaster information systems to accelerate emergency response after a severe earthquake. But the recent earthquakes revealed that the estimation accuracy of building damage and casualties is not high. Hence, it is desired to improve the estimation accuracy for effective and efficient response.

Many researchers have pointed out the following causes of the limit of the accuracy: a) variety of earthquake source characteristics, e.g. a predominant period, duration, input energy, etc., b) non-uniformity of structural parameters, e.g. natural periods, deformation and energy consumption capacities, etc., c) rough assumption of damage models; in a practical case, the damage grades are determined from a complex mode of buildings damage and are influenced by subjectivity of inspectors.

---

[1] Institute of Industrial Science, The University of Tokyo
[2] Department of Urban Environment Systems, Faculty of Engineering, Chiba University

In this paper, it is firstly clarified that the distribution of seismic capacities of buildings are different and there exists regionality in Japan based on seismic diagnosis data of wooden houses. Secondly, the vulnerability function is formulated that can reflect this regionality by considering both natural period distribution of wooden houses derived from seismic diagnosis data and acceleration response spectrum. Finally, the validity of the proposed function is checked based on the damage statistics and seismic records of the 1995 Hyogo-ken Nanbu (Kobe) earthquake.

REGIONALITY OF SEISMIC PERFORMANCES OF WOODEN HOUSES IN JAPAN

Seismic Diagnosis Method of Wooden Houses

In Japan, the method developed by the Japan Building Disaster Prevention Association in 1979 has come into wide use throughout the country. The method was revised in 1985, and published under two headings: “Seismic Diagnosis and Retrofit Method of Your Home” (Housing Bureau [1, pp. 1-6]) (hereinafter referred to as the “the simple diagnosis method”) offering a basic method of assessment for the general public, and “Accurate Seismic Diagnosis and Retrofit Method of Wooden Houses” (Housing Bureau [1, pp. 9-28]) (hereinafter referred to as the “the accurate diagnosis method”), which details methods of assessment for building engineers. These guidelines are currently in wide use (Sakamoto [2]).

While the simple diagnosis method is aimed for non-experts, the accurate diagnosis method is based on a more advanced engineering approach, e.g. expert’s on-site investigation of a structure and soil, consideration of drawings, geologic and geomorphologic reports, etc. As with the simple diagnosis method, this method assesses seismic capacity focusing attention on only first-story wall, which would be damaged more than a second-story wall in many cases. The total score, the seismic performance index, is evaluated by multiplying all scores: ‘A’, ‘B×C’, ‘D×E’, and ‘F’. With respect to B×C and D×E, smaller combination for beam and girder directions is adopted for evaluation.

Index of soils and foundation, A

The score A is determined by a combination of foundation type and soil condition; it is considered that soft soil amplifies seismic waves.

Index of eccentricity, B×C

The score B×C, which corresponds to the amplification factor of seismic load by eccentricity, is evaluated by the eccentric factor based on the location of the centers of gravity and rigidity; the center of gravity is determined by the allocation of a roof and a second floor, and the center of rigidity is determined by the allocation of bearing (earthquake resisting) walls as well as other walls without openings considering resisting force ratios.

Index of resistance force, D×E

The score D×E is evaluated based on the ratio between the total wall length and required wall length; the total wall length is calculated for bearing walls and other walls without openings considering resisting force ratios, and the required wall length is calculated based on the weight of upper structures.

Index of Deterioration, F

A low score of F is assigned when a house is degraded, decayed or damaged by termite.

The accurate diagnosis method assesses seismic capacity based on the ratio of resistance force retained by the first story of a house to that required by the Building Standard Law. To put it briefly, seismic capacity of a house is judged by the ratio of the resistance force to a seismic load whether it stands up against a moderate earthquake, which is assumed to come within its service life, once in about fifty years, without yielding any crack on its wall. Incidentally, the accurate method recommends checking the following items: the ground condition around a house, e.g. retaining walls, joint connections (joiner metal existence), the stiffness of horizontal diaphragm, etc. These check results are not reflected in the total score, but are very critical for seismic capacity.

Target buildings of this diagnosis method (also the simple diagnosis method) are limited to conventional wooden-frame structures, which mainly use walls and bracings to bear horizontal seismic forces. However, structures with large section beams and columns, which are considered as rigid or semi-rigid frame structures, are not included. With respect to the number of stories, one- and two-storied houses are the targets. Based on compulsion of the Building Standard Law, a three-storied wooden construction requires a structural analysis and the law may assure its seismic capacity. But there are some cases that the roof space was remodeled to an attic or a house was newly enlarged with an upper story without authorization. These houses often have problems in their seismic capacity.

Regionality of Seismic Performance of Wooden Houses

The regionality of seismic performance indices is investigated based on the data provided by Mokutaikyo, which is a cooperative association of private sectors retrofitting wooden houses. Figure 1 shows the regions for aggregation of data, and note that Hokkaido, Tohoku, Hokuriku and San'in are snowy regions. Total number of houses in each region is listed in Table 1. These data are the results of seismic diagnosis conducted from July 2000 to October 2003 by Mokutaikyo. The data were checked to have roughly the same distribution in terms of construction years and total floor areas as the statistical data of the 1998 Housing and Land Survey [3].

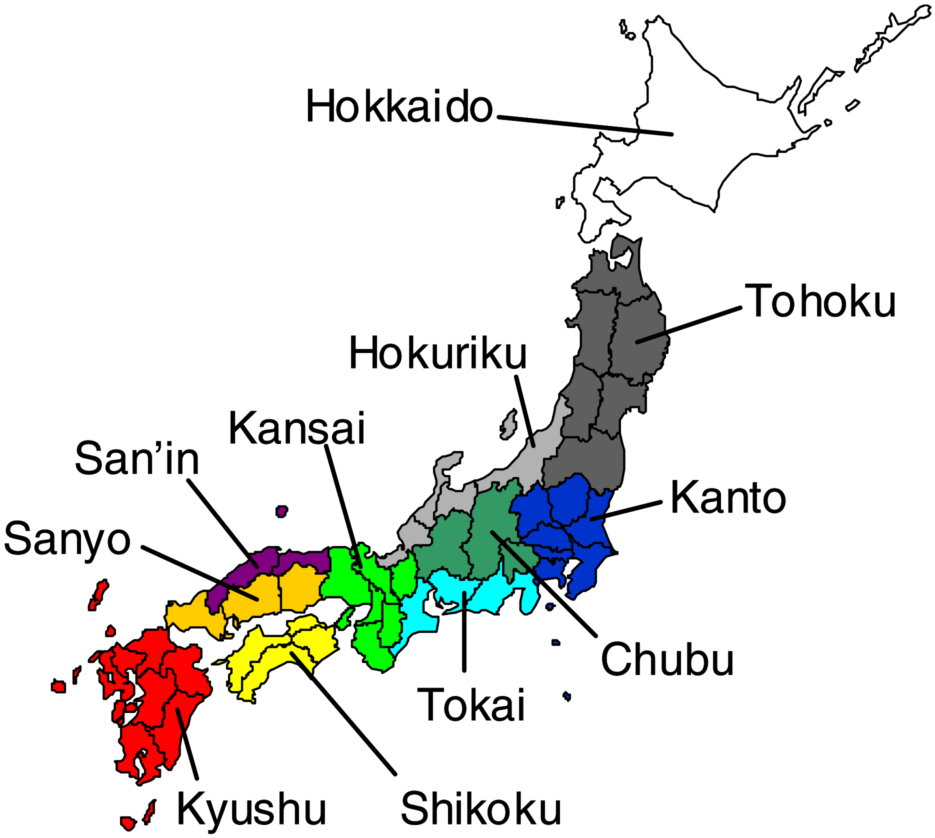

Figure 1. Aggregated areas to investigate regional differences in seismic diagnosis data.

Table 1. Number of buildings in aggregated areas to investigate regional differences in seismic diagnosis data.

Area name	Number of buildings in seismic diagnosis data
Hokkaido	89
Tohoku	1,448
Kanto	8,814
Hokuriku	495
Chubu	1,264
Tokai	12,470
Kansai	4,098
San’in	48
Sanyo	467
Shikoku	688
Kyushu	354
Total	30,235

Figures 2 and 3 depict the relative cumulative distribution of scores B×C and D×E in these regions, respectively. Clearly, regional differences are observed in the score distributions. However, some houses in Hokuriku and San’in have large section beams and columns and their diagnosis results may not be reliable. With respect to the score B×C, it is pointed out that snowy regions have more houses with poorly balanced walls or irregular plan. One of the causes of this may be that the north façade is apt to have fewer windows in order to reduce thermal energy loss in winter. Note that difference in distribution of score D×E suggests the difference in distribution of natural periods of houses. Hence, houses in Tohoku tend to have lager wall ratios, i.e., the natural periods tend to shorter than in other region. On the other hand, houses in Kansai region have relatively longer natural periods.

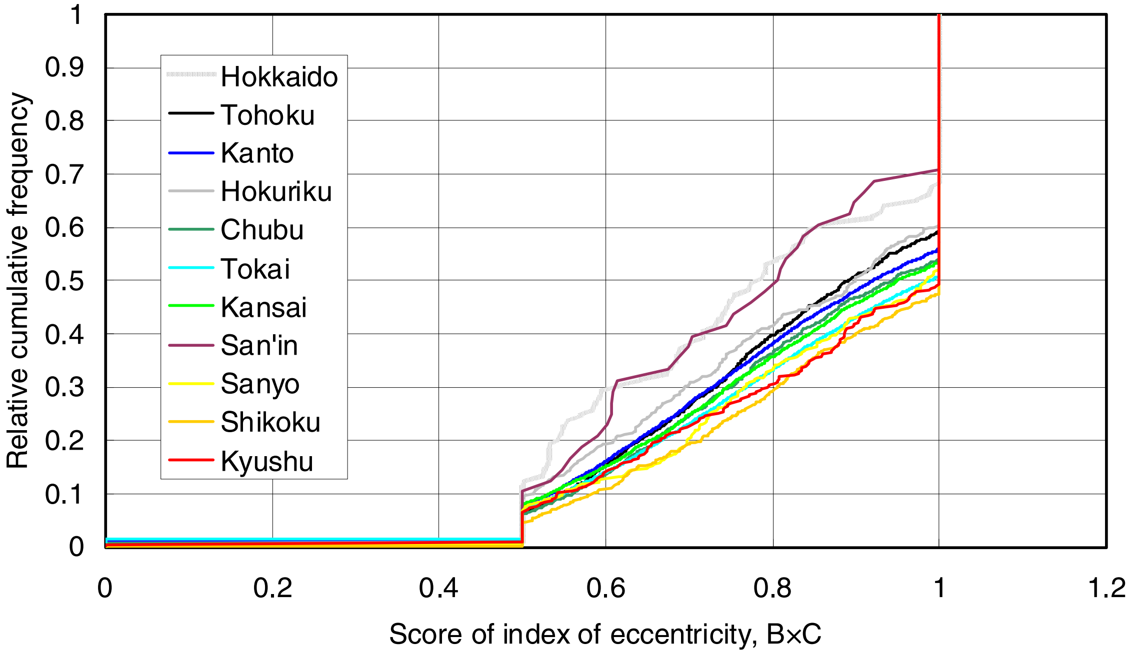

Figure 2. Regional differences in the distribution of score B×C.

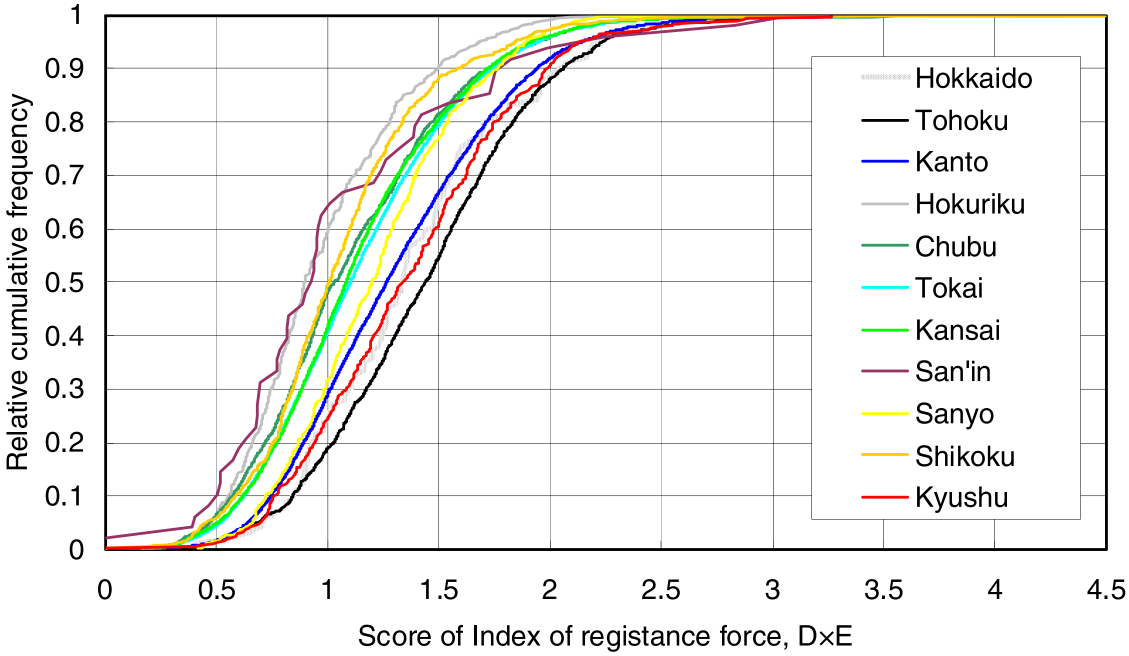

Figure 3. Regional differences in the distribution of score D×E.

To improve the estimation accuracy of building damage, it is important to consider both frequency content of seismic ground motion and the distribution of natural periods of structures in a site under consideration. In the next section, the vulnerability function is formulated, which employs acceleration response spectrum of input seismic motion and probability density function of scores of the seismic diagnosis.

FORMULATION OF VULNERABILITY FUNCTION BASED ON SEISMIC DIAGNOSIS DATA

Damage Model

In this study, the damage level that walls suffer from minor damage to yield clacks is focused on. Deformation with story drift angle equal to 1/60 rad would correspond well to this damage level according to the experiment using real scale house [4]. To this displacement level, the stiffness degradation of a wooden house is so small that it performs relatively linearly regarding relation of restoration force and displacement. Hence the linear behavior is assumed in the following formulation of vulnerability functions.

Input seismic motion

As mentioned in the previous section, consideration of both distribution of natural periods of structures and spectral characteristics of input seismic motion may improve accuracy of damage estimation. The proposed vulnerability function employs an acceleration response spectrum as an argument of the function. With respect to the damping ratio, 10% is assumed, which is intended for the story drift angle equal to 1/60 rad based on the results of experiments on [5], [6].

Formulation of Vulnerability Function

In this section, the vulnerability functions are derived based on the relation between seismic force and restoration force of a building, which is calculated from scores of seismic diagnosis.

One-Storied Houses

In the enforcement regulation of the Building Standard Law, the story drift less than 1/120 rad is allowed for wooden structure with the base shear $Ci = 0.2$. The minimal restoration force of the first story at this deformation level that the law regulates is denoted by Qr_0. When the seismic load, Qd_0, is caused by base shear $Ci = 0.2$, Qr_0 has the following relation:

$$Qr_0 = Qd_0 = Ci\ M\ g \tag{1}$$

where M is mass of the structure upper than the first story and g is acceleration of gravity.

Given a seismic force, Qd, loads on the structure. When the ratio, $Qr_0\ /\ Qd$ comes to less than 1/2, the deformation of the first story exceeds 1/60 rad and minor damage occurs to the structure under the assumption of the linear behavior with story drift angle up to 1/60 rad.

Given the first story of the structure has restoration force, Qr, with the drift angle 1/120 rad, and Qr is Rw times larger than the minimum restoration force required by the law, Qr_0, the restoration force, Qr, is:

$$Qr = Rw\ Qr_0. \tag{2}$$

The score of resistance force, I_{DE}, describes the ratio of the restoration force that the diagnosed structure retains to the force of the minimal low requirement. Actual houses have significant stiffness increase due to the contribution of perpendicular walls and moment resistance of the frames with widow back, etc. In addition, wall ratios used in structure design is defined by values with safety factor of 3/4 based on experiment results of the wall panel load tests. These effects of stiffness increase are considered by introducing coefficient, α_{DE}. Hence, it can be assumed that:

$$Rw = \alpha_{\mathrm{DE}}\ I_{\mathrm{DE}}. \tag{3}$$

When subject to response acceleration Sa with the shape factor, Fes, a seismic load, Qd, is derived as follows by substituting Equation (1):

$$Qd = Sa\ Fes\ M = Sa\ Fes\ Qd_0\ /\ (Ci\ g). \tag{4}$$

Fes increases the seismic load due to the building shape characteristics such as eccentricity or irregular elevation and the score of eccentricity, I_{BC}, corresponds to $1/Fes$.

In score of soils and foundation, amplification effect of soft soil to seismic ground motion is considered. However, acceleration response, Sa, which is used in the proposed vulnerability functions, includes also the amplification effect. Thus, this effect should be excluded from original score of soils and foundation. The different seismic diagnosis method [7] proposes to use two tables separately for increasing factor to amplified seismic load and for fragility of soils and foundation types. Table 2 shows the fragility, Rb, determined by the soils and foundation types, which may decrease the resistance force of the structure or the threshold of drift angle of minor damage. Rather than the original score of soils and foundation in the accurate diagnosis method, the score Rb is used for vulnerability function formulation and this is denoted by I_{A}.

Table 2. Scores of soils and foundation without soft soil amplification factor, *Rb* [7].

Foundation type	Soil type		
	Good or normal	Rather bad	Very bad
Strip foundation of reinforced concrete	1.00	1.00	1.00
Strip foundation of plain concrete	1.00	0.85	0.75
Frame-strengthened stone footing	1.00	0.85	0.75
Strip foundation of cracked concrete	0.70	0.60	0.50
Others	0.60	0.50	0.50

Deterioration could also reduce the restoration force or decrease the threshold of drift angle to yield minor damage. This factor is considered as Rd, which corresponds to the seismic diagnosis score of deterioration, I_F. Note that both I_A and I_F are smaller or equal to 1,

Given soils and foundation types and deterioration decrease the threshold of minor damage independently, the condition that a structure yields minor damage is:

$$Rb\ Rd\ Qr\ /\ Qd < 1/2. \tag{5}$$

By substituting Equations from (1) to (4) to Equation (5)

$$\frac{Rb\,Rd\,Qr}{Qd} = \frac{Rb\,Rd\,Rw\,Qr_0}{Sa\,Fes\,Qd_0/(Ci\,g)} = (Rb)\cdot\left(\frac{1}{Fes}\right)\cdot(Rw)\cdot(Rd)\cdot\frac{Ci\,g}{Sa}$$

$$= I_\mathrm{A}\ I_\mathrm{BC}\ \alpha_\mathrm{DE}\ I_\mathrm{DE}\ I_\mathrm{F}\ Ci\ g\ /\ Sa < 1/2,$$

$$\text{i.e., } I_\mathrm{A}\ I_\mathrm{BC}\ I_\mathrm{DE}\ I_\mathrm{F} < Sa\ /\ (2\ \alpha_\mathrm{DE}\ Ci\ g). \tag{6}$$

With respect to acceleration response, Sa is dependent to a natural period and damping of a structure. The lateral stiffness, St', of the minimum requirement of the law is:

$$St' = Qr_0\ /\ (h_1/120)$$

where h_1 is the first story height of a structure. In case of a one-storied house with h_1 equal to 290 cm, which is an approximate average, the natural period, T (s) is given by:

$$T = 2\pi\sqrt{\frac{M}{\alpha_\mathrm{DE} I_\mathrm{DE}\ St'}} = 2\pi\sqrt{\frac{M\cdot h_1/120}{\alpha_\mathrm{DE} I_\mathrm{DE}\ Qr_0}} = 2\pi\sqrt{\frac{M\cdot h_1/120}{\alpha_\mathrm{DE} I_\mathrm{DE}\ Ci\,M\ g}} = \frac{2\pi}{\sqrt{120}}\sqrt{\frac{h_1}{\alpha_\mathrm{DE} I_\mathrm{DE}\ Ci\ g}} \approx \frac{0.698}{\sqrt{\alpha_\mathrm{DE} I_\mathrm{DE}}}. \tag{7}$$

Suppose a probability density function, $p_p(I_\mathrm{DE}, I_\mathrm{ABCF})$ where $I_\mathrm{ABCF} = I_\mathrm{A}\cdot I_\mathrm{BC}\cdot I_\mathrm{F}$, is given from seismic diagnosis results of houses in a target area. When a seismic motion with the acceleration response Sa is applied to the houses, the probability to yield damage of minor or more, P_{fp}, is defined as the following vulnerability function:

$$P_{fp} = \int_{Ip} p_p(I_\mathrm{DE}, I_\mathrm{ABCF})\,dI \tag{8}$$

$$\text{where } I_p = \left\{ (I_\mathrm{DE}, I_\mathrm{ABCF}) \mid I_\mathrm{DE}\cdot I_\mathrm{ABCF} < \frac{Sa'(I_\mathrm{DE})}{2\alpha_\mathrm{DE} Ci\ g} \right\}, \tag{9}$$

$Sa'(I_\mathrm{DE})$ is the acceleration response spectrum that is redefined as the function of I_DE, i.e.,

$$Sa'(I_\mathrm{DE}) = Sa\ (T(I_\mathrm{DE}),\ h) \tag{10}$$

and h is a damping coefficient; 10% is assigned in the study.

Two-Storied Houses

As a typical two-storied house, it is assumed that upper and lower mass ratio in a two-degree-of-freedom model is 3 : 4, story heights are 290 cm, and the fundamental mode shapes a straight line. The first and second natural periods of this model are:

$$T_1 = 2\pi\sqrt{\frac{10}{7}}\sqrt{\frac{M}{k_1}} \approx \frac{0.834}{\sqrt{\alpha_\mathrm{DE} I_\mathrm{DE}}} \text{ and } T_2 = 2\pi\sqrt{\frac{2}{7}}\sqrt{\frac{M}{k_1}} \tag{11), (12}$$

where k_1 and M is the stiffness of the first story and total mass of the upper and lower, respectively.

With respect to the response of the first story, firstly, the second mode effect is considered. The maximum response is estimated by square root of sum of squares as follows:

$$\sqrt{\left|\beta_1 u_1^1\, S_d(T_1)\right|^2 + \left|\beta_2 u_2^1\, S_d(T_2)\right|^2} \approx \sqrt{\left|\beta_1 u_1^1\, S_a(T_1)/\omega_1{}^2\right|^2 + \left|\beta_2 u_2^1\, S_a(T_2)/\omega_2{}^2\right|^2} \tag{13}$$

where $\beta_i u_i^1$, S_d, S_a, ω_i are the element for the first story of the *i*-th modal participation function, a displacement response, a acceleration response, and the *i*-th circular frequency, respectively. The ratio of coefficients for the squared acceleration response in the right side of Equation (13) is calculated as follows:

$$\frac{\left(\beta_2 u_2^1 / \omega_2{}^2\right)^2}{\left(\beta_1 u_1^1 / \omega_1{}^2\right)^2} = \left(\frac{3M}{28k_1}\right)^2 \Bigg/ \left(\frac{25M}{28k_1}\right)^2 = \frac{9}{625} = 0.0144\,. \tag{14}$$

Hence, it can be concluded that the second mode has little influence for this model. Thus, by neglecting the second mode in Equation (13), the base shear is approximately given as:

$$\begin{aligned} & k_1 \sqrt{\left|\beta_1 u_1^1 S_d(T_1)\right|^2 + \left|\beta_2 u_2^1 S_d(T_2)\right|^2} \Big/ Mg \\ & \approx \frac{k_1}{Mg} \sqrt{\left|\beta_1 u_1^1 S_a(T_1) / \omega_1{}^2\right|^2} = \frac{k_1}{Mg} \beta_1 u_1^1 S_a(T_1) / \omega_1{}^2 = \frac{k_1}{Mg} \frac{25M}{28k_1} S_a(T_1) = \frac{25}{28} \frac{S_a(T_1)}{g}. \end{aligned} \tag{15}$$

Note that there is a coefficient of 25/28 = 0.8928··· in the right side of Equation (15), which is a reduction factor of the first story response due to the upper story existence. From this results, the vulnerability function of damage state of minor or more for two storied houses are derived by modifying Equations (8) and (9):

$$P_{fp} = \int_{Ip} p_p(I_{\mathrm{DE}}, I_{\mathrm{ABCF}})\, dI \tag{16}$$

$$\text{where } I_p = \left\{ \left(I_{\mathrm{DE}}, I_{\mathrm{ABCF}}\right) \mid I_{\mathrm{DE}} \cdot I_{\mathrm{ABCF}} < \frac{25}{28} \cdot \frac{Sa'(I_{\mathrm{DE}})}{2\alpha_{\mathrm{DE}} Ci\, g} \right\}. \tag{17}$$

VALIDITY STUDY AND COMPARISON WITH OTHER FRAGILITY CURVES

Study Area, Input Motion and Damage Statistics of Wooden Buildings

For the validity study to check that the proposed vulnerability function surely give accurate damage ratios, the damage statistics and strong motion records of the 1995 Hyogo-ken Nanbu (Kobe) earthquake are used, which Railway Technical Research Institute and the Committee of Earthquake Observation and Research in the Kansai Area provided. Note that the record of Amagasaki is corrected with respect to saturation [8]. The five strong motions records are used to evaluate acceleration response spectra, and the five areas within a radius of 100 m from the observation points and within the same geological and geomorphological zones as the observation points are selected as the study areas. Numbers of damaged wooden houses in these five areas are shown in Tables 3 and 4, which are based on the investigation results of local governments and the Architectural Institute of Japan and the City Planning Institute of Japan (AIJ&CPIJ) [9], respectively. The calculation results of damage ratios are also shown in the tables. Though there is no available statistics data of minor and no damages for Kakogawa City, it can be regarded that wooden houses in Kakogawa study area had little damage.

Table 3. Number of damaged wooden houses surveyed by local governments in the five areas.

	Areas of study				
Damage levels	Kakogawa	Suma	Higashi-nada	Amagasaki	Takarazuka
Major damage	0 in the city	26	14	11	93
Moderate damage	13 in the city	8	4	84	128
Minor damage	(no data)	13	28	69	50
No damage	(no data)	1	20	104	9
Total	N/A	48	66	268	280
Damage ratios	Almost 0%	97.9%	69.7%	61.2%	96.8%

Table 4. Number of damaged wooden houses surveyed by AIJ&CPIJ in the five areas.

	Areas of study				
Damage levels	Kakogawa	Suma	Higashi-nada	Amagasaki	Takarazuka
Major damage	(no data)	15	34	0	19
Moderate damage	(no data)	8	11	6	20
Minor damage	(no data)	12	47	59	30
No damage	(no data)	2	33	90	140
Total	(no data)	37	125	155	209
Damage ratios	Almost 0%	94.6%	73.6%	41.9%	33.0%

Seismic Diagnosis Data Used in the Study

Seismic diagnosis data of Mokutaikyo, but limited to those of houses constructed before 1996 in Hyogo Prefecture was selected to avoid the Kobe earthquake influence. Based on the Housing and Land Survey in 1993, Kakogawa City, Suma Ward, Higashi-nada Ward, Amagasaki City and Takarazuka City have one-storied houses with the ratios of 10.7%, 8.4%, 11.7%, 11.4% and 9.5% among the detached houses, respectively. Hence, the seismic diagnosis data of 902 two-storied houses are used for simplicity. Figure 4 shows the fitted probability density function, $p_p(I_{DE}, I_{ABCF})$, based on the seismic diagnosis data.

In calculation of damage ratio by the proposed function, the fitted density function was not used but the samples of the seismic diagnosis data themselves were used since they can be regarded as samples of the probability density function in Monte Carlo simulation. Here, weighting factors are introduced in order to adjust the distribution of seismic diagnosis data to the population of existing buildings. Figure 5 shows the distributions of construction years of wooden houses in cities and wards of the five study areas and Hyogo Prefecture based on the Housing and Land Survey in 1993. The distribution for the seismic diagnosis data is compared with them in the same graph. Weighting factors are derived from these ratios and are shown in Table 5. In calculation of damage ratio, firstly whether damaged or undamaged is checked on a house basis based on Equations (9) and (17). Then the number of damaged houses is compiled considering weighting factors. Finally, the damage ratio is given by the ratio between the weighted counts of damaged house and a total number of houses

Table 5. Weighting factors for seismic diagnosis data in the study areas according to construction years.

	Areas of study				
Construction year	Kakogawa	Suma	Higashi-nada	Amagasaki	Takarazuka
Before 1945	2.57	3.33	3.39	4.31	1.63
1945 - 1960	1.61	3.12	5.14	4.61	1.65
1961 - 1970	1.19	1.84	2.07	2.55	2.03
1971 - 1980	1.02	0.78	0.75	0.68	1.11
1981 - 1990	0.89	0.74	0.47	0.38	0.57
1991 - 1994	0.44	0.33	0.24	0.24	0.39

Note that a weighting factor of the magnitude 2.57 in the table means that a single house of seismic diagnosis data is to be dealt 2.57 houses in calculation of damage ratio.

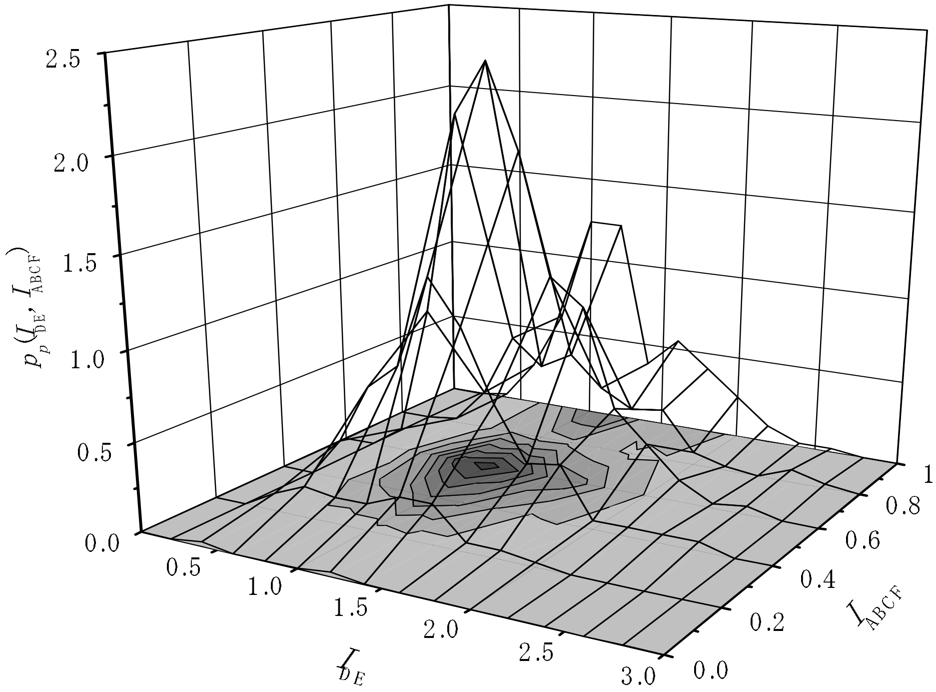

Figure 4. Fitted probability density function, $p_p(I_{DE}, I_{ABCF})$, based on seismic diagnosis data of two-storied houses in Hyogo Prefecture.

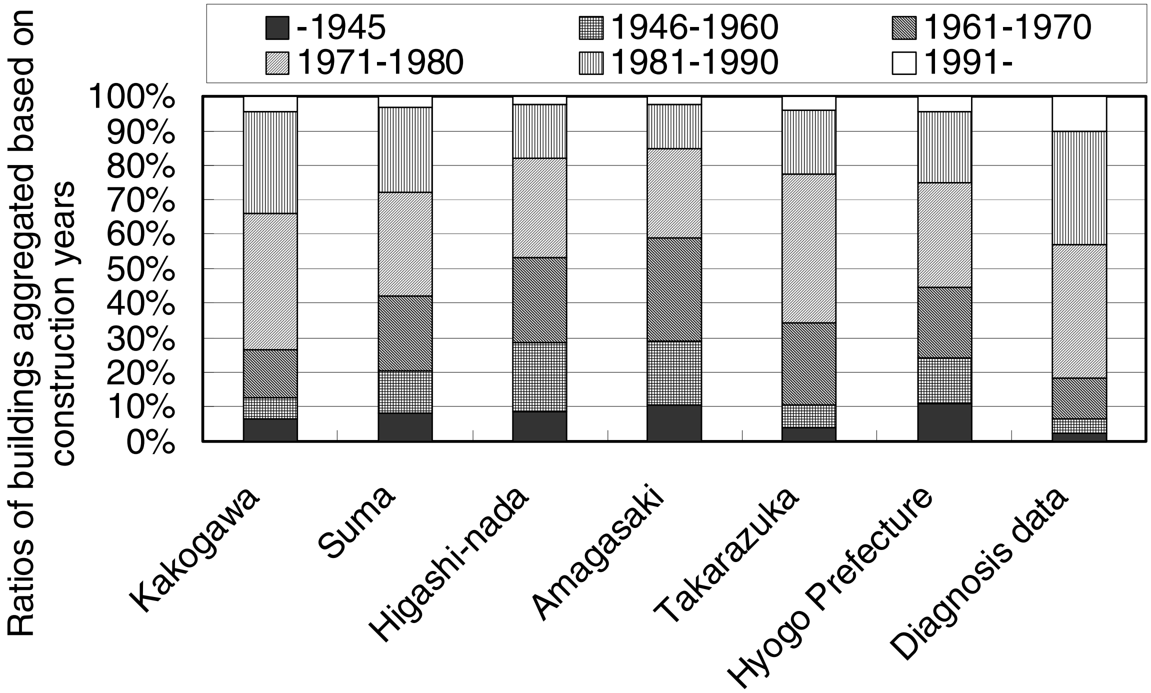

Figure 5. Distribution of construction years in cities and wards of study areas, Hyogo Prefecture and seismic diagnosis data of two-storied houses used in the study.

Evaluation of Damage Ratios and Comparison with Other Fragility Curves

With respect to the coefficient of stiffness increase effects, $\alpha_{DE} = 2$ is assumed by considering the several reports on building damage simulation of the Kobe earthquake and dynamic tests of real scale buildings. The damage ratios are evaluated for the five study areas, and with respect to Higashi-nada study area, the scatter plot of seismic diagnosis data, (I_{DE}, I_{ABCF}), and curves with acceleration response spectra projected to the I_{DE}-I_{ABCF} plane are shown in Figure 6. Since the seismic diagnosis data used in the study did not have information on the separate scores of north-south and east-west directions, the mean of acceleration spectra of two directions is used in calculation of damage ratios. The thick solid line in the figure shows the projected mean spectrum and the points under this curve represent damaged houses. Considering weighting factor in Table 5, the damage ratio is calculated as mentioned in the previous section.

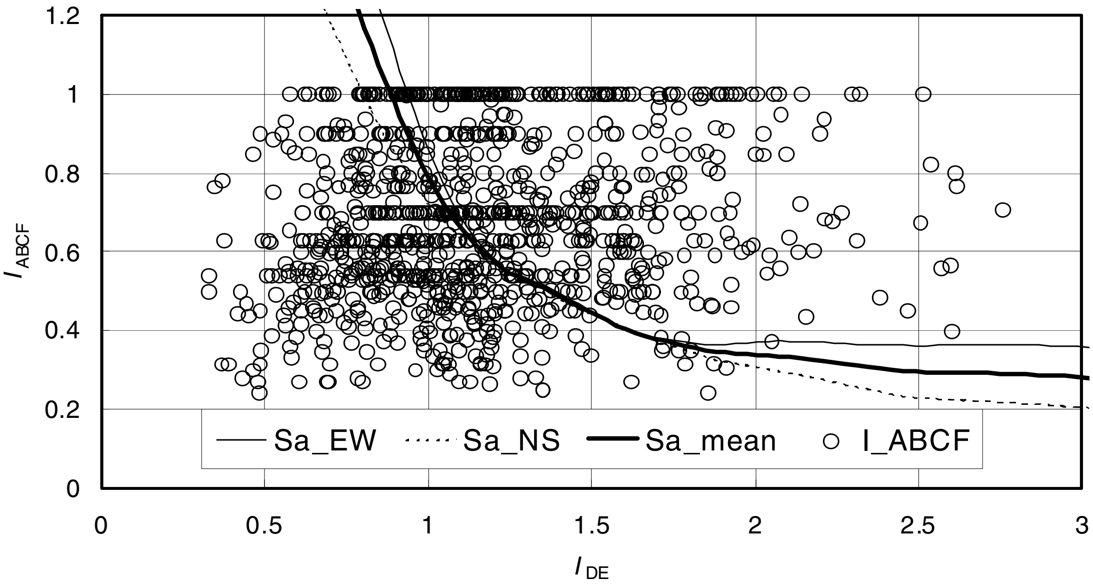

Figure 6. Scatter plot of seismic diagnosis data, (I_{DE}, I_{ABCF}), and curves with acceleration response spectra projected to I_{DE}-I_{ABCF} plane for the Higashi-nada study area.

The calculated damage ratios are compared with those of fragility curves proposed by [10], [11], [12] and [13] in Table 6. These fragility curves are statistically fitted to the selected data and information of the source data, i.e. types and locations of houses, is described in the table. Figure 7 compares actual damage ratios shown in Tables 3 and 4 and damage ratios calculated by the proposed vulnerability function and the fragility curves in the past literatures. Note that the proposed vulnerability function never uses peak ground velocity as an argument of the function; these results are plotted in the same graph just for the comparison with those of other methods. The root-mean-square error evaluated from the five study areas are shown in Table 7. It is observed that the proposed vulnerability function fits damage data surveyed by local governments better; in this case the root-mean-square error is 5.4%.

The compared fragility curves employ continuously changing curves along with peak ground velocity, e.g. lognormal distribution function. Hence, the estimated damage ratios are constrained by the shape of the monotonically increasing function. On the other hand, the proposed vulnerability function reflects the natural periods of structures and the estimated damage ratios are never constrained by the relation of monotonic increase; it can estimate damage ratios more accurately.

With respect to Kakogawa study area, the proposed function gives relatively lager damage ratio than the actual. This is due to existence of seismic diagnosis data with very low scores. Sometimes the accurate diagnosis method cannot evaluate the seismic capacity of traditional wooden-frame structures, which might have large section beams and columns and have very few walls. Building Research Institute and Japan Building Disaster Prevention Association are revising the accurate diagnosis method and the seismic diagnosis data evaluated by the improved method may overcome this problem.

Table 6. Calculated damage ratios of the proposed vulnerability function and several fragility curves in past literatures.

Vulnerability function and fragility curves	Areas of study				
	Kakogawa	Suma	Higashi-nada	Amagasaki	Takarazuka
Proposed vulnerability function	8.5%	92.2%	66.7%	66.8%	96.6%
Low-rise buildings in areas ranging from Kobe to Amagasaki [10]	13.4%	83.1%	61.6%	37.8%	63.9%
Low-rise buildings in Higashi-nada (construction year: -1974) [11]	14.2%	76.3%	55.6%	35.1%	57.7%
Low-rise buildings in Higashi-nada (construction year: 1985-) [11]	2.8%	30.7%	16.9%	8.5%	18.0%
Hanshin region [12]	0.2%	92.0%	51.9%	11.6%	56.7%
Wooden houses in Nada (construction year: -1950) [13]	18.0%	94.5%	78.6%	52.1%	80.6%
Wooden houses in Nada (construction year: 1982-94) [13]	0.7%	69.8%	33.0%	9.4%	36.2%

Note that buildings used to develop the fragility curves are described in the left side.

Table 7. Root-mean-square errors of estimated damage ratios

Vulnerability function and fragility curves	Source of damage statistics	
	AIJ&CPIJ survey	Local government survey
Proposed vulnerability function	25.4%	5.4%
Low-rise buildings in areas ranging from Kobe to Amagasaki [10]	16.3%	20.5%
Low-rise buildings in Higashi-nada (construction year: -1974) [11]	18.1%	24.8%
Low-rise buildings in Higashi-nada (construction year: 1985-) [11]	45.7%	57.1%
Hanshin region [12]	23.7%	29.7%
Wooden houses in Nada (construction year: -1950) [13]	19.0%	12.3%
Wooden houses in Nada (construction year: 1982-94) [13]	30.7%	41.2%

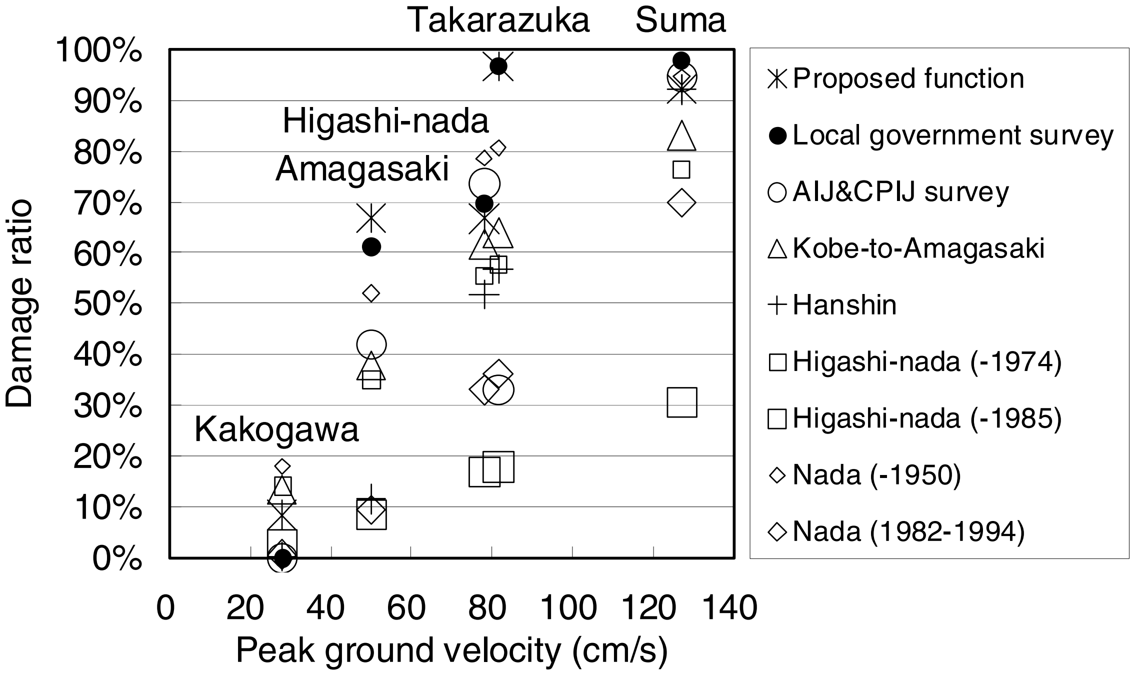

Figure 7. Comparison between actual damage ratios and damage ratios calculated by the proposed vulnerability function and the fragility curves in past literatures.

CONCLUSIONS

With respect to the seismic capacity of wooden houses in Japan, the regional difference is observed in scores of seismic diagnosis results. Since the score of resistance force relates to the natural periods, it is suggested that, in order to improve the accuracy of building damage estimation, it is important to consider both frequency content of seismic ground motion and the distribution of natural periods of structures in a site under consideration.

Based on the above findings, a new type of vulnerability functions are proposed and formulated. The functions employ seismic diagnosis data and acceleration response spectrum and they can reflect the regional difference in the distribution of natural periods of wooden houses. The validity of the proposed function is checked by using seismic records and damage data of the 1995 Hyogo-ken Nanbu (Kobe) earthquake. It is observed that damage ratios estimated by the proposed vulnerability function coincide fairly well to the actual damage surveyed by local governments.

The proposed vulnerability function can evaluate only damage ratio of minor or more because linear behavior is assumed in the formulation of the function. However, damage ratios of severer levels, e.g. collapse ratio, should be proposed. In addition, it may be useful if database of probability density functions of seismic diagnosis scores are developed or a simplified form of the vulnerability function is proposed to avoid gathering and handling large number of seismic diagnosis data. For these purpose, future studies are required.

ACKNOWLEDGEMENTS

This work is supported by Japan Society for the Promotion of Science: Grants-in-Aid for Scientific Research (B)(2), No. 14380189. The authors thank Mokutaikyo for seismic diagnosis data, Architectural

Institute of Japan, City Planning Institute of Japan, Building Research Institute, and local governments in Hyogo Prefectures for building damage data. The authors are also grateful to Dr. Kazue Wakamatsu for valuable suggestion in the validity study.

REFERENCES

1. Housing Bureau, Ministry of Construction (supervisor), the Japan Building Disaster Prevention Association and the Japan Federation of Architects and Building Engineers Associations (editors), "Accurate Seismic Diagnosis and Retrofit Method of Wooden Houses." 1985 (in Japanese).
2. Sakamoto I. "Standard for Assessment of the Earthquake Resistance of Wooden Houses." Kenchiku Bousai 1995; 208: 8-18 (in Japanese).
3. Statistics Bureau, Ministry of Public Management, Home Affairs, Posts and Telecommunications. "Housing and Land Survey: Results of the 1998 Survey (Statistical Tables)." 2000.
4. Tsuchimoto T, Ando N, Arima T, Nakajima S, Okazaki Y, Nakamura N. "A clarification of collapse modes and an establishment of evaluation methods of earthquake resistant properties on wooden houses." Annual Report of Housing Research Foundation 1998; 25: 259-270 (in Japanese).
5. Suzuki Y, Shimizu H, Suda T, Kitahara A. "Dynamic Characteristics and Seismic Performance of Two-Storied Wood Houses by Full-Scale Vibration Tests: Shaking Table Tests of Wooden Frames with Braces and Mud-Walls." Proceedings of the 11th Japan Earthquake Engineering Symposium 2002; 1377-1382 (in Japanese).
6. Arima T. "*Board-rui-wo Kugi-uchi-shita Tairyoku-heki-no Bairitsu-no Nintei-to Saikin-no Zairai-mokuzo-jutaku-no Kozo-tokusei* (Certification of wall ratio for bearing wall of nailed boards and structural characteristics of recent conventional wooden houses)." Mokuzai Kogyo 1982; 37(5): 213-220 (in Japanese).
7. Urban Housing Improvement Office, Housing Bureau, Ministry of Construction (supervisor), "Commentary on the Standard for Assessment of the Earthquake Resistance of Existing Wooden Buildings under the Act of Densely Inhabited Areas Improvement for Disaster Mitigation." Japan Building Disaster Prevention Association, 1998 (in Japanese).
8. Kagawa T, Irikura K, and Yokoi I. "Restoring clipped records of near-field strong ground motion during the 1995 Hyogo-ken Nanbu (Kobe), Japan earthquake." Journal of Natural Disaster Science 1996; 18(1): 43-57 (in Japanese).
9. Building Research Institute, Ministry of Construction. "Final Report of Damage Survey of the 1995 Hyogoken-Nanbu Earthquake." 1996 (in Japanese).
10. Hayashi Y, Miyakoshi J, Tamura K, Watanabe K. "Peak Ground Velocity Evaluation from Building Damage during Hyogo-Ken Nanbu Earthquake." Proceedings of the 1st Symposium on Near Fault Earthquake Disaster 1996; 89-92 (in Japanese).
11. Hasegawa K, Midorikawa S, Matsuoka M. "Seismic Risk Mapping of Wooden House in Large Area Using the Grid-Square Statistics part2 Vulnerability functions of wooden houses with different construction age and example of risk mapping." Journal of Structural and Construction Engineering 1998; 502: 53-59 (in Japanese).
12. Yamaguchi N, Yamazaki F. "Estimation of Strong Ground Motion in the 1995 Hyogoken-Nanbu Earthquake Based on Building Damage Data." Journal of Structural Mechanics and Earthquake Engineering 1999; 612/I-46: 325-336 (in Japanese).
13. Murao O, Yamazaki F. "Building Fragility Curves for the 1995 Hyogoken-Nanbu Earthquake based on CPIJ & AIJ's Survey Results with Detailed Inventory." Journal of Structural and Construction Engineering 2002; 555: 185-192 (in Japanese).