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SEISMIC RISK COMMUNICATION TECHNIQUE FOR INDIVUDUALS SUPPORTED BY STRUCTURAL HEALTH MONITORING OF DETACHED HOUSE

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ABSTRACT:

This paper proposes a risk communication system monitoring structural capacity of individual house and running with diagnosis of safety for inhabitants. First, we try to directly regress the structural scores concerning earthquake-resistant performance from the microtremors of detached houses. Second, we discuss the damage index function by which damage state of individual housing can be estimated for presumable seismic input motions, and propose the method for deducing the functions with structural scores measured from the microtremors of house. In the final step, we propose a bland new diagnosis method of human casualties in seismic damage houses by means of combining the damage index function of building with the death rate function of inhabitants. By systematizing the above processes we can provide the inhabitants with the informative system monitoring the seismic risk under their dwelling circumstances.

KEYWORDS: Wood frame building, Structural health monitoring, Microtremors, Human casualty, Risk communication, Damage estimation

1. INTRODUCTION

We must not forget the fact that the 1995 Kobe Earthquake killed many people by crashed non-engineered buildings of which structural system is wood frame structure of low-rise building and that is a basic structure in Japan. It is a goal of the high priority of earthquake protection planning that it does not kill and not injure the human in earthquakes; for the sake of improving seismic safety of individual housing, we discuss the structural health monitoring of low-rise and wood frame building, and we propose a method of transforming the monitored structural capacity of building into the seismic risk information of life or death for inhabitants. It is difficult to estimate the structural capacity of wooden houses, because the earthquake- resistant mechanism of their structures has not still analytically clarified by the reason why there are numerous factors as inhomogeneity of material properties and complexity of joint between columns and beams etc. affecting the seismic performance of wooden houses. We have been classified the structural performance into four levels based on the structural scores added up by means of the expertise diagnosis authorized by the Japan Building Prevention Association, that is, Risky, Moderate risky, Moderate safety, and Safety. The success or failure of the diagnosis strongly depends on the experience of the building experts. That is reason why it is impossible to entirely wipe out some arbitrary judgments by the diagnosis. The improvement of the seismic structural diagnosis based on measured values is expected so that the judgment can be objectively accepted. Considering the above situation, we try to directly measure the structural scores out of the microtremors of detached houses, and we investigate the way not to fix the microtremor measurement in the temporary diagnosis and to develop the measurement into a continuous monitoring system as structural health monitoring.

2. SEISMIC STRUCTURAL DIAGNOSIS OF JAPANESE CONVENTIONAL WOOD HOUSE

The seismic structural capacity evaluation for twenty seven Japanese conventional houses, which are wood frame structure of two story buildings, located at Nagoya city was executed in this paper. In July, 2004, the method for seismic diagnosis of wooden houses was revised by the Japan Building Disaster Prevention Association. The refined diagnostic methods based on the following several calculations are regulated.

2.1. Ultimate Capacity Evaluation

One of them is called Ultimate Capacity Evaluation. The structural score Q_d/Q_r is defined by the ratio of ultimate capacity Q_d, which means the total strength of exiting walls, and necessary capacity Q_r, which is story shear force generated by seismic ground motions.

2.2. Response and Limit Strength Calculation

This design method is based on the response spectrum of equalized single-degree-of-freedom system with building characteristic values of natural period and damping coefficient. The structural score Q_{si}/ Q_{sni} is defined by the ratio of limit strength Q_{si}, which is calculated by the response spectrum analysis, and acting seismic force Q_{sni}.

2.3. Dynamic Analysis

Japanese conventional house of which structure is wood frame of two story building (the height of each story is 3 meters) is idealized into a two-degree-of-freedom system with hysteric model. In this paper we adopt the model shown in Figure 1. The adopted hysteric model is an elasto-plastic and slip model proposed by Isoda and Kawai (2007). The maximum velocity of input ground motions, that are adopted in this paper are shown in Table 1, is standardized into 50 cm/sec. The structural score A/A_0 is defined by the ratio of the maximum acceleration A_0 in the case of reverting the standardized waves in velocity to accelerograms and the maximum acceleration A of input motions in the case that the response of building model extends to the safety limit 1/30 radian.

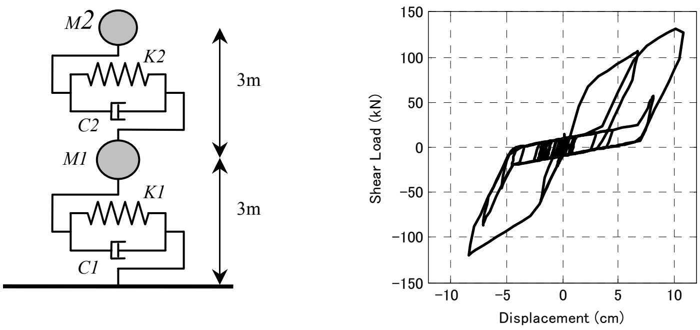


Figure 1 Idealized building system and its hysteric model

Table 1 Input ground motions adopted in this paper

Occurred Year	Earthquake Name	M	Seismograms	Peak Ground Acceleration in cm/sec^2	Peak Ground Velocity in cm/sec
1940	Imperial Valley	6.4	EL CENTRO-NS	341.7	34.2
1952	Kern County	7.7	TAFT-EW	175.9	16.9
1968	Tokachi-Oki	7.8	HACHINOHE-NS	229.7	33.7
1978	Miyagiken-Oki	7.4	TOHOKU-NS	258.1	36.2
1995	Kobe	7.3	OSAKA-GAS-FUKIAI	802.0	122.1
			JMA-KOBE	805.4	81.9
			JR-TAKATORI	603.6	119.9
2003	Tokachi-Oki	8.0	TOMAKOMAI-NS	86.7	26.7
2004	Niigataken-Chuetsu	6.8	OJIYA-EW	1307.9	125.9
2007	Niigataken-Chuetu-Oki	6.6	KASHIWAZAKI-NS	667.0	107.1
	Synthesized		BCJ2	355.7	52.1

Regardless of calculation method, the structural scores calculated by the above three types of design method give the same criteria of risk information as shown in Table 2.

Table2 Classification of structural scores

Structural scores	Judgment
Over 1.5	Safety (Building is not destroyed.)
Greater than or equal to 1.0 and less than 1.5	Moderate safety (Building is fairly not destroyed.)
Greater than or equal to 0.7 and less than 1.0	Moderate risky (Building is possibly destroyed.)
Below 0.7	Risky (Building is definitely destroyed.)

2.4. Comparison of Evaluated Scores

Figure 2 shows the results of the structural diagnosis for twenty seven samples of conventional houses. The horizontal axis means the scores calculated by Ultimate Capacity Evaluation Method and the vertical axis means the scores by other two methods. Although we can find some residual arisen from a difference between calculation methods, the scores indicate an equivalent diagnosis judgment each to each. Therefore, we try to directly regress the structural scores calculated from the microtremors of buildings in the next chapter.

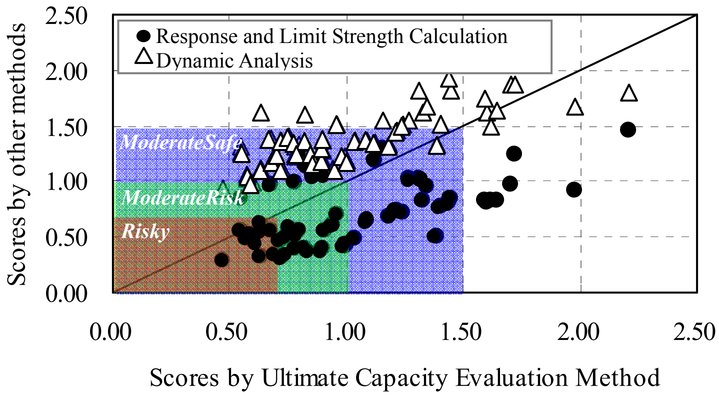


Figure 2 Results of structural capacity evaluation

3. EVALUATION MODEL BASED ON MICROTREMORS

3.1. Microtremor Measurement

We measured microtremors of each house in ten minutes through an observation system which was composed of three channels of servo type velocity seismographs with high frequency cut filters of 30 Hz. The microtremors were simultaneously observed at three points of each house, that is, the centers of first and second floors of the house and the ground level around 5 meters away from the house as a free field.

3.2. Characterized Indices of Wood Frame Structure

We adopted the following indices characterizing the vibration of building. That is, we calculated the natural period of building, the damping coefficient, and the chaos factor from the microtremors records.

3.2.1 Natural period: T_0

The first predominant period in the range of 0.1 to 0.5 seconds given by the Fourier spectrum ratio of the first floor record to the second floor record was regarded as the natural period of the house. The natural period strongly correlates with the stiffness of building. An example of microtremors recorded on the first and the second floors are shown Figure 3, and their Fourier spectrum ratio is shown in Figure 4.

3.2.2 Damping coefficient: h_{RD} (and h_{SI})

The damping coefficients relevant to vibration energy absorption were obtained. It is not easy to accurately determine the damping coefficient of building by means of microtremors, but we tried to estimate the values of each house by two kinds of technique. The damping coefficient h_{RD} can be obtained by the Random Decrement Technique (abbreviated to RD technique) proposed by Jeary (1986). Superimposing many records of microtremors of which starting point is the local maximum of acceleration, we obtain the free vibration waves and we approximate the exponential function to envelop of the waves (Figure 5).

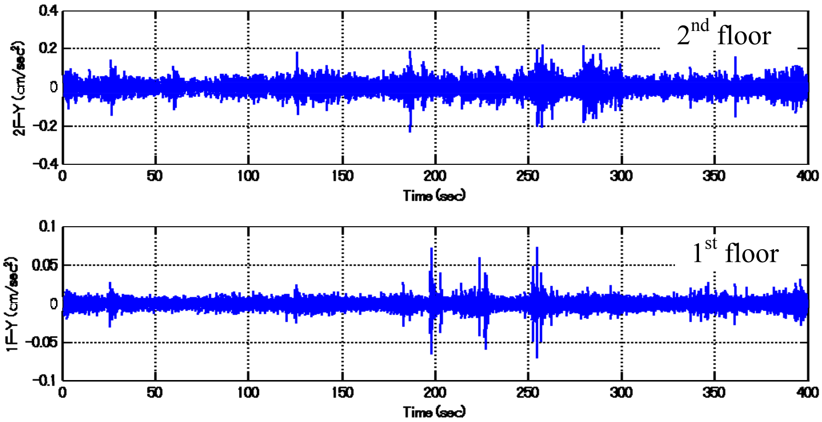


Figure 3 Example of microtremors recorded

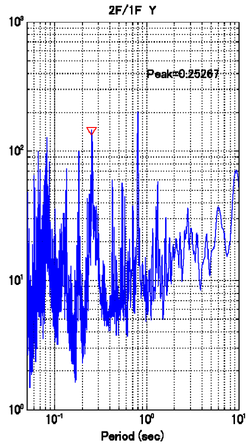


Figure 4 Fourier spectrum ratio

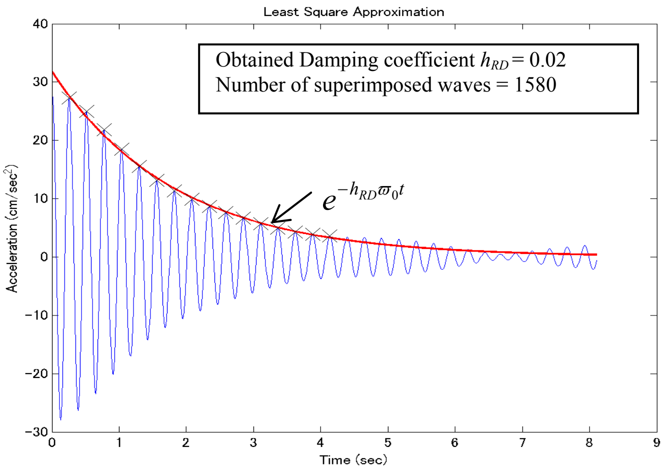
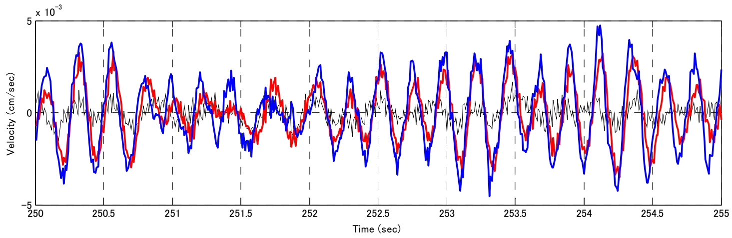


Figure 5 Estimation of h_{RD} by RD Technique

Another technique is based on the system identification. Japanese conventional houses are simplified by linear dynamic systems of which parameters are mass matrix, stiffness matrix, and damping matrix shown in Figure 1. Mass and stiffness matrices can be definitely obtained by Fourier spectrum analysis and Eigen value analysis. By supposing arbitrary damping coefficient we can compute the response of a linear dynamic model. We can regard it as the appropriate damping coefficients h_{SI} in the case of the minimum of residual errors between the body response and a model response (Figure 6).



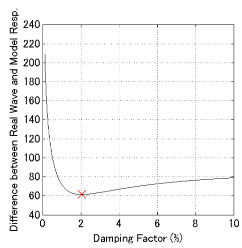


Figure 6 Comparison of responses of the objective house and a model.   Iteration process of residual and h_{SI}.

3.2.3 Chaos factor: Cha_{ANP}(or Cha_{RD}, and ARC)

For getting more information about earthquake-resistant performance from the microtremors of houses, we proposed the chaos analysis of microtremors. Chaos is an index showing the complexity of the vibration of building and it can be obtained by the following procedures. First, we select the time series samples $\boldsymbol{x(t)}$ of which duration is 5 sec out of the microtremors. Second, the time series $\boldsymbol{x(t)}$ is converted to a set of time-delayed data $\{x(t),x(t+\tau),x(t+2\tau),\cdots,x(t+(m-1)\tau)\}$ in m-dimensional space based on the embedded theorem. τ is phase delay and is defined by a quarter of natural period of building T_0. Third, the fractal dimension ν of the trajectories in the time-delayed space is determined from the following relation:

$$\nu = \frac{\log C(r)}{\log r}$$

where $C(r) = \lim_{n\to\infty} \frac{1}{n^2 \sum_{i,j=1}^{n} H\left(r - \left|x_i - x_j\right|\right)}$, and H is Heaviside function.

By increasing the embedded dimensional number m, the fractal dimension ν converges to a stable value by degrees. The converging value Dc, that is the chaos factor Cha, is finally obtained by approximating the following exponential function to the relation between embedded dimensional number m and fractal dimension ν.

$$\nu = -a\left(e^{-m/Dc} - 1\right)$$

The chaos factor Cha means more complex behavior as the values become bigger. The chaos factor is strongly depending on the characteristic of input motions as well, so that it is not easy to operate the factor describing the characteristic of structure system. For the sake of eliminating the characteristic of input motions we propose two kinds of procedures. One is calculating the chaos factor Cha_{ANP} in the range of analytical frequency restricted by using a narrow band filter of which central frequency is corresponding to the natural frequency of building. Another method is calculating the chaos factor Cha_{RD} from the superimposed waves by RD technique, waves which in a sense are equivalent to impulse responses.

Another index regarding chaos factor is proposed, that is, the ratio ARC between the chaos of microtremors in the second floor Cha_{ANP} and the chaos of ground motions Cha_G that is obtained in the same manner, for the purpose of eliminating chaotic characteristic held in input ground motions. We can discern such a negative correlation between the ratio ARC and the earthquake-resistant structural scores.

3.3. Multi Regression Analysis

Following the above procedures, we can obtain the indices of T_0, h_{RD}, h_{SI}, Cha_{ANP}, Cha_{RD}, and ARC for twenty seven houses. Using the indices as explanatory variables we executed multi regression analysis of which response variables are the structure scores by means of each structural diagnosis, that is, ultimate capacity evaluation, response and limit strength calculation, and dynamic analysis; and we obtained the following regression formulas:

$$S_{UCE} = -4.33T_0 - 0.50Cha_{ANP} + 0.15Cha_{RD} - 0.20h_{RD} + 3.70 \tag{1}$$

$$S_{RLSC} = -2.10T_0 - 0.61Cha_{ANP} + 0.08Cha_{RD} - 0.01h_{RD} + 2.83 \tag{2}$$

$$S_{5\%} = -4.35T_0 - 0.16Cha_{ANP} + 0.21Cha_{RD} - 0.03h_{5\%} + 2.40 \tag{3}$$

$$S_{RD}1 = -3.17T_0 - 0.17Cha_{ANP} + 0.19Cha_{RD} + 0.10h_{RD} + 1.62 \tag{4}$$

$$S_{RD}2 = -2.75T_0 - 0.52ARC + 0.15h_{RD} + 1.80 \tag{5}$$

$$S_{SI}1 = -3.39T_0 - 0.19Cha_{ANP} + 0.13Cha_{RD} + 0.10h_{SI} + 1.89 \tag{6}$$

$$S_{SI}2 = -3.41T_0 - 0.38ARC + 0.01h_{SI} + 1.98 \tag{7}$$

Because the scores by dynamic analysis are strongly depending on deterministic accuracy of damping coefficient h, we adopted three kinds of method determining coefficient, that is, the response variable $S_{5\%}$ in the same manner in which $h_{5\%}$ is fixed to 5 per cent as an ordinary dynamic analysis, the response variable S_{RD} regressed by h_{RD} in the manner of RD technique, and the response variable S_{SI} regressed by h_{SI} in the manner of system identification. Table 3 shows the coefficient of determination R^2 and the standard regression coefficients that mean the contribution of each explanatory variable to response variable.

Natural period T_0, chaos factor Cha_{ANP} and chaos ratio ARC in all regression formulas make negative contribution to structural scores and damping coefficient h_{SI} becomes positive contribution. It is meant that houses, of which rigidity and damping capacity are higher, are evaluated more antiseismic. This phenomenon agrees with general theory of building vibration. And earthquake resistance of houses is evaluated higher as the degree of chaos factor is smaller, which means the vibration mode of house is simpler. In detail, natural period T_0 and chaos factor Cha_{ANP} in Equation (2) are remarkably high, which means that the structural scores in the manner of response and limit strength calculation are almost decided by only the rigidity of house, and another chaos factor Cha_{RD} and damping coefficient h_{RD} merely play a role as correction factor in the regression formula.

Though the damping coefficient $h_{5\%}$ in Equation (3) in which damping coefficient is fixed at 5 per cent shows the negative contribution, this phenomenon is probably arisen from carrying out response calculation in this dynamic analysis with the usual assumption of constant value in respect of damping coefficient which should take the value characterized by each house. On the other hand, the regression models which specify a proper damping coefficient from microtremors show the positive contribution in Equations (4) to (7).

Table 3 Standard regression coefficients and Coefficient of determination

Equation No.	Response variables	T_0	Cha_{ANP}	Cha_{RD}	ARC	$h_{5\%}$, h_{RD}, h_{SI}	R^2
(1)	*Ultimate Capacity Evaluation*	-0.5130	-0.2420	0.0897		-0.2535	0.6839
(2)	*Response and Limit Strength Calculation*	-0.3366	-0.4089	0.0889		0.0332	0.6933
(3)	*Dynamic Analysis (h=5%)*	-0.5677	-0.0850	0.1974		-0.0706	0.6696
(4)	*Dynamic Analysis* ($h=h_{RD}$)	-0.4323	-0.0978	0.1846		0.2127	0.6754
(5)	*Dynamic Analysis* ($h=h_{RD}$)	-0.3642			-0.1257	0.3322	0.6122
(6)	*Dynamic Analysis* ($h=h_{SI}$)	-0.3453	-0.0818	0.0923		0.6315	0.8492
(7)	*Dynamic Analysis* ($h=h_{SI}$)	-0.3126			-0.0636	0.7130	0.8374

It is proven that the contribution of chaos factor lowers strikingly in dynamic analysis. Dynamic analysis describes the response of mass system based on a two-degree-of-freedom model of which parameters are completely designed. That is reason why such a synthesized index as chaos factor is not accepted as an explanatory variable in the diagnostic regression equation by dynamic analysis. While dynamic analysis removes the ambiguity of diagnosis, it requires serious attention for parameter setting to properly model the vibration characteristics of house. If it is possible to suitably decide the parameters of the mass system model by using microtremors, it is fairly straightforward to diagnose the houses by the proposed equations, and that means to open up the way to structural health monitoring for wood frame structures of low-rise house.

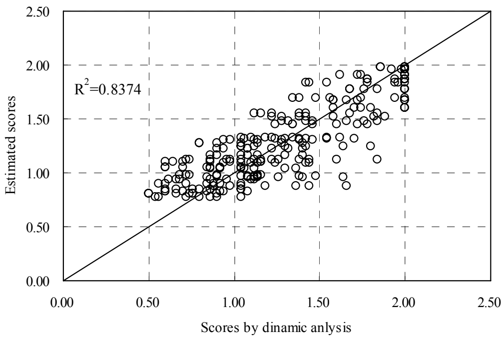


Figure 7 Correlation between the scores by dynamic analysis and the estimated scores by Equation (10)

The structural scores sensitively fluctuate depending on methods of the diagnosis, as described in Chapter 2.4. Generally, the diagnosis by dynamic analysis is much more reliable than any other diagnoses, and we regard the obtained equation (7) as the final result in this paper, the equation in which the response variable is recurred to the diagnosis results by dynamic analysis. Figure 7 shows the correlation between the scores by dynamic analysis and the estimated scores by Equation (7).

3.4. Demolition Experiment and Monitoring

For the purpose of verifying whether the proposed diagnostic method based on microtremor measurement can be applicable for assessment of the type of damage to buildings from slight damage to considerable structural damage, we tried to measure the microtremors of house under demolition. The objective house located at Nagoya city is a two-story wood building built in 1966. The demolition work was executed as following the schedule of removing walls that resist against force on the x-axis of the house. The demolition schedule and the structural scores calculated by dynamic analysis under the state of the house are shown in Table 4. The location of removed walls is indicated in a demolition order in Figure 8 in which the first floor plan of the house is depicted. The house retains high earthquake-resistant capacity for its building age. We measured the micromeres at each step of demolition, and estimated the structural scores by Equation (7). The results are shown in Figure 9. We can find the trend that the estimated scores based on microtremors trace the descending change of structural scores with demolition progress. The fact suggests that it is possible to recognize the characteristics of severe damage to building by monitoring the microtremors.

Table 4 Demolition schedule and the change of structural scores

Demolition's Order	Demolition schedule	Structural scores on the x-axis of 1st floor	Structural scores on the y-axis of 1st floor
1	Before demolition	1.54	1.90
2	Nonstructural wall in the north of Living Room	1.56	1.90
3	Walls in the north of Living Room, and Nonstructural wall in the west of Dining Room	1.59	1.89
4	Walls around Staircase, and Wall in the south of Lavatory	1.32	1.89
5	Wall in the south of Bathroom	1.25	1.89
6	Spandrel and hanging walls on the x-axis	1.00	1.89
7	Partition walls on the y-axis	1.03	1.45
8	Wall in the north of Washroom	0.93	1.45

The number in Figure 8 means demolition order.

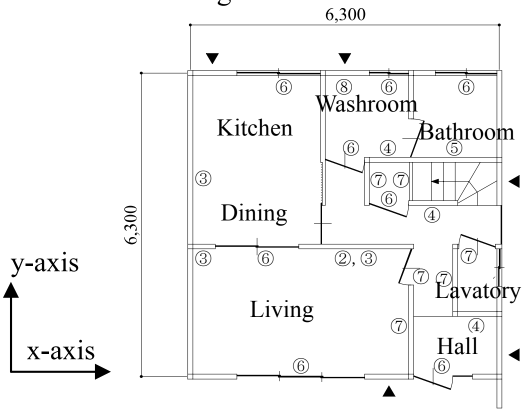


Figure 8 The first floor plan of the demolition house

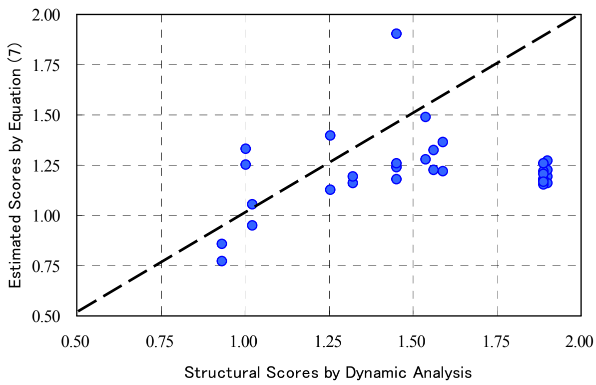


Figure 9 Corresponding change of scores with demolition

4. RISK INFORMATIVE TRANSFORMING

4.1. Damage Index Function of Wood House

For transforming the structural scores of houses into more intelligible information for inhabitants from the point of view of risk communication, we discussed Damage Index Function by which damage state of individual house can be estimated for assumable and forthcoming seismic input motions [Okada and Takai (2004)], and proposed the method for deducing the functions with structural scores of the load-carrying capacity for houses, and that means the informative process (shown in Figure 10) from diagnosis results by the structural health monitoring to disaster prevention information for individuals. Through the medium of the damage index function we can understand the damage state of our own house on the damage level of six classifications illustrated in Figure 10. The damage index function obtained is as follows:

$$x = 1 - e^{-(\log PGV/\eta)^m} \qquad (8)$$

where x is damage index meaning the state of damage degree of building, PGV is the peak ground velocity in assumable input motions, and m and η are the shape parameter and the scale parameter of the Weibull distribution, respectively.

We can apply the 3D nomograms (shown in Figure 10) of the obtained functions with three different types of parameters to utilize for various kinds 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.

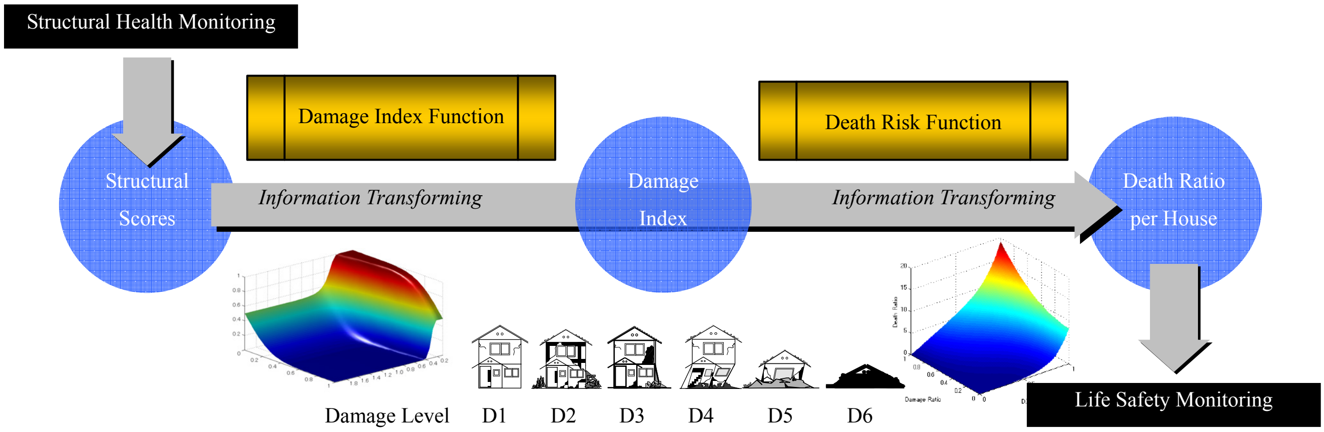


Figure 10 Information transforming process from structural scores to death ratio per house

4.2. Death Risk Function for Casualties per House

In the final step, we proposed the precise estimation model of human casualties in seismic damage buildings. Combining the data on damaged buildings surveyed in the field of earthquake engineering and the data on death bodies inspected in the field of disaster medicine in the 1995 Kobe earthquake, we found that earthquake casualties have close relation not only to the damage degree of their houses but also to the building damage ratio around the dwelling area [Tabata, Takai, and Okada (2004)]. We propose the death rate function with the parameters of them in order to precisely estimate casualties per house as follows:

$$D_r(x,y) = 0.0104e^{6.68x} + 11.0xy^2 \qquad (9)$$

where $D_r(x,y)$ is death ratio per house, x is damage index defined in Equation (8), and y is the ratio of destroyed houses in the vicinity.

The function is shown in Figure 10. Through the process depicted in Figure 10 it is possible to evaluate the death risk information in their own household according to the degree of earthquake-resistant capacity of house. Proposed functions are also applicable for the effective seismic reinforcement plan for the house to decrease the casualties in the municipality or governmental unit.

5. Conclusions

For the purpose of monitoring seismic safety for individuals living in non-engineered house like a Japanese wood-frame and low-rise building and supplying plain information for countermeasures, we discussed the bland new diagnosis methods applicable for seismic alert system from various points of view as vibration measurement, structural engineering, and human casualty.

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