PERFORMANCE LEVELS OF BUILDING STRUCTURES AGAINST THE EARTHQUAKE (CONCEPT OF PERFORMANCE-BASED DESIGN STANDING ON QUESTIONNAIRES)

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SUMMARY

The following were observed as the results of questionnaire survey for building users, owners and experts. They all had a clear idea and they want to suppress hazard severity to a small level. This is more evident for "hazard to human life" and "loss of property value" than for "function of building". If the fuzzy relationship is used, the membership functions with respect to the structural damage level can be obtained from the performance requirement level. The performance requirement level is determined by users and owners for "hazard to human life" and "loss of property value". It thus becomes possible to convert the performance requirement level determined by users and owners to a structural damage level. On the other hand, users and owners preferred presentation of earthquake resistant performance, which states performance level by describing the target performance (life safety, property protection, and function maintenance) to some levels of the groundmotion.

INTRODUCTION

The necessity for performance-based design of building structure has been emphasized in recent years. Authors have stressed that the three main elements of performance-based design are "clarification of target performance", "performance evaluation" and "performance statement". In the first stage of performance-based design, it is important for building experts to explain building structural performance to clients and owners. This is important in order to clarify the target performance from the point of view of protecting "human lives", "properties contents" and "building function". This paper quantifies the levels of earthquake resistant performance required by users, owners and experts as degrees of satisfaction. These are derived by fuzzy theory from the results of questionnaires. In the beginning of the questionnaire, it was specified that these investigations were part of a research project of the Ministry of Construction [Okada et al., 2000] [Aoki et al., 2000], and that the questions were mainly on earthquake resistant design of building structures. Therefore, the respondents considered about earthquake resistant safety, while their replies in the questionnaire, and the answers may differ slightly from their normal way of thinking. On the other hand, the method preferred by users and owners for statement of earthquake resistant performance level is discussed.

2. OUTLINE OF THE SURVEY BY QUESTIONAIRES

A series of opinion survey was carried out for "ordinary residents", "building owners", and "building experts". The survey by questionnaire for "ordinary residents" and "building experts" is outlined in the reference [Takahashi et al., 2000]. Here, the questionnaire for "building owner" is outlined. The opinions as building owners should be grasped by groups and organizations variously shown in Table 1 for each affiliation to which they belong. With the Cupertino of groups and organizations, random sampling of members fundamentally chose the respondents. Research methods are fundamentally a mail distribution and recovery system. The

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questionnaire was carried out in February 1998. It was sent to 815 persons, and there were answers from 496. The recovery rate was about 60.1%. The business speciality of respondents had been chosen, and they were asked to reply on the basis of their business speciality. In this research, the authors explain that the questionnaire had to be answered by a respondent who works on fundamental planning of buildings and is not a building expert.

3. PERFORMANCE REQUIREMENT

The main objectives of building structural design are to assure "safety of human life", "maintenance of function"" and "preservation of property". It is necessary to identify what level of performance is required to meet each objective in the design stage. Questions need to be asked in the event of a large earthquake. In making this assessment, the following items need to be considered: (1) the severity of hazard to human life (safety of human life), (2) the required function of the structure following a disaster (maintenance of function) and (3) the extent of loss in value of real estate and household effects (preservation of property). "New house" and "new building" were specified in the surveys. The former is for ordinary residents and the latter is for building owners and building experts.

1) Severity of hazard to human life
Select one of the following levels of injury: (1) no injury (2) light injury (3) injury of bone fracture level (4) serious injury or (5) death, which is the minimum performance that the structure should provide.

2) Required function following an earthquake
Select one of the following levels of damage: (1) can keep using it as it is (2) partial repair is necessary (3) can be used after repair and (4) necessary to rebuild, which is the state in which the building is deemed as being preserved.

3) Extent of loss in value of the real estate and household effects
Select one of the following levels of damage: (1) no loss of value (2) some loss can not be avoided (3) 50% loss can not be avoided and (4) almost total loss can not be avoided, which is the state in which the value of buildings, etc. is deemed to be preserved.

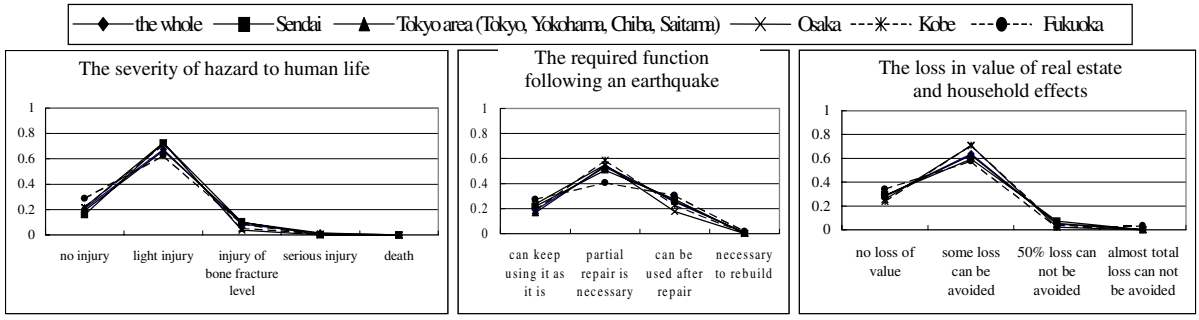
The survey results are shown in the form of membership functions of fuzzy theory [Zadeh, 1965] for damage level expressed by language in Figure 1. The derivation of the membership functions uses the number of respondents for the relevant option divided by the total number of respondents (ratio of each option selected). The evaluation points were evaluated as this membership value.

As for ordinary residents (Figure 1: (a)), the "severity for hazard to human life" and "loss in value of real estate and household effects" resulted in a larger maximum evaluation point and a smaller distribution range than that for the function following a disaster. Accordingly, it is found that ordinary residents have a clearer idea about "hazard to human life" and "loss in value of real estate and household effects" than about the other items.

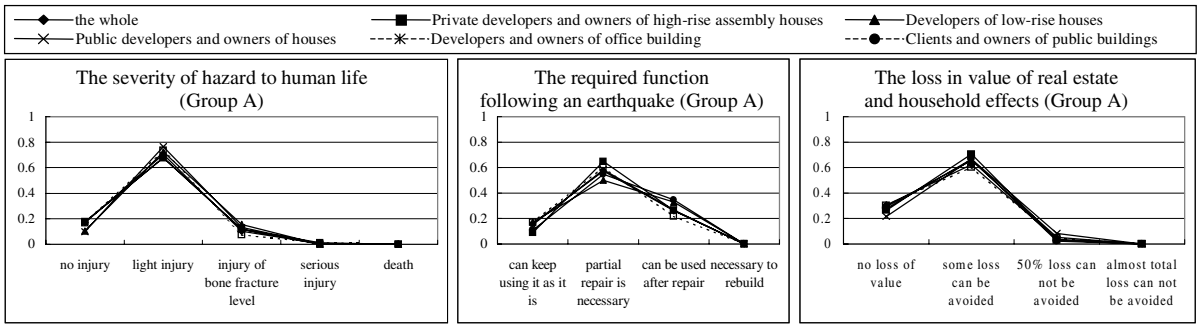
As for building owners (Figures 1: (b) and (c)), for "hazard to human life", the observed trend is similar to that for ordinary residents. For the "required function following an earthquake", the distribution of evaluation points resulted in almost the same configuration for every industrial classification. For "loss in value of real estate and household effects", the difference was also small among the evaluations for various industrial classifications. In the questionnaire for building owners, the number of respondents was distributed among industrial classifications. The influence of the small number of respondents was also included in the distribution. However, the following identical findings were made for building owners. The "severity of hazard to human life" and "loss in value of real estate and household effects" resulted in a larger maximum evaluation and a smaller distribution range than for the "required function following an earthquake". Accordingly, it is found that building owners have a clearer idea about the severity of "hazard to human life" and “loss in value of real estate and household effects" than about "the required function of the building".

As for building experts (Figure 1: (d)), for "severity of hazard to human life", it was light injury that scored the highest evaluation among the optional answers. It is found that building experts' idea of opting for damage to be at the light injury level is strong in the "severity of hazard to human life". For the "required function following an earthquake", the following was observed. There was a slight difference depending on the organization in the evaluation on usability after repair. The survey for Japan Structural Consultants Association resulted in a slightly higher evaluation for usability after repair than for other organizations. It is thus found that structural experts tend to accept a little more damage. Furthermore, in terms of "loss in value of real estate and household

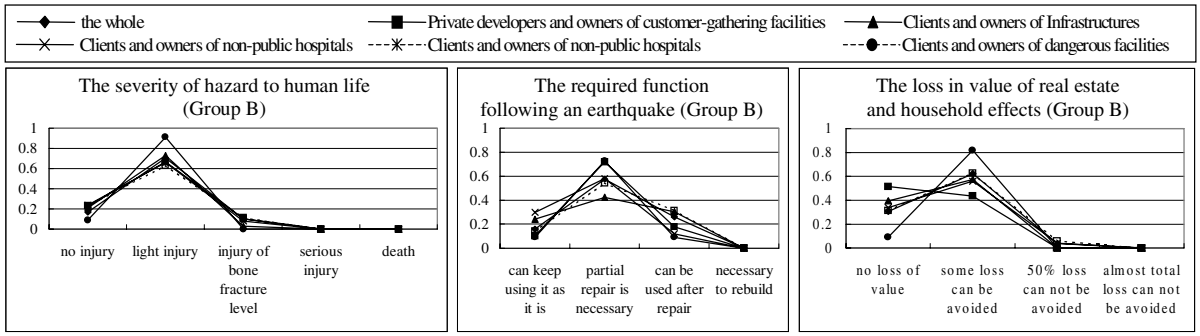
effects", "some loss" gained the largest evaluation. Building experts consider that "loss in value of real estate and household effects" should be small.



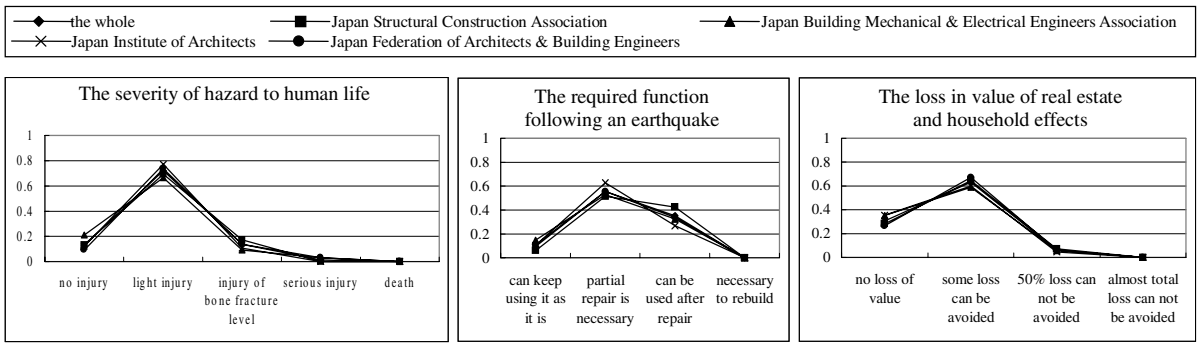
(a) Ordinary residents



(b) Building owners : Industrial classification group A



(c) Building owners : Industrial classification group B



(d) Building experts

Figure 1: The minimum performance that structure should provide, expressed by membership function

4. DAMAGE TO BUILDING STRUCTRES

Hazard to human life and loss in value of real estate and household effects due to damage to building structures should not be independently and individually evaluated, but should be properly correlated. Here, the

questionnaire survey was conducted for “hazard to human life" and "loss in value of real estate and household effects (It is called following, "loss of property value") " caused by structural damage. In the survey, respondents were requested to answer to "hazard to human life" and "loss of property value" according to the level of structural damage.

The questions in this questionnaire can be expressed by a fuzzy system [Kawamura and Yao, 1990] as shown in Figure 2. The studies were carried out for engineering and social evaluation for earthquake resistant safety of building structures using a fuzzy system. The effectiveness of the fuzzy system was also investigated [Nakashima et al., 1999]. The results obtained from the questionnaire can be interpreted to be the tool which gives the fuzzy relationship ($\mu_{R1}(x,y)$, $\mu_{R2}(x,z)$) in the fuzzy system.

The currently conducted questionnaire survey prepared questions on the following items, which are "hazard to human life" and "loss of property value". If these results are input into the two fuzzy relationships shown in Figure 2, the membership functions of the structural damage can be obtained by evaluating each of "hazard to human life" and "loss of property value" using the following equation.

$$\mu_A(x) = \max_{y \in Y} \{\mu_B(y) \wedge \mu_{R1}(x,y)\} \quad (1)$$

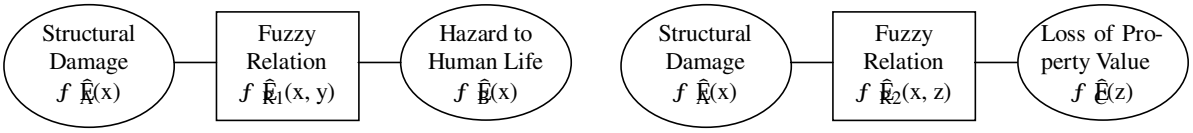
$$\mu_A(x) = \max_{z \in Z} \{\mu_C(z) \wedge \mu_{R2}(x,z)\} \quad (2)$$

Here, x, y and z correspond to the language expressions for structural damage, "hazard to human life" and "loss of property value", respectively. X, Y and Z denote the respective total base set. Furthermore, ^ in the equation denotes the min operation which takes the smaller number from both sides. The questionnaire questions were prepared in four stages for "loss of property value" of new buildings and household effects. Thus, the operation of equation (2) employed the four-stage evaluation for the fuzzy relationship obtained from the questionnaire. The membership functions for comprehensive structural damage can be obtained by applying the fuzzy maximizing decision [Bellman and Zadeh, 1970] on the membership functions obtained from equations (1) and (2).

For ordinary residents, the following results were obtained (Figure 3: (a)). The questionnaire on "hazard to human life" brought membership functions for structural damage. High membership values were found in " "slight through intermediate damage". In the questionnaire on the "loss of property value", the obtained membership functions gave the following results. These membership functions show clearer peaks than for "hazard to human life". It is thus found that ordinary residents have a clearer idea about "loss of property value" than about "hazard to human life".

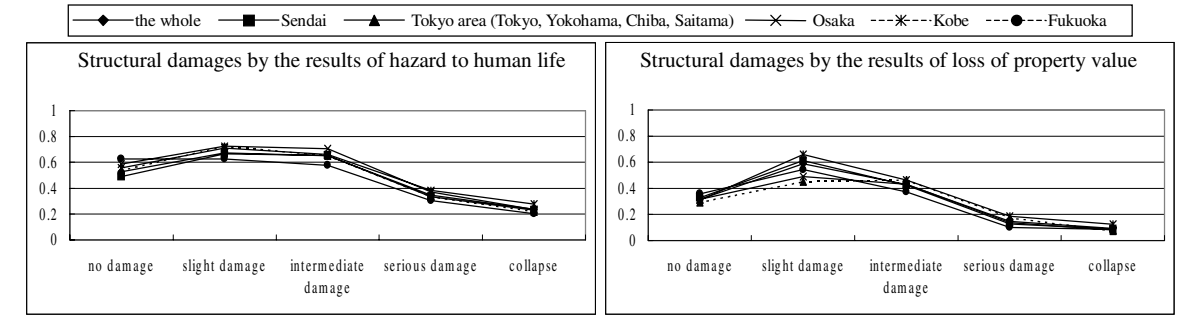
For building owners, the following results were obtained (Figures 3: (b) and (c)). The questionnaire on "hazard to human life" brought membership functions for structural damage. The distribution has clearer peaks in the groups of public hospitals, non-public hospitals and dangerous facilities than in the other industrial classification. In the industrial classification for customer-gathering facilities, an identical evaluation to the three stages from "no damage" to "intermediate damage" was achieved, same as those for ordinary residents. For the questionnaire on “loss of property value", the obtained membership functions for structural damage yielded the following results. Peaks of membership functions are found in slight damage in both industrial classification groups A and B. Clearer peaks are found here than in the "hazard to human life". It is thus found that building owners give a clearer evaluation on "loss of property value" than on "hazard to human life".

For building experts, the following results were obtained (Figure 3: (d)). The questionnaire on "hazard to human life" brought the membership functions for structural damage. High membership values are found in "slight damage". It is thus found that building experts have a clearer idea about "hazard to human life" and structural damage than ordinary residents and building owners. Furthermore, the results of the Japan Structural Consultants Association show larger membership values in larger damage (intermediate and serious damage) than in other organizations. For the questionnaire on "loss of property value", the obtained membership functions for structural damage yielded the following results. The structural damage appears in the distribution having peaks in "slight damage". Furthermore, the observed peaks are clearer than those for "hazard to human life". The following are found in the same way as for ordinary residents and building owners. Building experts have a clearer idea about "loss of property value" than about "hazard to human life".

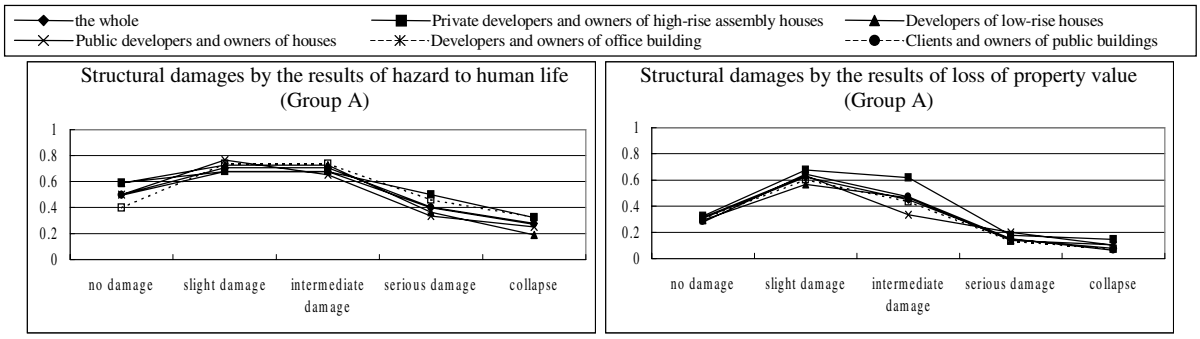


(a) Structural damage and hazard to human life (b) Structural damage and loss of property value

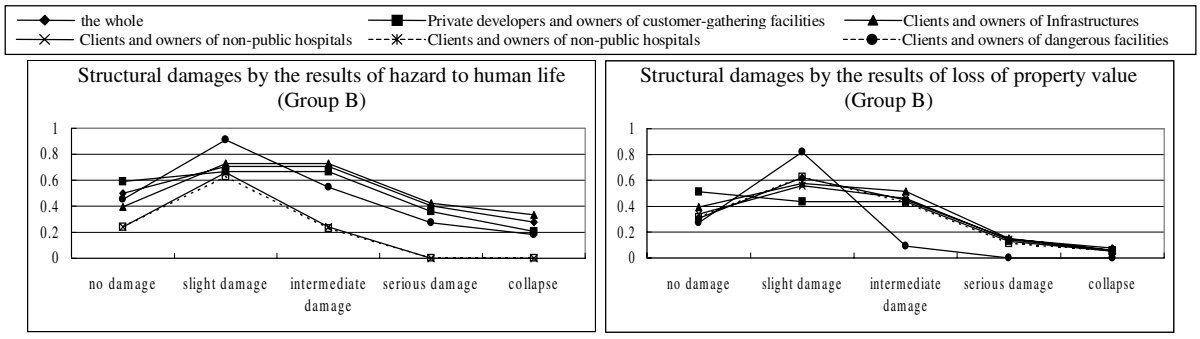
Figure 2 Questionnaire contents expressed by the fuzzy relations



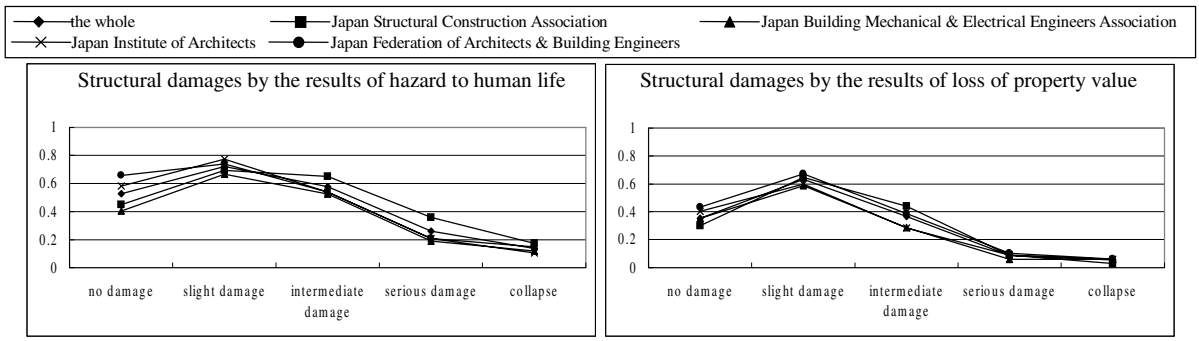
(a) Ordinary residents



(b) Building owners : Industrial classification group A



(c) Building owners : Industrial classification group B



(d) building experts

Figure 3: The distribution of membership function of structural damage

5. PERFORMANCE STATEMENT OF EARTHQUAKE RESISTANCE

To determine which statement is better for residents and owners to understand earthquake resistant performance, a question was asked, which required respondents to select one of six choice (Tables 2.1-2.6) which expresses the earthquake resistant performance of the building by dividing it into grades. As a result, Table 2.2 was preferred, which states performance level by describing the target of the building (life safety, building protection, and function maintenance) to some levels of the groundmotion.

Table 2.1 (ordinary residents : 20.8%, building owners : 19.2%)
Table 2.2 (ordinary residents : 47.7%, building owners : 47.5%)
Table 2.3 (ordinary residents : 3.8%, building owners : 4.1%)
Table 2.4 (ordinary residents : 5.2%, building owners : 5.7%)
Table 2.5 (ordinary residents : 8.5%, building owners : 11.6%)
Table 2.6 (ordinary residents : 1.8%, building owners : 5.0%)

6. CONCLUSIONS

Building users, owners and experts had a clear idea and they want to suppress hazard severity to a small level. This is more evident for hazard to human life and loss in value of real estate and household effects than for the required function of the building. If the fuzzy relationship is used, the membership functions with respect to the structural damage level can be obtained from the performance requirement level. The performance requirement level is determined by users and owners for "hazard to human life" and "loss of property value". It thus becomes possible to convert the performance requirement level determined by users and owners to a structural damage level. On the other hand, users and owners preferred presentation of earthquake resistant performance, which states performance level by describing the target performance (life safety, property protection, and function maintenance) to some levels of the groundmotion.

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Table 1: Distributions and Recoveries of Questionnaires for Owners

Channel	Num. of distributions **a**	Num. of recoveries **b**	Ratio of **b/a** **c=b/a*100**
①Private developers and owners of high-rise assembly houses (**Private high-rise houses**)	**75**	**34**	**45.3**
・Members of Japan High-Rise Condominiums Association	75	34	45.3
②Public developers and owners of houses (**Public houses**)	**80**	**60**	**75.0**
・Housing Supply Corporations	57	49	86.0
・Housing and Urban Development Corporation	10	2	20.0
・Local governments of ④	13	9	69.2
③Developers and owners of office buildings (**Office building**)	**158**	**93**	**58.9**
・ Member of Japan Building Owners and Managers Association	158	93	58.9
④Clients and owners of public buildings (**Public buildings**) ・Local governments Miyagi-Prefecture, Sendai-City, Chiba-Prefecture, Chiba-City, Saitama-Prefecture, Tokyo-Met., Kanagawa-Prefecture, Yokohama-City, Osaka-Prefecture, Osaka-City, Hyogo-Prefecture, Kobe-City, Fukuoka-Prefecture, Fukuoka-City	90	83	92.2
⑤Clients and owners of customer-gathering facilities (**Customer-gathering facilities**)	**52**	**39**	**75.0**
・Members of Japan Stores Association	19	16	84.2
・Members of Japan Hotels Association	33	23	69.7
⑥Clients and owners of infrastructures (**Infrastructures**)	**88**	**33**	**37.5**
・Banks	18	3	16.7
・Members of the Federation of Electric Power Companies	10	10	100.0
・Members of Telecommunication Carriers Association	30	11	36.7
・ Members of The National Association of Commercial Broad Casters in Japan	30	9	30.0
⑦Clients and owners of non-public hospitals (Non-public **hospitals**)	**150**	**50**	**33.3**
・Random sampling from a list of private hospitals extraction	150	50	33.3
⑧Clients and owners of public hospitals (**Public hospitals**)	**13**	**11**	**84.6**
・Local governments of ④	13	11	84.6
⑨Clients and owners of dangerous facilities (**Dangerous facilities**)	**35**	**35**	**100.0**
・ Members of Engineering Advancement Association of Japan	35	35	100.0
⑩Developers of low-rise houses (**Low-rise houses**)	**74**	**58**	**78.4**
・Members of Japan 2×4 Home Builders Association	36	27	75.0
・Members of Japan Association of House Builders	20	15	75.0
・Members of Japan Prefabricated Construction Suppliers & Manufactures Association	18	16	88.9
Total	**815**	**496**	**60.1**

Table 2.1: The earthquake resistant performance is stated at each levels of the ground motion of the 4 levels. The content of the earthquake resistance performance is expressed by the damage of the building.

The level of the Ground motions		Small	Moderate	Large	Very Large
The grad of the building	A	No damage	No damage	Slight damage	Little damage
	B	No damage	Slight damage	Little damage	Intermediate damage
	C	Slight-damage	Little damage	Intermediate damage	Serious damage
	D	Little- damage	Intermediate damage	Serious damage	(Not assumed)

Table 2.2: The earthquake resistant preference is stated at each levels of the ground motion of the 4 levels. The content of the earthquake resistance performance is expressed according to the target of the Building.

The level of the Ground motions		Small	Moderate	Large	Very Large
The grade of the building	A	Life safety Property protection Function maintenance	Life safety Property protection Function maintenance	Life safety Property protection Function maintenance	Life safety Property protection
	B	Life safety Property protection Function maintenance	Life safety Property protection Function maintenance	Life safety Property protection	Life safety
	C	Life safety Property protection Function maintenance	Life safety Property protection	Life safety	The human life is Not always safe
	D	Life safety Property protection	Life safety	The human life is not always safe.	(Not-assumed)

Table 2.3: The earthquake resistant performance is expressed at the probability, which the damage is generated for 50 years.

Damage		Slight damage	Little damage	Intermediate damage	Serious damage
The grate of the building	A	5%	2%	1%	0.01%
	B	10%	5%	2%	0.1%
	C	20%	10%	5%	1%
	D	50%	20%	10%	5%

Table 2.4: The level of the ground motion is assumed with the seismic intensity of 6 strength (JMA), and the content of the earthquake resistant performance is expressed by the damage of the building.

The grade of the building	A	B	C	D
Expected damage	Little-damage	Middle-damage	Large-damage	It may collapse.

Table 2.5: The level of the ground motion is armed with the seismic intensity of 6 strength (JMA), and the content of the earthquake resistant performance is expressed by the target performance.

The grade of the building	A	B	C	D
The target earthquake resistant performance	Life safety Property protection Function maintenance	Life safety Property protection	Life safety	The human life is not always safe

Table 2.6: Regardless of the level of the groundmotion, the earthquake resistant performance is expressed at the ratio of the strength for the standard grade.

The grade of the building	A	B	C	D
The radio of the strength	2.0	1.5	1.0	0.7