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SEISMIC CAPACITY INDEX OF EXISTING HIGH-RISE RC BUILDINGS IN JAPAN

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ABSTRACT

In design, it is confirmed that seismic response not exceed the criteria, however, the seismic capacity of building is not apparent. Seismic capacity index is the numerical value that expresses how much the seismic capacity a building has. In Japan, the method of calculating seismic capacity index for RC buildings of 60m or less has been already proposed, on the other hand, the method for RC buildings over 60m (high-rise RC building) has been not proposed yet. This paper shows the calculation method of seismic capacity index to reparability limit state and ultimate limit state of existing high-rise RC buildings. The seismic capacity indexes are calculated to frame models which correspond with seismic capacity of the existing high-rise RC buildings. The seismic capacity indexes of existing high-rise RC buildings are examined in order to clarify relationship between the indexes and structural characteristics, and relationship between the indexes and seismic responses. Main conclusions of this paper are summarized as follows. (1) The seismic capacity of existing high-rise RC building can be shown clearly with numerical value using the proposed method in this paper. (2) It is found that the seismic capacity index of existing high-rise RC building also increases as the value ($C_B \times T_1$) which multiplied base shear coefficient (C_B) and natural period (T_1) increases.

Keywords: High-rise RC building, Seismic capacity index, Reparability limit, Ultimate limit, Design phase

INTRODUCTION

So far, more than 500 high-rise RC buildings were built in Japan. However, the structural characteristics of these existing high-rise RC buildings differ depending on the designed phases. In addition, seismic capacity of the existing high-rise RC buildings is not grasped. It is necessary to grasp the seismic capacity of the existing high-rise RC buildings not only to understand the present situation but also to enhance the earthquake resistance capacity of high-rise RC buildings.

In design, it is confirmed that seismic response not exceed the criteria, however, the seismic capacity of building is not apparent. Seismic capacity index is the numerical value that expresses how much the seismic capacity a building has. In Japan, the method of calculating seismic capacity index for RC buildings of 60m or less has been already proposed (Architectural Institute of Japan, 2004). On the other hand, the method for RC buildings over 60m (high-rise RC building) has been not proposed yet.

The Purpose of this paper is to propose the calculation method of seismic capacity index to reparability limit state and ultimate limit state of existing high-rise RC buildings. In this paper, the seismic capacity indexes are calculated to frame models which correspond with seismic capacity of the existing high-rise RC buildings. These frame models are constructed in the existing research by the authors (Akita et al., 2012). The seismic capacity indexes of existing high-rise RC buildings are examined in order to clarify relationship between the indexes and structural characteristics, and relationship between the indexes and seismic responses.

CALCULATION METHOD OF SEISMIC CAPACITY INDEX

This chapter describes the calculation method of seismic capacity index for existing high-rise RC buildings. This calculation method is based on the method of calculating seismic capacity index for

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RC buildings of 60m or less proposed by Architectural Institute of Japan in 2004 (Architectural Institute of Japan, 2004). Figure 1 presents the evaluation diagram of the seismic capacity index. In this paper, the calculation method is applied to the beam collapse type building, so that the target member of the evaluation is beam.

Evaluation for limit state of member

Figure 2 shows the restoring force characteristics of member and the member deformation corresponding to the limit states (Serviceability limit state, Reparability limit state I, Reparability limit state II and Ultimate limit state). A tri-linear model which has a cracking point and a yielding point is adopted to the restoring force characteristics of member. A ductility factor (DF) which calculated by yielding deformation (R_y) defines the limit states of member. It is assumed that a member reaches the serviceability limit state when DF is equal to 1. Similarly, the ductility factors corresponding with the reparability limit state I, reparability limit state II and ultimate limit state are 2, 3 and 4, respectively. In this calculation method, damage index of member is defined by ductility factor as shown in figure 2 The damage index of member is divided in 5 rank.

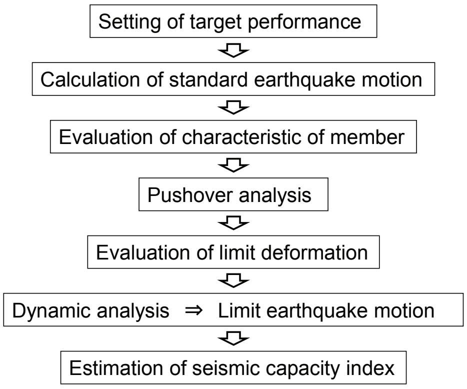


Figure 1. Evaluation diagram

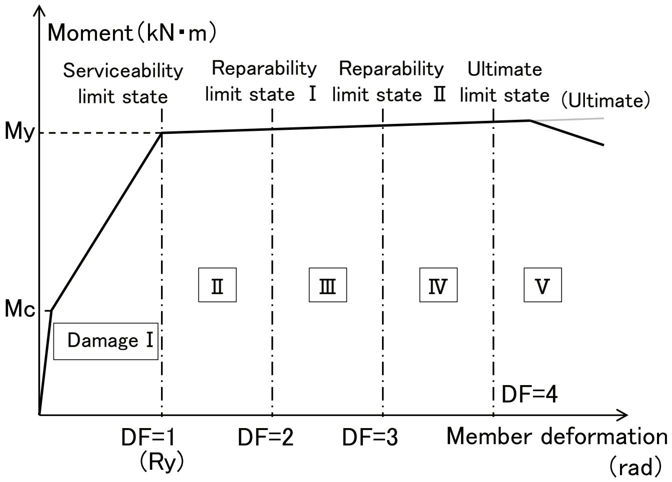


Figure 2. Restoring force characteristics and limit states

Evaluation for limit state of story

In this calculation method, equivalent column ductility factor is calculated from the beams in which the column is connected. Then, damage index of column is evaluated by the equivalent column ductility factor as shown in table 1.

Table 1. Relationship between damage index of column and equivalent ductility factor of column

Damage index of column	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ
Equivalent ductility factor of column	0～1	1～2	2～3	3～4	4～

Figure 3 shows the example for calculation of equivalent ductility factor of column. The equivalent ductility factor of column is an average of ductility factors of beams in which the column is connected. As shown in figure 3, the equivalent ductility factor is 1.75 in the case of 2 beams and the equivalent ductility factor is 2.25 in the case of 4 beams. And then, from the table 1, the damage index of column is II in the case of 2 beams and the damage index of column is III in the case of 4 beams.

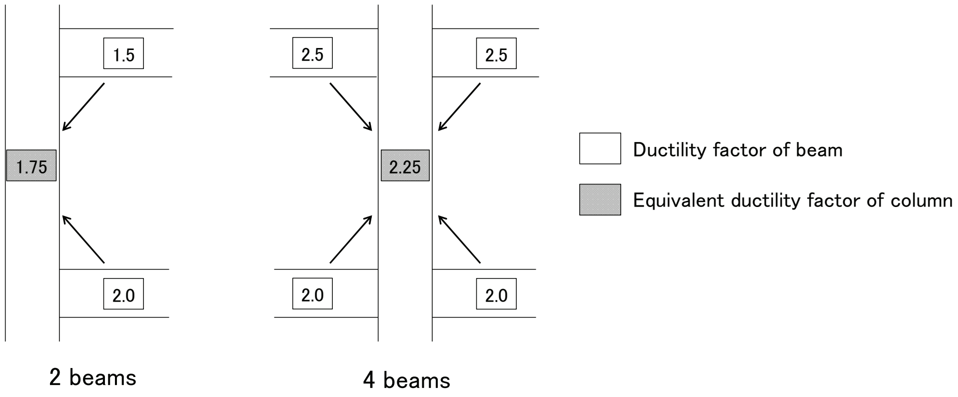


Figure 3. Example for calculation of equivalent ductility factor of column

Limit state of story is evaluated by shear force ratio of columns which has same equivalent column damage index. Then, limit story drift angle is defined by the story drift angle corresponding to limit state of story. Non-linear pushover analysis is conducted to obtain the limit story drift angle in this calculation method. Table 2 shows the relationship between limit states of story and shear force ratio of columns. The values in table 2 are determined considering a value proposed by AIJ (Architectural Institute of Japan, 2004).

Table 2. Relationship between limit state of story and shear force ratio of columns

Limit state of story	Shear force ratio of columns (Equivalent column damage index)				
	（Ⅰ）	（Ⅱ）	（Ⅲ）	（Ⅳ）	（Ⅴ）
Reparability limit state Ⅰ	－	0%	0%	0%	0%
Reparability limit state Ⅱ	－	－	20%	0%	0%
Ultimate limit state	－	－	－	－	0%

Estimation of limit earthquake ground motion

In this calculation method, limit earthquake ground motion is estimated by time history response analysis. The intensity of limit earthquake ground motion is examined by comparison of limit story drift angle derived from non-linear pushover analysis and the maximum story drift angle derived from time history response analysis.

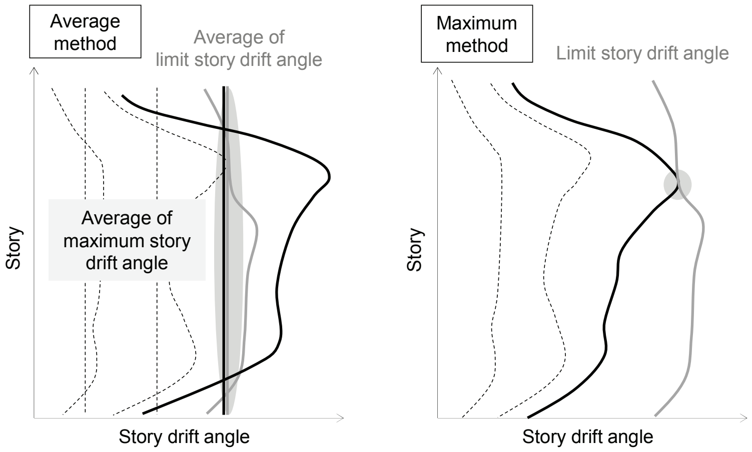
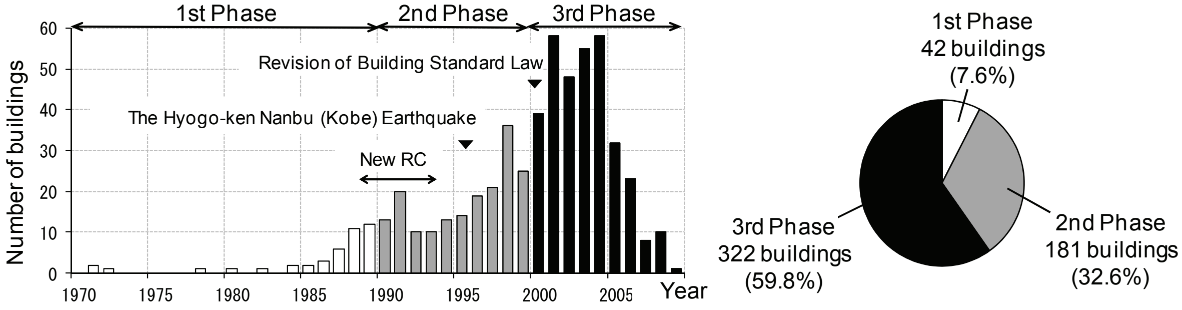


Figure 4. Two estimation method of limit earthquake ground motion

Figure 4 shows the two estimation method of limit earthquake ground motion. In this paper, the average method is applied to estimating reparability limit state I and II, and the maximum method is applied to estimating the ultimate limit state. In the average method, the intensity of limit earthquake ground motion is determined when average of the maximum story drift angle reaches average of the limit story drift angle. On the other hand, in the maximum method, the intensity of limit earthquake ground motion is determined when the maximum story drift angle reaches the limit story drift angle. The seismic capacity index is calculated as ratio of maximum velocity of the limit earthquake ground motion to maximum velocity of standard earthquake ground motion.

FRAME MODEL

In this chapter, outline of frame models are explained. Frame models are constructed based on structural planning and structural characteristics of the existing high-rise RC buildings. The structural planning and the structural characteristics were obtained from existing research conducted by the authors (Izumi et al., 2012).



(a) Transition of number of buildings (b) Rate of three design phases

Figure 5. Structural design phases for high-rise RC buildings

Table 3. List of seismic capacity index of the frame model

Design pahse	1st Phase						2nd Phase						3rd Phase					
Model	1G20		1G25		1G30		2G20		2G30		2G40		3G20		3G30		3G40	
Direction	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
Height (m)	60.75		75.5		90.25		61.7		91.7		121.7		63.6		94.6		125.6	
Building stories	20		25		30		20		30		40		20		30		40	
Typical story height (m)	2.95		2.95		2.95		3		3		3		3.1		3.1		3.1	
Typical floor area (m^2)	675		787.5		945		600		900		1050		585		936		1170	
Typical floor area supported by a column (m^2)	22.5		22.5		22.5		30.0		30.0		30.0		39.0		39.0		39.0	
Span length (m)	4.5	5	4.5	5	4.5	5	5	6	5	6	5	6	6	6.5	6	6.5	6	6.5
Number of spans	6	5	7	5	7	6	5	4	6	5	7	5	5	3	6	4	6	5
Aspect ratio	2.25	2.43	2.40	3.02	2.87	3.01	2.47	2.57	3.06	3.06	3.48	4.06	2.12	3.26	2.63	3.64	3.49	3.86
Design compressive strength of concrete [Fc] (N/mm^2)※1	36		36		42		36		48		60		42		54		70	
Tensile yield strength of longitudinal bar (N/mm^2)※2	390		390		390		390		490		490		490		490		490	
Average weight (kN/m^2)※3	14.5[11.2]		14.3[11.3]		14.8[11.9]		15.5[11.8]		14.9[11.9]		14.4[11.7]		15.4[11.6]		14.3[11.4]		13.4[10.9]	
Natural period [T1] (sec)	1.11	1.12	1.36	1.36	1.65	1.66	1.17	1.17	1.69	1.71	2.27	2.35	1.27	1.28	1.79	1.92	2.34	2.40
Base shear coefficient [C_B]	0.163		0.130		0.113		0.145		0.105		0.074		0.134		0.090		0.068	

※1 : The maximum value of design compressive strength of used concrete.

※2 : The maximum value of tensile yield strength of used longitudinal bars.

※3 : The value calculated from typical floor weight divided by typical floor area which excluded balcony.
(The value inside [ ] is including balcony.)

Organization of Frame Model

555 high-rise RC buildings designed from 1971 to 2009 were collected from the performance evaluation sheet (The Building Center of Japan, 1967-2009) and classified into the three design phases by means of the development of structural techniques on high-rise RC buildings as shown in figure 5. Table 3 summarizes the specifications of the frame models. Three frame models are constructed in each designed phases, thus nine frame models are constructed. These nine frame models are called "Standard model".

In this paper, "Strong model", "Weak model", "High-stiffness model" and "Low-stiffness model" are constructed based on the standard model. Capacity varies in the strong model and the weak model compared with the standard model. Stiffness varies in the high-stiffness model and low-stiffness model compared with the standard model. These models have nine buildings, respectively. Therefore, frame models using in this paper are 45 in total.

Variety of Frame Model

The strong model and weak model have 1.15 times capacity and 0.85 times capacity compared with the standard model, respectively. The high-stiffness model has 1.2 times stiffness of beams and 0.8 times weight compared with the standard model. The low-stiffness model has 0.8 times stiffness of beams and 1.2 times weight compared with the standard model. Figure 6 shows the relationship between designed base shear coefficient (C_B) and natural first period (T_1) of the frame model, together with the relationship of the existing high-rise RC buildings. The value (C_BxT_1) of the first design phase, the second phase, and the third phase is 0.19, 0.18 and 0.17 respectively. As shown in Figure 6, the frame model can simulate distribution of the existing high-rise RC buildings in every design phase.

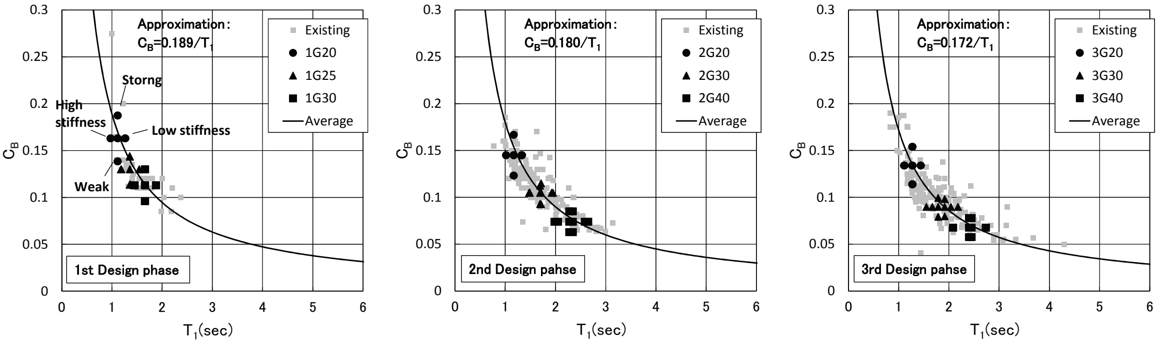


Figure 6. Correspondence between existing high-rise RC buildings and frame model

DISTRIBUTION OF SEISMIC CAPACITY INDEX

This chapter presents the calculation of seismic capacity indexes of frame models and distribution of seismic capacity indexes. The seismic capacity indexes are examined in order to clarify relationship between the indexes and structural characteristics, and relationship between the indexes and seismic responses.

Analysis Condition

Three-dimensional framed model with rigid floor which considered the elasto-plastic characteristics of beam and column member is used. The framed model has the tri-linear skeleton curve for beams and columns, and the TAKEDA MODEL is applied to the hysteresis characteristics of beams and columns. Reduction index of unloading stiffness is 0.50 (for beam) or 0.40 (for column). The viscous damping in proportion to momentary stiffness is assumed and the damping factor of the first mode is 0.03.

One simulated earthquake ground motion called "BCJ-L2" which was issued by Building Center of Japan is used as input earthquake ground motion. BCJ-L2 has maximum velocity 57cm/sec, maximum acceleration 356cm/sec^2 and duration time 120sec.The intensity of the input earthquake ground motion varies to calculate the seismic capacity index. For example, "BCJ-L2(1.2)" stands for 1.2 times intensity compared with original BCJ-L2. In this paper, one direction of the frame model is conducted in static and dynamic analysis.

Calculation of Seismic Capacity Index of Frame model

The average method is applied in estimation of limit earthquake ground motion of the reparability limit state I and II while the maximum method is applied in estimation of limit earthquake ground motion of the ultimate limit state. Figure 7 shows an example of the estimation result of limit earthquake ground motion in the reparability limit state I and the ultimate limit state. As shown in figure 7, the average method estimates the limit earthquake ground motion by the intensity in which the average of story drift angle reaches the average of response story drift angle. A list of the seismic capacity index of the frame model is shown in Table 4.

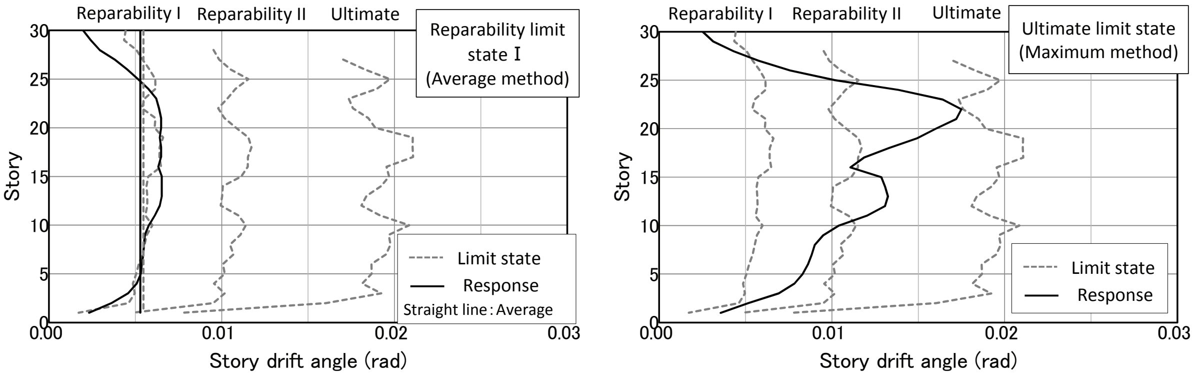


Figure 7. Correspondence between existing high-rise RC buildings and frame model

Table 4. List of seismic capacity index of the frame model

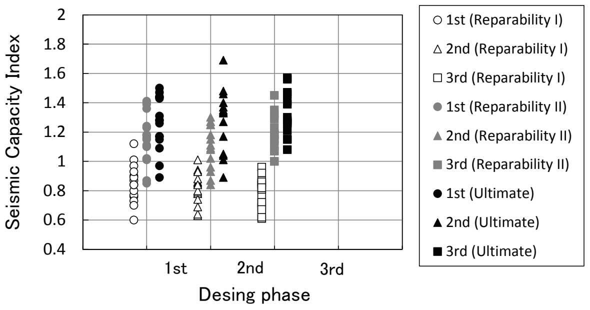
Design phase	Number of story	Standard model			Strong model			Weak model			High-stiffness model			Low-stiffness model		
		Reparability		Ultimate	Reparability		Ultimate	Reparability		Ultimate	Reparability		Ultimate	Reparability		Ultimate
		I	II		I	II		I	II		I	II		I	II	
1st	20	0.90	1.01	1.09	1.01	1.16	1.26	0.76	0.85	0.89	1.12	1.39	1.47	0.87	1.18	1.28
	25	0.77	1.24	1.44	0.89	1.41	1.50	0.60	1.15	1.28	0.80	1.11	1.17	0.73	1.10	1.17
	30	0.84	1.02	1.15	0.97	1.18	1.31	0.70	0.87	0.97	0.93	1.36	1.43	0.84	1.23	1.44
2nd	20	0.78	1.09	1.27	0.94	1.27	1.46	0.63	0.93	1.05	1.01	1.27	1.33	0.86	1.25	1.34
	30	0.78	1.02	1.48	0.85	1.15	1.69	0.64	0.87	1.01	0.88	1.25	1.33	0.79	1.11	1.4
	40	0.80	0.96	1.04	0.93	1.08	1.17	0.69	0.84	0.89	0.84	1.30	1.37	0.74	1.18	1.35
3rd	20	0.84	1.18	1.28	0.96	1.35	1.46	0.69	1.00	1.08	0.92	1.07	1.15	0.85	1.14	1.26
	30	0.72	1.29	1.41	0.87	1.45	1.56	0.61	1.11	1.21	0.86	1.23	1.39	0.77	1.07	1.27
	40	0.72	1.15	1.30	0.81	1.32	1.47	0.62	1.00	1.15	0.82	1.19	1.26	0.67	1.18	1.57

Distribution of Seismic Capacity index of Frame model

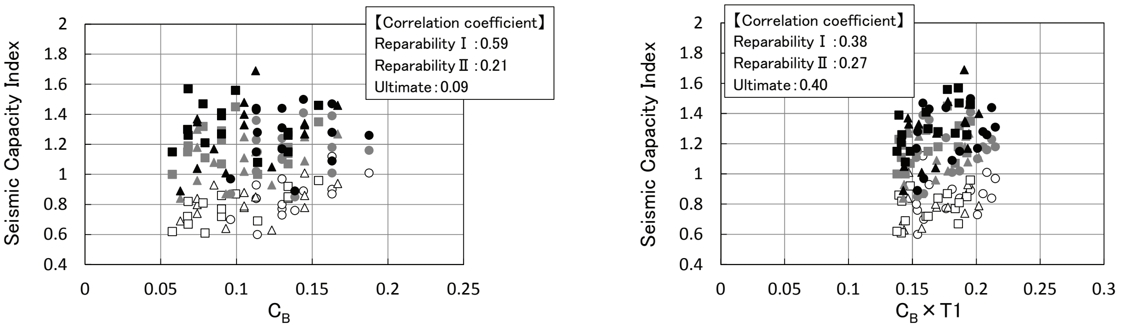
Relationship between Seismic Capacity Index and Structural Characteristic

Figure 8(a) shows the relationship between seismic capacity index and design phase. The seismic capacity index by proposed method of reparability limit state I almost indicates from 0.6 to 1.0, the index of reparability limit state II almost indicates from 0.8 to 1.4 and the index of ultimate limit state almost indicates from 1.0 to 1.6. The seismic capacity index of reparability limit state II and ultimate limit state in the third design phase are over 1.0, so that it is relatively high compared with the other design phases.

Figure 8(b) shows the relationship between seismic capacity index and designed base shear coefficient (C_B), and figure 8(c) shows the relationship between seismic capacity index and the value (C_BxT_1). The relationship between seismic capacity index and C_B has slight positive correlation because T_1 is not taken into account. On the other hand, there is a little strong positive correlation in the relationship between seismic capacity index and the value (C_BxT_1). It is found that the seismic capacity index of existing high-rise RC building also increases as the value (C_B×T_1) increases.

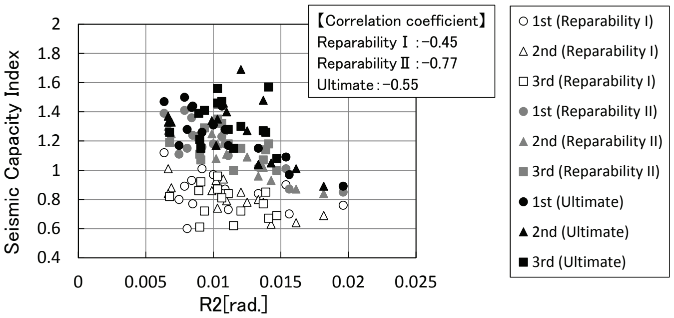


(a) Design phase

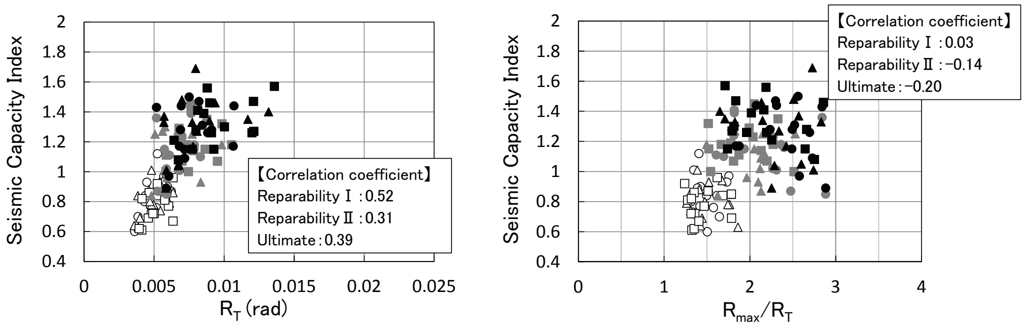


(b) Base shear coefficient (C_B) (c) C_B x T_1

Figure 8. Relationship between seismic capacity index and structural characteristic



(a) Story drift angle (R2)



(b) Representative deformation angle (R_T) (c) R2/R_T

Figure 9. Relationship between seismic capacity index and structural characteristic

Relationship between Seismic Capacity Index and Seismic Response

The relationship between the seismic capacity index and maximum story drift angle (R2) due to BCJ-L2(1.0) as shown in figure 9(a). It is guessed that the capacity index increases according to decreasing of R2 due to BCJ-L2(1.0). Figure 9(a) indicates the strong negative correlation, so that it is clearly that the capacity index increases according to decreasing of R2.
Figure 9(b) shows the relationship between the seismic capacity index and representative deformation angle (R_T) when the intensity of earthquake ground motion brings limit states (Reparability limit state I, Reparability limit state II and Ultimate limit state). Where the representative deformation angle (R_T) is calculated at the two thirds of building's height. Figure 9(b) indicates the positive correlation, so that it is found that the tendency that the seismic capacity becomes greater according to increasing of R_T.
Figure 9(c) shows the relationship between the seismic capacity index and R_{max}/R_T. R_{max} is maximum story drift angle when the intensity of earthquake ground motion brings limit states. R_{max}/R_T stands for the distribution of story drift angle. For example, R_{max}/R_T is large when the deformation of particular story is large. As shown in figure 9(c), a weak negative correlation is obtained. It is expected that the tendency that the seismic capacity decreases according to increasing of R_{max}/R_T. This tendency means seismic capacity index is underestimated when the deformation of particular story is large.

CONCLUSIONS

In this paper, the calculation method of seismic capacity index of existing high-rise RC buildings is proposed. Furthermore, the seismic capacity indexes are examined in order to clarify relationship between the indexes and structural characteristics, and relationship between the indexes and seismic responses. The findings obtained in this study may be summarized as follows.

1. The seismic capacity of existing high-rise RC building can be shown clearly with numerical value using the proposed method in this paper.
2. The seismic capacity index by proposed method of reparability limit state I indicates from 0.6 to 1.0, the index of reparability limit state II indicates from 0.8 to 1.4 and the index of ultimate limit state indicates from 1.0 to 1.6 when using "BCJ-L2" earthquake ground motion.
3. In the every limit state, the seismic capacity of existing high-rise RC building doesn't have particular difference among three design phases.
4. It is found that the seismic capacity index of existing high-rise RC building also increases as the value ($C_B \times T_1$) which multiplied base shear coefficient (C_B) and natural period (T_1) increases. Therefore, the seismic capacity of existing high-rise RC building can be probably predicted by the value ($C_B \times T_1$).

ACKNOWLEDGMENTS

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