A GUIDELINE TO EVALUATE SEISMIC PERFORMANCE OF EXISTING MEDIUM- AND LOW-RISE REINFORCED CONCRETE BUILDINGS AND ITS APPLICATION

by

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ABSTRACT

Outline of the guideline to evaluate seismic performance of existing medium and low-rise reinforced concrete buildings was described. A good correlation between the unified seismic performance index of structures proposed in the guideline and the building damage in the past earthquakes was also shown.

INTRODUCTION

It has been strongly recognized since the 1968 Tokachi-Oki Earthquake in Japan that dynamic and ultimate design concept should be adopted in the seismic design of medium- and low-rise reinforced concrete buildings as well as high-rise buildings. One response to such recognition was a code revision. The Japanese Building Code for Seismic Design was revised in 1971 and further revision is scheduled in near future. Another response was an evaluation of seismic performance capacity of existing buildings constructed before the code revision.

In order to develop a practical method to evaluate the seismic performance of existing medium- and low-rise reinforced concrete buildings, a task committee chaired by the author was established in Japan Special Building Safety Center Foundation (Japan Association for Building Disaster Prevention, since 1979), in July 1976 sponsored by the Ministry of Construction, Japanese Government, and the guideline including the practice for strengthening was published in April 1977 [1], [2]. The guideline has been popularized into Japanese engineers and used for the structural design of new building as well as for existing buildings.

Recently, the SPRC (Seismic Performance of Reinforced Concrete Buildings) Research Committee also chaired by the author has developed the computer program to use the guideline and proposed the decision criteria for the safety to severe earthquake. The seismic performance of the structural system of the buildings experienced actual earthquakes in Japan has also been examined to verify the reliability of the guideline.

The primary purpose of this paper is to describe the basic concept of the guideline with emphasis on the unified seismic performance index for ductile moment-resisting frame, shear wall and wall-frame buildings and the application of the guideline to the damaged and undamaged reinforced concrete buildings in the past severe earthquakes.

UNIFIED SEISMIC PERFORMANCE INDEX OF STRUCTURES

The unified seismic performance index of structure (I_s) up to six stories is evaluated by the following equation at each story and to each direction.

$$I_s = E_0 \cdot G \cdot S_D \cdot T \qquad \cdots\cdots(1)$$

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where E_o = basic structural index calculated by ultimate horizontal strength, ductility, number of story and story level considered

G = local geological index to modify the E_o-index

S_D = structural design index to modify the E_o-index due to the grade of the irregularity of the building shape and the distribution of stiffness

T = time index to modify the E_o-index due to the grade of the deterioration of strength and ductility

The overall method consists of three level procedures; first, second and third level procedures. The first level procedure is the simplest, but most conservative of the three, while the basic concept is common for all three.

BASIC STRUCTURAL INDEX (E_o)

Since the G-, S_D-, and T-indices are the reduction factors less than or equal to 1.0* and the E_o-index usually predominates, the outline for evaluating the E_o-index is described here.

General Procedure: The E_o-index consists of strength index (C), the ductility index (F), and the story index (β). The evaluation starts from classifying each column and wall at the story due to failure type. The types of failure used for the first, second, and third level procedures are shown in Table 1.

All cloumns and walls at the story level are classified again into smaller number of groups. In the first level procedure, the number of groups is not more than three. First group; Group 1, consists of extremely short columns, Second group; Group 2, walls and the third group; Group 3, columns.

In the second and third level procedures, the number of groups is not more than four, First group, Group 1; consists of extremely brittle columns. Other members are classified into three groups based on their ductility indices (F). Group 2 consists of the members having the smallest F-indices except the Group 1. Then, the strength index (C) and the ductility index (F) of each group are defined. Final procedure/is to estimate the E_o-index depending upon the C-indices and F-indices of the groups and the story index (β) at the story.

Classification due to Failure type: In the first level procedure, the vertical members are classified into three groups shown in Table 1 depending upon the size proportion of the members.

In the second level procedure, shear force at ultimate bending capacity and ultimate shear capacity of columns and walls are calculated and compaired each other. If the ultimate shear capacity is less than the shear force at ultimate bending capacity, the member is defined as brittle member and it's F-index is defined as shown in Table 1. If the clear hight-to-depth ratio of brittle column is not more than 2.0, the member is classified into the extremely brittle column. Other members are designated as ductile members and classified based upon their F-indices described later on. In the calculation of column capacity, strong beam concept is assumed. For wall, an inflection point due to lateral force is assumed at a half level of overall height of the wall. As an exception, if the wall does not continue to the upper story, the inflection point is assumed at the top of the wall.

In the third level procedure, a concept of frame analysis is introduced.

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* As an exception, S_D-index of a building with basement can be increased up to 1.2 .

The failure type of frame is judged and all columns and walls are classified into one of the failure types in Table 1. For examples, if the frame has strong beams, the procedure is same as in the second level procedure. In the case of weak beam frame, the failure type of beams; bending or shear, controls the failure type of columns.

C-Index: The C-index of each group is calculated by Eq. 2.

$$C_j = \Sigma Q_j / \sum_{i}^{n} w_k \qquad \cdots\cdots(2)$$

where, ΣQ_j = sum of story shear of Group-j at ultimate stage
Σw_k = building weight above the story
n = total number of stories
i = story level under consideration; i=1 designates first story

Both in the first and second level procedures, a strong beam concept is assumed. In the first level procedure, story shear (Q_j) at ultimate stage of columns and walls are approximated by Eq. 3.

$$Q_j = \tau \cdot A \qquad \cdots\cdots(3)$$

where, τ = shear stress shown in Table 2
A = cross sectional area shown in Table 2

In the second level procedure, an ultimate bending capacity of column and wall is calculated by a full plastic theory and a shear capacity by empirical formulas. In the third level procedure, each frame capacity is calculated by a limit analysis theory based on member capacities.

F-Index: The F-index indicates grade of frame ductility, however, in the case of the first and second level procedure, member ductility substitutes for the frame ductility because a strong beam concept is assumed. In the first level procedure, all columns and walls are conservatively assumed as brittle members as shown in Table 1. In the second and third level procedures, the F-indices of ductile members are evaluated by their ductility as shown in Table 1.

β-Index: The story index (β) indicates the ratio of response shear coefficient of a single degree of freedom system and the i-th story response shear coefficient, when both systems reach at the same level of damage. Assuming uniform mass distribution and height, and the linear mode shape, the β-index becomes,

$$\beta = 2(2n+1)/3(n+i) \qquad \cdots\cdots(4)$$

where, n = total number of stories

The use of Eq. 4 is critical side for a multi-story building having weak columns and strong beams. Therefore, in the first and second level procedure, Eq. 5 is proposed as a consevative assumption instead of the Eq. 4.

$$\beta = (n+1)/(n+i) \qquad \cdots\cdots(5)$$

Eq. 5 expresses a ratio of the response base shear coefficient and the response i-th story shear coefficient based upon the same assumption for Eq. 4.

Evaluation of E_0-Index: In the first level procedure, Eq. 6 and Eq. 7 are used according to the adopted criteria.

used. The variables were the strengths and the earthquake ground motions; El Centro 1940 (NS), and Hachinohe 1968 (NS). The maximum ground acceleration were modified to 30% of the acceleration of the gravity. Since the ultimate of the wall and the yield displacement of the frames were assumed constant, the initial natural periods of the systems were proportional to their strengths; 0.1 sec - 0.6 sec.

As recognized by the figures, the use of Eqs. 8 and 9 in evaluating the seismic capacities of the frame-wall R/C buildings seems satisfactory for practical purpose,while more·detailed investigation is necessary to refine the method.

APPLICATION-2

In order to investigate a decision criteria to use the unified seismic performance index for the judgement of seismic safety of existing R/C buildings, the I_S-indices of the buildings which had experienced severe earthquake were examined. Fig. 4 shows the wall ratio-to-average shear stress diagram proposed by T. Shiga et al [4]. The abscissa expresses the wall cross sectional area (A_W)-to-sum of the floor area above the story ratio and the ordinate expresses the average shear stress assuming the story shear coefficient of 1.0 and the average building unit weight of $1000 kg/m^2$. The circles (O) show the undamaged buildings during the 1968 Tokachi-Oki Earthquake [4] and the 1978 Miyagiken-Oki Earthquake [5]. The buildings marked (X) suffered from structural damage. All buildings are supposed to experience the ground motion of 25% - 35% g level. Since the I_S-index for the first level procedures are approximated by the units of the abscissa and the ordinate, the level of the I_S-index is also shown in the figure.

The correlation between seismic index value and the degrees of structural damage is satisfactory and the I_S-index of 0.7 - 0.9 is suggested to be a border of damage and undamage in those earthquake. Fig. 5 shows the I_S-indices by the second level procedure of the buildings experienced the 1968 Tokachi-Oki Earthquake, the 1978 Miyagiken-Oki Earthquake and the 1978 Izuoshima-Kinkai Earthquake [1],[6],[7]. The level of the ground motion of the 1978 Izuoshima-Kinkai Earthquake is supposed to be about a half of the other two.

It is suggested that the value of I_S-index of 0.5 - 0.6, in the second level procedure, is the border between damaged and undamaged buildings experienced 25% - 30% g level ground motion.

SUMMARY

Outline of the guideline to evaluate seismic performance of medium- and low-rise R/C buildings was described and the application was also shown. A good correlation between calculated indices and real damage was obtained.

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[3] Hisano, M. and Okada, T. "Earthquake Response of Low-Rise Reinforced

$$E_o = \beta(C_2+0.7C_3) \cdot F_2 \quad \cdots\cdots(6)$$

$$E_o = \beta(C_1+0.7C_2+0.5C_3) \cdot F_1 \quad \cdots\cdots(7)$$

where, suffix (j); group number
C_j ; C-Index of Group j
F_j ; F-Index of Group j

When the extremely column does not exist, the Eq. 6 is used. The Eq. 6 expresses the E_o-index when the wall fails first. If the wall does not exist, column becomes Group 2. When the extremely short column exists, both Eqs. 6 and 7 are used. The Eq. 7 expresses the E_o-index when the extremely short column fails first and the Eq. 6 is used to calculate the E_o-index after the extremely short column fails. If the failure of the extremely short column results to the building fatal damage, the E_o-index calculated by the Eq. 7 should be used.

In the second and the third level procedures, Eqs. 8, 9, and 10 are used.

$$E_o = \beta(C_2+\alpha_3C_3+\alpha_4C_4) \cdot F_2 \quad \cdots\cdots(8)$$

$$E_o = \beta\sqrt{E_2^2+E_3^2+E_4^2} \quad \cdots\cdots(9)$$

$$E_o = \beta(C_1+\alpha_2C_2+\alpha_3C_3+\alpha_4C_4) \cdot F_1 \quad \cdots\cdots(10)$$

where, suffix (j); group number
C_j ; C-index of Group j
F_j ; F-index of Group j
E_j ; $C_j \cdot E_j$
$\alpha_2,\alpha_3,\alpha_4$; values given in Table 3 or 4

When the extremely brittle column does not exist, the greater value of the E_o-indices calculated by Eqs. 8 and 9 is used. The Eq. 8 expresses the E_o-index when the group 2 fails and the Eq. 9 expresses the E_o-index when the group 4 fails finally. When the extremely brittle columns exist, the Eq. 10 is also used, which expresses the E_o-index when the extremely brittle columns fail.

Whether the failure of the extremely brittle columns causes the fatal damage to the building should be judged by the engineer as same as in the first level procedure.

APPLICATION-1

A group of the single story buildings consisting of shear walls and ductile frames is used as an example for the second level procedure. The shear wall is categorized as Group-2 and the ductile frame is Group-3. Since the fourth group does not exist, the C_4-index and E_4-index in Eqs. 8 and 9 become zero. The relationship of the story shear and story drift of the buildings is assumed as illustrated in Fig. 1. A quarter of the circle in Fig. 2 shows Eq. 9, and the seismic capacities of the buildings on the line are considered as same level in this method. The decision criterion is at the ultimate stage when the most ductile members fail. The broken line in Fig. 2 shows Eq. 8, and the criterion is at the ultimate stage of the shear walls.

The results of the computer simulation were used to assess the adoptability of Eqs. 8 and 9 [3]. The earthquake response of the structural models representing the wall-frame R/C single story buildings to the recorded ground motions were expressed in the E_2-E_3 domain as shown in Fig. 3. In the simulation, one-mass models supported on the nonlinear parallel spring system consisting of the origin-oriented hysteretic model, which represented the shear walls, and the degrading trilinear model which represented the frames were

Concrete Buildings with Structural Walls (SDF Parallel Wall-Frame System) (in Japanese)", Transactions,Annual Convention of AIJ,October, 1975.
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[5] Shiga, T. "Earthquake Damage to Buildings in 1978 Miyagiken-Oki Earthquake (in Japanese)", Research Report of Structural Engineering Lab., Department of Architecture, Faculty of Engineering, Tohoku University, 1978.
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[7] SPRC Research Committee, "Damage to R/C Buildings due to 1978 Izuoshima-Kinkai Earthquake (in Japanese)", Report of SPRC Research Committee, Japan Association for Building Disaster Prevention, 1979.

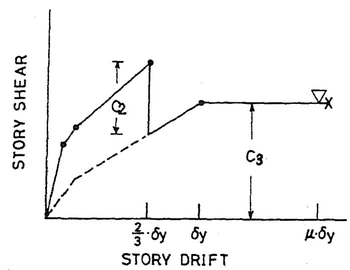


Fig. 1 Assumed Story Shear vs. Story Drift

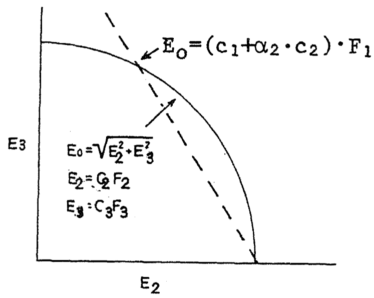
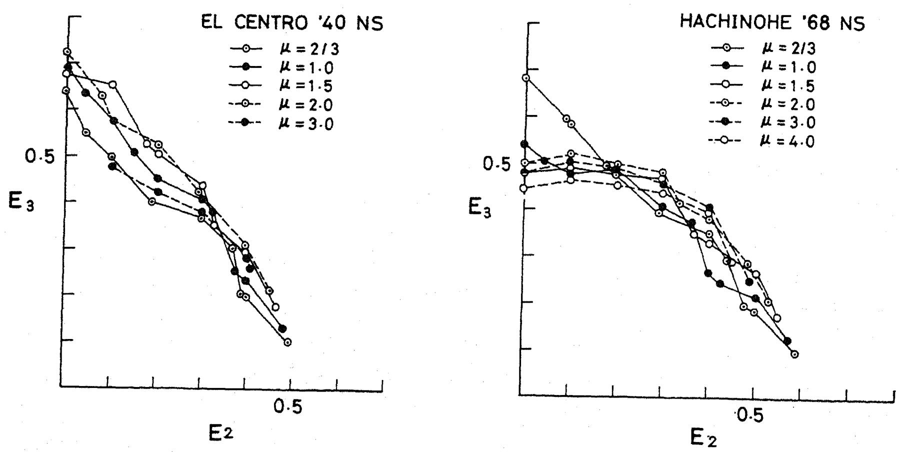


Fig. 2 Seismic Capacity of Frame-Wall Buildings



a) El Centro 1940

b) Hachinohe 1968

Fig. 3 Earthquake Response vs. E_0-Index

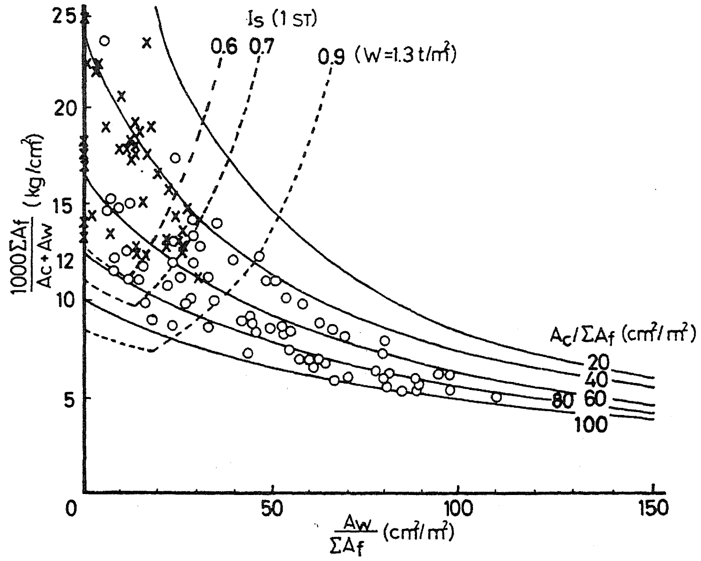


Fig. 4 I_s-Index in First Level Procedure vs. Earthquake Damage

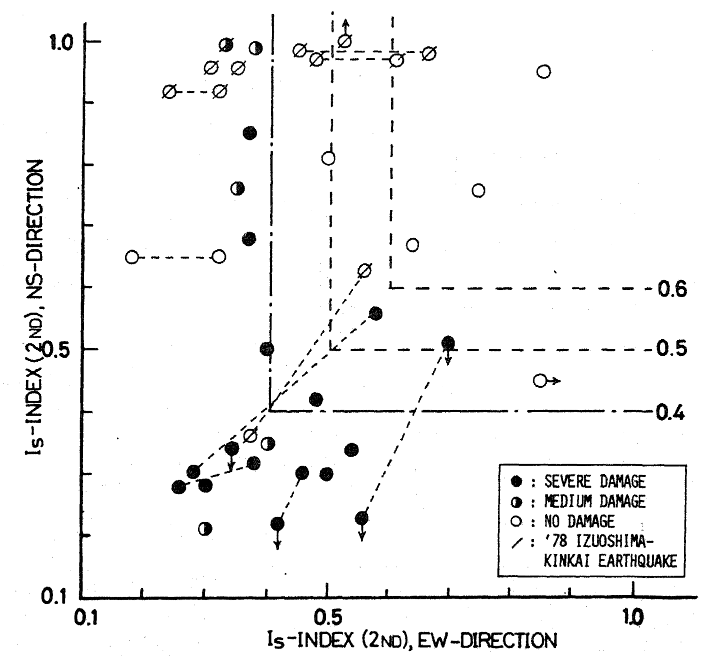


Fig. 5 I_s-Index in Second Level Procedure vs. Earthquake Damage

Table 1. Type of Failure and F-Index

Type	F-Index	Level of Procedures
Extremely Short Column	0.8	First
Wall	1.0	
Column	1.0	
Extremely Brittle Column (fails in shear)	0.8	Second & Third
Brittle Column-1 (fails in shear)	1.0	
Brittle Wall (fails in shear)	1.0	
Ductile Column-1 (fails in bending)	1.27-3.2 1)	
Ductile Wall-1 (fails in bending)	1.0 -2.0 2)	
Brittle Column-2 (fails in beam shear)	1.5	Third
Ductile Column-2 (fails in beam bending)	3.0	
Ductile Wall-2 (fails in overturning)	3.0	

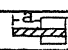
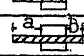
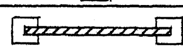
1) $F = \dfrac{\sqrt{2\mu - 1}}{0.75(1+0.05\mu)}$ μ=ductility factor

2) $F = 10(Q_{su}/Q_u - 1.3) + 1.0 \leq 2.0$, and ≥ 1.0

Q_{su} : ultimate shear strength

Q_u : shear force at ultimate bending capacity

Table 2. Shear Stress for the First Level Procedure

	Cross Section*	τ (kg/cm^2)
Extremely Short Column		15
Column		10 for $h_o/D \leq 6$ 7 for $h_o/D > 6$
Wall-1	 **	10
Wall-2	 **	20
Wall-3		30

* A in Eq. 3 is the area of hatched portion in cm^2
** If $(a+b) \leq 45$cm, they are classified into columns

Table 3. α_3, α_4 in Eq. 8

Second Group / Third, Fourth Group	Brittle Column or Brittle Wall	Others
Ductile Wall	1.0	1.0
Ductile Column	0.7	1.0

Table 4. $\alpha_2, \alpha_3, \alpha_4$ in Eq. 10

Brittle Column Brittle Wall Ductile Wall	Others
0.7	0.5