Bull. ERS, No. 22(1989)

RELIABILITY ANALYSIS ON SEISMIC CAPACITY OF EXISTING REINFORCED CONCRETE BUILDINGS IN JAPAN

Tsuneo OKADA[1)] and Yoshiaki NAKANO[2)]

SUMMARY

This paper describes the seismic capacities of existing reinforced concrete buildings in Japan, comparing with those of damaged buildings due to recent severe earthquakes. Statistical data used herein are the seismic capacities of existing public reinforced concrete buildings in Shizuoka Prefecture, both before and after strengthening, together with those of damaged buildings due to Tokachi-Oki- and Miyagi-Ken-Oki Earthquakes. From a probabilistic point of view, damage ratios due to severe earthquakes and effects by strengthening are also estimated.

INTRODUCTION

It is of great importance to assess the seismic risk of existing buildings located in a high seismic region to avoid destructive damages due to severe earthquakes. It is, therefore, necessary to estimate the seismic capacity of structures and strengthen them if required. It is also well recognized, however, that structural safety may be rarely evaluated with certainty due to uncertainties of ground motion, ultimate strength and ductility of structures, and earthquake response etc. and should be regarded probabilistically rather than deterministically.

This paper will focus on 1) the seismic capacity of buildings damaged due to recent severe earthquakes in Japan, 2) the seismic capacity of

---

* Most part of this paper was presented at "The Ninth World Conference on Earthquake Engineering Symposium", 1988.8.

1) Professor, Institute of Industrial Science, University of Tokyo

2) Graduate Student, University of Tokyo

existing buildings both before and after strengthening, 3) the relationship between the decision criteria and the seismic capacity of damaged and existing buildings, and 4) applicability of probabilistic approach to estimate the earthquake damage ratio and effects by strengthening.

SEISMIC CAPACITY OF EXISTING AND DAMAGED BUILDINGS

Fig. 1 shows the histogram of seismic capacity index (Is-Index) of 1,615 existing R/C buildings in Shizuoka Prefecture, where Is-Indices of each building in both directions are evaluated by the "Japanese Standard for Evaluation of Seismic Capacity of Existing Reinforced Concrete Buildings(Ref. 1)". Is-Index can be calculated by Eq. (1) at each story and in each direction.

$$Is = Eo \cdot G \cdot S_D \cdot T \quad \cdots\cdots (1)$$

where Eo is a basic structural seismic capacity index calculated by ultimate lateral strength and ductility of structures. G, S_D, and T are reduction factors to modify Eo in consideration of local geological condition, structural configuration, and deterioration after construction, respectively.

Most of the 1,615 buildings are three or four storied school buildings, designed and constructed before the code revision in 1970. As shown in the figure, the distribution of the Is-Indices may be approximated by a log-normal probability density function (curve ①).

The hatched area in Fig. 1 shows the histogram of Is-Indices for moderately or severely damaged buildings due to 1968 Tokachi-Oki Earthquake or 1978 Miyagi-Ken-Oki Earthquake. In this figure, the frequency of damaged buildings was modified so that the number of damaged buildings should be 10% of the total number of buildings, because damage ratios due to these two earthquakes were approximately 10%(Refs. 2,3).

Fig. 1 suggests the earthquake damage is not deterministic but probabilistic, and the uncertainty of ground motion, ultimate strength, ductility, and earthquake response etc. should be taken into account to assess earthquake damages. In Fig. 2 shown a schematic expression of the Is-Index of both existing and damaged buildings. The shape of Fig. 1 is quite similar to Fig. 2(b). If the required seismic capacity is deterministic, and hence structures with less than a certain value of Is-Index are totally damaged, the damage ratios in the past two earthquakes would be greater than 10% (Fig. 2(a)). Fig. 1 reflects a probabilistic feature of decision criteria for screening sound buildings.

Defining p_{Is} and p_{ET} which represent the probability density functions of Is-Index and load effect designated as E_T-Index, respectively, the damage ratio **V** (ratio of damaged buildings to total buildings) is expressed in the following general formula;

$$\mathbf{V} = \int_0^{\infty} p_{Is}(x) \cdot [1 - \int_0^{x} p_{ET}(r)dr]dx \qquad (2)$$

where p_{ET} means the probability distribution of required seismic capacity, E_T-Index, and therefore the term in the square bracket represents the probability of failure for structures with Is-Index equal to x. Note that the uncertainty associated with ground motion is only taken into account and the seismic capacity for each building was assumed deterministic in Eq. (2) to simplify the subsequent discussions. Setting

$$v(x) = p_{Is}(x) \cdot [1 - \int_0^{x} p_{ET}(r)dr] \qquad (3)$$

the term of v(x) may be considered to represent the distribution of Is-Indices of damaged buildings shown in Fig. 1. Substituting the function p_{Is} in Fig. 1 approximated by a log-normal probability density function (curve ①) and the relative frequency of Is-Indices of damaged buildings shown as hatched part in Fig. 1 into Eq. (3), the probabilistic distribution of E_T-Indices (p_{ET}) can be calculated as shown in Fig. 3.

Assuming the normal distribution for p_{ET}, the probability density function of E_T-Indices is obtained as shown in Fig. 3 (curve ②). The curve ③ in Fig. 1 is obtained by Eq. (3), where function p_{Is} in Fig. 1 (curve ①) and function p_{ET} in Fig. 3 (curve ②) are used. The distribution of damaged buildings is successfully simulated by the proposed procedure. Table 1 shows an example of E_T-Indices required in the lowest seismic zone in Shizuoka Prefecture, where the predicted acceleration to building base is approximately twenty three percent of the gravity (0.23g). These values in Table 1 are obtained by non-linear earthquake response analyses in consideration of ground acceleration level, soil condition, and type of failure, in which 5% probability of failure was accepted as a risk level. Consequently, a building with Is-Index listed in Table 1 may avoid damage in 95% probability. Table 1 indicates that Is-Index larger than about 0.6 should be required to survive a severe earthquake, of which intensity is nearly equal to Tokachi-Oki or Miyagi-Ken-Oki Earthquake(Ref. 4). This value is approximately upper bound of E_T-Index shown in Fig. 3.

It should be noted that the earthquake intensity during both Tokachi-Oki Earthquake and Miyagi-Ken-Oki Earthquake is assumed about 0.23g. In Fig. 4, the damage ratios to 0.36g and 0.45g earthquake calculated by Eqs. (2) and (3), where the mean value of p_{ET} is multiplied in proportion to the ground acceleration level, are also illustrated. The damage ratio is three times for 0.36g earthquake and five times for 0.45g earthquake as much as that for 0.23g earthquake, respectively.

SEISMIC CAPACITY OF STRENGTHENED BUILDINGS AND ITS EFFECTS

Fig. 5 shows the distribution of Is-Indices of 242 strengthened buildings in Shizuoka Prefecture, comparing with that of existing buildings shown in Fig. 1. Most of them are three or four storied school buildings. In order to estimate the effects by strengthening, the distribution of Is-Indices and the damage ratio after strengthening are calculated with assumption that 1) the distribution of Is-Indices can be approximated by a log-normal probability density function as shown in Fig. 5, and 2) the mean value and the standard deviation of Is-Indices of strengthened buildings remain constant even if the number of strengthened buildings are increased. The distribution of Is-Indices after strengthening, therefore, can be defined as ;

$$p_{Rs}(x) = p_{Is}(x) - Rs \cdot p_{BS}(x) + Rs \cdot p_{AS}(x) \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (4)$$

where, $p_{Rs}(x)$: distribution of Is-Indices for total buildings including strengthened buildings

$p_{Is}(x)$: distribution of Is-Indices for unstrengthened buildings (curve ①)

$p_{BS}(x)$: distribution of Is-Indices for strengthened buildings before strengthening (log-normal function)

$p_{AS}(x)$: distribution of Is-Indices for strengthened buildings after strengthening (log-normal function)

Rs : strengthened ratio; i.e. ratio of number of strengthened buildings to that of total buildings

x : Is-Index

Fig. 6 shows the distribution of Is-Indices corresponding to strengthened ratio Rs equal to 10%, 20%, 30%, 40%, respectively, which indicates the distribution shifts to the larger value in Is-Index and the peak value also shifts around 1.0 with increase of strengthened buildings.

Finally, the damage ratios after strengthening were estimated by the following two different procedures;

First, a) the failure probability $[1-\int p_{ET}(r)dr]$ of buildings with the same Is-Index is constant to the same ground acceleration level, whether the buildings have been strengthened or not. Replacing $p_{Is}(x)$ in Eq.(2) with previously defined $p_{Rs}(x)$ in Eq.(4), the damage ratio **V**, therefore, can be calculated as ;

$$\mathbf{V} = \int_0^\infty p_{Rs}(x) \cdot [1-\int_0^x p_{ET}(r)dr]dx \quad \cdots\cdots (5)$$

Secondly, b) buildings in which failure occurs, as represented by v(x) in Eq.(3), are strengthened and the strengthened buildings shall never suffer from earthquake damage. By modifying the term v(x) in Eq. (3), the damage ratio **V**, therefore, can be calculated as ;

$$V = \int_0^\infty [v(x) - Rs \cdot p_{BS}(x)]dx \; ; \quad [v(x) - Rs \cdot p_{BS}(x)] \geq 0 \quad \cdots\cdots (6)$$

The results are shown in Fig. 7. These two procedures a) and b) are considered to represent the lower and upper bound of effectiveness by strengthening, respectively. Fig. 7 shows that when Rs=40%, the damage ratio reduces to almost zero to 0.23g earthquake, but still remains more than 20% to 0.45g earthquake.

CONCLUDING REMARKS

1) Damage ratios due to past earthquakes were successfully estimated by applying probability concept.
2) E_T-Indices in Table 1 approximately correspond to the upper bound of distribution of E_T-Indices in Fig.3 derived from the seismic capacity relationship of existing and damaged buildings.
3) It may be possible to estimate the damage ratio to different level of ground acceleration with the modification of function p_{ET} in the Eq.(2), because the mean value of p_{ET} may be proportional to the level of ground acceleration.
4) It is possible to estimate the effects by strengthening applying probabilistic procedures proposed in this paper.

ACKNOWLEDGEMENTS

The authors express their sincere thanks and appreciation to the members of SPRC Committee chaired by Prof. H. Umemura at the Japan Disaster Prevention Association for their helpful suggestions and to the Shizuoka Prefectural Government for their cooperation in collecting the data.

REFERENCES

1. Japan Building Disaster Prevention Association, "Guideline for Evaluation of Seismic Capacity of Existing Reinforced Concrete Buildings", 1977. (in Japanese)
2. Architectural Institute of Japan, "Report on Damage due to 1968 Tokachi-Oki Earthquake", 1968. (in Japanese)
3. Architectural Institute of Japan, "Report on Damage due to 1978 Miyagi-Ken-Oki Earthquake", 1980. (in Japanese)
4. Umemura, H., Okada, T. and Murakami, M., "Seismic Judgement Index Values for Guideline for Evaluation of Seismic Capacity of R/C Buildings", Proceedings of Annual Convention of Architectural Institute of Japan, 1980.10. (in Japanese)
5. Nakano, Y., "Seismic Capacity of Existing Reinforced Concrete Buildings"
Proceedings of The Seventh Japan Earthquake Engineering Symposium, 1986.

Table 1 : E_T-Indices for Maximum Ground Acc. of 0.23g Earthquake (Ref. 4)

N \ T_G	0.3 sec.	0.4 sec.	0.5 sec.	0.6 sec.	0.7 sec.	0.8 sec.
1	0.80 (0.70)	0.70 (0.70)	0.65 (0.65)	0.60 (0.60)	0.55 (0.55)	0.50 (0.50)
2	0.70 (0.60)	0.70 (0.60)	0.65 (0.60)	0.60 (0.60)	0.55 (0.55)	0.50 (0.50)
3	0.65 (0.60)	0.65 (0.60)	0.65 (0.60)	0.60 (0.60)	0.55 (0.55)	0.50 (0.50)
4	0.60 (0.55)	0.60 (0.55)	0.60 (0.55)	0.60 (0.55)	0.55 (0.55)	0.50 (0.50)
5	0.60 (0.55)	0.60 (0.55)	0.60 (0.55)	0.60 (0.55)	0.55 (0.55)	0.50 (0.50)
6	0.60 (0.50)	0.60 (0.50)	0.60 (0.50)	0.60 (0.50)	0.55 (0.50)	0.50 (0.50)

N : Number of Stories T_G : Predominant Period of Ground
Values in parentheses are for ductile buildings

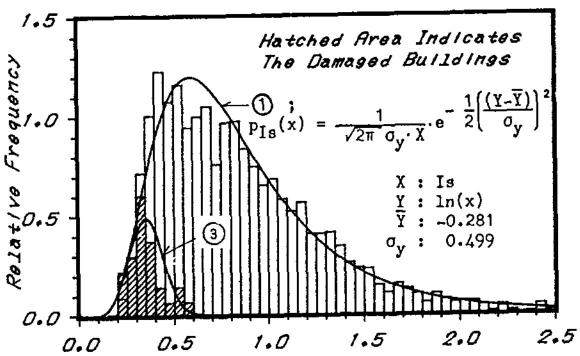
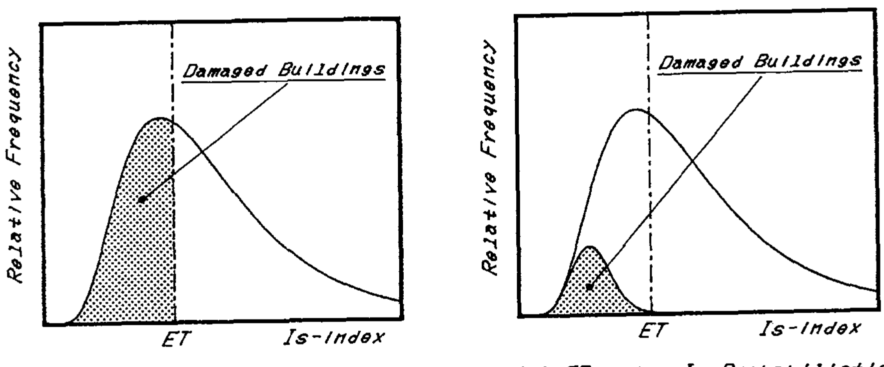


Fig.1 : Distribution of Is-Index For Existing And Damaged Buildings



(a) ET-Index Is Deterministic

(b) ET-Index Is Probabilistic

Fig.2 : Distribution of Is-Index For Damaged Buildings

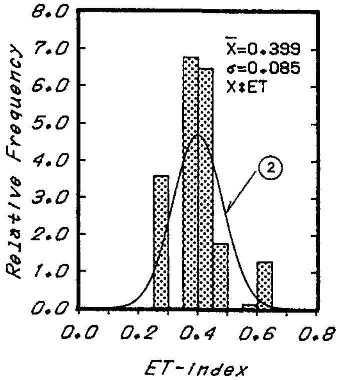


Fig.3 : Distribution of ET-index

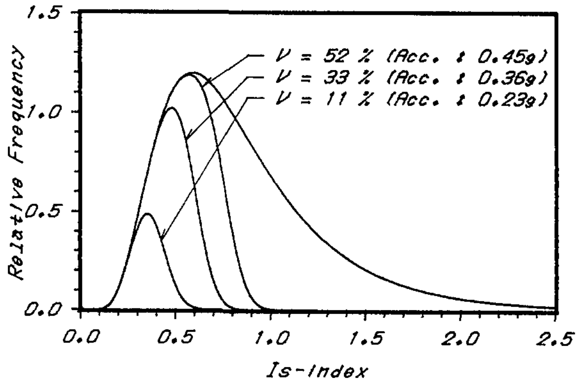


Fig.4 : Damage Ratio V

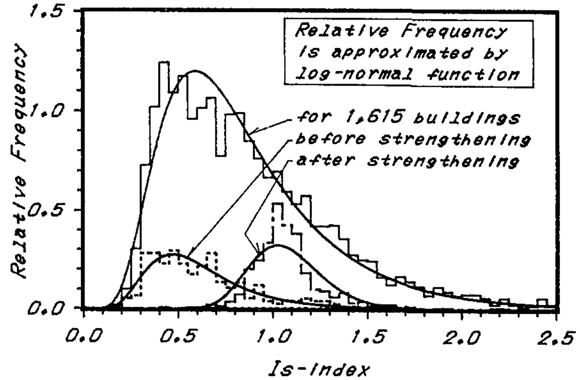


Fig.5 : Distribution of Is-index For Strengthened Buildings

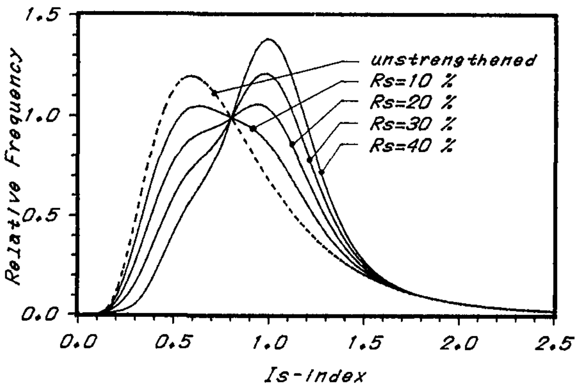


Fig.6 : Distribution of Is-index After Strengthening

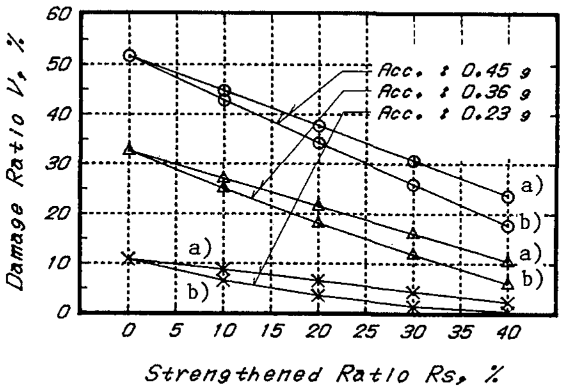


Fig.7 : Damage Ratio vs. Strengthened Ratio