SIMPLIFIED PERFORMANCE-BASED SEISMIC EVALUATION OF BUILDINGS

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ABSTRACT :

Simplified, performance-based seismic evaluation of one-story and multistory irregular existing buildings with rigid diaphragms, parallel framing systems, firm and regular foundations is introduced considering impulse responses in addition to damage concentration responses using shear and torsion strength capacity ratios to the corresponding linear shear forces and torsion moments in the x- and y-directions, respectively, in high seismic urban areas. Maximum nonlinear story drift response of each story of buildings can be obtained based on the shear and torsion strength capacity ratio, energy constant and return period concepts considering not only positive slopes but also negative slopes of the skeleton curves in the yielding frames of structures. Allowable or working stress design is not necessary in this method. However, effects of aftershocks are still uncertain. The paper: RECOMMENDATIONS FOR SIMPLIFIED, PERFORMANCE-BASED SEISMIC DESIGN OF BUILDINGS WITH IRREGULARITIES AND DESIGN EXAMPLES presented to 11th US-JAPAN workshop at KOBE, Oct. 17-19, 2006 is much improved in this paper.

KEYWORDS: maximum displacements, irregular buildings, torsion, impulse and damage concentration responses

1. INTRODUCTION

Perfect performance-based seismic evaluation of irregular existing buildings has not been established so far. In this paper, simplified, performance-based seismic evaluation methodology of ductile existing buildings with firm foundation and various kinds of irregularities in high seismic urban areas except heavy snow areas has been developed based on recent publications (SEAOC VISION 2000 1995, NEHRP 1997, Strength Capacity and Deformation Capacity in Seismic Design of Buildings 1996, EUROCODE 8 1998, INTERNATIONAL BUILDING CODE 2000) and several papers, when ductile and irregular existing buildings are subjected to strong earthquake ground motions.

The concepts of the seismic evaluation methodology are as follows:
(1) Simplified, performance-based seismic evaluation of ductile existing buildings with safe side estimation considering impulse responses or shock responses (Tanahashi 1937 and Alavi, Krawinkler 2000) in addition to damage accumulation or damage concentration responses at a particular story (Akiyama, H. 1999, Ozaki, et al. 1988).
(2) Public expectations for life safety, almost no damage, reparable damage, operational functions, construction economy and life span of buildings and so on are considered using return period concept.
For the above concepts, linear and non-linear dynamic response analyses such as a step-by-step time history response analysis and random vibration response analysis are extensively used, when buildings are subjected to strong earthquake ground motions.

2. BASIS OF SIMPLIFIED, PERFORMANCE-BASED SEISMIC EVALUATION

Buildings with a times b framing systems in plans are represented by the corresponding 2 times 2 shear wall systems considering stiffness and strength capacities of buildings, as shown in Figure 1. The x- and y-directions are the coordinates of building plans, respectively, where C and S are the center of stiffness and the center of strength, respectively. Horizontal shear forces in the x-and y-directions and torsion moments due to the corresponding shear forces are considered for the 2 times 2 shear wall systems. Shear forces and torsion moments for linear structural systems without yielding are defined as the linear shear forces and linear torsion moments, respectively. The effects of various and complicated characteristics of linear responses in structural systems with plan-irregularity rapidly decrease as a single response exceeds the yield level of the structures (Ozaki, et al. 1988, Ozaki, et al. 1994, Ozaki, et al. 1998) and the center of stiffness C moves to the center of strength S after a single excursion of responses beyond yield levels of the 2 times 2 shear wall systems.

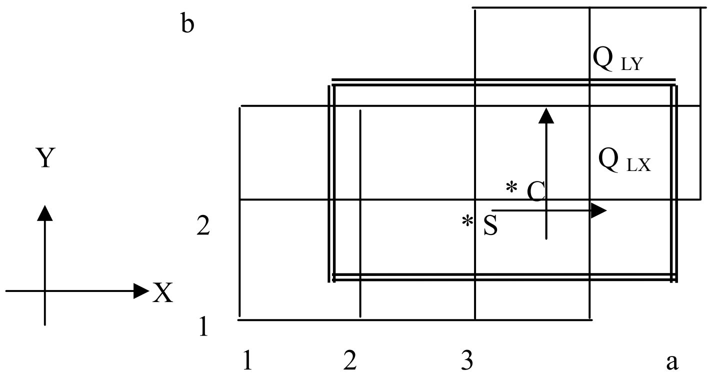

Figure 1 Building plan with irregularity
(= : Replaced 2 times 2 shear wall system)

Therefore, the shear and torsion strength capacity ratios Rx and Ry to the corresponding linear shear forces and linear torsion moments in the x- and y-directions for one-story buildings and each story of multistory buildings are expressed, regardless of stiffness, strength and mass eccentricities, as follows. (Yasuda, et al. 1984, Ozaki, et al 1988, Ozaki, et al 1994, et al 1998, Ozaki, et al 2006):

$$R_X = \frac{0.85}{\dfrac{Q_{LX}}{Q_{PX}} + \dfrac{0.5T_{LY} + T_{LX}}{Tp}} \quad \text{and} \quad R_Y = \frac{0.85}{\dfrac{Q_{LY}}{Q_{PY}} + \dfrac{0.5T_{LX} + T_{LY}}{Tp}} \tag{1}$$

where Q_L and Q_P are the linear shear forces acting on each story of structures and the strength capacities of the corresponding story in the direction under consideration, respectively, when the structures are subjected to strong earthquake ground motions. The linear torsion moments acting on each story of structures with respect to the center of strength S and the torsion strength of the corresponding story are denoted by T_L and T_P, respectively.（See APPENDIX）Considering the orthogonal strength interaction of two directional seismic actions, A = 0.85 is used. Coefficient B is 0.5 considering the two–horizontal components of strong earthquake ground motions (Ozaki, et al. 1994). Equations (1) can be used for each framing systems of the m times n framing systems including perimeter frames of each story of buildings. For practical design, Equations (1) can also be used for multistory buildings with weak -beam and strong-columns systems.

Maximum or large nonlinear story drift response for each frame of each story in buildings can be obtained based on energy constant concept due to a single excursion of impulse responses beyond the yield level as shown in Figure 2.

The following well-known Newmark's equations can be used, regardless of the hysteresis characteristics of each frame and regardless of structural systems considering not only positive slopes but also negative slopes of the skeleton curves of the yielding frames in structures.

$$\omega = 0.5\,(1 + 1/R^2x)\,\theta \quad \text{and} \quad \omega = 0.5\,(1 + 1/R^2y)\,\theta \tag{2}$$

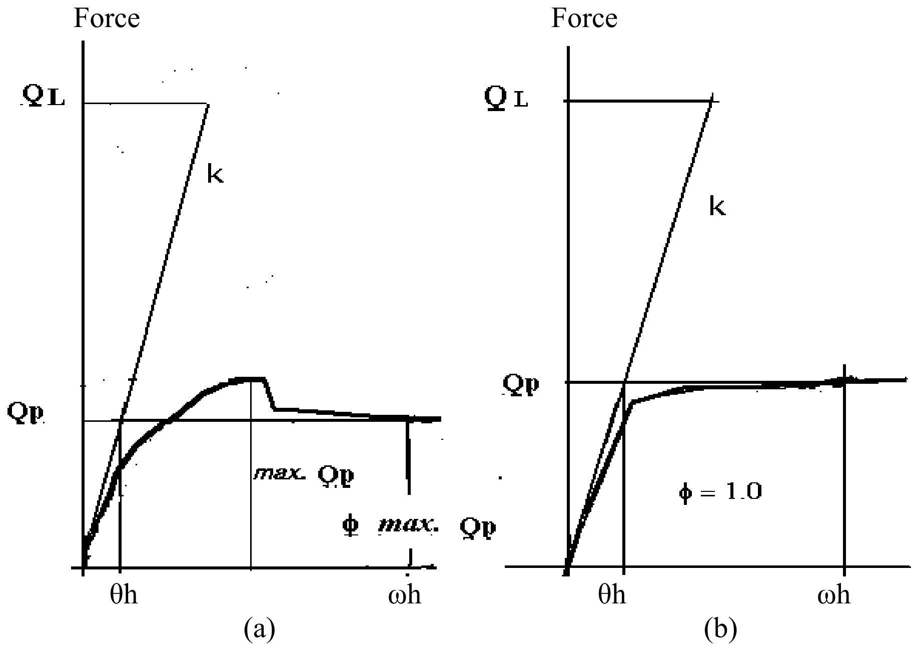

Figure 2 Force- displacement relationship （1.0 ≥ϕ≥ 0.7.）

In the above equations, θ is elastic story drift angles of frames at the strength capacity level $_FQ_P$ considering the whole structural systems (Rx or Ry level). And ω is angles obtained by impulse responses and should be smaller than acceptable nonlinear story drift angles of the corresponding frames of the story. Maximum values of acceptable story drift angles ω are considered to be 1/60. However, story drift angles ω=1/100 are used for RC and SRC structural systems considering effects of aftershocks in this paper.

In Figure 2, $_FQ_L$ is linear forces for frames of each story, and h and k are the story height and the linear stiffness based on static analysis, respectively. Strength reduction factor ϕ is considered as 1.0~0.7. This means that the axial force ratio for each member should be limited. Values of Rx and Ry are considered to be 0.25~0.6. For most buildings, it is often satisfactory to examine the story drifts of perimeter frames in acting shear force sides with respect to the center of strength S in each story in the x- and y-directions, respectively. Two-steps repeating computation procedure, push-over analysis, advanced analysis and so on can be used considering overturning moment effects due to vertical distributions of seismic forces in order to obtain the strength capacity level $_FQ_P$ and so on of each frame for each story of buildings in the direction under consideration. The advanced analysis may be some methods to obtain each story strength capacity and so on along the building height with various failure modes.

3. EVALUATION OF GROUND MOTIONS

Minimum values of seismic coefficients A_V representing the peak velocity-related acceleration and seismic coefficients C_0 for one-story and multistory buildings in a high seismic urban area are tentatively predicted. (Ozaki, et al. 1978) Considering return periods based on the past earthquake data during A.D1626~1972 (All of maxima during the years were used), Dr. Kanai's formula (Kanai, 1960) and the theory of extremes (Fisher, Tippett 1928, Gumbel E. J. 1958) are used. Seismic coefficients C_0 are also shown in Table 1. However, seismic coefficients C_0 for S_A, and S_F are not specified in this paper.

Table 1 Seismic coefficients based on return periods Standard values[#1]

Level Return period (years)	Velocity-related Acceleration Av (g)	Velocity V_1 at 1 sec. period (kine)	Seismic coefficient C_0 Critical period cT (sec.) S_B	 S_C	 S_D	 S_E	max. V_0[#2] (kine)
Level 1.0 (500years)	0.40	50	1.0	1.0	1.0	1.0	10
(10% probability of exceedance in 50 years)			0.4	0.6	0.8	1.2	
Story drift angle is less than 1/250[#3] for ground motions with return period more than 70 years.							
Level 1.5 (1000 years)	0.60	75	1.5	1.5	1.5	1.5 or [#4]	15
(10% probability of exceedance in 100 years)			0.4	0.6	0.9	1.3 or [#4]	
(5% probability of exceedance in 50 years)							
Story drift angle is less than 1/250[#3] for ground motions with return period more than 150 years.							

[#1] Upper value for structures is about 1.2 times standard value, (INTERNATIONAL BUILDING CODE 2000)
[#2] Mean values of maximum horizontal velocity at earthquake engineering base rock
[#3] No damage angle for various kinds of finishing materials
[#4] Site-specific geo-technical investigation and dynamic site response analysis

where

S_B Rock, Stiff deposits of geology. (Landmark)

S_C Stiff soil with 360 m/s<v_s≦760m/s or with either N>50 where N is average field standard penetration test for the top 30m. (Or Japanese soil profile type I)

S_D Soft soil with 180 m/s ≦v_s≦360m/s or with either 15≦**N**≦50. (Or Japanese soil profile type II)

S_E A soil profile with v_s<180m/s or any profile with more than 3m of soft clay defined as soil with PI>20, w≧40%, and s_u<25 kPa where PI and w are plasticity index and moisture content in percent, and s_u is average undrained shear strength. (Or Japanese soil profile type III)

S_F Soil requiring site-specific evaluation.

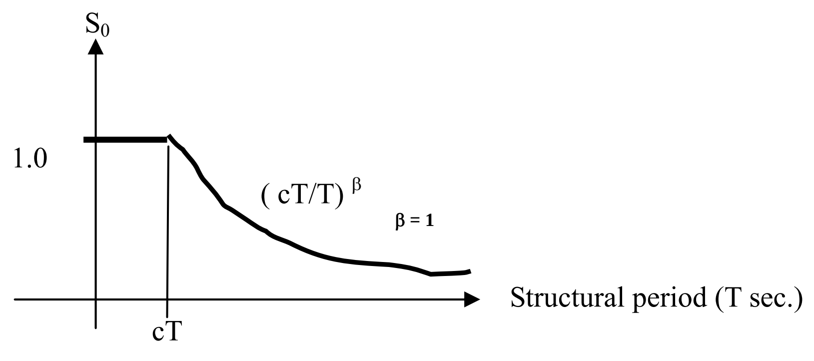

Figure 3 Standard value S_0 for linear spectrum (Structural damping ξ =5%)

Standard value S_0 for linear spectrum is illustrated in Figure 3, where T and cT are structural period and critical period of the soil condition, respectively. Instead of seismic coefficients C_0 in Table 1 and linear **e**valuation spectra S_0 shown in Figure 3, any reasonable seismic coefficients and/or linear evaluation spectra can be specified based on engineering investigation.

4. LOAD COMBINATIONS

The seismic actions at the near-source site in seismic urban areas expect heavy snow areas are considered as shown in Equations (3):

$$[1.0+0.5Av]D+1.0L+1.0E \quad (3.1)$$
$$[1.0-0.5Av]D+1.0E \quad (3.2)$$

where D: Dead load
L: Live load
E: Earthquake load

5. SEISMIC EVALUATION OF ONE-STORY AND MULTISTORY BUILDINGS

5.1 Seismic Base Shear V

The seismic base shear in a given direction is

$$V=C_BW \quad (4)$$

where C_B: Evaluation base shear coefficient.
W: The total weight.

5.2 Evaluation Base Shear Coefficient C_B

Evaluation base shear coefficients C_B are expressed as

$$C_B= Z\ S_0\ C_0 \text{ mini } (Rx) \quad (5.1)$$
$$C_B= Z\ S_0\ C_0 \text{ mini } (Ry) \quad (5.2)$$

where Z : Seismic zone factor (Z=1.0~0.8. Z=0.7 Okinawa)
S_0 : Linear evaluation spectrum for soil profile characteristics of the site as shown in Figure 3.
C_0 : Seismic coefficient based on return periods as shown in Table 1.
mini (Rx) or mini (Ry) is the minimum value of Rx or Ry among stories in each direction of buildings.

5.3 Vertical Distribution of Seismic Forces

The lateral seismic shear forces are determined by reasonable seismic force distribution methods or reasonable seismic shear force distribution coefficient methods. Approximate structural periods Tx,y for buildings with firm foundations can be estimated based on the top displacement at the center of stiffness using an inverse triangular-shaped seismic force distribution along the height of buildings with the firm foundation to the ground. Reasonable stiffness reduction factor can be used for shear walls. Walls with perfect slits are considered as bending- type columns.

6. SPECIAL CONSIDERATIONS

(1) Stiffness of brittle structural elements can be neglected.
(2) Multistory buildings with strong beams and weak columns systems: Each beam should be sufficiently strong compared with strength of each column or each shear wall at all the joints of structures. Severe damage or extremely large deformation of ductile buildings subjected to strong earthquake ground motions is often concentrated at a particular story with relatively small value of Rx or Ry (Akiyama 1999, Ozaki, et al. 1988). However, other stories with Rx and Ry larger than mini(Rx) and mini(Ry) are recommended to examine in the x-and y-directions, respectively. Shear failures of beams with RC slabs should be carefully examined.
(3) Multistory buildings with weak-beams and strong-columns systems: Strength increase of beams with monolithic RC slabs should be considered. For beam strength capacity, the whole width of slab seems to be effective in frame systems with monolithic RC slabs, when the torsion stiffness and torsion strength of the orthogonally crossing beams are rigid and strong after the large deformation of buildings. (Soda, Ozaki 1987)

(4) The center of story shear forces should be located inside the replaced 2 times 2 shear wall systems in order to avoid unstable and large responses of structures.
(5) Maximum structural period T<2.0 (sec.). Maximum building height H should be not more than 60 m.. Maximum T should be not more than H/30.
(6) Standard structural damping ξ is considered as 5% in this paper. For structural systems with a different damping value from the standard structural damping, reasonable damping correction factor η=Root $(7/(2+\xi))\geq 0.7$ for the values of linear design spectrum should be used in the corresponding direction. (EUROCODE 8, 1998) It is very difficult to estimate exact damping values of structures. However, linear dynamic response analysis such as a step-by-step time history response analysis are often used for design of high-rise buildings considering low structural damping 2~3%.
(7) Accidental torsion should be considered. Linear responses indicate that additional torsion (5% of plan dimension perpendicular to the direction of the applied forces) is needed. (Shiga 1976, SEAOC Blue Book, Chopra, Goal, 1993, Ozaki, et al. 1988)
Torsion correction coefficients can be used to obtain the corrected distributed frame shear forces of perimeters considering torques due to two acting horizontal story shear forces in the x- and y-directions using D values method by Professor Muto (Muto, 1956). The distributed frame shear forces Q_{px} and Q_{py} of the perimeters in the x- and y-directions should be multiplied by the following torsion correction coefficients α_{px} and α_{py} to obtain the displacements of the corresponding perimeters in each story plane of buildings.

$$\alpha_{px} = 1 + (\sum D_{nx} \cdot e_y)\, l_{py} \;/\; (Jx + Jy) > 1.0 \tag{6,1}$$

$$\alpha_{py} = 1 + (\sum D_{ny} \cdot e_x)\, l_{px} \;/\; (Jx + Jy) > 1.0 \tag{6.2}$$

where $D_n = Q/\delta \div [\,12EK/h_n^2\,] = Q/\delta \div [\,12EI/h_n^3\,]$ （D_n is D value of structural element in the n story.）
Q and δ are shear force and displacement. . E and h_n are Young's modulus and the n^{th} story height, respectively.
$12EK/h_n^{2:}$ **:** Story stiffness of structural element
x, y**:** Distance from the center lines of D values in the x- or y-direction, respectively
Jx, Jy**:** Second moment of D values in the x- or y-direction, respectively
$e_{x,}\, e_y$**:** Stiffness eccentric distance including accidental torsion in x-or y-direction
l_{px}, l_{py}**:** Distance between the center of rigidity and the corresponding perimeter in the x-or y-direction.
For the distributed frame shear forces Q_{px} and Q_{py} of the opposite side perimeters in the x-and y-directions, the following equations α_{px} and α_{py} can be used as torsion correction coefficients considering linear dynamic response analysis.

$$\alpha_{px} = 1.0 \tag{6.3}$$

$$\alpha_{py} = 1.0 \tag{6.4}$$

Three dimensional frame analyses can also be available to obtain the exact solution of displacements of the perimeters in each story of buildings.
(8) Twenty percent of base shear can be reduced, when soil-structure interaction is considered. However, additional deformation increase due to the soil-structure interaction should be carefully considered.
(9) Other special considerations such as shear failure of short columns and buckling of structural members, soil-structure interaction, aftershocks, foundation evaluation, large spanning structures, inspection, construction management, monitoring, good advisers needed. Etc.
(10) Each numerical value in this paper is subject to change

7. CONCLUSIONS

(1) Simplified, performance-based seismic evaluation method of one-story and multistory ductile buildings with various types of irregularity subjected to several levels of strong earthquake ground motions can be developed using shear and torsion strength capacity ratios in the x- and y-directions, respectively.
(2) Working or allowable stress evaluation will not be necessary, when simplified, performance-based seismic evaluation of ductile buildings with various irregularities is successfully established.
(3) Performance-based seismic evaluation is considered to be the future direction in seismic evaluation and engineering for buildings. However, available knowledge for science and engineering to establish perfect performance-based seismic evaluation of buildings is limited and difficult. Therefore, simplified, performance-

based seismic evaluation of buildings seems to be much practical and useful for practicing engineers.

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APPENDIX DEVIATION OF EQUATIONS (1)

Strength capacity ratios Rx and Ry considering two horizontal seismic actions for 2 × 2 shear wall system with torsions

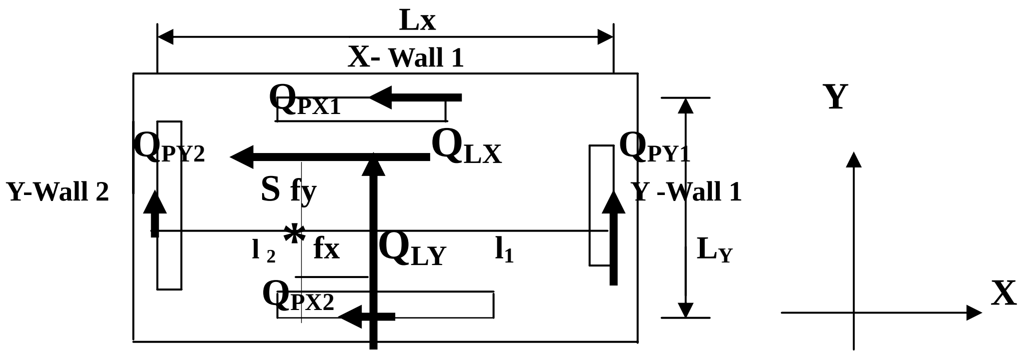

Figure 1A Plan of 2 × 2 shear wall system with torsion

In the above Figure 1A, the following notations are used:
Q_{LX} and Q_{LY} are acting story shear forces in the X- and Y- directions, respectively
L_X and L_Y are distance between two opposite shear walls in the X- and Y- directions, respectively
fx and fy are strength eccentric distances in the X- and Y- directions, respectively
Large damages are predicted in shear walls: X- Wall 1 and Y- Wall 1 located in acting shear force sides with respected to the center of strength in the X- and Y- directions, respectively.
And torsion strength capacity is expressed by the following equation:

$$Tp = Lx\, Q_{PY1} + L_Y Q_{PX1} \tag{1A}$$

Therefore, the shear and torsion strength capacity ratios Rx and Ry to the corresponding linear shear forces and linear torsion moments in the x- and y-directions are as follows:

$$R_X = \frac{0.85}{\dfrac{Q_{LX}}{Q_{PX}} + \dfrac{0.5T_{LY} + T_{LX}}{Tp}} \quad \text{and} \quad R_Y = \frac{0.85}{\dfrac{Q_{LY}}{Q_{PY}} + \dfrac{0.5T_{LX} + T_{LY}}{Tp}} \tag{1}$$

REFERENCES

Akiyama, H., (1999).Earthquake-Resistant Design Method for Buildings Based on Energy Balance. Gihodo Publishing Co. Japan
Alavi, B. and Krawinkler, H., (2000).Consideration of Near-Fault Ground Motion Effects in Seismic Design,

Proc. of 12 WCEE.
Azuhata, T., Takahashi, T., Ozaki, M., (1992).Damage Estimation of Buildings with Weak Beams and Strong-rigid Columns, *Proc. of Structural Engineering, Architectural Institute of Japan,* **Vol. 38 B**, pp. 627~628.
Chopra, A, Goel, R., (1993).Evaluation of US Seismic Code Provisions for Asymmetric-Plan Systems *STRUCTURAL ENGINEERING IN NATURALHAZARDS MITIGATION*, **Vol. 1,** Structural Congress.
EUROCODE, 8, (1998), EARTHQUAKE RESISTANT DESIGN OF STRUCTURES, PART 1-1: GENERAL RULES AND RULES FOR BUILDINGS**.**
Fisher, R.A., Tippett, L.H., (1928). Limiting Form of the Frequency Distribution of the Largest or Smallest Member of a Sample, *Proc., Cambridge Phil.,* **Soc. 24,** pt 2, 1928.
Gumbel, E.J. (1958). Statistics of Extremes, Columbia University Press, 1958
INTERNATIONAL BUILDING CODE, (2000).INTERNATIONAL CODE COUNCIL, pp 363
Kanai, K., (1960). An Empirical Formula for the Spectrum of Strong Earthquake Motion, *Proc., of II WCEE,* **Vol. 111**
Members of Architectural Institute of Japan, (1990).Strength Capacity and Deformation Capacity in Seismic Design of Buildings, Architectural Institute of Japan,
Muto, K.(1956).Seismic Analysis of Reinforced Concrete Buildings. The first World Conference on Earthquake Engineering.
NEHRP (1997), Recommended Provisions For Seismic Regulations For New Buildings**,** *1997 Editions.*
Ozaki, M., Azuhata, T., Chen, J., Soda, S. (1988).SEISMIC DESIGN FOR MULTISTORY BUILDINGS WITH ECCENTRICITY SUBJECTED TO TWO-DIRECTIONAL GROUND MOTIONS. *Proceedings of Ninth World Conference on Earthquake Engineering,* **Vol. V.** 233~238
Ozaki, M., Azuhata, T., Takahashi, T., Mu, S.(1994).Inelastic Deformation of One-story Asymmetric-Plan Systems Subjected to Strong Earthquake Ground Motions. *EERI Earthquake Spectra,* **10-4**, pp. 777~790
Ozaki, M., Azuhata, T., Hu, M.(1998).SIMPLIFIED, PERFORN|MANCE- BASED SEISMIC DESIGN METHODOLOGY OF DUCTILE BUILDINGS CONSIDERING INELASTIC DEFORMATION LIMITS. *Proc., THE FIFTH INTERNATIONAL CONFERENCE ON TALL BUILDINGS*, **Vol. 2,** pp. 831~836
Ozaki, et al. (2006).RECOMMENDATIONS FOR SIMPLIFIED, PERFORMANCE-BASED SEISMIC DESIGN OF BUILDINGS WITH IRREGULARITIES AND DESIGN EXAMPLES, *11th US-JAPAN workshop at KOBE, Oct. 17-19,* pp 1-12
Ozaki, M., Kitagawa, Y., Hattori, S. (1978).Study on Characteristics of Earthquake Motions in Japan (Part 1). *Transaction of Architectural Institute of Japan,* **No. 266,** pp. 31-40.
SEAOC: VISION (2000, 1995).Performance-Based Seismic Engineering of Buildings. *Structural Engineers Association of California*.
Shiga, T..,(1976).Vibrations of Structures**.** Kyoritsu Publishing Co.
Soda, S., Ozaki, M.,(1987).Experimental Study on Seismic Stability of Mixed Frame Structures with Monolithic Slabs. *Bulletin, 35-1,* **No. 67**, Faculty of Engineering, Chiba University.
Tanahashi, R., (1937).On the Resistance of Structures to Earthquake Shocks. Memoirs of the Collage of Eng., Kyoto Imperial University.
Yasuda, Ozaki, Soda and Fukai, (1984).Analytical Study on Elastic-Plastic Seismic Response of Multi-Story Structures with Eccentricity, Structures, Architectural Institute of Japan**, No. 266,** pp 805-806.