# DEVELOPMENTS AND CASE STUDIES OF THE DRAFT CODE FOR PERFORMANCE-BASED SEISMIC DESIGN OF BUILDINGS IN TAIWAN

**Q. Xue[1] C.W. Wu[2] C.C. Chen[3] K.C. Chen[4]**

[1] *Senior Research Scientist, Section Chief, Civil and Hydraulic Engineering Research Center, Sinotech Engineering Consultants Inc., Taipei, Chinese Taiwan*
[2] *Research Scientist, CHER Center, Sinotech Engineering Consultants Inc., Taipei, Chinese Taiwan*
[3] *Deputy Manager, CHER Center, Sinotech Engineering Consultants Inc., Taipei, Chinese Taiwan*
[4] *Manager, CHER Center, Sinotech Engineering Consultants Inc., Taipei, Chinese Taiwan*
*Email: qxue@sinotech.org.tw*

**ABSTRACT :**

This paper summarizes the development of the performance-based seismic design draft code for buildings in Taiwan and presents results of case studies following the guideline in this paper. Based on the examination of the existing seismic design code provisions, several key issues are identified to determine the scope of performance-based seismic design methodologies to be incorporated into. The proposed seismic design objectives and criteria including drift limits, site feasibility requirements, conceptual design scopes and basic rules have been explained. Procedures for preliminary design and seismic performance evaluation have been presented. Suggestions on seismic performance criteria and performance evaluation of existing buildings have been made. According to the case studies, it is believed that seismic performance will be ensured with enhanced confidence through implementation of performance-based seismic design methodology into the current code of practice.

**KEYWORDS:** Code, Performance, Seismic, Design, Building

## 1. INTRODUCTION

Lessons learned from the devastating Chi-Chi earthquake has waked up the scientific community in Taiwan to consider new seismic design methodologies. Performance–based seismic design (PBSD) has been recognized as an ideal method for use in the future practice of seismic design. According to international researches and practices, researches on performance-based seismic evaluation of existing structures and performance-based seismic design of new structures have been carried out in research organizations in Taiwan. Recognizing an increasing need for performance-based seismic design guidelines or provisions for local engineers to follow, in 2003, the Architecture and Building Research Institute (ABRI), Ministry of the Interior, sponsored Sinotech Engineering Consultants Incorporated to propose a framework for a performance-based seismic design code, applicable to current engineering practices. Based on the state-of-the-art (ATC-40 1996, FEMA 273 1997, FEMA 356 2000) and the state-of-the-practice (SEAOC 1999, IBC 2003, JSCA 2000, King and Shelton 2004, Heidebrecht 2004), the current seismic design code provisions are examined according to the theoretical basis of PBSD to identify which methodologies of PBSD need to be incorporated into the current seismic design code. Following the framework, the ABRI sponsored another project for the same research group to propose a seismic design draft code for buildings by introducing performance-based design methodologies. In this paper, key issues of the PBSD draft code with focus on structural performance for buildings without base isolation systems and energy dissipative devices are presented. In order to encourage and help engineers to apply the draft code provisions correctly in practice, the design procedures are illustrated through examples.

## 2. INTRODUCING PBSD METHODOLOGY INTO TAIWAN

### *2.1. Advantages of PBSD*

In order to identify which methodologies of PBSD need to be incorporated into the current seismic design code in Taiwan, the general concept, the state of the art and the state of the practice have been reviewed. The advantages of PBSD over the traditional design methodologies are summarized as the following six key issues:

(1) Multi-level seismic hazards are considered with an emphasis on the transparency of performance objectives.
(2) Building performance is guaranteed through limited inelastic displacement or damage in addition to strength and ductility.
(3) Seismic design is oriented by performance objectives interpreted by engineering parameters, performance criteria.
(4) An analytical method through which the structural behavior, particularly the nonlinear behavior is rationally obtained, is required.
(5) The building will meet the prescribed performance objectives reliably with accepted confidence.
(6) The design will ensure the minimum life-cycle cost.

### *2.2. Deficiencies of The Existing Seismic Design Code for Buildings in Taiwan*

The current seismic design code is partially performance-based. However, according to the theoretical basis of PBSD. Several deficiencies have been found in the existing seismic design codes in Taiwan. Conventional seismic design objectives lack transparency. For example, the performance objective of an important building is adjusted by increasing the considered earthquake level through an importance factor I, while keeping the expected performance level the same as that of a general building. This is the case even for the maximum considered earthquake level with a return period of 2500 years. Engineers do not know the corresponding intensity scale of such an amplified earthquake because an earthquake with a return period of 2500 years corresponds to the maximum intensity scale already for most places in Taiwan. Therefore, the design criteria and expected performance of the building are not understood well by the public. Building stiffness or displacement is not as important as strength and ductility. The current seismic design code emphasizes structural strength and ductility. Drift limits, associated with structural stiffness, are only provided for earthquakes that occur frequently. The expected performance of buildings has not been evaluated using rational analysis methods. Structural responses to high-level earthquakes may not be predicted accurately. Even engineers may not be sure why the criteria specified in the current seismic design code would allow the building to meet the performance goals. Due to time and budget limit, introducing performance-based seismic design methodology in the current seismic design code will focus on the first 4 key issues listed above in this research.

## 3. THE PBSD DRAFT CODE

According to the above discussion, the main task of this research is to establish transparent seismic design objectives for buildings of different use groups qualitatively and interpreted quantitatively as performance criteria including drift limits under all hazard level, to address site feasibility requirements and conceptual design basic rules considering different performance objectives, to employ performance-based approach for preliminary design, to select a rational analysis method and to provide the contents for seismic performance evaluation. For the completeness, guidelines for direct-displacement-based design methods and suggestions on both performance criteria and performance evaluation of existing buildings are also provided.

### *3.1. Performance Objectives and Criteria*

The purpose to establish individual performance objective for buildings of different seismic use group is to provide a platform for information exchange between the owners and the designers so that they can achieve a common view about the structural performance under different level of earthquake excitation. Therefore, transparency of the design objectives is very important. In the draft code, a building is classified as being in one of three use groups I, II and III with increasing importance or damage consequences. Performance objectives for seismic use groups I, II and III are depicted in Figure 1. In

Figure 1, OP, IO, DC, LS and CP stand for operational, immediate occupancy, damage control, life safety and collapse prevention, respectively. EQ1, EQ2 and EQ3 mean level 1, level 2 and level 3 earthquakes, respectively.

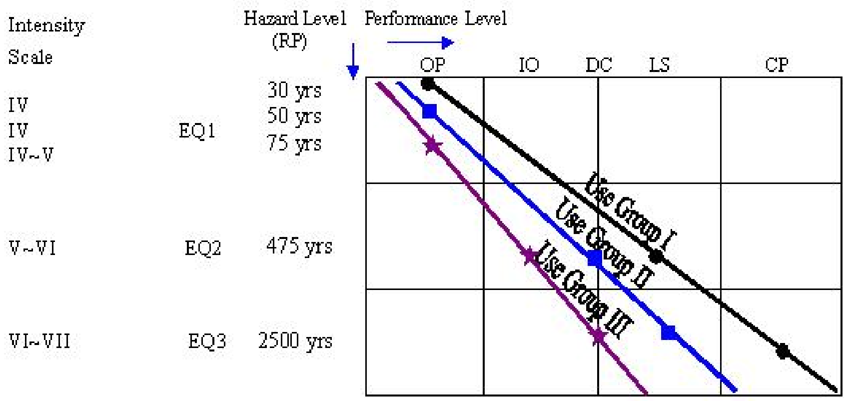



Figure 1 Performance objectives

The performance objectives must be transformed into performance criteria for engineering design. Each seismic hazard level is quantified by an elastic design spectrum corresponding to the construction site. In the case of a higher hazard level that may cause the structure to respond inelastically, either an equivalent elastic design spectrum or an inelastic design spectrum will be adopted. Regarding the inelastic design spectrum, Newmark-Hall (1982) reduction factors have been employed with slight modifications according to the local seismic hazard analysis. Regarding the equivalent elastic design spectrum, the effective damping model in equation (8) proposed by Iwan and Gates (1979) is suggested to use so as to conform to the inelastic design spectrum (Xue 2001).

Each performance level is quantified by parameters associated with strength, stiffness and ductility. Regarding strength, OP corresponds to an elastic behavior. Overstrength must be ensured for other performance levels and no large strength degradation can occur beyond the ductility limit. No weak story exists and the structure has enough vertical capacity.

Regarding ductility, the concept of inelastic displacement demand ratio (*IDDR*) (SEAOC 1999) is employed. *IDDR* represents the ratio of inelastic displacement demand over the ultimate inelastic displacement capacity. Acceptable values $IDDR_a$ associated with structural system performance levels OP, IO, DC, LS, and CP are 0, 0.2, 0.4, 0.6 and 0.8, respectively. Subscript a stands for the allowable value. For structural members, no less than 80% of the elements need to meet the same criteria.

Regarding stiffness, the maximum inter-story drift ratio (*IDR*) is considered to limit building lateral displacement. It is not easy to reach an agreement on the drift limit. In this research, based on references such as the SEAOC blue book (1999), FEMA 450 (2003), IBC 2003 (2003), JSCA (2000), AS/NZS 1170 (King and Shelton 2004) and NBCC 2005 (Heidebrecht 2004) and according to the local seismic hazard analysis and opinions from the advisory committee of this project, the IDR limits in Table 1 are suggested. It should be noted that the limit of the maximum inter-story drift ratio is used as a performance assessment criterion but may result in an unreasonable demand for some structural systems, particularly for less ductile structural systems if a direct displacement based design method is used for the preliminary design. A detailed discussion on this issue can be found through the comparison study of an example to be presented later in this chapter.

Table 1: The Maximum Allowable Inter-Story Drift Ratio

| Structural System | Performance Level | | | | |
|---|---|---|---|---|---|
| | CP | LS | DC | IO | OP |
| Systems with Masonry Shear Walls | 0.009 | 0.007 | 0.007 | 0.007 | 0.005 |
| Other Systems | 0.025 | 0.020 | 0.015 | 0.010 | 0.005 |

It is important to point out that the draft code suggested performance objectives and criteria provide the minimum protection to the buildings. An increase in the performance objectives is allowed upon the owner's request.

### *3.2. Site Feasibility*

This research focuses on the determination of very weak soil layers and the liquefaction potential of sandy soil so that the coefficient of subgrade reaction can be reduced by a reduction factor $D_E$. Under EQ1 level earthquakes, liquefaction is not acceptable. For EQ2 and EQ3 level earthquakes, soil liquefaction may occur but is limited to an allowable degree through the maximum allowable value of $D_E$, which is set to be 0, 1/3 and 2/3 for buildings of seismic use groups I, II and III, respectively. If this limit is exceeded, soil improvement is needed. For buildings of seismic use groups II and III, the back off distances from type 1 active faults, which are identified active during the past 10,000 years, and other hazards such as landslides must be taken into consideration.

### *3.3. Conceptual Design*

Basic conceptual design rules are given with an emphasis on the redundancy and uniform continuity of strength, stiffness and ductility, respectively. The ductile capacity of each system is represented by a given ultimate ductility ratio $\mu$ according to its relative capacity to dissipate energy after yielding. Building height limits, horizontal and vertical irregularities, and expected energy dissipation and yielding mechanisms have been defined. Flexibility is given to allow design of special structural systems based on reliable technology.

### *3.4. Preliminary Design*

Performance based design implies that the design procedure is oriented by the performance objective. It can be achieved through either an indirect or a direct displacement-based design method. Since approaches of the latter method are not mature enough to be applied directly to various structures, they are summarized in the appendix for reference only before detail parametric and case studies. For the purpose of application in engineering practice, at the current stage, the draft code should be used together with the existing material design codes for structural component detailing. Repeated nonlinear static analysis during the design procedure is not preferable. Therefore, the former method, which employs a force-based design procedure combined with a check on the inter-story drift ratio, is adopted.

#### *3.4.1 The lateral design force*

Similar as traditional force-based design method, fundamental period of the structure system is given by empirical formula. Regarding EQ1 in Figure 2, the lateral design force is $V_d = \frac{S_a}{\alpha_y} \times W$, where $S_a$ is the spectral acceleration corresponding to the fundamental period reading from the elastic design spectra of the considered hazard level. $W$ is the total weight. $\alpha_y$ is the system yielding level amplification factor by which the first significant yielding level is amplified. Regarding EQ2 and EQ3, the lateral design force is $V_d = \frac{1}{1.4\alpha_y} \times \left(\frac{S_a}{F_u}\right) \times W$, where 1.4 stands for overstrength from the system yielding level to the ultimate strength. $F_u$ is the ductility reduction factor defined in Eqn. (1).

$$F_u = \begin{cases} \mu_a & ; \quad for \quad T \geq T_S \\ \sqrt{2\mu_a - 1} + \left(\mu_a - \sqrt{2\mu_a - 1}\right) \times \dfrac{T - 0.6T_S}{0.4T_S} & ; \quad for \quad 0.6T_S \leq T \leq T_S \\ \sqrt{2\mu_a - 1} & ; \quad for \quad 0.2T_S \leq T \leq 0.6T_S \\ \sqrt{2\mu_a - 1} + \left(\sqrt{2\mu_a - 1} - 1\right) \times \dfrac{T - 0.2T_S}{0.2T_S} & ; \quad for \quad T \leq 0.2T_S \end{cases} \tag{1}$$

$T_S$ is the corner period of the response spectra. The target allowable ductility ratio $\mu_a$ is related to $IDDR_a$ by Eqn. (2).

$$\mu_a = 1 + IDDR_a(\mu - 1) \tag{2}$$

where $\mu$ and $IDDR_a$ have been defined earlier in this paper. Since $\mu$ has been derived by including some margin of safety, it corresponds to 80-90% of the ultimate inelastic displacement capacity. Accordingly, during preliminary design, acceptable values $IDDR_a$ associated with structural system performance levels OP, IO, DC, LS and CP are revised to be 0, 2/9, 4/9, 2/3 and 1, respectively. However, for sites within the Taipei Basin, these values are revised to be 0, 1/6, 1/3, 1/2 and 1, respectively, considering a large number of cyclic excitations.

*3.4.2 Analysis and design*

The same as in the current design code, elastic analysis can be used at this stage. Static analysis or modal spectrum analysis can be selected according to building height and system irregularity. Element design can be conducted in the usual way according to the existing design specifications and tools.

*3.4.3 Preliminary check on the inter-story drift ratio*

Regarding concerns arising from complexity of inelastic analysis during detail seismic performance assessment in the next step, a simple method for preliminary check on the inter-story drift ratio is employed so that deficiency associated with stiffness can be noticed at an earlier stage.

N modes with 90% modal mass participating are considered. Alternatively, N=3 is allowed. Under earthquake level EQ2 or EQ3, for each mode *i* with period of $T_i$, inelastic spectral displacement $S_d^i$ associated with the corresponding performance level ($_{PL}$) is calculated through Eqn. 3.

$$S_d^i = \frac{\mu_{a,PL}^i}{F_u} * \left(\frac{T_i}{2\pi}\right)^2 * S_{ae}^i \tag{3}$$

where $S_{ae}^i$ is the elastic design spectral acceleration corresponding to $T_i$. For the first mode, $\mu_{a,PL}^1$ is equal to $\mu_{a,PL}$ estimated by Eq. (1) with revised *IDDR*. For other mode, the same value may be assumed or $\mu_{a,PL}^{i\neq 1}$ =1. $S_d^i$ also represents the inelastic target displacement of the equivalent single degree of freedom (ESDOF) system under mode i. Modal superposition is applied by either SRSS or CQC rule to obtain the displacement of ESDOF system. Finally, the maximum inter-story drift ratio is calculated by Eqn. 4 (SEAOC, 1999).

$$IDR = x^*/(h_n k_1 k_2) \tag{4}$$

where $h_n$, $k_1$ and $k_2$ are height at roof level, factor of effective height, factor of displacement shape function defined in SEAOC (1999).

It should be noticed that this approximate method is very rough and is most suitable for a structure whose behavior is dominated by its first mode. For more flexibility, preliminary design according to the current force-based design method is allowed as long as the performance criteria are acceptable after detail performance assessment. It is suggested to use together with preliminary check on the inter story drift ratio.

***3.5. Detailed Seismic Performance Assessment***

*3.5.1 Seismic performance analysis*

In this research, the minimum allowable analysis method to be employed for performance assessment is suggested in Table 2. The following sections focus on nonlinear static analysis.

Table 2 The Minimum Allowable Analysis Method for Performance Assessment

| Seismic hazard level | Static analysis used in the preliminary design | Dynamic analysis used in the preliminary design | |
|---|---|---|---|
| | | $T \le 3.5T_s$ | $T > 3.5T_s$ |
| EQ1 | Linear Static | Linear Dynamic | Linear Dynamic |
| EQ2 | Nonlinear Static | Nonlinear Static | Nonlinear Dynamic |
| EQ3 | Nonlinear Static | Nonlinear Static | Nonlinear Dynamic |

*3.5.2 Structural simulation and modeling*

Structural simulation and modeling are as important as selection of the analysis method. Plastic hinge properties of different elements can be adopted from reliable experiments or research reports. Cracking of a RC element is considered in the same way as suggested in FEMA 356 (2000). Influence, particularly adverse influence of non-structural walls (such as the infill walls) on the structural damage mechanism and deformation capacity must be considered.

*3.5.3 Nonlinear static pushover analysis*

A 100% dead load plus no less than a 25% live load are applied priory to the lateral load in the nonlinear pushover analysis. It is suggested to employ either of two types of load patterns. One is proportional to the fundamental mode. The other is the uniformly distributed load pattern proportional to the story mass. Other adaptive load patterns based on reliable studies are also allowed. The monitoring point is the mass center of the roof story including the penthouse. The end point of the capacity curve corresponds to an ultimate or failure state which is identified when the structure loses stability, or 80% of the elements reach their deformation limit, or more than 20% (maximum or effective) of the base shear strength was reduced after yielding, whichever is critical.

*3.5.4 Seismic performance evaluation*

The performance point of the structure that responds to the considered hazard level is evaluated through the seismic coefficient method (FEMA 273 1997, FEMA 356 2000) or the capacity-spectrum method (ATC-40 1996). The structure is pushed again to the target displacement associated with the performance point to access the behavior of both the structural system and the elements if such a hazard level occurs. Performance criteria regarding all performance goals are examined regarding structural systems and elements.

*Structural systems*

- Regarding vertical load carrying capacity, the structure should not collapse due to loss of any element.
- Regarding lateral strength, damage and weak story mechanisms can be clearly understood through hinge location and hinge formation sequences. Strength deterioration is controlled by the definition of failure state during nonlinear pushover analysis.
- Regarding lateral deformation capacity, the maximum inter-story drift ratio *IDR* and inelastic displacement demand ratio *IDDR* are calculated and compared with the acceptable performance criteria. Extremely soft story and extreme torsion irregularities must be avoided. That is, each story's stiffness should not be less than 60% of that of the story directly above it or less than 70% of the average of the 3 stories above it. The maximum displacement along the horizontal direction that the earthquake applies should not exceed 1.4 times the average displacement along both horizontal directions.
- Building separation distance must be no less than either the maximum story displacement under EQ2 or 70% of that under EQ3 to avoid pounding.

*Structural elements*

- Elastic behavior examination is conducted for elements that need to remain elastic according to the damage mechanism.
- Deformation capacity examination is conducted for deformation-controlled behavior based on

the moment-rotation or force-displacement relationship employed in the nonlinear static analysis. According to the performance criteria, only no less than 80% of the elements need to meet the same allowable $IDDR_a$ as that of the structural system.

- Strength capacity examination is conducted for force-controlled behavior so that the lowest bound of strength will not be less than the estimated force induced by the considered loading.

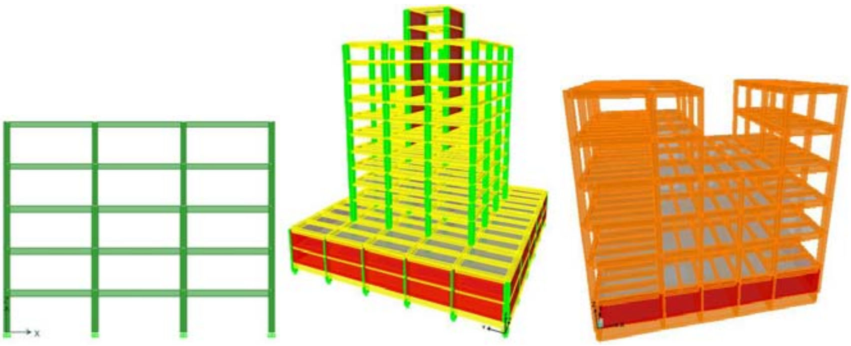
In this research, element performance examination is not applied to the performance goal associated with the CP performance level where global system stability is of the main concern.

## 4. SEISMIC PERFORMANCE EVALUATION OF EXISTING BUILDINGS

Looser restrictions on seismic performance goals and criteria except for those associated with life safety and collapse prevention are allowed for existing buildings in comparison with new buildings. Detailed seismic performance evaluation is conducted in the same way as for new buildings. The major difference is that structural modeling should be based on site investigation of the real structure.

## 5. CASE STUDIES

The three buildings shown in Figure 2 have been considered to demonstrate feasibility of the draft code design procedure. Example 1 is a steel moment resisting frame. Example 2 is a RC building with a moment resisting frame in the Y direction and a duel system (with coupled shear wall) in the X direction. Example 3 is an irregular RC moment resisting frame. Due to paper size limit, only important finds are summarized in this paper.



1) regular steel building 2) regular RC building 3) irregular RC building

Figure 2 The example structures

According to the study of example 1, it is found that the proposed method for preliminary check on the inter-story drift ratio may help designers to find stiffness deficiency at an early stage before conducting nonlinear pushover analysis for performance check.

According to the study of examples 2 and 3, if member size standards and construction convenience has been considered for structural detailing in the same way as in engineering practice, it is found that such a structure usually has a lower ductility capacity than that specified in code. Although structural ductility is not uniformly distributed, structural strength and stiffness are increased. Therefore, the performance objectives are usually satisfied. If an idealized detailing has been used without considering construction convenience, the ductility capacity is in very good agreement with the code value.

All examples have shown that seismic performance of the design structures could be easily understood and clearly interpreted through the performance-based design procedures. The engineers may have more confidence in the seismic performance of the designed structure under different level of earthquake excitation. By adopting the performance criteria in Table 1, direct displacement-based design procedures have been applied successfully for the moment resisting frames in these three examples without relying on engineering experience for preliminary sizing, but failed in the X direction of example 2. Such criteria should not be used either as optimized design criteria or in a direct displacement-based design procedure for less ductile structures. The current force-based preliminary design procedure gives identical lateral design force in both directions of example 3. Performance check by nonlinear pushover analysis reveals a larger seismic capacity left in the X direction under the same level earthquakes such as EQ2 or EQ 3. However, by using direct displacement-based design methods, smaller lateral design force is obtained in the X direction. Therefore, different demands in the two directions of the irregular building can be clearly captured by using direct displacement-based design methods.

## 6. CONCLUSIONS

The performance-based seismic design draft code introduces a transparent platform in which the owners and designers can exchange their views on the expected seismic performance of the buildings under different levels of earthquakes. For buildings of different seismic use groups, specific performance goals are established without employing an importance factor. Performance levels are quantified through parameters associated with structural strength, stiffness and ductility. Limitations on the degree of liquefaction potential of the construction site are given. Conceptual design rules with focuses on redundancy and uniform continuity of strength, stiffness and ductility are specified. A performance objective oriented preliminary design procedure is presented with consideration of flexibility. Instead of ensuring a system possessing the prescribed ductility capacity through ductile design, the expected behavior or performance of the preliminarily designed structure is analyzed and evaluated through an analytical method, which may capture the real behavior of the structures rationally. Engineers may have more confidence in the seismic performance of the designed structure under different levels of earthquake excitation. Although performance-based engineering covers a wide range of field and the methodology sounds ideal, it is believed that the methodology will lead to a safer and more economic society if the performance can be clearly related to damage, life cycle cost, reliability and risk.

## ACKNOWLEDGMENTS

This work is the result of a research project sponsored by Architecture and Building Research Institute, Ministry of The Interior, under grant No. 093301070000G3015, No. 094301070000G1018 and No. 095301070000G1025. Special thanks are given to the reviewers and the advisory committee members of this project for their valuable comments.

## REFERENCES

ATC-40, (1996). *Seismic Evaluation and Retrofit of Concrete Buildings*, Vol.1, Applied Technology Council, Redwood City, California, USA.
FEMA 273, (1997). *NEHRP Guidelines for Seismic Rehabilitation of Buildings*, Washington, DC, USA.
FEMA 356, (2000). *Prestandard and Commentary for The Seismic Rehabilitation of Buildings*, Washington, DC, USA.
FEMA 450, (2003). *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, Part 1: Provisions*. BSSC, Washington, DC, USA.
Heidebrecht, A. (2004). Code development issues arising from the preparation of the seismic provisions of the national building code of Canada, *13WCEE*, Vancouver, Canada, Aug.1~6.
IBC 2003, (2003). *International Building Code 2003*, International Code Council, USA.
Iwan, W. D. and Gates, N. C. (1979). Estimating Earthquake Response of Simple Hysteretic Structures, *Journal of The Engineering Mechanics Division* 105:3, 391-405.
JSCA, (2000). *Design Methodologies for Response Controlled Structures*, Japan Structural Consultants Association (Specifications), Tokyo, JAPAN. (In Japanese)
King, A. and Shelton, R. (2004). New Zealand advances in performance-based seismic design, *13WCEE*, Vancouver, Canada, Aug.1~6.
Newmark, N. M. and Hall, W. J. (1982). *Earthquake Spectra and Design*, Earthquake Engineering Research Institute, Berkeley.
SEAOC, (1999). *Recommended Lateral Force Requirements and Commentary*, Structural Engineers Association of California-Seismology Committee, CA, USA.
Xue, Q. (2001). Assessing the accuracy of the damping model used in displacement-based seismic demand evaluation and design of inelastic structures, *Earthquake Engineering and Engineering Seismology* 3:2, 37-45.