

COVER SHEET

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ABSTRACT

The USNRC has initiated a project to determine if any of the likely revisions to traditional earthquake engineering practice are relevant to seismic design of the specialized structures, systems and components of nuclear power plants and of such significance to suggest that a change in design practice might be warranted. As part of the initial phase of this study, a literature survey was conducted on the recent changes in seismic design codes/standards, on-going activities of code-writing organizations/communities, and published documents on displacement-based design methods. This paper provides a summary of recent changes in building codes and on-going activities for future codes. It also discusses some technical issues for further consideration.

1. INTRODUCTION

The NRC is in the process of updating its requirements for earthquake engineering design of nuclear power plants. The regulation governing seismic criteria and design, Appendix A to 10 CFR Part 100, was revised in December 1996. Regulatory guides and associated Standard Review Plan sections treating the identification of seismic sources and determination of the Safe Shutdown Earthquake ground motion were published in March 1997 along with a revised Regulatory Guide on seismic instrumentation and new Regulatory Guides on OBE exceedence criteria on post-earthquake shutdown and re-start.

Revisions to the Regulatory Guides and Standard Review Plan sections devoted to earthquake engineering practice are currently in process. The intent is to reflect changes in engineering practice that have evolved in the twenty years that have passed since those criteria were originally published. Additionally, field observations of the effects of the Northridge (1994) and Kobe (1995) earthquakes have inspired some reassessment in the technical community about certain aspects of design practice. In particular, questions have arisen about the effectiveness of basing earthquake resistant designs on resistance to seismic forces and then evaluating tolerability of the expected displacements. Efforts are now underway to assess the desirability of using, as an alternative, a design based on limits for displacements. Based on past PRA/SMA studies, components and failure modes that are considered to be "displacement sensitive" are identified and listed in Table 1.

Table 1. Displacement Sensitive Components/Failure Modes

COMPONENTS	FAILURE MODES
Category II Structures (e.g., Turbine Building)	Excessive inelastic deformation
Adjacent Buildings (e.g., Reactor & Turbine Buildings)	Pounding between buildings
Masonry Walls	Out-of-plane bending
Seismic Interaction	Flexible distribution systems impacting equipment Category II structures over Category I Equipment
Piping	Differential anchor motions Relative motion between buildings (Buried pipes)
Core Assembly	Bending of cores Deflection of guide tubes
Rotating Equipment	Deflection of pump shaft Deflection of fan blade
Non-Structural Components (partitions, doors, glasses, hang ceilings)	Adverse affects on operators
Ductile Components (in general)	Excessive inelastic deformation

2. RECENT CHANGES IN BUILDING CODES

The historical evolution of U.S. seismic design codes, prior to the 1994 Northridge and the 1995 Kobe earthquakes, are described in detail in Structural Engineering Association of California (SEAOC) and Applied Technology Council (ATC) publications. A comprehensive review of design codes/standards was also conducted under NRC sponsorship in 1995 in conjunction with the proposed design of advanced reactors (Ref. 1).

This paper summarizes more recent code changes issued after the Northridge and Kobe events. Most are associated with work performed as part of the National Earthquake Hazards Reduction Program (NEHRP) and the Federal Emergency Management Agency (FEMA). This includes the 1997 NEHRP Guidelines for Rehabilitation of Buildings (FEMA 273 & 274), the 1997 Uniform Building Code (UBC), the 1997 NEHRP Provisions for New Buildings (FEMA 302 & 303), and ATC-32 (Bridge Design).

2.1 1997 NEHRP Guidelines for Seismic Rehabilitation of Buildings (FEMA-273, 274)

The guidelines are the first performance based seismic criteria adopted at the national level. The evaluation criteria are displacement based and the main concepts are briefly described below. A brief summary as well as application of the guidelines to various existing buildings are also available in open publications (Ref. 2 and 3).

Performance Criteria

The building performance levels, which represent the post-earthquake condition of a building, are expressed as a combination of the structural performance levels (S-1, S-3 and S-5) and ranges (S-2 and S-4), and the nonstructural performance levels (N-A through N-E).

A total of four (4) performance levels, i.e., four combinations of structural and nonstructural performance levels, are recommended for possible performance objectives:

- (S-1 + N-A).....Operational Level; very little damage
- (S-1 + N-B).....Immediate Occupancy Level; green tag
- (S-3 + N-C).....Life Safety Level; significant reserve strength
- (S-5 + N-E).....Collapse Prevention Level; remain standing

The structural performance levels are illustrated in Fig. 1, in which the Life Safety Level would be able to experience at least 33% greater lateral deformation before the building failure. The guidelines also recommend story drifts corresponding to the structural performance levels.

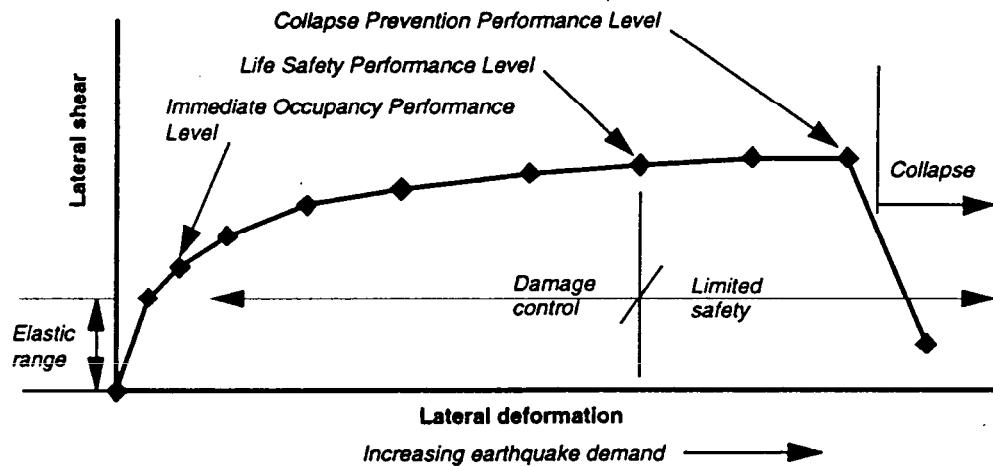


Figure 1 Performance and Structural Deformation Demand for Ductile Structures (Ref. FEMA-274)

Linear Analysis Procedure

Although the guidelines strongly recommend the use of nonlinear analysis procedures for the evaluation of existing buildings, linear analysis procedures (linear static, LSP, and linear dynamic, LDP) are still acceptable given the following restrictions:

- the demand-capacity ratios (DCRs) in primary components are less than 2.0
- when the maximum DCRs are larger than 2.0, linear analysis procedures can still be used if:
 - no significant in-plane discontinuity
 - no significant out-of-plane offset
 - ratios of DCRs between adjacent stories less than 1.25 (no soft story)
 - no significant torsional problem

Nonlinear Analysis Procedure

A nonlinear static analysis procedure (NSP) is recommended for the evaluation of most buildings given that the contribution from higher modes is not significant, i.e., the story shear from higher modes contributes less than 30% of that of the fundamental mode. All the necessary parameters for pushover analysis (NSP) are tabulated in FEMA 273.

2.2 1997 Uniform Building Code (UBC)

The UBC Seismic Provisions have been updated based on the revised recommendations of the SEAOC Blue Book, on a 3 year cycle, through the 1980's and 1990's. The 1997 version contains many significant changes. It is considered to be the last version of this code since it will be replaced by the International Building Code (IBC) in the year 2000. The IBC will be the first "national" building code to be used throughout the United States. The main purposes of the new changes were:

- to reflect lessons learned from the Northridge and Kobe earthquakes.
- to be more consistent with the NEHRP Provisions for a smooth transition to the 2000 IBC.

A large number of publications and articles are available for understanding the technical basis for the new changes. Some of the major changes in the 1997 UBC, which are considered to be directly or indirectly related to displacement based design, are discussed below.

In the 1997 UBC, the constant velocity portion of the design spectrum is defined by $1/T$, instead of $1/T^{2/3}$, to be consistent with the 1997 NEHRP Provisions. Near-source factors, N_s and N_v , have also been introduced in recognition that the ground motions near earthquake rupture could be larger than previously assumed. This phenomenon was very evident in the Kobe earthquake. The drift limits in the 1997 UBC also were revised to be consistent with the NEHRP Provisions and redundancy/reliability parameters and a soil classification were introduced.

Another significant change is the adoption of the strength design (SD) approach over allowable stress design (ASD) approach. Accordingly, the basic load combination has been changed to be consistent with the American Society of Civil Engineers (ASCE) standard, ASCE 7-95, and the 1997 NEHRP Provisions.

The current versions of seismic design codes, including the 1997 UBC and the 1997 NEHRP Provisions, are still not considered to be completely performance based. These design codes, however, are becoming increasingly more explicit regarding the "real" response of buildings during a design earthquake event.

2.3 1997 NEHRP Provisions for New Buildings (FEMA 302, 304)

The seismic provisions of the first national building code, 2000 IBC, will be based largely on the 1997 NEHRP Provisions. The changes made in the NEHRP Provisions from the 1994 version are relatively minor, and in parallel with the changes in UBC, except that the near-source factors were not adopted in the NEHRP Provisions. The major changes are:

- Response spectral values are used to define the design spectrum, instead of the effective peak acceleration, A_s , and velocity-related acceleration, A_v (Similar to UBC).
- Velocity constant portion of design spectrum is defined by $1/T$ instead of $1/T^{2/3}$
- Adoption of redundancy/reliability parameter (same as UBC).

2.4 ATC-32, Bridge Design

Although the bridge design codes are not directly related to the seismic design of NPPs, some interesting developments in performance based design can be found in ATC-32. The ATC-32 recommends the use of inelastic static analysis (pushover analysis) for all bridges. Also, the State of California Department of Transportation (Caltrans), the main user of the recommendations, intends to use both nonlinear static and dynamic analyses as a routine design procedure.

3. ONGOING ACTIVITIES FOR FUTURE BUILDING CODES

3.1 Vision 2000

The Vision 2000 Committee has been formed by SEAOC to outline the conceptual framework for the next generation seismic codes based on performance based engineering. The Committee's report (Ref.4) consists of the recommendations of performance criteria, overview of current (before 1995) building codes, and discussions on prospective performance based design approaches for future development.

A total of six performance based design approaches are discussed in the Vision 2000 report, as listed below in the decreasing order of sophistication:

- Comprehensive Design Approach
- Displacement Based Design Approach
- Energy Based Design Approach
- General Force/Strength Design Approach
- Simplified Force/Strength Design Approach
- Prescriptive Design Approach

3.2 2000 International Building Code (IBC)

As mentioned earlier a draft of 2000 IBC is being developed as the first "national" building code." The draft was not available for review during the initial phase of this study.

3.3 Recent Studies by Researchers

A displacement-based design method has been proposed by N. Priestley for R.C. structures with flexural failure modes (Refs. 5). The proposed method is based largely on the substitute structure approach developed by Gulkan and Sozen and Shibata and Sozen. According to Priestley, the traditional force-based design approach has the following disadvantages:

- does not directly address the inelastic nature of a structural system;
- requires the use of somewhat arbitrary force-reduction factors;
- provides little insight into actual structural behavior; and
- does not provide a consistent level of protection against reaching a specified limit state.

S.A. Freeman originally developed the capacity spectrum method as a rapid evaluation method for the U.S. Navy. Subsequently, it has been incorporated in the TriService Seismic Design Guidelines (Ref. 6).

UC at Berkeley (Ref. 7) and the Univ. of Illinois (Ref. 8) are performing studies based on similar concepts which employ a nonlinear displacement spectrum method. As the starting point, both studies cited an earlier study by Shimazaki and Sozen.

To characterize the high drift demands due to velocity pulses from a near-source earthquake, the drift demand spectrum has been developed by W.D. Iwan (Ref. 9). Simple uniform shear beam models, defined either by the fundamental period, T, or the height of the model, are used as the structural model, and the maximum shear stress is calculated through a time history analysis to represent the drift demand of the ground motion.

A reliability based and displacement based design methodology has been proposed by W.K. Wen, et al (Ref. 10) to directly account for the uncertainties in the seismic hazard, soil effects, and structural analysis.

4. TECHNICAL ISSUES FOR FURTHER CONSIDERATION

There are a number of technical issues that need to be addressed before displacement based seismic design methods could be fully introduced into the seismic design criteria for NPPs. These are discussed further below.

4.1 Is Nonlinear Analysis Warranted for Seismic Design of NPPs?

The implementation of a displacement based design would require consideration of some type of nonlinear response analysis. The reasons for “no” to the above question may be:

- The current criteria for seismic design of Category I SSCs are considered to be significantly more conservative than conventional building codes because the strength reduction factor, R-factor, is not used. The SSCs designed under such conservative criteria are not expected to develop a significant nonlinearity during a design earthquake event.
- The design of some components, such as pressure vessels, piping and containments, may not be controlled by seismic loads. A high overstrength factor is expected for such components.

The possible reasons for “yes” may be:

- There seems to exist a large discrepancy in seismic margins between rigid brittle components and flexible ductile components. To make the design criteria more risk-consistent, some type of nonlinear analysis should be allowed for flexible ductile components.
- In the US, a large number of old NPPs exist which were designed mostly in the 1960's and 1970's. Problems associated with age-related degradation have also been reported. Nonlinear analyses and displacement based criteria may be used for re-evaluation of the seismic margins for such plants.

Resolution of this question may be possible through: 1) evaluation of overstrength factors for typical structures and components based on previous studies on seismic margins, and 2) comparison of seismic margins between linear analysis/force-based and nonlinear analysis/displacement-based methods for components.

4.2 Technical Bases for Displacement /Drift Limit Values

Statistical studies on the displacement capacities have been performed in the past for reinforced concrete components and steel structures. The deformation limits in the 1997 NEHRP Guidelines are considered to be the most comprehensive so far. For the design of NPPs, additional considerations are required for safe shutdown and maintaining hot/cold shutdown states. Studies to illuminate this issue should include:

- Tabulation and comparison of various recommended displacements limits.
- Statistical analysis of existing test data.
- Development of displacement/drift limits related to safe shutdown and maintaining hot/cold shutdown states.

4.3 Approximation of Nonlinear Responses

In the implementation of the displacement-based criteria to either new plant design or seismic margin evaluation, an approximation of nonlinear responses may be required except when the direct nonlinear time history analysis is used. The approximate equations included in some of the methods discussed above are not considered to be accurate in the high frequency range. Furthermore, most of the existing approximate equations are based on responses of ground motions with a broad-banded spectrum. Topics in this area include,

- Review/refinement of existing equations for building analysis, particularly in the high frequency range.
- Additional considerations for narrow-banded floor motions.

4.4 Structural Analysis Methods

It appears that pushover analysis is becoming an increasingly popular analysis tool for displacement based design. This analysis method, however, is not applicable to genuinely 3-D structures such as nuclear piping. Some issues that need to be resolved in this area include:

- Is pushover analysis recommended for the design of NPP's structures/components? If so, for what types of structures/components?
- Can some type of combination rule (for different loading directions, X, Y and Z) be used to apply to nonlinear 3-D structures such as nuclear piping?

4.5 Application to Fragility Analysis

In the past fragility analysis of NPPs (including IPEEE), very conservative failure criteria were used for certain classes of components due partly to the lack of available test data. As the overall volume of seismic test data is increasing, more realistic displacement based criteria may be applied to various components, which have been analyzed using highly conservative criteria. The issues related to this area include:

- What types of components are best suited for the consideration of displacement based criteria?
- Are enough test data available to confidently apply the displacement based criteria?
- What is the significance of the application of the displacement criteria in terms of the calculated fragility values?

5. CONCLUSIONS

Efforts are continuing to study the applicability of displacement based seismic design methods to nuclear power plant structures, systems and components. The technical bases will be developed for any proposed changes in NRC seismic design guidance necessary to conform to changes in design practice being undertaken by the earthquake engineering community. The bases for any recommendations to continue with current practice will also be developed.

ACKNOWLEDGEMENT

This paper was based on a detailed study performed by Dr. Young J. Park who died suddenly during the course of this project. Dr. Park was an exceptional engineer who had keen insights and enormous capabilities in the areas of nonlinear dynamic analysis and seismic probabilistic risk assessment. He will be sorely missed by his colleagues and the entire earthquake engineering community.

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