RESEARCH NEEDS IDENTIFIED
DURING PREPARATION OF THE 2003 EDITION OF THE
NEHRP RECOMMENDED PROVISIONS FOR SEISMIC REGULATIONS FOR NEW BUILDINGS AND OTHER STRUCTURES (FEMA 450)

Introduction

As part of its efforts to regularly update the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*, the Building Seismic Safety Council (BSSC) is charged by the Federal Emergency Management Agency (FEMA) to identify research needed to advance the state of the art of earthquake-resistant design and serve as the basis for future refinement of the *Provisions*. During the project to generate the 2003 edition of the *Provisions*, the various working groups identified specific needed research that is beyond the scope of the *Provisions* update effort as well as particular topics for investigation that most likely will be addressed during the next update using existing data. The basic research needs are listed first below followed by specific topics proposed for investigation during preparation of the 2008 *Provisions*. Additional information can be obtained by writing Claret Heider at cheider@nibs.org.

Basic Research Needs

1. Needed are rational procedures for establishing elastic design coefficients. In this context, see the appendix to this document for a proposal calling for the review and clarification of system response parameters. This proposal was developed in 2000 and, while work on some aspects of the proposal has been initiated, underlying research justification is still needed..

2. A comprehensive review should be made of experimental (e.g., centrifuge) and analytical studies conducted by the Pacific Engineering Research Center (PEER) and others to provide a better understanding of foundation behavior under dynamic, cyclic seismic loads. The effects of combined vertical, lateral, and moment loading on bearing capacity, stiffness, and foundation transient and permanent displacements need to be better understood to permit the evaluation of criteria for parameters such as ultimate bearing capacity and phi-factors for ultimate strength design (USD) and of criteria for modeling foundation stiffness for dynamic analyses.

3. Research is needed to develop a basic approach for establishing gross overturning stability capacity for earthquake motions for vertical cantilever type structures that are supported by a single footing considering both vertical and horizontal motions.

4. Research is needed on the optimal moment curvature and corresponding detailing for moment frame structural system column to footing connections. This research question is for all materials. Structural engineers typically try to fix this connection by embedding columns into footings. This may not be the optimal design solution. A better solution may be to have the column footing connection have the same type of moment curvature relation as a beam column connection (including any weakening effects provided by dog-bones, etc)and not have hinging occurring in the columns.

5. Research is needed to serve as the basis for improved design requirements for anchorage to concrete with special emphasis on requirements for supplementary reinforcement and large diameter anchors. In addition, research is needed on the seismic capacity (tension and shear) of large anchor bolts commonly used in nonbuilding structures (in industrial facilities such as refineries and power plants) with diameters larger than 2 inches and embedments greater than 24 inches. Seismic capacity should include the presence of reinforcing steel commonly found in such construction. Such bolts are currently prohibited from use by ACI-318 because of lack to testing even though they are commonly used.

6. Research is needed on the seismic performance of tilt-up wall type structures for commonly used configurations commonly designed for current *Provisions* and ACI 318 seismic design loads and detailing.

7. Further analytical and experimental study of the maximum amount of reinforcing steel permitted in masonry shear walls (i.e., $\rho_{\max}$) is needed. This includes a study of the effect of vertical compressive force on the inelastic deformation capacity of reinforced masonry wall, which could lead to additional studies to justify R and C_d values for various shear wall types and direct comparisons with identical reinforced concrete shear walls. Verification of the effect of boundary elements on the performance of shear walls and research to determine whether $\rho_{\max}$ is applicable to all shear walls regardless of aspect ratio are also of interest. Related subjects in need of investigation are the amount of joint reinforcement needed for ductility, the minimum amounts of joint reinforcing that can be relied upon as reinforcement, the appropriate bond and development lengths for joint reinforcing used as reinforcement, and the ability of joint reinforcement to hold cracked sections together.

8. Anchorage to masonry, like anchorage to concrete, is a subject requiring research. Included should be an assessment of the capacity of masonry anchors mechanically attached to joint reinforcement.

9. Research to document the benefits of shear keys and, if determined to be beneficial, examination of the most efficient lengths, depths, and spacing.

10. Study is needed to determine how the seismic load due to the weight of veneer is resisted in low-rise buildings where the weight of the veneer is supported directly by the foundation.

11. Studies that have been conducted to determine the seismic performance of staggered truss systems, which are widely used in areas of lower seismicity for high-rise residential and hotel-type buildings, should be assessed.

12. The use of 65 ksi steels in seismic applications should be studied. The seismic applications and seismic requirements for steel that might not be valid with 65 ksi steel (e.g., slenderness limits, local buckling parameters, flange bracing) should be identified.

13. Research is needed to provide for the efficient design of gusset plates for braced frame systems (special concentrically braced frames, ordinary concentrically braced frames, eccentrically braced frames, and buckling restrained braced frame). Many special concentrically braced frame designs result in very large, unwieldy gusset plates. Recent laboratory research tests on buckling restrained braced frame subassemblages had a final failure mode in the connection plates, albeit at very large displacements after numerous cycles.

14. Research is needed on the seismic capacity of steel ordinary concentrically braced frames, steel ordinary moment frames, and the base plate and anchor bolt connection for the variety of configurations commonly used in buildings and nonbuilding structures designed to reflect the *Provisions* and AISI 341 seismic design loads and detailing.

15. Research is needed on the design of composite metal deck concrete diaphragms supported by steel framing with vertical offsets and openings.

16. Research efforts to address engineered design of bracing materials used for conventional construction (e.g., gypsum wallboard and fiberboard) should be continued.

17. Research is needed on the seismic capacities (accelerations and relative displacement) for most common nonstructural components currently found in buildings which are designed for the current *NEHRP Recommended Provisions* seismic design loads and detailing. This is a major effort because the very wide variety of nonstructural components and the lack of research in this area. Damage to nonstructural components accounts for well over half the damage and downtime to buildings caused by recent earthquakes in the United States. This is particularly relevant given the importance of quantifying the behavior of nonstructural components in performance-based seismic design.

18. Improved procedures are needed for determining the demands on nonstructural components considering in-structure motions, component dynamic amplifications and component inelastic deformations.

19. Mixed structural systems should be investigated to determine the interaction of materials and form. Structural systems with dissimilar materials are typically simplified to account for the stronger material response and the weaker and often more brittle materials are ignored to allow calculations to be completed in a simple form. However, the stiff weak materials often dictate the displacement patterns and concentrated demands on the designated structural system resulting in premature failures. Also, if two structural forms are placed in the same line of action, the current methods dictate that the system with the lower *R* factor controls and the entire system is designed accordingly. However, the combined system should actually perform more as a composite system and improved understanding of this issue would improve the design methods for additions and mixed systems.

20. Although for several cycles, the *NEHRP Recommended Provisions* requires that the seismic performance of Designated Seismic Systems be certified by the manufacturer, fulfilling this requirement is very problematic. The principal problem is that everything in an essential building is deemed to be a Designated Seismic System since it has an $I_p = 1.5$. Therefore, everything requires seismic qualification but this is not the intent. Designated Seismic Systems should have some special attributes that make their superior performance necessary to meet the performance goal of the structure. Needed is a comprehensive approach that will allow a designer, owner, or building official to determine which nonstructural components are actually required to function to meet the performance objectives of the Seismic Use Group. This might entail development of fault trees for typical nonstructural systems, and fragility analysis of common nonstructural components. Only those components that are truly essential and cannot be shown to be sufficiently “robust” should have to have special seismic qualification testing.

21. In the 2005 edition of ASCE 7, the tables for nonstructural systems and equipment have undergone substantial revision. Components are now grouped and classified in a more consistent and rational manner. However, with minor exceptions, the actual design values for the coefficients were not updated. A similar revision of the table for architectural components and systems should be undertaken. Assuming that the revised table is incorporated into the next edition of the *Provisions*, the design coefficients should reviewed and modified, to more closely reflect the expected behavior of the different components. Consideration should be given to developing design coefficients based on the nature of the component or system. For example, exterior nonstructural wall elements and connections all have same design coefficients, whether they are precast concrete, stucco on metal studs, or an aluminum curtain wall system. Each of these systems performs differently, and has different seismic response characteristics.

22. Data are needed on the behavior of long encased composite columns under cyclic loads, particularly when high-strength steel or concrete are used. Moreover, data on the importance of the detailing of the transverse reinforcement on the performance of these columns are lacking.

23. For concrete-filled steel tube beam-columns, more accurate axial, flexural, and interaction formulas are needed, particularly with emphasis on the use of high strength concrete and high performance steel materials. Moreover, with respect to connections, more detailed design provisions are needed for both braced and unbraced frames to facilitate the design of such systems.

24. Research is needed to determine the influence of partial composite action on the performance of diaphragms – The current values for shear stud strengths have been found to be optimistic and the issue of connector ductility needs to be investigated for cases of low interaction such as occurs when the studs are only used to transfer the diaphragm shears to the lateral load-resisting system.

25. Needed is a literature search that will identify and summarize the extent and type of damage (and lack of damage) to nonbuilding structures with building-like systems in moderate and large earthquakes.

26. Impulsive and convective load distribution in elevated water tanks has become an important topic for the American Waterworks Association standard development committees. Needed is shake table testing and finite element modeling of different tank configurations and styles to correlate the distributions now being assumed with limited background work. A Housner distribution model currently is used and a conservative lower limit is set.

27. There is a need to study the *R* factor basis for tanks. The study should address cylindrical welded steel, bolted steel, reinforced concrete, prestressed concrete, rectangular concrete, and different base joints used in concrete tanks (fixed, hinged and free).

28. Needed are improved procedures for determining code level sloshing heights in large diameter storage tanks.

29. Needed are improved procedures for determining the correct code level design forces for connections for structures supported by other structures.

30. Needed are improved procedures for determining the determining the proper seismic design forces and detailing the anchorage of tall vertical vessels where the nonlinear behavior occurs primarily in the anchorage.

31. Needed is testing of palletized steel storage racks with typical contents for near field ground motions to determine the seismic safety of these structures and the adequacy of current content securing approaches.

Issues Identified for Attention during the 2008 *NEHRP Recommended Provisions* Update Cycle

1. The PUC subcommittee responsible for seismic design mapping expects to:

    a. Develop vertical design spectra for the maximum considered earthquake (MCE).

    b. Refine requirements concerning long-period ground motions as new research becomes available. It is possible that, with the help of the USGS, the long-period maps generated during the 2003 cycle can be improved.

    c. Assist the committee responsible for nonbuilding structures on the specification of long period motions for tank sloshing calculations.

2. The PUC subcommittee responsible for design and analysis expects to:

    a. Develop performance-based seismic design definitions and requirements. During the 2003 update cycle, an unsuccessful attempt was made to add "charging" language to specifically allow the use of performance-based seismic design methods in lieu of the prescriptive design methods outlined in the *Provisions*. Coordination with other interested committees is required to develop consistent set of performance definitions and design requirements.

    b. Significantly simplify the *R* factor table. Some modification and simplification was achieved during the 2003 cycle but there remain approximately 80 systems listed in this table. Of this number, there are many systems for which the listed design factors are very similar. In addition several systems' design factors appear inconsistent with those of similar systems. A significant change is warranted. It is envisioned the table could consist of between 8 and 12 entries and that these entries would be based anticipated level of ductility (ordinary, intermediate and special), rather than material type. Likewise, the need for the system to be dependent on Seismic Design Category and the need for height limits should be reviewed and re-verified. Finally, the *R*-factor basis should be verified (i.e., whether seismic designs be based on "life safety" or "collapse"). This determination would be based, at least in part, on the efforts undertaken as described in Item a above.

    c. Review and reverify the use of Seismic Design Categories. It is not entirely consistent that design requirements vary by Seismic Design Category to the degree currently specified in the *Provisions*.

    d. Review and reverify the use of the 2% in 50 years ground shaking as the MCE. In addition, the use and definition of the "deterministic plateau" needs reconsideration. There have been numerous comments that the level of seismic hazard being used in design, especially in the central and eastern United States, results in design values that are unreasonably high. The current definition of seismic hazard was developed in the mid-1990s by the Seismic Design Procedures Group (SDPG) and another SDPG-like effort is suggested.

    e. Review and clarify the orthogonal requirements. As currently written, the orthogonal provisions vary by Seismic Design Category and the actual requirements, in some instances, need clarification in order to be properly interpreted.

    f. Consolidate modeling rules that are currently located in various sections of the *Provisions*. Some requirements are associated with a specific analysis procedure while others are covered with deformation compatibility provisions. The resulting modeling rules are, in some instances, in conflict with each other, which should be corrected.

    g. Review and update the vertical acceleration requirements and the associated load combinations. The introduction of the vertical accelerations requirements was originally undertaken as part of the 1997 Uniform Building Code (UBC) update. The main purpose of the provisions was to keep consistency between the older load combinations for concrete with the new ASCE load combinations that were introduced into the UBC. Now that the vertical acceleration requirements are embedded in the *Provisions*, updated, technically-based coefficients should be developed that are consistent with the potential seismic hazard.

3. The PUC subcommittee responsible for foundations and geotechnical considerations expects to:

    a. Evaluate and refine the provisions introduced as appendix material in the 2003 *Provisions* for the geotechnical ultimate strength design (USD) of foundations for seismic loading as a proposed replacement for the allowable stress design (ASD) approach.

    b. Evaluate and refine the provisions introduced as appendix material in the 2003 *Provisions* for the nonlinear stiffness modeling of foundations, which is needed for realistic modeling of foundation-soil flexibility for the nonlinear time history dynamic analysis method and the nonlinear static analysis method (pushover analysis).

4. The PUC subcommittee responsible for concrete structure design expects to:

   a. Develop and validate design strategies that can ensure performance levels higher than the collapse prevention level that is focus of the current seismic provisions for concrete structures.

   b. Improve design requirements for tilt-up concrete structures.

   c. Improve design requirements for precast concrete diaphragms.

5. The PUC subcommittee responsible for masonry structure design expects to:

   a. Align allowable stress design provisions with strength design provisions using analytical and experimental verification to prevent unacceptable differences in results.

   b. Study the reinforcing detailing requirements for the different shear wall types as it pertains to each of the maximum reinforcement methods.

   c. Assess and rationalize the R, C_d and Ω_0 factors specified in ASCE 7 and send recommendations to the ASCE 7 Seismic Task Committee.

6. The PUC subcommittee responsible for steel structure design expects to:

   a. Improve the requirements for ordinary and intermediate moment frame applications to provide a set of more rational, technically based system limitations.

   b. Consider new AISI standards for cold formed steel design addressing both moment frame/braced frame applications and shear walls and diaphragms.

   c. Review the new Metal Building Manufacturers' Association (MBMA) *Seismic Design Manual* (guideline document, not an ANSI-standard).

   d. Review the codes used in Europe, New Zealand and Australia, Japan, Canada, etc., to determine whether they include structural system approaches that could be emulated in the United States.

   e. Working with other subcommittees, consider relaxation of the height and other limitations of lower ductility systems (e.g., ordinary concentrically braced frames) as the lateral force resisting system in base isolated buildings. Since these systems are designed to remain essentially elastic above the isolators, the height and other limitations imposed for fixed based structures should not be applied.

    f. Working with other subcommittees, assess how best to put forth quality assurance requirements. The *IBC* and *NFPA 5000* use different approaches to quality assurance and more specific requirements are to be included in the 2005 edition of AISC Seismic.

    g. Working with other subcommittees, column base design is an area that needs to be addressed. AISC Seismic attempts to bridge the gap in requirements between the foundation and the superstructure but more work needs to be done.

    h. Working with other subcommittees, foundations, including the interface with structural system elements, will be addressed. Subjects to consider include a reduction in *R* for foundation rocking, the overstrength factor (or not) for rebar and anchor bolt design at foundation/structure interface, and strength design of piles and uplift connectors.

7. The PUC subcommittee responsible for wood structure design expects to:

    a. Continue development of seismic design coefficients for commonly used wood braced frame systems considering whether the use of combined materials modifies structural behavior.

    b. Continue to evaluate the provisions addressing torsional irregularities by documenting the application of current provisions to an open front structure.

    c. Evaluate current provisions for diaphragm flexibility and horizontal distribution of forces for a variety of wood building configurations. Performance and behavior issues associated with different distribution assumptions should be documented. Guidance for distribution of forces can be modified or expanded as needed.

    d. Re-examination of the underlying basis for existing *Provisions* requirements for wood is needed especially where the *Provisions* requirements differ from those in design standards and building codes. The goal should be to eliminate discrepancies where they are unintended or no longer appropriate.

8. The PUC subcommittee responsible for mechanical and electrical systems and building equipment and architectural elements expects to review the revisions of the design coefficient tables for nonstructural systems and equipment made for the 2005 edition of ASCE 7. Components are now grouped and classified in a more consistent and rational manner; however, with minor exceptions, the actual design values for the coefficients were not updated. A similar revision of the table for architectural components and systems should be undertaken and, assuming that the revised table is incorporated into the next edition of the

Provisions, the design coefficients should reviewed and modified to more closely reflect the expected behavior of the different components. Consideration should be given for developing design coefficients based on the nature of the component or system. For example, exterior nonstructural wall elements and connections all have same design coefficients, whether they are precast concrete, stucco on metal studs, or an aluminum curtain wall system. Each of these systems performs differently, and has different seismic response characteristics.

9. The PUC subcommittee responsible for low-rise and residential structure design expects to develop guidance on how to determine the appropriate R, C_d and Ω_0 factors to address the cantilevered column issues for manufactured metal buildings. This effort reflects a commitment made to the International Code Council.

10. The PUC subcommittee responsible for base isolation and energy dissipation systems expects to:

    a. Develop a comprehensive commentary for structures with damping systems.

    b. Consider changes to reflect the state-of-the-art and the state-of-practice in damping system and base isolation technology (e.g., changes in the prototype testing specifications of seismic isolators).

    c. Introduce provisions and commentary for new technologies such as hybrid, active, and semi-active systems.

11. The PUC subcommittee responsible for nonbuilding structures expects to consider requirements for LNG piers and wharves at import terminals, which are not currently addressed well by NFPA 59A and pose a risk that needs to be studied and a standardized approach developed. Experience suggests that the design approach for these structures is project (and engineering firm) specific and highly variable. To date, there is no definitive set of engineering and maintenance standards for liquefied natural gas (LNG) marine terminals. A Proposal by California State Lands Commission was approved to begin developing these standards, and the project is scheduled to begin July 1, 2004. The goal of these new standards will be to prevent LNG spills by reducing the amount of damage to LNG port facilities resulting from earthquakes, mooring/berthing incidents or other possible environmental or man-made hazards. Much of the performance-based design and analysis will be similar to that used for the Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS). The Commission intends to spend up to $300,000 over a two-year period toward the task of developing standards for the newly proposed liquefied natural gas marine terminals in the state of California. The Commission does not have sufficient expertise and background in LNG marine terminals within its own staff to perform this work

and the PUC subcommittee recommends consideration of finding a mechanism for supporting this work on a broader basis.

APPENDIX

Proposal to Review and Clarify System Response Parameters

BSSC System Response Project Planning Group:
G. Deierlein, R. Hamburger, J. Harris, W. Holmes (chair), J. Hooper, C. M. Uang
March 13, 2000

Project Objective

The primary objective of this project is to develop a procedure that can establish consistent and rational design response parameters (R, C_d, Ω_0) for the linear design methods traditionally used in building codes. This procedure is intended to be used by code writers to set minimum acceptable design criteria for standard code-approved systems and to provide guidance in the selection of appropriate design criteria for other systems when linear design methods are applied.

A secondary objective of this project is to provide a basis for evaluating the current tabulation of and limitations on code-approved structural systems for adequacy to achieve the inherent design performance objectives, and where appropriate, to modify or eliminate those systems or requirements which can not reliably meet or do not relate to these objectives.

Background

The linear design procedure contained in modern building codes has evolved over nearly a century, based on three primary principles: historic precedent, observation of the performance of real structures in actual earthquakes, and engineering understanding of the basic principles of structural mechanics. The basic idea of the linear design procedure is to convert the complicated non-linear dynamic behavior of a building structure under seismic excitation to an equivalent linear problem. When combined with certain capacity design concepts, the procedure is well suited for seismic design of new buildings. Capacity design refers to the technique of designing elements for the largest force that can be delivered from connecting elements, thus decoupling the design of many members from the detail of the ground motion demand; designated element or systems are designed for inelastic response and to act as fuses. Capacity design can be applied to a single element or the structure as a whole. Codes have incorporated limited capacity design techniques for years, most notably the provisions for ductile concrete.

For the last half-century, the design process has started with the selection of a basic seismic force resisting system for the structure. The code specifies a series of prescriptive requirements for structures conforming to each such system. These prescriptive requirements regulate configuration, size, materials of construction and detailing, as well as minimum required strength and stiffness. Strength and stiffness requirements are controlled through the assignment of a series of system response coefficients (R, C_d, Ω_0). Based on the linear dynamic response characteristics of the structure (period, mode shape, mass distribution) and these response coefficients, a pattern of design lateral forces are applied to a model of the structure. These are distributed to the various structural elements using linear analysis techniques and the resulting member forces and structural deflections are calculated. Members are required to be proportioned to have adequate strength to resist the calculated forces in combination with other prescribed loads and also to ensure that calculated displacements do not exceed maximum specified values.

Commentary to the code provisions indicate that structures designed in accordance with these provisions should be capable of resisting maximum considered earthquake ground motions, having a low probability of occurrence, without collapse and relatively frequent and more probable ground motions without damage. Although these design performance objectives have only recently been formalized in the commentary, they have served as the informal intent of the provisions throughout much of the development history.

Early code design provisions were formulated before engineers had a good understanding either of the intensity and characteristics of ground motion, or the dynamic response characteristics of structures. It was noted, in observing earthquake induced effects, that damage appeared to result largely from a lateral (horizontal) shaking of the ground, which induced inertial forces in the structure. Lacking precise technical understanding of the physics of the problem, engineers adapted existing techniques for design to resist other lateral loads, principally wind, to the problem of earthquake resistant design. In the earliest editions of the *Uniform Building Code*, structures in seismically active regions, and situated on poor soils were specified to be designed for lateral forces equivalent to 10% of the supported weight of the structure, establishing a precedent which has been preserved in somewhat modified form to this day.

Even before linear design methods were developed, observations of performance led to rules for detailing; e.g., rules for "bond iron" in brick walls appeared following the Hayward earthquake of 1857. This process has continued throughout this century. Eventually these prescriptive requirements became quite detailed, addressing a multitude of construction characteristics ranging from permissible material specifications to the size and penetration of nails.

Engineers also observed that certain types of seismic force resisting systems, for example moment-resisting frames, or bearing walls, seemed as a class to have better or poorer ability to withstand earthquake shaking than others. As a result, coefficients were introduced into the code that either increased or decreased the required design lateral forces for structures, based on the type of system employed. Later, as understanding of structural dynamics improved, additional coefficients were introduced to directly account for the affect of structural period on response. By 1957, the code specified calculation of design forces, using a base shear equation that accounted for seismicity (seismic zone), structural period, structural system and the supported mass, the same basic factors included in current code procedures. A total of four structural systems were defined — box systems, in which load bearing walls provided both gravity and lateral force resistance; frame systems in which separate elements were provided for gravity and lateral resistance, respectively; moment-resisting frame systems; and dual systems, in which lateral resistance was provided by a combination of moment-resisting frames and walls and/or braced frames.

By the late 1960s, two facts became well understood within the community of researchers and advanced practitioners: 1) structures designed to resist the lateral forces specified by the building code would experience significant inelastic response and 2) the ability of structures to do so was dependent on the structural detailing. The San Fernando earthquake of 1971 brought home some of the deficiencies in this regard in codes of that era. One of the results of improvements to seismic design provisions during this period was an expansion of the collection of the code-approved seismic force resisting systems, with many individual systems classified by the type of detailing used. For each increment in detailing, which results in different but often unquantified levels of inelastic response capability, response coefficients were assigned in the code, based largely on judgment and qualitative comparison with the known response capabilities of other systems. The result is that today's code includes more than 70 individual structural systems, each with individual system response coefficients somewhat arbitrarily assigned. Many of these recently defined structural systems have never been subjected to any significant level of earthquake ground shaking and the potential response characteristics and ability to meet the design performance objectives is both untested and unknown.

Although the R-factor design procedure had its start in an empirical manner, its potential for continuing to be a useful design method in the future lies in several advances in the 1990's. First, the structural response parameters have been formulated and the *R*-factor procedure has been theorized, helping to clarify and categorize the empirical components of the design procedure. Second, computer simulations of non-linear dynamic response, which can permit more rational calibration of linear procedures, have achieved a level that gains the confidence of design engineers. And finally, a significant amount of experimental data on cyclic response of structural components is available. These advances provide an opportunity to re-examine and to rationalize an improved linear seismic design procedure, where the seismic response parameters are determined more scientifically.

Shortcomings

While code development efforts have made progress in rationalizing the R-factor design method, many of the associated refinements have been blamed as over-complicating the design process while offering few real improvements in the reliability and performance of buildings. For example, recent code updates have expanded the table of seismic response factors (R and C_d) in the 1997 *NEHRP Recommended Provisions* and 2000 *IBC* to include over 69 structural system types, each with their own seismic response factors, design criteria, and usage limitations. Such refinement has been questioned on both technical and philosophical grounds. From the technical standpoint, there is insufficient data to substantiate this level of refinement, and from the philosophical standpoint, the perceived accuracy and complexity of the design procedures can lead one to lose sight of important issues fundamental to design.

In developing a plan to re-examine linear design procedures, it is instructive to consider a few of the inconsistencies and concerns (aside from those already noted) of the R-factor criteria in the 1997 *NEHRP Recommended Provisions* and the 2000 *IBC*:

- In spite of the large number of structural system definitions, the current designations fail to distinguish between significant behavioral affects of the controlling design mechanisms. For example, the designations make no distinction within a given system type to account the extent to which strength versus stiffness (i.e., drift) controls the design, e.g., the system designations make no allowance for differences in building height, floor plan dimensions, and other attributes of the structure that affect the balance of strength versus drift. Or, another example is that the shear wall system designations do not differentiate between walls that are controlled by flexural versus shear failure mechanisms.

- The usage limitations that prohibit certain systems from regions of higher seismicity suggest that there are inconsistencies in the extent to which the seismic response values (R and C_d) are truly “system dependent” properties that consistently limit inelastic deformation demands to levels that the structural details can resist. Ideally, if the system response parameters and detailing provided consistent performance, then usage limitations would be unnecessary. At present, there is an inconsistency between the reliability of well-detailed ductile systems (permitted in all seismic design categories) and other systems with limited ductility.

- Related to the above concerns, there should be more consistency between the seismic response parameters and the extent to which the material-dependent design requirements enforce capacity design concepts. In some cases capacity design requirements are applied in a fairly rigorous and transparent manner (e.g., eccentrically braced steel frames) whereas in many other systems they are not.

- The 1997 *NEHRP Recommended Provisions* implemented new seismic hazard maps that defined a “maximum considered earthquake” with seismic intensity measures that are roughly 1.5 times larger than the design level earthquake forces. This gave more explicit recognition that while structures are proportioned based on the design level earthquake, the intent is to prevent collapse under the “maximum considered earthquake”. However, while the 1997 maps introduced these concepts, it has yet to be verified whether or not the current seismic response parameters and design requirements achieve the desired objectives.

- A relationship has not be established between a given R-factor (or R x I combination) and performance. If a major readjustment to all or most R-factors is contemplated, the performance objective of the “nominal” code should be better defined.

Approach

In order to accomplish the stated objectives, it is proposed to establish a standard procedural methodology by which the inelastic response characteristics and performance of typical structures designed to a set of structural system provisions can be quantified and the adequacy of the structural system provisions to meet the design performance objectives verified. The methodology must directly account for the potential variations in structure configuration of structures designed to a set of provisions, the variation in ground motion to which these structures may be subjected and available laboratory data on the behavioral characteristics of structural elements.

While the methodology should be grounded upon the nonlinear dynamic response of structures, additional issues that are reflected in current provisions must be addressed such as: (a) interaction of vertical and lateral load system, e.g., bearing wall versus frame system, (b) redundancy and reliability, e.g., single versus dual systems, (c) usage limitations dictated by occupancy or seismicity, and (d) effects of designing for the Maximum Considered Earthquake ground motion (MCE) versus the Design Basis Earthquake ground motion (DBE).

A three phased approach for the project is suggested. These phases are as follows:

Phase I — Methodology Development and Verification. The principal objective of this is development of the procedural methodology. There are several general criteria for the study methodology. The methods should:

- be transferable to related building systems
- be useable by other parties doing similar work in the future
- be repeatable
- cover the range of feasible configurations for a given system.

In addition, in order to assure that the methodology can be applied to the various structural systems, is practical to implement, and provides reasonable and supportable information on the behavior of the various structural systems, a small number of benchmark structural systems will be evaluated using the methodology. The work should also take advantage of the ongoing studies of steel frames with welded moment-resisting joints and of light wood frame construction.

In order to gain insight regarding all materials and on a variety of systems, the following four structural building types are recommended:

1. Light framed wood shear wall
2. Reinforced masonry bearing wall with concrete floors (box system)
3. Concrete shear wall with gravity frame
4. Steel moment frame

The following are issues and questions that should be addressed in developing system response factors for the various systems and refining linear design procedures:

- Establishment of desired performance levels – Explicit target performance levels (e.g., immediate occupancy, collapse prevention) should be established as underlying criteria for the design provisions. The performance levels can either be indexed to given seismic hazard levels (e.g., 10% in 50 year earthquake) or probabilities of exceeding certain limit states.

- Establishment of general requirements of evaluation methods – General principles and guidelines should be formalized to evaluate seismic performance and establish the seismic response factors. It is expected that these principles will reflect: (1) review of test and analysis data to determine acceptance criteria for structural component, (2) evaluation of inelastic deformation demands in prototypical structural designs using inelastic time history analyses, and (3) overall reliability and integrity of systems as determined through a combination of past performance and engineering judgment considering such issues as redundancy, interdependence of gravity and lateral load system, etc.

- Reconciliation of available technologies for seismic simulation – The proposed effort should, from the outset, make allowance for the extent to which available knowledge and technologies permit accurate simulation of seismic response for various structural systems. For example, through the SAC Joint Venture and other research efforts, extensive data and robust analytical technologies are available to simulate the nonlinear behavior of steel moment frames. On the other hand, for many systems – particularly those with minimal seismic detailing – techniques for accurately predicting their inelastic response are much less developed. Therefore, allowance needs to be made for determining seismic response factors for the wide range of available systems with a realistic expectation of the degree of sophistication in the analytical performance evaluation.

- Limitations on systems and design requirements – Current codes include a variety of limiting requirements that reflect the inherent limitations of the design requirements. Some of these take the form of usage limitations that restrict the application of certain systems (or the height of certain systems) in higher seismic design categories. Others are related to maximum strength and stiffness irregularities permitted in the systems, or penalties imposed on certain systems. Many of these limitations have been introduced into the code in a piecemeal fashion over many years to the extent that their net effect on the resulting design is not clear. Therefore, the proposed initiative provides a good opportunity to review all of these limiting requirements and, if appropriate, delete or recast them in different ways in the refined linear design procedures.

- Stiffness and Strength Criteria – While the immediate motivation for this initiative was to refine existing seismic response parameters (R, C_d, and Ω_o), in light of the broader considerations outlined above, the refinements should include a review of all major criteria that affect the resulting design. One such criterion is the limitation on inter-story drifts, which is known to control the design of most moment frame buildings and several other systems. It is ironic that while the assignment of R and C_d values has received significant debate, very little attention has been given to the imposed drift limits. Associated with this are the many aspects of design and analysis, apart from the ratio of C_d/R, that affect the calculation of drifts (e.g., modeling assumptions, approximation of effective stiffness properties, use of the calculated building period versus the upper bound period in determining applied forces for strength and drift checks, etc.). These and other issues should be reviewed and revised as appropriate in the proposed evaluation methodology and linear design procedures.

Phase II — Implementation. In the implementation phase, the methodology will be applied to a representative subset of the series of structural systems contained in the current code provisions, to verify the adequacy of current design procedures. The subset may consist of from 10 to 20 additional systems.

If the extent of this phase is limited by funding, selection of structural types should consider the following characteristics:

- Basic systems that may be needed to complete a thorough study of the overall set of code approved buildings, such as dual systems and rigid wall-flexible diaphragm buildings,

- Buildings and systems that are representative of construction expected in the future. There are not great statistics for distribution of costs by type of frame, but there are fair statistics for distribution by functional type,

- There should be a bias towards construction sensitive to seismic ground motions; this means heavy construction and probably mid-rise construction (to get periods in the range of the most significant amplification of ground motion).

Where it is determined that current procedures are inappropriate to meet the design performance objectives, modification to current code provisions will be recommended. It is anticipated that following conclusion of this phase, the methodology itself, together with the resulting recommendations for specific *structural systems* would be adopted into to an appendix of the *NEHRP Recommended Provisions*.

Phase III — General Use. This is not foreseen as a formal, funded phase. The methodology will be applied to the remaining systems that are of interest on an as-needed basis (and as funds are available), or to proposed new systems by their advocates.

Organization & Execution

Phase I

It is suggested that the Phase I project be implemented by a 5-person Project Engineering Panel (PEP). Tentatively, it is recommended that the PEP include persons with the following background and capabilities:

- Structural engineer familiar with advanced structural analysis and the characteristics of ground motion
- Structural engineer with broad experience in the design of a range of structures
- Researcher familiar with dynamic inelastic response characteristics of various structural systems
- Researcher familiar with the inelastic behavior of structural elements with various types of detailing
- Researcher familiar with methods of quantifying structural reliability

The members of the PEP should be compensated for their efforts. They should not be associated with any specific materials industry or be in the employ of any industry associations or interests. This should not be intended to indicate that researchers who have been occasionally funded by such interests would be exempt from participation.

It is recommended that the “generalist” structural engineer described above, or an additional structural engineer with similar capabilities and experience be named as the Project Director to call and chair meetings and otherwise lead the PEP. However, technical decisions should be made by the PEP as a whole.

To supplement the resources and capabilities of the PEP, it will be necessary to retain a limited number of consultants. The following consultants have tentatively been identified:

- *Ground motion consultant (1)* – To recommend a suite of suitable ground motion characterizations. The consultant shall be familiar with developing probabilistic ground motions for a variety of source zone and soil conditions.

- *Case History consultants (2 to 3)* – To perform the benchmark evaluations of the methodology on the trial structural systems. The consultant shall be familiar with the design of structures and capable of performing nonlinear dynamic analyses.

It is proposed that a Project Oversight Committee (POC) be appointed to review the work performed by project engineering panel, to provide advice and consultation and to serve as a liaison to the materials industries and code writers. The POC is tentatively planned to include representation of each of the 4 major materials industries (wood, steel, concrete, masonry) as well as perhaps 6 independent structural design experts knowledgeable about code issues in general, or concerning a particular material. It is anticipated that the materials representatives would be sponsored by their industries, but that the independent code experts will be compensated.

It is anticipated that Phase I project will have a duration of approximately 12 – 18 months. During this phase of the project, the PEP will meet approximately once per month. The POC will meet with the PEP approximately once every three months. In order to help build acceptance for the methodology within the code development community, two workshops are anticipated to be held as follows:

- Workshop 1 – Present project objectives, key decisions and proposed approach – to be held approximately 3 months after project inception.
- Workshop 2 – Present preliminary methodology – to be held approximately 9 months after project inception, prior to implementation of methodology on trial system types

In addition, preliminary results should be presented at conveniently timed structural or seismic conferences to encourage input from interested parties.

The level of effort to complete Phase I is summarized in Table I below.

Table I

Group/Event	Number of Participants	Number of Meetings	Other Time on Project[1]
Project Engineering Panel (PEP)	5	12	900 hrs ea
Specialty Consultants	5 tasks	6	500 hrs/task
Project Oversight Committee (POC)	10[2]	4	80 hrs ea
Workshop	50	3	--

Notes:

1 In addition to meetings; based on a 40-hour work week.

2 Of the ten participants, six will require funding.

Milestones Schedule: 18 months

Milestones	Month
Develop detailed work plan	1
Develop preliminary methodology	3
Workshop 1	4
RFP for consultants	7
Complete methodology, Workshop 2	8
Select consultants	9
Complete studies	14
Write up results	16
Contingency	18

Phase II

The Phase I PEP will be retained for Phase II of the project as well. In the Phase II project, the PEP will have the following responsibilities:

- Perform preliminary evaluation of the list of structural systems contained in the current code provisions and recommend a subset of these systems to be evaluated during the second phase. There may be a need to evaluate up to 30 systems in addition to those done in Phase I.
- Provide oversight for implementation of the methodology to the selected subset of structural systems.
- Develop a report to detail the methodology and how it can be implemented, as well as the recommendations for revised system design values.
- Select consultants to perform the application of the methodology to specific structural systems.

The POC will also be retained during the Phase II project. They will meet on a semi-annual basis to review the progress of the work and provide consultation.

Most of the actual application of the methodology to specific structural systems will be performed by consultants. Approximately five to ten consultant teams will be assigned two (or possibly three) systems each.

The level of effort to complete Phase II is summarized in Table II below.

Table II

Group	Number of Participants	Number of Meetings	Percent of Time on Project[1]
Project Engineering Panel (PEP)	5	12	800 hrs ea
Per structural system	20[3]	6	400 hrs ea
Project Oversight Committee (POC)	10[2]	4	80 hrs ea

Notes:

1 In addition to meetings; based on a 40-hour work week.
2 Of the ten participants, six will require funding.
3 20 shown here; up to 30 may be required.

Milestone Schedule

Milestone	*Month*
Develop detailed work plan	1
RFP for consultants	3
Refinement of code methods and system selection	6
Consultant selection	7
System calculation (4 mo per system)	19

Write report	21
Contingency	24

Phase III

The phase III project will be implemented over a series of years. Funding would be provided directly by the materials industries or other advocates of specific systems. If such systems are proposed for inclusion in the *Provisions R* factor table, the PUC would provide review of results of the procedure.