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U.S. BUILDING-CODE PROVISIONS FOR BUCKLING-RESTRAINED BRACED FRAMES: BASIS AND DEVELOPMENT

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SUMMARY

Buckling restrained braces have recently been introduced into U.S. engineering design practice. To facilitate the use of the system, the Structural Engineers Association of California has collaborated with the American Institute of Steel Construction in the development of a set of building-code provisions. The provisions are intended to achieve a reasonable balance between criteria relative to the requirements and expected performance of other systems and more objective performance goals. The paper provides some background on the evolution of buckling-restrained braces and the context for seismic code development in the United States, describes the process followed in the development of the provisions, gives an overview of the main requirements of the provisions, and summarizes the expected process for eventual formal adoption of the provisions as regulatory code requirements.

INTRODUCTION

It is well understood that braces are efficient structural elements for resisting lateral forces. They are generally regarded as less effective for seismic loads, however, because they are unable to dissipate energy or provide ductile behavior without buckling, which involves degradation of both strength and stiffness. In contrast to conventional braces, buckling-restrained braces are able to achieve stable, balanced hysteretic behavior and substantial ductility by accommodating compression yielding before the onset of buckling. Typical buckling-restrained braces consist of a central yielding steel member that carries the entire axial load of the brace, confined by a steel-only or a combined steel-and-concrete outer member, which provides the brace flexural, and hence buckling, resistance.

Interest in buckling-restrained braces has grown quickly in the U.S. over the last four years. This type of brace has been used extensively in Japan, where the first application was in the mid-1980s. There are now more than 200 buildings in Japan that incorporate buckling-restrained braces, of which more than half are taller than 15 stories.

The concept of enhancing the axial compression capacity of a column by external means to prevent buckling is not new and first appeared some 30 years ago. In Japan in the 1980s it was extended to tension-compression yielding brace elements specifically for seismic resistance, where more than six

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different concepts and configurations have evolved. Iwata [1] recently evaluated the cyclic behavior of four different types of buckling-restrained brace. The development of buckling-restrained braces has not been confined to Japan. In Canada research has led to at least one building application, as described by Tremblay [2], and in India, various experimental investigations have assessed their effectiveness for resisting seismic loads (Kalyanaraman [3]).

In Japan, buckling-restrained braces have been used primarily as energy dissipation elements in steel moment-resisting frame systems. A "damage tolerant" design philosophy described by Wada [4] has generally been followed for these applications. Such an approach aims to keep the primary gravity load-carrying structural frame elastic under seismic loads, and to confine the ductility and energy dissipation demands to the structural elements – such as buckling-restrained braces – that are best able to provide this type of behavior. In the U.S., damage tolerant design is embodied in a general sense in the overall concept of performance-based seismic design, but the approach has not been explicitly used for the design of any of the implementations of buckling-restrained braces to date. Rather, the application of buckling-restrained braces in the U.S. has been based on the recognition and utilization of the brace as a superior brace, specifically, a ductile brace element that does not buckle and which at the same time possesses energy-dissipation and deformation characteristics better than those of a conventional brace. Designs have been developed based on lateral-force-reduction-factor methods and equivalent static analysis, as permitted by existing code provisions for conventional braced-frame and moment-resisting frame systems.

The first U.S. applications utilized a type of brace called the "Unbonded Brace." This brace type consists of a yielding steel core plate confined by an outer steel tube with concrete infill. Other types of brace have recently been developed and have already seen application in several projects in California and Utah. The first building in the U.S. to use buckling-restrained braces was constructed in 2000, and by mid-2003 there were nearly 30 projects either completed or underway. Projects have included both retrofit and new construction; to date all of the retrofits have been concrete buildings.

Engineers in California quickly recognized the value of buckling-restrained braces as a system that could provide better performance than conventional concentrically braced frames, with design and construction costs less than those of other high performance systems (e.g., ductile moment frames, base isolation, and supplementary damping). However, the system's uncodified status has required that special procedures, such as peer review or more extensive design analyses, be undertaken to give building officials assurance of satisfactory seismic safety. In many cases such requirements make the system unattractive for typical projects; under these circumstances the potential benefits of the system to the public are not being realized.

The Structural Engineers Association of Northern California (SEAONC) undertook to change this situation. SEAONC's Seismology Committee charged its subcommittee on steel structures with developing a set of design provisions for buckling-restrained braced frames. Their work, with the participation of other organizations, has subsequently resulted in the *Recommended Provisions for Buckling-Restrained Braced Frames* (hereafter referred to as the *Recommended Provisions*) [5].

FUNDAMENTAL ISSUES FOR PROVISIONS

Type of Structural System

The Recommended Provisions assume that buckling-restrained braced frames constitute the entire seismic-force-resisting system of a building, and thus that the braces are not being used as energy dissipation devices that are supplemental to some other primary seismic-force-resisting system. This second design approach is already defined in the energy dissipation system design provisions of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*

(BSSC [6]). All of the early U.S. projects considered buckling-restrained braced frames as conventional braced frame systems, but with improved seismic resistance characteristics. The need for provisions that recognized this design philosophy was an important motivating factor in the development of the *Recommended Provisions*.

Performance Expectations

Conventionally, U.S. building codes have addressed the design of new structures to provide life-safety performance for a seismic hazard with a 10% probability of exceedance in a fifty-year period, the "design basis earthquake" (SEAOC [7]). Design of structures for this hazard has been considered to imply operational performance for lower hazard levels and collapse prevention for higher ones. However, no specific hazard levels were matched to those performance levels, and it was recognized that the hazard levels corresponding to these levels of performance may vary significantly between different types of structural systems. Even the life-safety performance goal was not rigorously addressed, as requirements are generally based on judgment and observation of damage in previous earthquakes (Hamburger [8]).

In order to create a more explicit relationship between seismic design and performance, SEAOC established definitions of performance levels in its *Vision 2000* document (SEAOC [9]). These definitions were used in *FEMA 273: NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (BSSC [10]), which provides for design to "safety objectives." Each safety objective includes multiple hazards and corresponding performance levels. FEMA 273 is intended for use in the seismic retrofit of buildings; to date, multiple hazard levels with corresponding performance goals still have not been included in design codes for new structures, although FEMA-368 contains the beginnings of a multiple-hazard-level approach.

For the purposes of establishing design provisions for the buckling-restrained braced frame system, the performance objective was of fundamental importance. While it was assumed that the typical building code-procedures for determining design forces and force distributions would be used, other issues of performance-based design remained. Given the inherent ductility and stiffness of buckling-restrained braces, high levels of inelastic behavior at low levels of seismic excitation might be expected for buckling-restrained braced frames designed to lower forces than those used for conventional braced frames. At the other extreme, buckling-restrained braces might not have sufficient ductility capacity for the demands at the most severe levels of excitation if their design is based solely on the design-basis earthquake.

Performance at higher hazard levels was considered in the context of the expected performance of other systems. While design standards for steel moment resisting frames have been recently revised to provide for reliable performance during very rare earthquakes, the reliability of concentrically braced frame structures is markedly lower, as shown by Uriz [11].

System Design Factors

One fundamental task in developing building code provisions for buckling restrained braced frames was the determination of factors and coefficients required for the overall structural system design. Design procedures in building codes in the U.S. are based on equivalent (static) lateral force methods. The equivalent lateral force is used to determine the required force capacity of the elements that comprise the primary seismic-load-resisting system as well as the expected building drift. This equivalent lateral force is determined by reducing the force established from a response spectrum by a Response Modification Coefficient (R); this factor is intended to represent the effects of hysteretic damping, ductility, and overstrength (ATC [12]). The required strength of members expected to have no significant ductility demand is determined by multiplying the forces from the equivalent lateral force analysis by an Overstrength Factor (Ω_o). Expected building drifts are determined by multiplying the drifts from the equivalent lateral force analysis by a Displacement Amplification Factor (C_d) (BSSC [6]; ASCE [13]; ICC [14]).

Two conflicting objectives existed in the determination of appropriate values for these three system design factors. First, the values should be objectively correct. A buckling restrained braced frame building designed using the suggested value of R should perform consistently with the stated intention of building codes: to provide for life safety in the design basis earthquake. Columns, beams, and connections, elements designed with amplified force determined using the W factor should not buckle or fail during an earthquake. The drifts determined using the factor C_d should accurately reflect the maximum drifts experienced by the structure.

Second, the factors R, Ω_o and C_d should be relatively correct, defining the system according to its ductility and performance in a manner consistent with the factors already established for other structural systems, such as conventional braced frames, eccentrically braced frames, and moment-resisting frames. As the factors for these other systems were arrived at in a gradual process involving observation of damage and judgment of the code writers, rather than a systematic reliability-based or performance-based approach, questions remain as to whether certain systems, such as conventional braced frames, can actually provide the required performance level with sufficient reliability. Therefore, calibrating requirements for buckling-restrained braced frames to those of conventional braced frames could fail to assure acceptable performance, while imposing stricter requirements could create unfortunate and unintended incentives for designers to choose the system with worse performance.

CONTEXT FOR PROVISIONS

Issues Regarding Welded Steel Moment-Resisting Frames

The January 17, 1994 Northridge earthquake in Los Angeles had a tremendous effect on the scrutiny to which steel systems are held. Fractures that occurred in beam-column connections of moment-resisting frames raised questions concerning previous assumptions of the reliability of welded steel moment resisting frames. Engineers also reconsidered their practice of relying upon a small number of tests, often of reduced-scale specimens, to demonstrate the performance of a system or assemblage. In the wake of these developments, the design of welded steel moment-resisting frames for a time tended to require project-specific testing to demonstrate the adequacy of the proposed connection details.

The United States Federal Emergency Management Agency (FEMA) funded a five-year project to develop methods of designing reliable new welded steel moment-resisting frame structures as well as for evaluating and repairing existing ones. This project was overseen by the SAC Joint Venture, which comprised three organizations: the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and California Universities for Research in Earthquake Engineering (CUREe).

The SAC Joint Venture analyzed designs of typical steel moment-resisting frame structures and established expected rotational demands on the beam-column connections corresponding to three different hazard levels: 50%, 10% and 2% probabilities of exceedance in a fifty-year period. In conjunction with this, SAC coordinated the testing of a large number of different connection types. The test results were eventually used to establish ranges of steel member sizes within which a specific connection detail could be considered to be “prequalified” for certain rotational demands determined through reliability analyses (BSSC [15]); connections could only be considered prequalified if they maintained a certain level of resistance at deformations corresponding to a very rare earthquake (2% probability of exceedance in a fifty-year period). These prequalifications are thus tied, albeit indirectly, to expected performance at multiple hazard levels.

These prequalifications naturally had an effect on project-specific testing. As the prequalification recommendations gained acceptance, project-specific testing returned to being the exception rather than the rule. Nevertheless, engineers have remained keenly aware of the importance of successful large-scale testing to validate their designs.

Requirements for Protective Systems

The broader context in which buckling-restrained braced frame design provisions were to be developed also involved consideration of existing requirements and guidelines for the testing of seismic isolation and damping devices. These requirements are defined for seismic isolation devices in several code documents (ICBO [16]; ICC), and for energy dissipation devices in recommended provisions (BSSC [6]). In these cases, testing is required to demonstrate acceptable device behavior under design-level force and deformation demands. It is further required that tests also confirm that the device is capable of accommodating the deformations corresponding to a more severe earthquake without instability or failure.

Changing Code Regime

The development of the *Recommended Provisions* comes at a time when the U.S. is moving from a system of regional model codes to a single national code. Under the old system, the seismic requirements of the regional model code used in California, the Uniform Building Code (ICBO), were based on the recommendations of the Seismology Committee of the Structural Engineers Association of California (SEAOC) in its *Recommended Lateral Force Requirements* (e.g., SEAOC [7]).

Currently, there are two competing national model codes (the *International Building Code* [ICC], and the *NFPA 5000* [17]), although their structural provisions do not differ substantially and will differ less and less as more of their content is adopted from the same set of consensus-based national standards (Bonneville [18]). Both model codes require that steel structures comply with the American Institute of Steel Construction's (AISC) *Seismic Provisions for Structural Steel Buildings* (AISC [19]). These provisions are researched, written, and adopted through a carefully defined consensus process. Changes or additions to the requirements for steel structures are discussed in various organizations, including SEAOC, but they must ultimately be coordinated with AISC, which remains the single point of responsibility (Malley [20]).

EVOLUTION OF PROVISIONS

Participating Organizations

The development of the *Recommended Provisions* was begun by the SEAONC steel subcommittee. Such regional subcommittees work in concert with the state (SEAOC) seismology committee. For the *Recommended Provisions* to become part of the building code they must be incorporated into the AISC *Seismic Provisions*. It was therefore beneficial to involve the AISC Task Committee on the *Seismic Provisions* in the development of the *Recommended Provisions* at an early stage of the process. SEAOC and AISC formed a joint task group to oversee the development of the provisions and to direct the SEAONC steel subcommittee in its execution. The structure of this process of code development may serve as a model for future efforts.

Technical Basis

In order to gain a better understanding of the behavior of buckling-restrained braced frames, a series of nonlinear time-history analyses was conducted. These were performed using ground motions developed as part of the SAC steel project. Typical structures of three and of six stories were designed using Response

Modification Coefficients of 6 and 8 and were subjected to suites of earthquake ground motions representing different hazard levels (Sabelli [21]). These studies were used to gauge the sensitivity of the system to these parameters, and to help determine appropriate values of system design factors for the *Recommended Provisions*. They also established expected maximum and cumulative brace ductility demands for the design basis earthquake (Sabelli [22]). These dynamic analyses were supplemented by static studies which helped identify the basic post-elastic modes of behavior of buckling-restrained braced frames.

In parallel with the study of buckling-restrained braced frames, a series of analyses were conducted on conventional braced frames designed with the ductility requirements for Special Concentrically Braced Frames in the AISC *Seismic Provisions*. These studies, which incorporated brace fracture criteria, indicated that the performance to be expected of conventional braced frames is below that expected of other systems (Sabelli [22]).

Existing data from previous tests of buckling-restrained braces indicate that the maximum deformation capacity and cumulative cyclic deformation capacity of these types of braces can be substantially greater than the demands corresponding to one (or even several) design-level seismic events (Iwata; Aiken [23]).

Format of Provisions

The fundamental objective in establishing the *Recommended Provisions* was to create a system of requirements that would lead to buildings that can be relied upon to perform at least as well as other seismic structural systems already recognized in building codes. This objective recognized the possibility that measures requiring a performance level higher than that expected for existing structural systems would likely create a disincentive for use of the system and thereby negate the increased seismic safety such measures were intended to provide. As a practical matter, the objective carried with it two implications that are open to question: first, that currently defined systems have similar reliability and performance; and second, that this level of performance is appropriate. The committee therefore considered the reliability studies performed on steel moment frames in the SAC project and the performance criteria employed in order to maintain objective criteria for the buckling-restrained braced frame system.

The design procedure likely to be employed by most engineers is the equivalent lateral force procedure. Thus if any consideration of post-elastic behavior is necessary, it must be explicitly required by the provisions. It was decided that capacity design of connections and frame members (in which the strength of these elements is required to equal or exceed the maximum forces that the braces can impose) is necessary. Overstrength factors are therefore required to be determined from brace tests. These over-strengths include a factor to reflect material strain hardening in the post-yield range of deformation, and a separate factor to reflect observed overstrength in compression due both to material behavior and to brace mechanics. These test-determined overstrength factors are applied to the brace yield force for the connection design forces. For frame members, a system over-strength factor is used. This factor is determined based on required brace overstrength resulting from resistance factors in the design equations, likely strain hardening, and comparison with other systems. The low system overstrength factor reflects the fact that the California buildings using the system to date have been sufficiently stiff with brace sizes determined using required strength.

Because buckling-restrained braces are expected to have less overstrength than other ductile systems such as welded steel moment-resisting frames, yielding of braces is likely to occur at a lower level of seismic excitation. Although consideration of performance levels and damage control at low hazard levels is not a requirement of building codes, it is an implicit expectation of building officials and the public.

Consideration of deflections at these lower hazard levels formed the basis of certain requirements in the provisions, such as beam deflection resulting from yielding of braces in the chevron configuration.

Higher hazard levels were not explicitly considered in the development of the *Recommended Provisions*. Thus, although the provisions provide for seismic performance above that of many other systems for the design-basis earthquake (that is, a level of ground motion with a 10% probability of exceedance in fifty years), they do not guarantee any minimum performance level for the maximum credible earthquake (2% probability of exceedance in fifty years). While this is consistent with the requirements for many other conventional structural systems, it is not consistent with the trend in design requirements toward a multiple-hazard-level approach.

System Factors

Parametric studies using a range of values of the Response Modification Coefficient (R) revealed a very minor effect of this design term on the building performance. It was therefore set to 8.0 (the highest value for any system, that used for welded steel moment-resisting frames), although a higher value could be justified based on the results of the analytical studies.

The Overstrength Factor (Ω_o) was set to 2.0, as small a value as possible considering the design strength resistance factor, strain hardening, and the observed brace overstrength in compression. This factor has a significant effect on the cost of other elements of the seismic-load-resisting system, so that the use of the system could be discouraged by an unnecessarily high value.

The Displacement Amplification Factor (C_d) was set to 5.5, matching that of concentrically braced frames. This value does not correspond well to maximum drifts calculated in the non-linear time-history analyses. On the other hand, the value for concentrically braced frames underestimates displacements to a greater degree. It was therefore decided to use the same value, but to require consideration the larger displacements that are expected in the design and testing of the buckling-restrained braced frames, thus satisfying the objective criteria for its design, while being correct relative to other systems.

Testing Requirements

The *Recommended Provisions* are based on the use of buckling-restrained brace designs that are qualified by testing, which is intended to confirm acceptable brace behavior under the required design deformations. The rationale of the testing requirements contained in the *Recommended Provisions* is similar to the FEMA/SAC and AISC approach for the testing of steel moment-resisting frame connections: tests must be conducted to confirm acceptable behavior but such tests need not be project-specific, rather prior testing of appropriately similar elements may be used to qualify a brace design and concept.

The *Recommended Provisions* recognize the potential for important interactions between a buckling-restrained brace and the surrounding structural frame, and therefore define tests of individual braces (which may involve only uniaxial loading), as well as brace-subassemblage tests (which must incorporate axial and rotational demands). It is required that the subassemblage test be performed for a brace with an axial force capacity that is not less than the largest to be used in the construction. In the case of very large axial force braces, for which testing may be impractical, alternative testing methods or analyses may be permitted under certain circumstances.

The *Recommended Provisions* define a loading program that consists of fully-reversed cycles of loading at increasing amplitudes of deformation. The maximum brace deformation in the test must be at least 1.5 times the brace deformation corresponding to the Design Story Drift. Alternative loading protocols may be used, so long as they are shown to be of equal or greater severity in terms of both maximum deformation and cumulative plastic demand. An acceptable brace test is one in which the test specimen shows increasing force with increasing deformation, there is no fracture, brace instability or brace connection failure, and the ratio of maximum compression force to maximum tension force is within a specified limit.

These requirements are based on providing adequate performance for the design basis earthquake. In order to provide for adequate performance during a very rare earthquake, significantly greater maximum ductility, and somewhat greater cumulative ductility, is required of the braces (Fahnestock [24]). Such higher brace requirements are not, however, beyond the capacities of the brace types currently in use in the U.S. as demonstrated by recent testing (Fahnestock, Aiken). Thus there appears to be little disincentive to requiring consideration of a higher hazard level in brace testing protocols.

Current Status of Provisions

Although part of its long-term goals, the AISC committee on *Seismic Provisions* has not yet adopted the *Recommended Provisions for Buckling-Restrained Braced Frames*. Nevertheless, the *Recommended Provisions* have some standing with AISC and are to be published in an upcoming volume of the AISC Engineering Journal. The establishment of several U.S. manufacturers of buckling-restrained braces has increased the interest of AISC in the *Recommended Provisions*, and the testing requirements portion of the *Recommended Provisions* have played an important part in the development testing that has been undertaken.

In the interim prior to AISC adoption of the *Recommended Provisions* they have been approved for inclusion in the 2003 update of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* (BSSC [6]), a forward-looking document produced as part of the Federal Emergency Management Agency's program of national seismic hazard reduction. These provisions are not directly part of any building code but are recommendations to those writing and revising codes. In the proposal to adopt the *Recommended Provisions* for NEHRP, the technical committee on steel structures selected a Response Modification Coefficient (R) of 7 for buckling-restrained braced frames, thus equating the system performance with that of eccentrically braced frames. The inclusion of the provisions in NEHRP ballot has subsequently placed them under consideration by AISC for inclusion in the 2005 edition of the *Seismic Provisions*. Should AISC eventually adopt provisions for buckling-restrained braces based upon the *Recommended Provisions*, it would represent the concluding phase in the evolution of code design requirements for a new type of seismic lateral force resisting system in the U.S.

As part of the AISC adoption process, the *Recommended Provisions*provisions are currently undergoing or evaluation in a consensus-based process. In this review, the question of whether a multiple-hazard-level approach is appropriate has been revisited. Such consideration would result in an increase of the required maximum and cumulative ductilities in the brace testing protocol, and consideration of correspondingly larger displacements in the design of the braces. At the time of writing, this issue remains unresolved.

CONCLUSIONS

The *Recommended Provisions for Buckling-Restrained Braced Frames* reflect current thinking regarding seismic design requirements for steel structures in the U.S. They are based on component and subassemblage testing and on adequate performance as determined from analytical models of typical buildings. Their creation required careful negotiation of these objective concerns with logical requirements relative to other systems. Decisions made in the development of these provisions, such as whether to consider multiple hazard levels, as has long been done for seismic isolation and energy dissipation systems, may influence the criteria used in the development of requirements for other new systems. Existing systems may also be reevaluated based on evolving conceptions of acceptable seismic performance.

The *Recommended Provisions* have already been applied, either in part or in total, for the design of perhaps a half a dozen projects and are emerging as important part of the Office of Statewide Health Planning and Development's overall requirements for the design of buckling-restrained braced frames for California hospital projects (Ko [25]). The testing requirements portion of the *Recommended Provisions* has also been utilized by several U.S. buckling-restrained brace manufacturers in their development testing activities.

The *Recommended Provisions*, with some minor changes, have been approved for inclusion in the 2003 edition of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*, a step which puts them on a path for inclusion on the 2005 update of the AISC *Seismic Provisions for Structural Steel Buildings*.

While still yet to be formally implemented as regulatory code requirements, the *Recommended Provisions* have already played a significant role in the application of buckling-restrained braces in the U.S., and also in the development of U.S. types of buckling-restrained braces. The creation of the *Recommended Provisions* by a joint AISC/SEAOC task group may eventually prove to be a useful model for future code-development efforts for new seismic structural systems.

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REFERENCES

1. Iwata M, Kato T, Wada A. "Buckling-restrained braces as hysteretic dampers." Mazzolani F Tremblay R Editors. Proceedings of the International Conference on Behavior of Steel Structures in Seismic Areas, Montreal, 21-24 August 2000. Rotterdam: Balkema, 2000.

2. Tremblay R, Degrange G, Blouin J. "Seismic rehabilitation of a four storey building with a stiffened bracing system." Proceedings of the 8th Canadian Conference on Earthquake Engineering., Canadian Association for Earthquake Engineering, Vancouver, B.C., 1999: 549-554.

3. Kalyanaraman V, Sridhara BN, Thairani V. "Core Loaded Earthquake Resistant Bracing Design." Proceedings of the 2nd Intern. Conference on Steel Construction, San Sebastian, Spain, 1998.

4. Wada A, Connor J, Kawai H, Iwata M, Watanabe A. "Damage tolerant structure." ATC-15 Proceedings of Fifth US Japan Workshop on the Improvement of Building Structural Design and Construction Practices. Redwood City, California: ATC, 1994.

5. SEAONC (Structural Engineers Association of Northern California). Recommended provisions for buckling-restrained braced frames. San Francisco: SEAONC, 2001.

6. BSSC. FEMA-368: NEHRP Recommended provisions for seismic regulations for new buildings and other structures. Washington, D.C.: FEMA, 2000.

7. SEAOC. Recommended Lateral Force Requirements and Commentary. Whittier, California: ICBO, 1999.

8. Hamburger R. “A Framework for Performance-Based Earthquake Resistive Design.” EERC-CUREe Symposium in Honor of Vitelmo V. Bertero, Berkeley, California, 1997.

9. SEAOC (Structural Engineers Association of California). Vision 2000 - A Framework for Performance Based Earthquake Engineering. Vol. 1, Sacramento: SEAOC, 1995.

10. BSSC (Building Seismic Safety Council). FEMA-273: NEHRP Guidelines for the Seismic Rehabilitation of Buildings FEMA-273. Washington, D.C.: FEMA, 1996.

11. Uriz P, Mahin SA “Seismic vulnerability of special concentrically braced steel frames.” Proceedings, SEAOC 2003 Convention, Squaw Creek California, September 2003

12. ATC (Applied Technology Council). ATC-19: Structural Response Modification Factors. Redwood City, California: ATC, 1995.

13. ASCE (American Society of Civil Engineers). ASCE-7: Minimum design loads for buildings and other structures. New York: ASCE, 1998.

14. ICC (International Code Council). International Building Code. Falls Church, Virginia: ICC.

15. BSSC 2000. FEMA-350: Recommended seismic design criteria for new steel moment frame buildings. Washington, D.C.: FEMA, 2000.

16. ICBO (International Conference of Building Officials). Uniform Building Code. Whittier, California: ICBO, 1997.

17. NFPA (National Fire Protection Association). NFPA-5000 Building code. Quincy, Maryland: NFPA, 2001.

18. Bonneville DR, Bachman RE. The evolving process of US seismic code development. Proceedings of the of the 7th U.S National Conference on Earthquake Engineering, Boston, 2002.

19. AISC (American Institute of Steel Construction). Seismic provisions for structural steel buildings. Chicago: AISC, 1997.

20. Malley JO. “Update on US seismic design requirements for steel structures.” Proceedings of the of the 7th U.S National Conference on Earthquake Engineering, Boston, 2002.

21. Sabelli R, Mahin SA, Chang C. “Seismic demands on steel braced-frame buildings with buckling-restrained braces.” Engineering Structures, 2003.

22. Sabelli R. EERI/FEMA NEHRP Professional fellowship report: Research on improving the seismic behavior of earthquake-resistant steel braced frames. Oakland, California: Earthquake Engineering Research Institute, 2001.

23. Aiken I, Kimura I. The Use of Buckling-Restrained Braces in the United States. Proceedings of the Japan Passive Control Symposium, Tokyo Institute of Technology, Yokohama, Japan, 2001.

24. Fahnestock LA, Sause R, Ricles JM, & Lu, LW. Ductility demands on buckling-restrained braced frames under earthquake loading. Earthquake Engineering and Engineering Vibration, Vol.2, No.2, 2003.

25. Ko E, Mole A, Aiken I, Tajirian F, Rubel Z, Kimura I. Application of the Unbonded Brace in Medical Facilities. Proceedings of the of the 7th U.S National Conference on Earthquake Engineering, Boston, 2002.