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ESSENTIAL ELEMENTS OF EQUIPMENT QUALIFICATION FOR BUILDING CODES BY SHAKER TABLE TESTING

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ABSTRACT

Most consulting engineers deal with seismic code compliance requirements for the primary building structures of critical facilities as a site-specific activity. In contrast, manufacturers of equipment (operational and functional components) that are used in critical facilities can only be competitive by spreading the cost of seismic compliance testing across a product line family for the widest possible market coverage.

This paper details a generic methodology that equipment suppliers can follow to determine the major scope of end user seismic code requirements for its products, and the essential role that an industry recognized test protocol plays in a type test campaign. Without a building code recognized test protocol it will be shown that qualification testing is inconsistent at best, with low confidence of meeting code intent.

From lessons learned in the development of the first industry recognized shake table protocol for the U.S. building codes it is suggested that a similar protocol could be developed for compliance verification to the 2005 National Building Code of Canada.

Introduction

From the perspective of the academic researcher or practitioner (consulting engineer) the differences between application specific testing and that of type testing may not be obvious but they are a reflection of how each approaches their respective customer. The practitioner's goal is to provide an engineering solution with unique needs associated with the geotechnical site requirements, building structural system, site specific code requirements and the customer's expectations. Such requirements dictate a site-specific approach to the engineering process for the practitioner. To be competitive a manufacturer qualifies equipment such that a maximum number of standard design variations can be adaptable for use with minimal location specific considerations.

Building codes are universally interpreted by design professionals to address project specific needs. This project specific basis can be problematic for the manufacturer when code driven performance compliance is required without reference to industry standards that establish how compliance is to be met. Such was

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the lesson learned when U.S. building codes implemented major revisions to the seismic design provisions starting with the shift from stress to strength based structural design in the 1997 UBC.

This paper will discuss how to plan an effective shaker table type test program for equipment that can be installed, for most cases, without regard to determining site-specific seismic requirements. Also covered is the need for an industry-recognized test protocol, such as ICC ES AC156 (ICC ES 2004) that was developed for the U.S. codes, to clearly translate building code requirements into test requirements. A well thought out test plan developed around the proper test protocol is essential for a manufacturer to provide competitive pre-engineered equipment to the widest possible market geographic area with demonstrated code compliance. To take an approach that physical testing is required for each site specific application would simply not be practical from either a cost perspective or the reality that there would be a significant shortfall of available test facilities and time to do so. Outside of the scope of this paper is shaker table testing of equipment for public utility, nuclear or telecommunications applications. These facilities have special engineering requirements for seismic qualification that are not addressed by building codes.

Drivers of Change for New Earthquake Building Codes – The Events

Causes of earthquakes do not have national boundaries or sometimes commonality within. For example the massive and deadly intraplate Gujarat earthquake of 2001 has more in common with the New Madrid seismic hazard area in the Mississippi River Valley of the eastern U.S. than those of California. The hard lessons learned from Mexico City 1985, Loma Prieta 1989, Northridge 1994 and Kobe 1995 to buildings which were built to what were considered to be the most rigorous seismic building codes in the world, clearly demonstrated that new codes were required (DeVall 2003). Many of these lessons learned were embodied in the 1997 NEHRP (National Earthquake Hazard Reduction Program) Provisions (FEMA 302 1997) and Commentary and were the basis of significant seismic code changes for the 2005 National Building Code of Canada (NBCC 2005) and all U.S. model codes since 1997. These changes also surfaced the absence of criteria in the code to establish test requirements for shake table testing and lead to the development of the first industry recognized methodology for the 1997 UBC (ICBO 1998), 2000 IBC (ICC 2000), NFPA 5000 (NFPA 2003) and ASCE-7 (ASCE 7 2002).

NEHRP was created and funded in the 1970's by the U.S. Congress through NIST (U.S. National Institute of Standards and Testing), with oversight by FEMA (U.S. Federal Emergency Management Agency), to the BSSC (Building Seismic Safety Council) with active support of the USGS (United States Geological Survey) and NSF (U.S. National Science Foundation). CANCEE and the National Research Council of Canada are participants in NEHRP (http://www.bssconline.org/mbr/membershipc.html).

An informal review of the current seismic model building codes around the world will reveal a great deal of commonality in new approaches to seismic hazard mapping, geotechnical and earthquake structural engineering requirements. As the various technical communities come closer to a convergence on research, that influence localized building codes, the global community of earthquake engineering is getting smaller. Therefore the authors firmly believe that the lessons they have learned from participating in ground breaking advances in the development of shaker table testing protocols (Gatscher 2003) and methodology, to insure that the intent of the new generation of U.S. building codes is met, can be of benefit to the earthquake engineering community outside of the United States.

Pre-Engineered Equipment – Design & Qualify Once

Custom ordered building equipment is referred to in building codes as either nonstructural building components or operational and functional components (OFC's) and are what manufacturers refer to as "pre-engineered" equipment. The term pre-engineered is used to refer to a product family for which the base product and a few or large number of variations are only designed once during new product development. An integral activity to the product development phase of a pre-engineered product family is the generation of design records for the equipment base design and variations of the records for options.

“Design records” in this context are technical documents, completed prior to the commercial release of a new product family to production, that will be used by manufacturing during assembly to insure that design intent of product is complied with.

Design Assurance Testing and the Role of Industry Standards

Practitioners refer to industry standards, in their project plans and specifications, to insure appropriate levels of performance, safety and code compliance and desired functionality for the facility when their customer takes possession. To meet these requirements manufacturers will include in their new product development process design assurance testing for verification of compliance to those codes and standards. These standards include a wide range of performance requirements that include safety, environmental, operational life cycle performance and other functionality relevant end use expectations.

With pre-engineered products, testing is conducted on a carefully selected number of samples with rationalized design features representative of the product family (Fig. 1). These rationalized test samples are chosen to verify that the base design and other pre-engineered variations of the product family will fulfill the requirements for the design intended purpose of the equipment when it is installed, maintained and operated as per the manufacturer’s instructions and applicable codes and standards. Properly selected the test type test sample(s) will be representative of a highly variable product family and is commonly referred to as an “umbrella test”.

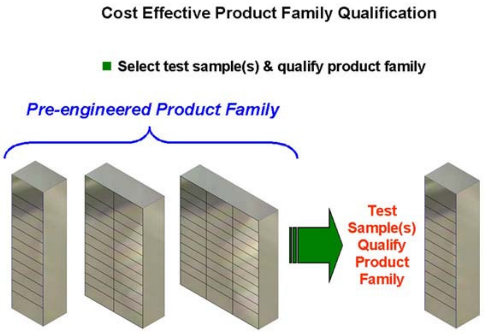


Figure 1. Establish test sample(s) that envelope product family with similar construction features.

The following general criteria are offered as an illustrative example for establishing test specimen (unit under test or UUT) configuration requirements for representing an equipment product line. It is recognized that industry specific product types will likely offer unique rationalization challenges that may deviate from the general rules provided here:

1. Structural Features: A rationale shall be provided explaining that the selected UUT’s structural configuration is one offering the least seismic withstand capacity compared to other options that are available within the product line being qualified. The UUT’s force-resisting systems shall be similar to the major structural configurations being supplied in the product line. If more than one major structure is a configurable option, then these other structural configurations shall be considered in the equipment product line extrapolation and interpolation rationalization process.

2. Mounting Features: A rationale shall be provided that explains that the selected UUT’s mounting configuration is one offering the least seismic withstand capacity compared to other mounting options that are available within the product line being qualified. The configuration mounting of the UUT to the shake-table shall simulate mounting conditions for the product line. It would be impractical and uneconomically justified to test every possible anchorage system available in the marketplace (wedge, undercut, sleeve, shell, adhesive and various cast-in-place types). Thus seismic testing of equipment is typically conducted using the smallest diameter tie-down bolt size

(or minimum weld size) that can be accommodated with the provided tie-down clearance holes (or base structural members) on the equipment. If several mounting configurations are used, they shall be simulated in the test.

3. Subassemblies: A rationale shall be provided explaining that the selected UUT's subassemblies are representative of production hardware and offer the least seismic withstand capacity of the UUT compared to other subassembly options that are available within the product line being qualified. The components shall be mounted to the structure using the same type of mounting hardware specified for proposed installations. Substitution of non-hazardous materials and fluids is permitted for verification of equipment or subassemblies that contain hazardous materials or fluids, provided the substitution does not reduce the functional demand on the equipment or subassembly.

4. Mass Distribution: A rationale shall be provided explaining that the selected UUT's mass distribution is one contributing to the least seismic capacity of the UUT compared to other mass distribution options that are available within the product line being qualified. The weight and mass distribution shall be similar to the typical weight and mass distribution of the equipment being represented. Weights equal to or heavier than the typical weight shall be acceptable.

5. Equipment Variations: A rationale shall be provided explaining that the selected UUT's overall variations contribute to the least seismic withstand capacity of the UUT compared to other variations that are available within the product line being qualified. Other equipment variations, such as number of units/components in production assemblies, indoor and outdoor applications, etc., shall be considered in the equipment product line extrapolation and interpolation rationalization process.

Development of Type Test Plan First Step – Market Requirements, Where Is the Bar?

To maximize seismic building code compliance to the widest possible number of applications, the first step for a manufacturer is to establish the maximum test requirements for each served available market area of interest. By qualifying to the maximum application requirements there will be a minimum number of site specific restrictions (based on the equipment being properly installed with adequate anchorage). In other words, if the outcome of the type test campaign is such that the equipment can be applied with no site-specific restrictions, then the task of specifying and supplying is greatly simplified for both the practitioner and supplier.

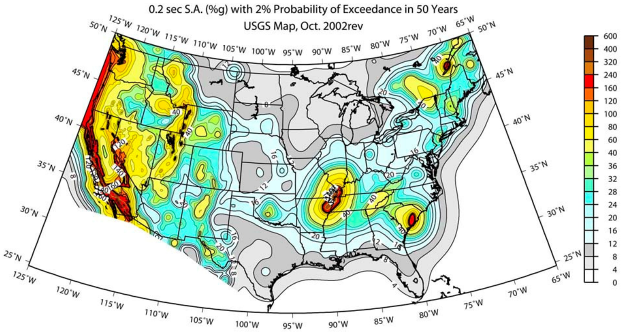


Figure 2. Site specific ground motion values are used to determine the simplified design spectra for the design basis of the facility (Frankel 1996).

The starting point for a design professional is to refer to the site geotechnical report and seismic hazard map data and appropriate building code to determine the required seismic loads for a specific building location. In contrast, a manufacturer looks at all maps and codes relevant to the target market to seek maximum requirements. The introduction of probabilistic seismic hazard maps into building codes in the U.S. (Fig. 2) has caused much confusion for those that were familiar with the “UBC seismic zones” but this is the future for a long list of reasons that are beyond the scope of this paper.

Probability based seismic hazard maps were first proposed in 1948 by F. P. Ulrich and have evolved into the widely accepted form of probabilistic seismic hazard ground motion maps. The basis of these maps is “Engineering Seismic Risk Analysis” introduced in Mexico in 1967 by Luis Esteva (Esteva 1967) and in the United States in 1968 by C. Allin Cornell (Cornell 1968). Having been widely accepted globally as a state of the art approach to engineering for critical facilities, their introduction into model building codes is an overdue evolutionary next step.

Canada implemented the next generation of building code seismic hazard maps (Fig. 3) with the publication of the 2005 National Building Code of Canada (NBCC) in September of 2005. This is the fourth generation of seismic hazard maps (previous editions: 1953, 1970, 1985) and incorporates new information that improves the hazard estimate. The technical basis of these maps was supplied by Geological Survey of Canada (Adams 2003) and is virtually identical in format to those supplied by USGS (Frankel 1996) for their first use in the 2000 IBC. The most variance between spectral ordinate values occurs at the border along the West Coast. This variation will be minor and is due to differences in the assessment of the contribution of ground motion by earthquakes from the Cascadia Subduction Zone as interpreted by USGS and CGS, otherwise the probability distributions at the border are very similar. The only technical difference the design professional must be aware of is that the USGS maps are based on a referenced site condition of geotechnical site class B and the CGS maps are based on site class C (site class designations and definitions are the same for both cases). Also it must be noted that the spectral ordinate values, that are used to link a hazard probability and a ground motion response, are for a free field geometric mean of the two horizontal components that represent an intensity measure. Caution should be exercised when using these geometric mean values for engineering calculations that require a maximum response for a single horizontal component (Baker 2006).

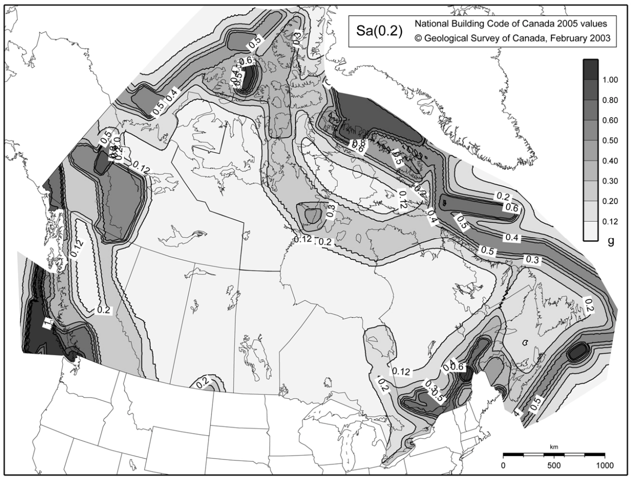


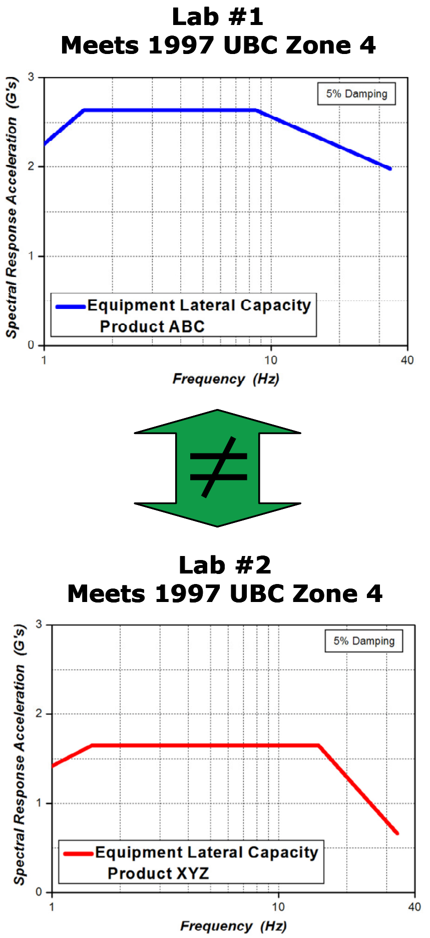
Figure 3. 0.2 second spectral ordinate map created by CGS for the 2005 NBCC based on probabilistic seismic hazard analysis methodology (Adams 2003).

Development of a Type Test Plan – Selection of Standard for Shaker Table Testing

Once market requirements are determined, the next step is to identify the most appropriate industry recognized standard for shaker table testing. For the U.S. prior to 2000, industry standards for shaker table testing of equipment were mostly limited to those published by Telcordia GR-63 NEBS, IEEE ®-344 (IEEE 1987) and to IEEE ®-693 (IEEE 2005). While these three seismic testing protocols share a common technical origin, used as the basis to create IEEE-344, each was designed to insure that application specific end use technical requirements are met for telecommunications, nuclear and utility substations and were only intended to be used in the context they were created for. For example it is inappropriate to solely use IEEE-693 certification for equipment that is applied in class 1E safety related applications in nuclear power plants. Like wise the sole use of IEEE-344 would not be acceptable to a utility for qualification of high voltage transmission components for utility substations.

Telcordia GR-63 NEBS is the most common set of safety, spatial and environmental design guidelines applied to telecommunications equipment in the United States. The NEBS (Network Equipment Building System) equipment design guideline is a comprehensive set of environmental qualification criteria of which seismic is but a small part. There are hundreds of requirements in NEBS, miss one and the product is not NEBS qualified. The NEBS concept was first introduced by Bell Labs in the 1970's to simplify the design and deployment of telecommunications equipment in the Bell System by defining typical equipment and the environment they must function in. None of these standards directly translates model building code requirements into a test requirement to satisfy the intent of any building code and any attempt to do so, even for a subject matter expert, can be a daunting task.

For the U.S., seismic requirements for equipment were not specifically mentioned prior to the 1988 Uniform Building Code. No shaker table test standard had ever been developed to specifically meet the intent of the model building codes or clearly defines pass/fail criteria. In the absence of an industry standard the use of ad hoc procedures, based on elements of existing standards, had been common practice for most labs when developing a test plan for building code qualification. This ad hoc practice resulted in wide variation of test criteria for the same level of compliance (Fig. 4). Advances in building


Lab #1
Meets 1997 UBC Zone 4

Lab #2
Meets 1997 UBC Zone 4

Figure 4. Ad hoc protocols resulted in inconsistent model code test requirements prior to ICC ES AC156.

codes can be expected in the future to render attempts to “reverse engineer” intent from the building code even more confusing and inconsistent than current state. Attempts to use test protocols that are not developed as a synergetic activity along with development of code resource documents have only lead to confusion.

The 1997 UBC (ICBO 1997) introduced a significant change in the basis for structural seismic design with a shift from a stress based design to strength based design (Bachman 1998). This change resulted in much confusion among commercial test labs and manufacturers that highlighted a need for an industry recognized testing protocol developed specifically to meet the intent of model building codes. Ad hoc shaker table testing protocols will almost always result in inconsistent test plans when created by different people. Having been assigned to the task of resolving this impasse by Schneider Electric the authors accepted an invitation from TS8 of the BSSC to collaborate in the development of a generic shaker table test protocol for nonstructural building equipment that met the intent of the seismic design provisions of U.S. model building codes in May of 1999.

Approved in January of 2000, ICBO ES AC156, prior to the consolidation of ICBO ES, BOCA ES and SBCCI ES into the ICC ES organization in early 2003, is one such protocol that is intended solely for shaker table testing equipment to a model building code. With a protocol, such as ICC ES AC156, a manufacturer can clearly develop a test plan that targets seismic model code compliance for the U.S. market areas and applications it wishes to serve. Another benefit of a standard developed for model building code qualification is the establishment of criteria for determining pass/fail.

Essential Elements of a Model Building Code Shaker Table Test Protocol for Equipment

To meet the requirements of a new generation of NEHRP based U.S. building codes TS8, of the BSSC (Building Seismic Safety Council Nonbuilding and Nonstructural project group), established the goal of developing a generic dynamic qualification test method for seismic validation of equipment for commercial (non-nuclear) service, which would be consistent with the intent of the static lateral force design requirements for nonstructural components. To be generic it was necessary that such a protocol define shake table demand for OFC’s without regard to how they are attached to the building structure.

The foundation of ICC ES AC156 is the establishment of a repeatable shake table shock response spectra (Fig. 5). Along with a defined broad band random time history and a generic pass/fail criteria a consistent test criteria can be established. Because the test basis is well defined the only remaining variation of actual test demand from lab to lab will be primarily due to the ability of the test facility to control their table motion. The generic pass/fail of AC156 establishes the post test capability for the equipment under test. If the equipment is to be installed in critical facilities, that have to be operational after the event, the passing criteria is determined by verifying nothing happened during the test that would prevent the essential functionality of the equipment from being restored after the test without having to be taken off-line for an extended time for repairs. Also no release of hazardous materials, contained in the equipment can occur. Consistent with the code, this test demand can be established from grade level to roof top level. AC156 is flexible so that it can be used when the floor spectra is provided for application specific evaluation, based on site specific building code parameters or the maximum requirements for a target market. AC156 first became effective in January of 2000 and has been used to qualify a wide variety of OFC’s by industry and academic research and is now referenced in Chapter 13.2.5 of ASCE 7-05, the basis of the 2006 IBC and NFPA 5000 seismic requirements for OFC’s.

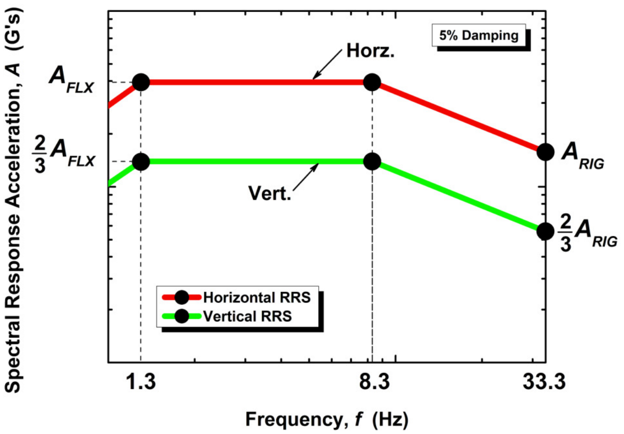


Figure 5. Translating building code parameters to a shake table shock response spectra is how ICC ES AC156 establishes a repeatable dynamic test to meet the intent of the building code.

The approach taken to develop ICC ES AC156 can be used for any building code. The elements consisted of:

1. Development of the technical basis (intent) for the requirements/methods and relate them to relevant interpretations of the 1997 and 2000 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures. This collaboration involved a variety of subject matter experts from TS8 along with input from industry which was critical to insure compliance with intent.

2. Define a test time history criteria that was broad enough to envelop the Maximum Considered Earthquake (MCE) time history without knowledge of site specific geotechnical, fault source, or topographic considerations. These criteria were derived from widely accepted procedures.

3. Account for above grade elevation equipment installations with or without knowing the dynamic characteristics of the primary support structure (i.e., primary structure dynamic properties not necessary, but if available, may be used).

4. Define and established a verifiable pass/fail acceptance criterion for the seismic qualification test based upon the equipment importance factor consistent with code intent.

5. Develop a generic rationalization criterion that can be used to establish test unit configuration requirements to represent highly variable product line families.

6. Recommend the development of nonstructural requirements flow-down guideline, such that model building code requirements are correctly specified up-front and can be captured and incorporated into equipment bid specifications.

7. Gain national acceptance for the resulting seismic qualification test protocol and technical NEHRP interpretations by at least one credible model building code organization.

Typical Shaker Table Test Campaign Planning

The development of a test plan is greatly simplified by following the requirements outlined in a test protocol like ICC ES AC156. It is important to develop the test plan with participation of the test facility to insure that it can be complied with and the goals are realistic. A detailed review of the RRS (Required Response Spectra) must be conducted with the technical staff to verify that the shaker table is capable of providing the required motion. A discussion with the lab is required to insure data required to verify pass/fail criteria compliance is recorded. If there are any special requirements for data collection these must be identified and provisions made to record the data in an appropriate format for later use and analysis. The set up and installation of the test sample(s) on the shaker table must be reviewed and plans made for any special test fixtures be made to avoid delays in test program.

Conclusions

Using ad hoc interpretations of model building code requirements, manufacturers of nonstructural equipment have pursued seismic qualification testing of nonstructural components on an inconsistent basis for many years. Shake-table testing is the preferred industry approach for qualifying nonstructural equipment to meet the seismic design requirements contained in model building codes. However, building code provisions do not define nor offer any guidance on how to correctly translate static lateral force requirements into a dynamic shake table test criteria. This situation results in multiple code interpretations and ultimately results in manufacturers claiming seismic qualification against building code requirements that were tested using different shake-table demand test levels.

Resolution of this inconsistency in code interpretation regarding qualification testing must be addressed by a generic test procedure that has been endorsed by a national body of subject matter experts in earthquake engineering as meeting the intent of the code. Such a test procedure can be used to validate seismic withstand capacity for any nonstructural building component as defined by the model building code of reference. The development of the seismic qualification demand test levels are based upon the existing nonstructural lateral force procedure in conjunction with the building design response spectrum and adjusted to reflect data from instrumented buildings that have been subjected to significant events. This approach accounts for above grade level equipment installations, with or without knowledge of the building’s dynamic characteristics. A well-defined pass/fail acceptance criterion must be established that utilizes the equipment importance factor to define post-test acceptability. In essence, this generic test protocol establishes the seismic qualification shake-table test demand for any nonstructural component for any given equipment location in a building and for any given building location in the country or locality of relevance.

While developed specifically for qualification testing to model U.S. building codes, the fundamental approach taken to develop ICC ES AC156 can be applied to other model codes and thereby eliminate a number of inconsistencies in shaker table testing.

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References

Adams, J., Halchuk, S., 2003. Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada, *Geological Survey of Canada Open File 4459*.

ASCE 7, 2002. ASCE/SEI 7-02 Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, Reston, Virginia.

Baker J. W., Cornell C. A., 2006. Which Spectral Acceleration Are You Using?, EERI Spectra 22 (2), 293-312.

Cornell C. A., 1968. Engineering Seismic Risk Analysis, Bulletin of Seismological Society of America 58, 1583-1606.

DeVall, R. H., 2003. Background information for some of the proposed earthquake design provisions for the 2005 edition of the National Building Code of Canada, Canadian Journal of Civil Engineering, 30, 279-286.

Esteva L., 1967. Criteria for the construction of spectra for seismic design, 3rd Pan-American Symposium of Structures, Caracas, Venezuela, 3-8 July.

FEMA 302, 1997. National Earthquake Hazards Reduction Program Provisions, U.S. Federal Emergency Management Agency, http://www.bssconline.org/pubs/downloads.html

FEMA 413, 2004. Installing Seismic Restraints for Electrical Equipment, 2004, http://www.fema.gov/plan/prevent/earthquake/professionals.shtm

FEMA 450-1, -2, 2003. National Earthquake Hazards Reduction Program, Part 1: Provisions, Part 2: Commentary, http://www.bssconline.org/

Frankel A. D., Mueller C. S., Barnhard T., Perkins, D., et al, 1996. Open-File Report 96-532, http://earthquake.usgs.gov/research/hazmaps/publications/hazmapsdoc/Junedoc.pdf

Frankel A. D., Petersen M. D., Mueller C. S., Haller K. M., Wheeler R. L., et al, 2002. Open-File Report 02-420, http://pubs.usgs.gov/of/2002/ofr-02-420/OFR-02-420.pdf

Gatscher J. A., Caldwell P. J., Bachman R. E., 2003. Nonstructural Seismic Qualification: Development of a Rational Shake-Table Testing Protocol Based on Model Building Code Requirements, *ATC 29-2 Proceedings of Seminar on seismic design, performance and retrofit of nonstructural components in critical facilities*, 63-75.

ICBO, 1998. 1997 Uniform Building Code, International Conference of Building Officials, Whittier, California.

ICC ES, 2004. Acceptance Criteria 156, International Code Council Evaluation Services, Whittier, California, http://www.icc-es.org/Criteria/pdf/ac156.pdf

ICC, 2000. 2000 International Building Code, International Code Council, Country Club Hills, IL.

ICC, 2002. 2003 International Building Code, International Code Council, Country Club Hills, IL.

IEEE Standard 344®-1987, 1987. IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations, The Institute of Electrical and Electronic Engineers, Inc.

IEEE Standard 693®-2005, 2005. IEEE Recommended Practice for Seismic Design of Substations, The Institute of Electrical and Electronic Engineers, Inc.

McKevitt, W. E., 2003. Proposed Canadian code provisions for seismic design of elements of structures, nonstructural components, and equipment, Canadian Journal of Civil Engineering 30, 366-377.

NBCC, 2005. National Building Code of Canada 2005, Canadian Commission on Building and Fire Codes, National Research Council of Canada, Ottawa, Ontario.

NFPA, 2003. NFPA 5000® Building Construction and Safety Code, 2003 Edition, National Fire Protection Association, Quincy, Massachusetts.