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NEED FOR OBJECTIVE TEST STANDARDS FOR SIMPLIFYING CODE COMPLIANCE AND VERIFICATION

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ABSTRACT

Seismic qualification of electrical power distribution and control equipment, referred to as operational and functional components (OFC's) or nonstructural components, is often assumed to increase product cost. Frequently compliance cost can be reduced for the life cycle of a product when economies of scale are coupled with a well planned and executed product development process. Such a cost reduction realization is much harder or impractical to achieve when compliance is only considered after commercialization. Essential for a cost effective solution is a well planned and executed qualification strategy which considers market requirements, engineering simulation tools, proprietary testing experience, identification of qualification methodology and incorporation of lessons learned from earthquakes early in the concept phase of new product development. No one qualification method will be appropriate for all situations. This paper will discuss the emerging trend in the U.S. to develop a clear and objective test protocol for qualification of acceleration sensitive nonstructural components (OFC's). The implications for reducing cost of compliance extend well beyond the manufacturer and touch all aspects from design to completion of the construction cycle and will be discussed also.

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 need. The practitioner's goal is to provide an engineered structural solution to meet the unique needs associated with the project specific earthquake ground motion hazard, geotechnical site requirements, code compliant requirements and the customer's expectations. Such requirements dictate a project-specific approach to deliver a cost effective engineering challenge for the practitioner within the owners' budget. To be competitive a manufacturer qualifies equipment such that a maximum number of standard design variations can be adaptable for use with minimal project-specific considerations.

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Since very few equipment manufacturers speak “structural engineering” this situation becomes more complicated when equipment seismic qualification is required without reference to clear and objective industry qualification standards which were developed to meet the intent of the relevant model building code and any referenced standards. Such was the lesson learned when U.S. building codes implemented major revisions to their seismic design provisions starting with the incorporation of the “near source” factor and the shift from stress to strength based structural design in the 1997 UBC (ICBO 1998). It was this change which resulted in the authors collaborating with the Building Seismic Safety Council to develop a shake table test protocol to meet the intent of both the 1997 UBC and 2000 IBC model building codes (Gatscher 2003) for acceleration sensitive nonstructural components.

This paper will discuss how to plan an effective qualification program for equipment to address the maximum number of project-specific seismic requirements within the seismic demand capacity of the equipment under consideration. Also covered is how objective test standards reduce the cost of compliance and verification for all stake holders in the complete project life cycle from owners’ concepts to the end of life. A top level overview of equipment qualification for public utility, nuclear or telecommunications applications, which are outside of the scope of building code applications, will be covered to demonstrate how each has evolved qualification standards to address unique engineering associated with of these specialized applications.

An informal review of current and future seismic model building codes around the world by the reader will reveal a great deal of commonality in new approaches to seismic hazard mapping (Global 1999), geotechnical and earthquake structural engineering requirements. As the various technical communities come closer to a convergence on research, which influence localized building codes, the global community of earthquake engineering is getting smaller. Therefore the authors firmly believe the concepts used in the development of clear and objective shake table testing protocols (Gatscher 2003) to meet the intent of U.S. building codes, can be of benefit to the earthquake engineering community outside of the United States in the development of similar localized qualification protocols.

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, used by manufacturing during assembly to insure that design intent of the product is complied with. Should new product seismic qualification not be considered until close to commercialization any design changes required to meet market requirements introduce the possibility of unplanned project expenses and delays to targeted product launch dates.

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. These rationalized test samples are chosen to verify that the base design and other pre-engineered variations of the product family will fulfill 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 type test sample(s) will be representative of a highly variable product family and is commonly referred to as an "umbrella test".

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 which 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. Inputs into the rationalization process might include any or a combination of finite element analysis, proprietary testing experience database, expert opinion, peer review by equipment subject matter experts in the equipment design, lessons learned from previous earthquakes (Roper 1995) and product marketing.
2. Mounting Features: A rationale shall be provided which explains 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) which 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 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 which 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 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 which 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.

Market Requirements, Optimized Coverage Simplified

To maximize seismic building code compliance, to the widest possible number of project specific applications, the first step for the 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 project specific restrictions (based on the equipment being properly installed with adequate seismic anchorage). With a clearly stated project-specific equipment seismic capacity ($S_{DS,}$ for the 2006 IBC or ASCE 7-05), then the practitioners work content for specifying and verification of project specific code compliance is greatly simplified (OSHPD OSP-0001-10).

The introduction of spectral response seismic hazard maps into U.S. model building codes (USGS) is still a source of much confusion for those familiar with the now obsolete "UBC seismic zones. Despite their first obsolescence as early as 1992 in the U.S. regional model codes, the NBC, SBC and concluding with the 1997 UBC, the authors still receive frequent inquiries about how to meet "IBC Zone 4" or "IBC Zone D". In addition to the legacy of "zone 4" mythology also to be anticipated is the incorrect association of code equivalent static lateral force procedures with dynamic test criteria. Such inquiries are an indication of how poorly the intent of seismic building code requirements for equipment are and always have been misunderstood by those outside of the earthquake engineering community involved in the code creation process. For this confusion to still be rampant in the marketplace ten years after the first publication of the IBC is compelling evidence that clear and objective code qualification protocols have to be developed synergistically with model codes.

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

Once market requirements are determined, the next step is to identify the most appropriate industry recognized standard for shake table testing. For the U.S. prior to 2000, industry standards for shake 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 address application specific end use technical requirements for telecommunications, nuclear and utility substations therefore they are only intended to be used in the context they were created for.

For example IEEE 344 is only relevant for the purpose certification for equipment to be applied in class 1E safety related applications in nuclear power plants (NPP) but it is not a stand alone requirement. Implementation of an NPP safety related qualification program requires multiple requirements from other associated IEEE (and multiple other industry standards as required by the U.S. NRC for licensing review, some are even obsolete) to be specified such as custom derived floor spectra for each installed location within the NPP. This floor spectra begins with a costly custom site specific seismic hazard analysis which considers all contributions from all known active and inactive faults, latest generation of attenuation relationships, site geology, historic seismicity based 10,000 year (or more) probability of exceedance return period. The summary of these studies can exceed 1,000 pages and cost more than the total completed cost of most building code relevant projects. Also required is the determination of the acceptance criteria for electrical performance of the equipment under test and the total oversight from the equipment design, qualification test and manufacturing under a quality assurance program such as IEEE 323 or other approved dedication program. For critical safety related applications the electrical operational performance criteria is established by the development and evaluation of an application specific failure modes analysis of the specific safety related system it is an integral part of. Because of the extensive engineering work content required to establish an IEEE 344 compliant qualification program the dedication cost for equipment can range from three to one hundred times the cost of the same equipment for commercial applications. Clearly IEEE 344 based specifications are something to be avoided for building code related projects.

IEEE 693 is also problematic for use as the basis of building code related projects. As stated in the introduction to this standard it is intended to be used to establish "recommended practice for the seismic design of substations." The focus of this standard is on major utility substation components rated 115 kilovolts and above. A quick review of this standard will also reveal that like IEEE 344 the end user must develop a comprehensive specification to establish the acceptance criteria. In other words statements such as "qualified to IEEE 344 or IEEE 693" are much to vague to convey any indication of project specific requirements even for NPP and substation applications and while sounding impressive they are without context and therefore have no have meaning to establish project specific compliance.

Telcordia GR-63 NEBS (Bellcore 1995) 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 shake table test standard had ever been developed to specifically meet the intent of the model building codes or clearly define 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. Advances in buildings codes can be expected in 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 which have not been developed as a synergetic activity along with development of code resource documents have a demonstrated history which states the outcome of such an approach only results in chaos and confusion.

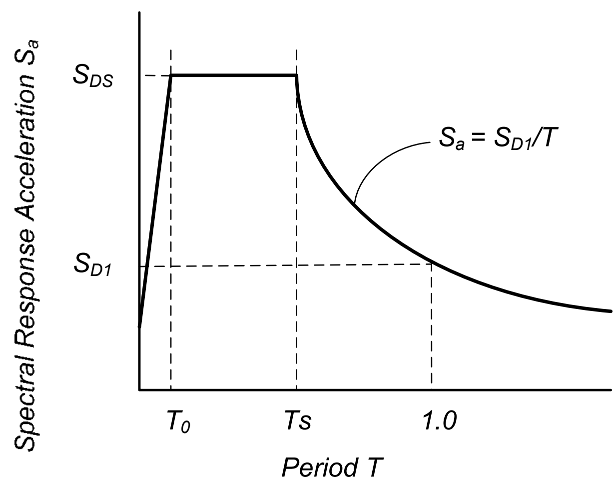
The 1997 UBC (ICBO 1998) introduced a significant change in the basis for structural seismic design with the introduction of a "near source factor" and a shift from a stress based design to strength based design. This change resulted in much confusion among commercial test labs and manufacturers and finally highlighted a need for a building code recognized testing protocol developed specifically to meet the intent of model building codes. Ad hoc shake table testing protocols will 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 nonstructural committee of the Building Seismic Safety Council (Building Seismic Safety Council Nonbuilding and Nonstructural committee, BSSC TS8) to collaborate in the development of a generic shake table test protocol for nonstructural building equipment based on the intent of the seismic design provisions of U.S. model building codes in May of 1999. The BSSC is charged with the responsibility to produce the NEHRP Provisions (FEMA 302 1997) which was a significant code resource document for the 2000 IBC.

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) (ICBO ES 2000) is one such protocol intended solely for shake table testing of acceleration sensitive nonstructural building components for both the UBC and IBC. With a clear and objective protocol, such as ICC ES AC156, an equipment manufacturer can easily develop a compliance qualification strategy 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 which were never clearly stated in model codes and subject to many interpretations.

Like IEEE 693 and Telcordia GR63, AC156 draws on shake table test methodology used in IEEE 344. This broad band time history shake table methodology was extensively vetted by the

U.S. Nuclear Regulatory Agency from 1970 through 1990 in many field and laboratory research programs. Because of the common heritage it is a very straightforward process for any equipment supplier with this type of existing shake table testing, done to any of these non-building code standards, to review and evaluate the existing test data to the criteria of AC156 to establish the building code compliant equipment seismic capacity, S_{DS} (OSHPD OSP-0006-10). This is a simple process and ten years later some manufacturers are finally realizing the obvious. That it has taken ten years for equipment manufacturers to "see the light" is further evidence of how enormous the gap is between the building code creation process and those who specify build and install mechanical and electrical equipment.

Essential Elements of a Model Building Code Shake Table Test Protocol



1997 NEHRP FEMA 302 Figure 4.1.2.6 Design response spectrum

The foundation of ICC ES AC156 is the establishment of a repeatable shake table shock response spectra which is compatible with the relevant building design spectra (FEMA 302 1997 Figure 4.1.2.6). 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, which have to be operational after the event, the passing criteria is determined by verifying nothing happened during the test which would prevent the equipment from being restored to it intended functionality 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 project 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 nonstructural building components, or OFC's, by industry and academic research and is now referenced in Chapter 13.2.5 of ASCE 7-05 (ASCE 2006).

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 which is broad enough to envelop the Maximum Considered Earthquake (MCE) time history without knowledge of project 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.

Conclusions

Shake-table testing is the preferred approach for qualifying nonstructural equipment to meet the seismic design requirements contained in model building codes. 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. The simplified equivalent static lateral force procedure of 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 has resulted in multiple code interpretations and ultimately in manufacturers claiming seismic qualification based on incorrectly interpreted building code static force requirements and testing using different shake-table demand test levels for a given qualification claim.

Resolution of this inconsistency in code interpretation regarding qualification testing can only be addressed by a clear and objective generic test protocol which has been endorsed by a national body of subject matter experts in earthquake engineering who are responsible for codifying seismic design criteria and performance goals into model building codes. 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 seismic qualification demand test levels must be based on the building design response spectrum and adjusted to reflect data from instrumented buildings which have been subjected to significant events. This approach must also account 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 acceleration sensitive 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 shake table testing.

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