Generic Methodology to Establish Model Building Code Compliance Acceptance Criteria for Qualification of OFC's by Shake Table Test

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ABSTRACT:

Structural engineers address the seismic resilience of facilities essential for post earthquake recovery on a site specific design basis. Manufacturers of Operational and Functional Components (OFC's, also referred to as nonstructural building components) cannot economically afford to consider seismic resilience of their equipment on a site specific basis at a price the market is willing to bear. Therefore manufacturers pursue a cost effective qualification process which envelopes a wide variety of product configurations to meet or exceed the seismic requirements for the maximum geographic area possible. Typically the design professional relies on an accepted model building code to insure a minimum level of earthquake performance. For the latest generation of model codes (similar to the USA FEMA NEHRP Provisions, National Earthquake Hazards Reduction Program) the trend is to improve and more directly address the prescriptive requirements for OFC's. While it is now possible for a modern model building code to better state seismic requirements for OFC's, they cannot communicate the intent behind these requirements because of their prescriptive nature. Therefore an acceptance criteria created by those who established the referenced model code foundation is essential to guide manufactures on how establish a qualification by test program for OFC's to insure consistency in compliance. This paper details a generic methodology to create an acceptance criteria for OFC's based on lessons learned from the creation of the first such acceptance criteria for the NEHRP influenced USA model building codes, ICC ES AC156.

KEY WORDS: shake table, qualification, testing, nonstructural, equipment, OFC

1. INTRODUCTION

The determination that a facility is essential for post event recovery triggers the need to insure that identified essential systems in the facility can be restored to operational status without repair. These systems, such as emergency power, are sometimes referred to as seismic designated systems. To have high confidence that these systems can be restored to operation the design professional, or local building code, may require critical equipment associated with these systems be certified by the manufacturer to meet the seismic demands for the project site. The common methods of seismic qualification are:

- Testing
- Analysis
- Experience data

This paper's focus is on shake table testing, the most preferred method for many applications. Other allowed methods will be reviewed with a brief discussion of when it is appropriate to use them. The goal is to add clarity for the design professional on how to select, specify and verify equipment seismic compliance. Because it embodies many concepts from the global science of earthquake engineering this paper is based on concepts from the latest U.S. NEHRP Provisions and Commentary (National Earthquake Hazards Reduction Program - FEMA 450), the seismic design basis of the International Building Code, IBC, the U.S. national model building code and ASCE/SEI 7-05.

Lessons learned from global, post-earthquake studies consistently demonstrate proper anchorage is the single most significant contributor for mitigation of damage to nonstructural building components. This evidence is the justification for special inspections in Chapter 17 of the U.S. 2006 International Building Code® (2006 IBC®). Roles and responsibilities of the equipment-to-anchorage interface will be reviewed for important considerations to insure compliance is maintained. Finally, seismic mitigation for nonstructural building components is a constant process for the entire life cycle of the facility, and methods for implementing long-term oversight are reviewed. The expertise of the authors is in the qualification of electrical power distribution and control equipment.

2. TOP LEVEL CONSIDERATIONS FOR METHOD OF COMPLIANCE

2.1 Shake Table Testing

When it is possible to do so, qualification by shake table testing is the most reliable method to qualify equipment for many applications. By subjecting the equipment to simulated earthquake motions, the entire assembly from the point of anchorage to its internal components and subassemblies are dynamically excited and stressed. This establishes a higher degree of confidence of compliance with the requirement of post-earthquake functionality.

2.2 Qualification by Analysis

Analysis is often chosen instead of testing when it is not possible to qualify electrical equipment on a shake table, for many applications, because of table limitations or other technical issues. The analysis generally is performed by Finite Element Analysis (FEA) modeling the structural system of the equipment and evaluating it for linear elastic performance. If the results of the analysis verify linear elastic performance of the load path from the attachment points of significant components, or assemblies in the equipment to the point of seismic anchorage, then it is assumed that the probability of the equipment being functional after a seismic event is high. Because the active mechanical and electrical subsystems in the equipment are not dynamically excited to verify post event functionality sole compliance by this method may not be acceptable. The analysis may have to be combined with other shake table test or experience.

2.3 Qualification by Experience

The third option sometimes considered when testing is not possible is to qualify equipment by experience. This approach has a precedent in the U.S. EPRI sponsored Seismic Qualification Utility Group (SQUG). In the 1970's new methodologies began to emerge for determining seismic attenuation relationships and site response, which resulted in an increase in the seismic design basis for forty nine operational commercial nuclear power facilities in the U.S. This increase in seismic design levels posed a problem for the continued operation of these facilities since the reserve capacity of the equipment, above the original design basis, was not well understood.

To address this issue the Seismic Qualification Utilities Group (SQUG) was formed in January, 1980 to evaluate the performance of common industrial equipment, representative of that also found in commercial nuclear power plants, which had experienced strong motion earthquakes. This "qualification by experience" proposal was found to be a more acceptable approach since requalification of existing equipment would be prohibitively costly or impractical [Yanev]. A pilot of this approach for eight classes of equipment was completed by September of 1982 and demonstrated its viability.

This was an extensive program with oversight of the data collection process by the NRC, Lawrence Livermore National Laboratory and EG&G. In order to be considered for inclusion in the database the ground motion records from seismographs near the facility had to be obtained. This ground motion data could then be compared to the required response spectra (RRS) for the nuclear power plant.

The rules for implementing the use of experience data are described in the Generic Implementation Procedure (GIP) and are proprietary to SQUG. The proprietary experience database was originally maintained by the Electric Power Research Institute. This database is a collection of findings from detailed engineering studies by a number of cross-discipline subject matter experts for twenty classes of equipment from a variety of utility and industrial facilities that experienced strong motion earthquakes.

The use of this data involves inclusion rules that must be satisfied. These rules address physical characteristics, manufacturer's classification and standards, and findings from testing, analysis, and expert consensus opinion. Four criteria are used to establish seismic qualification by experience:

- Seismic capacity vs. demand (a comparison with the SQUG bounding spectrum)
- Earthquake experience database caveats and inclusion rules
- Anchorage evaluation
- Seismic interaction evaluation

Two caveats can become problematic in order to qualify equipment by experience. The first is the maximum qualification level of the equipment from the experience database and the installation specific qualification requirement of the project. This can be problematic for a critical facility located at site of moderate to high seismicity due to a lack of data from significant events.

The second limiting consideration is due to changes in the design and construction of newer generations of equipment as compared to the equipment in the SQUG database. In some cases the equipment may have undergone two or three new design iterations and have a structural system that performs very differently from the same equipment class in the data base.

3. QUALIFICATION STANDARDS OVERVIEW

3.1 Nonbuilding Based Code Seismic Qualification Standards

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 std 344™ (IEEE 1987) and to IEEE std 693 (IEEE 2005). IEEE std 344 outlines a wide variety of qualification methods which are primarily based on linear elastic performance with varying acceptance criteria for an operating basis event and a design basis event [Hansen]. Because sites for commercial nuclear power plants are carefully chosen for seismicity the qualification levels used as a design basis are typically very low. While these three seismic testing protocols share a common technical origin, used as the basis to create the Trial-Use and Comment Standard IEEE std 344-1971, 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 for which they were created. For example it is inappropriate to solely use IEEE std 693 certification for equipment that is applied in class 1E safety related applications in nuclear power plants. Likewise the sole use of IEEE std 344 would not be acceptable to a utility for qualification of high voltage transmission components for utility substations.

IEEE std 693 was created by collaboration between utilities and manufacturers of power system transmission equipment in the 1970's and formalized into a standard in the 90's. Qualification is based on three discrete levels – low (0.1 g peak ground acceleration or less), moderate (0.5 g peak ground acceleration or less) and high (1.0 g peak ground acceleration or less). These levels do not correlate directly to a building code requirement, and it is the utilities responsibility to determine if the qualification level is appropriate for their use. Market practice is for the utility to pay for the cost of this qualification. Due to the prohibitive cost of the test samples, limitations of the test facilities and the desire of the utility to place the equipment into service, it is common practice to test the equipment to the "RRS" level. This level is half of the performance level or (i.e. actual qualification level), and this can be the source of much confusion for the design professional. The caveat that must be satisfied to test at the RRS level is that the failure modes must be known and the test sample instrumented to verify linear elastic performance of the structural system. Test specimens that contain composite structural elements require very specialized instrumentation to test at the RRS level.

Telcordia 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. Physical Design criteria are included in document GR-63, NEBS Requirements: Physical Protection. Electrical criteria are included in document GR-1089, Electromagnetic and Electrical Safety Criteria for Network Telecommunications Equipment. Both documents together are considered the “NEBS Requirements”.

There are hundreds of requirements in NEBS and seismic qualification of equipment is but a small part. 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 in which they must function. Telcordia and its predecessor Bellcore have maintained the NEBS documents since the divestiture of the Bell System in 1984. The most frequent application of NEBS is to design and test equipment intended for use in Regional Bell Operating Company (RBOC) central offices. The NEBS terminology is “telco speak” and can lead to confusion when applied outside of those applications. The NEBS standards are primarily equipment focused, as the RBOC central office building environment is unique and well defined.

4. BUILDING BASED CODE SHAKE TABLE SEISMIC QUALIFICATION STANDARD

Current model building code requirements for nonstructural components are specified using prescriptive lateral force procedures. One major prerequisite for effectively translating static loading requirements into dynamic test requirements for shake table testing is the development of a standard procedure that meets the intent of the code. Satisfying this prerequisite was the motivation to create ICC ES AC156 [Gatscher, 63-75].

First introduced in 2000, ICC ES AC156 has since been widely used by researchers and industry to qualify a large variety of nonstructural building components such as partition walls, suspended ceiling systems, mechanical and electrical equipment. This industry standard was developed in collaboration with TS8 of the Building Seismic Safety Council (BSSC), ICBO Evaluation Services (now, ICC ES) and Schneider Electric. AC156 was based on well-established methodologies from existing standards and adapted to be compatible with the intent of the seismic provisions of the building code. The goal was to create a generic test protocol that provided a consistent methodology for shake table qualification of nonstructural building components to satisfy the building code requirements. It was specifically developed to be consistent with acceleration demands (i.e., force requirements) of the NEHRP Provisions [FEMA 302, 303, 450-1,-2] as well as ASCE/SEI 7 for nonstructural components. Other national model codes which are closely based on the same NEHRP concepts, such as the 2005 National Building Code of Canada (2005 NBCC) and yield the same site specific design force requirements for OFC’s (McKevitt) can benefit directly from AC156 because it directly establishes a generic table demand from the building code referenced site specific short period (0.2 second) spectral ordinate and NEHRP criteria.

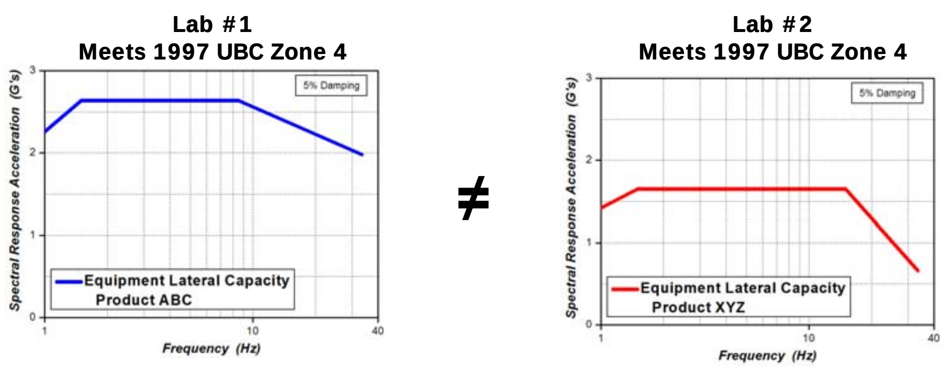

Figure 1, Ad hoc test protocols resulted in inconsistent test requirements prior to the introduction of ICC ES AC156. Illustration by: Jeff Gatscher & Scott Littler

Without the use of a test protocol recognized by the building code authority, experience has shown that qualification testing is inconsistent and confusing for both the manufacturer and the design professional to verify (Figure 1). For NEHRP based building codes the use of ICC ES AC156 simplifies the designers' task of compliance verification since this standard was developed to directly translate the intent of NEHRP for nonstructural building components into a clear and unambiguous shake table test requirement. For many types of applications the use of this standard also insures the collection of minimum test plan and report deliverables to clarify compliance requirements.

If the design professional decides not to use a building code recognized test protocol as a basis of shake table compliance, the following requirements for an alternative should be considered:

- Provide a description of how the protocol meets the intent for the project specific requirements and relevant requirements of the reference building code.
- Define a shake table testing time history criteria that is broad enough to envelop the site specific Maximum Considered Earthquake time history.
- 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).
- Define how shake table input demands were derived.
- Define and establish a verifiable pass/fail acceptance criterion for the seismic qualification test based upon the equipment importance factor consistent with code intent and project specific design intent.
- Develop rationalization criteria that can be used to establish test unit configuration requirements to represent highly variable equipment product line families.
- Recommend the development of nonstructural requirements flow-down guideline, such that project-specific requirements are correctly specified up-front and can be captured and incorporated into equipment bid specifications.

5. ANCHORAGE

All nonstructural building components attached to the building develop seismic loads during an earthquake that must be transferred to the structural system through a continuous load path to the foundation. That portion of the path which begins at the point of attachment of equipment hard point to the building and terminates to the building structural system is termed the "seismic restraint load path."

In most cases for floor anchored electrical equipment, the seismic restraint load path begins with the interface between the anchor bolt and equipment tie-down location and continues through an embedded anchor to the concrete housekeeping pad to the rebar/concrete matrix and the distribution of forces to the reinforced concrete or steel beam/column building structural system. It is the responsibility of equipment manufacturers to qualify their equipment to the equipment hard points. It is the responsibility of the design professional to provide the detail for the seismic restraint load path. For installation examples see FEMA 413, "Installing Seismic Restraints for Electrical Equipment." Failure to properly anchor equipment will result in invalidating the equipment seismic qualification.

The most common cause of electrical equipment failure during earthquakes is the primary failure of the equipment anchorage [Roper, pp 27-38]. A key finding of the SQUG program was that damage to anchored equipment was rare. The few occasions where equipment damage was noted were usually related to inadequate anchorage [Yanev]. Documented root cause failure modes of the seismic restraint path include, but are not limited to, a lack of seismic restraint (i.e. no anchor bolts), incorrect anchor type, or incorrectly installed anchors, and improperly detailed housekeeping pads (e.g. pad not doweled to floor).

6. TOOLS FOR LONG TERM MITIGATION

Seismic mitigation is a continuous activity for the total life cycle of a building to insure that the performance expectations of the orignial design professionals goals are met. FEMA 74, *"Reducing the Risks of Nonstructural Earthquake Damage a Practical Guide"* and the Canadian Standards Association CSA-832-01, *"Guideline for Seismic Risk Reduction of Operational and Functional Components (OFC) of Buildings"*, are examples of tools that could form the foundation of a facilitie's guideline for ongoing seismic risk mitigation management.

7. CONCLUSIONS

Of the three allowed methods of qualification, shake table testing is preferred when possible for many applications. Shake table qualification based on standards other than one developed specifically to meet the intent of the reference building code can impose a great deal of complexity for both the manufacturer and the design professional for building code applications. It is advisable that the use of other standards or ad hoc protocols be carefully considered and used only when project-specific requirements cannot be met otherwise.

Failure to maintain the integrity of seismic load restraint path for equipment and its associated anchorage is by far the most common root cause of electrical equipment failure during earthquakes. Proper performance starts with the detailing of the seismic restraint system by a registered structural engineer who is competent in seismic design and concludes with the correct field installation. Improperly installed or missing anchorage invalidates seismic qualification for permanently installed equipment for which qualification was based on.

Long-term seismic mitigation of a facility is the responsibility of the owner, and it requires the development and implementation of an ongoing monitoring and mitigation program. Survey guides such as FEMA 74 or CSA-S832-01 could be used to formulate an ongoing mitigation program.

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