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A RATIONAL APPROACH TO SEISMIC QUALIFICATION TESTING OF NONSTRUCTURAL BUILDING COMPONENTS

Jeffrey A. GATSCHER[1], Philip J. CALDWELL[2], Robert E. BACHMAN[3]

SUMMARY

A rational procedure is developed for applying equivalent nonstructural static force design requirements to generate a dynamic qualification test method for seismic validation of equipment for commercial (non-nuclear) service. The equipment qualification required response spectrum (RRS) is derived based on the National Earthquake Hazard Reduction Program's (NEHRP) lateral force procedure in conjunction with the building design earthquake response spectrum. This approach accounts for above grade elevation equipment installations, with or without knowing the building dynamic characteristics. Provisions are included to extend the qualification methodology to families of products by employing type-testing rationalization techniques. A well-defined pass/fail acceptance criterion is established that utilizes the equipment importance factor to define post-test acceptability. This procedure is the first recognized seismic qualification test protocol for shake-table testing to address secondary system and nonstructural building component requirements as defined by the primary model building codes being employed in the United States.

INTRODUCTION

Seismic qualification of nonstructural building components to meet the requirements specified in model building codes introduces significant challenges to equipment manufactures. Nonstructural components are defined as the entire group of miscellaneous building structural subsystems, architectural elements, mechanical and electrical equipment, and elements permanently attached to primary structures. The challenge presents itself on three areas: (1) translation of the building codes' nonstructural lateral force requirements into dynamic test parameters, (2) implementation of an equipment qualification strategy that is compatible with given requirements and (3) promoting awareness for shared responsibility between equipment manufactures, operators and installers in order to maximize the probability that equipment will be intact and functional after a seismic event. All of these issues require close examination and are the focal points of this paper.

[1] Senior Staff Engineer, Schneider Electric, Nashville, TN, USA. Email: gatscher@squared.com
[2] Staff Engineer, Schneider Electric, Seneca, SC, USA. Email: caldwelp@squared.com
[3] Structural Engineer, Bachman Consulting, Sacramento, CA, USA. Email: rebachmanse@aol.com

Regarding the first issue, present model building code requirements for nonstructural components are specified using prescriptive lateral force procedures. This implies that for any given nonstructural component, the seismic requirement is prescribed by a force magnitude, which is simply an equivalent static acceleration coefficient times the component weight. Therefore, the seismic demand requirement for any nonstructural component is a static lateral force value that is dependent upon several design factors and parameters as specified in code provisions. The magnitude of this lateral force coefficient is then the component "design requirement" and a manufacturer can use analytical methods to verify that the component's seismic capacity exceeds the prescribed demand. However, design assurance validation based on analytical techniques is less reliable than dynamic shake-table testing, especially for operating equipment. In addition, there is a growing marketplace interest in providing design assurance that seismic capacity exceeds demand based on results of shake-table qualification testing, since this is the only practical way to verify equipment functionality after the seismic event. Therefore, from the manufacturer's perspective, the desire is to achieve seismic qualification via dynamic shake-table testing in order to satisfy the lateral force procedures that are specified in the model building codes. The key issue is defining a building code specific test standard that is universally accepted in industry such that all nonstructural component suppliers are rating their equipment offerings using a common yardstick.

Regarding the second issue of implementing an effective nonstructural qualification strategy, manufacturers need the ability to seismically qualify a wide variety of equipment types. Within each major type category, there may exist several product families, each of which may offer configurable variations. Each equipment type will have fundamental structural differences in design construction and thus offer various levels of seismic resistance. In other words, some equipment platforms may be less resistant to lateral forces than other types and need to be qualified to lesser acceleration levels. In addition, testing every possible configuration of a given product platform is neither practical nor feasible. Therefore, it is necessary to select test specimens that adequately represent the entire equipment product line family for seismic qualification. This necessitates the establishment of a generic rationalization criterion that can be used to determine test unit configuration requirements for the proper representation of product platform families.

The third issue concerns promoting general awareness of seismic risk mitigation and the concept of shared responsibility between the primary stakeholders. Mitigating seismic risk and achieving the lowest possible risk associated with seismic performance of nonstructural equipment depends on the concept of shared responsibility between equipment operators, installers, and manufacturers. It is the responsibility of equipment manufacturers to conduct seismic qualification testing programs in alignment with the intentions of code writing authorities by using standardized test procedures. The equipment manufacturer determines that the equipment will be functional following a seismic event via shake-table testing. However, proper anchoring of nonstructural components is absolutely critical. The manufacturer can design equipment based on successful shake-table test results, but if the equipment is not attached to the building structure in accordance with the minimum standards recommended by the structural engineer of record, the equipment might overturn or shear the attachment devices and slide off its foundation. Such movement may damage either the building structure or other components. History has time-after-time told us that improperly anchored equipment will not perform satisfactorily during the seismic event and will likely cause catastrophic damage. It is the equipment specifier/installer's primary responsibility to determine that the nonstructural component is rigidly supported and will not leave its foundation during a seismic event. This point cannot be overstated. Incorrectly anchored or even worse unanchored equipment is a recipe for disaster and is not compatible with a seismic risk mitigation philosophy.

The problem faced by equipment manufacturers is to correctly interpret and relate the model building code requirements for nonstructural components into dynamic qualification test requirements for seismic validation of equipment designs in a uniform fashion that can be implemented in industry. Based on the above stated reasons, it is clear that secondary systems and nonstructural building components should be the subject of a practical and comprehensive seismic qualification testing protocol in order to eliminate subjective interpretations and non-uniform test methods. The approach presented herein provides the foundation needed to standardize equipment qualification practices by establishing methodologies and acceptance criteria, thereby consistently meeting the nonstructural seismic requirements as stated in the model building codes that are utilized in the United States.

INCREASED IMPORTANCE OF SECONDARY SYSTEMS

In spite of their name, secondary systems are far from being secondary in importance. It is now widely recognized that the survival of secondary systems and nonstructural building components is essential to provide emergency and recovery services in the aftermath of an earthquake. However, the evolution of model building codes in the United States has been a process that fundamentally focused on the primary structural system—the building. Consideration for secondary systems and nonstructural components has historically been given much less attention than that given to the primary structural systems. Nonetheless, in the last decade, nonstructural components have been given a renewed interest from code writing authorities and have been strongly influenced by the National Earthquake Hazards Reduction Program, BSSC [1] and BSSC [2]. This focus has led to the enactment of significant changes in this area.

It is uniformly accepted that damage to secondary systems represents a threat to life, may seriously impair a building's function, and may result in major direct and indirect economic losses. During the 2001 Nisqually earthquake that hit the Seattle/Tacoma region, it was estimated that the majority of the estimated $2 billion dollar loss was associated with damage to nonstructural components, Filiatrault [3]. In regard to the economic impact caused by the failure of nonstructural components, evidence from past earthquakes has repeatedly shown that the cost associated with the loss of the nonstructural components themselves, the loss of inventory and the loss of business income may easily exceed the replacement cost of the building that houses those nonstructural components, EERI [4] and Naeim [5].

The principal contributor for recent building code changes effecting the nonstructural component requirements is related to the increased availability of seismic experience data. The United States Geological Survey and the California Geological Survey have made significant progress in the widespread field installation of seismic monitoring instrumentation and in collecting seismology records over the past two decades. This earthquake experience data has been reduced, analyzed and the results have been incorporated into the NEHRP source provisions for nonstructural components, Gillengerten [6].

Advancing the state of the art by enriching and effectively "bringing some science" to the empirically driven design requirement definition for secondary systems and nonstructural components is a major step forward for the model building codes. It is now up to industry to keep in step and standardize on a uniform equipment qualification test protocol that can be generic in its application, and yet specific enough in its implementation, such that seismic hazard risk mitigation becomes a relatively straightforward design assurance activity that all equipment manufacturers can pursue.

THE SEISMIC RISK MITIGATION PHILOSOPHY

Building owners, developers and industrial enterprises impose upon their subcontractors and suppliers the requirements detailed in the prevailing building code being employed at the building site location. These building code requirements are captured by the equipment specifying agent and then imposed upon both equipment manufacturers who are supplying equipment to these locations and to the equipment installer who performs the required installation tasks. Mitigating seismic risk and achieving the lowest possible risk associated with seismic performance of nonstructural components depends on the concept of shared responsibility between equipment operators, installers, and manufacturers.

At the surface, this concept appears simple and strait forward to implement. However, in reality the responsibility boundaries between the primary stakeholders are not clearly understood by the respective parties. The manufacturer must properly design and detail the equipment's force resisting members and subassemblies and also provide the means for tie-down attachment to the primary support structure. The equipment manufacturer's primary responsibility is to determine that the equipment will be functional following a seismic event via shake-table testing using seismic qualification testing programs that are in alignment with the intentions of code writing authorities. It is the responsibility of the building owner's structural engineer of record to properly design and detail the equipment's anchorage system. The building's structural engineer is primarily responsible to determine that the equipment is rigidly supported and will not leave its foundation during a seismic event. The equipment installer must properly install the equipment based on the installation recommendations made by both the equipment manufacturer and anchorage system manufacturer.

It should be noted that in addition to anchorage details, the structural engineer of record should evaluate potential seismic interaction of the equipment with other nearby features including distribution systems attached to it. Impact and differential displacement on attached systems have been major contributors to nonstructural component failures in past earthquakes. Attached conduit, tubing and interface elements require adequate slack and flexibility. Adequate clearance should be provided to prevent impact with other features. These issues are "system-level" nonstructural seismic concerns that are not explicitly captured by shake-table testing performed by equipment manufactures. The rest of this paper is dedicated to describing a generic test procedure that can be used to satisfy the nonstructural manufacturers portion of the shared responsibility with the overall goal to maximize the probability that the equipment will be intact and functional after a seismic event.

EQUIPMENT QUALIFICATION TESTING PROTOCOL

Objectives

Square D / Schneider Electric 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 lateral force design requirements for nonstructural components. The approach taken was to:

- Develop the technical basis for these 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, BSSC [7] and BSSC [8].
- 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 and establish a verifiable pass/fail acceptance criterion for the seismic qualification test based upon the equipment importance factor.
- Develop a generic rationalization criterion that is used to establish test unit configuration requirements for representing product line families.
- Utilize recognized and accepted procedures for the development of the time history waveform used during the dynamic shake-table test.
- Gain national acceptance for the resulting seismic qualification test protocol and technical NEHRP interpretations by at least one credible model building code organization.
- Promote concept of shared responsibility between equipment operators, installers, and manufacturers compatible with a comprehensive seismic risk mitigation philosophy

Standards Development Background

The development of standardized equipment qualification test protocols is an activity that has been performed for several industries in the United States. The nuclear power industry has a rich history of advancing seismic qualification test procedures. The primary organization driving that effort has been the IEEE (Institute of Electrical and Electronics Engineers), and the IEEE has guided the process for seismic qualification of equipment for nuclear power generating stations for many years, IEEE [9]. A more recent IEEE undertaking was directed at establishing recommended practice for seismic design of power distribution substations, IEEE [10]. The telecommunications industry developed its own seismic qualification procedure, which was strongly influenced by work performed at Bell Laboratories, Bellcore [11]. However, none of these existing procedures relate specifically to the seismic demand requirements for secondary systems and nonstructural components as defined in the US model building codes. Because of the broad definition of nonstructural components covered under building code provisions, the aforementioned test procedures do not adequately address these more generic nonstructural seismic requirements.

The model building codes indicate that physical test data (e.g., shake-table testing) can provide basis for the earthquake-resistant design of a particular type of nonstructural component, but do not offer any guidance on how to perform testing and more important on how to interpret seismic code requirements. Simply stated, building code authorities recognize that shake-table testing provides design assurance verification of meeting code seismic requirements, but has conceded to not define a uniform test standard to accomplish it.

The International Code Council (ICC) organization offers an Evaluation Service group (ICC ES) that is responsible for performing technical evaluations and interpreting UBC and IBC code provisions. The evaluation process culminates with the issuance of reports or listings on code compliance to show that product and systems, which pass established physical testing criteria, meet code requirements. This was the process that was followed and successfully completed by Square D / Schneider Electric for establishing a generic acceptance criterion for seismic qualification testing of nonstructural building components, ICBO [12]. The development of this nationally accepted test procedure (as described herein) is a first attempt to meet an industry need for performing shake-table testing of nonstructural components. The authors view this procedure as an initial "line in the sand" until future seismic research efforts can lay the necessary foundation for more precise test methods and procedures.

Test Specimen Rationalization Criteria

Testing every single configuration of a given equipment product line may not be feasible, nor economically justified. Therefore, it may be necessary to select test specimens that adequately represent the entire equipment product line. 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:

- *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.
- *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.

- *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 major subassembly components shall be included in the UUT. These components shall be mounted to the specimen structure at locations similar to those specified for proposed installations. The components shall be mounted to the structure using the same type of mounting hardware specified for proposed installations. Substitution of nonhazardous 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.
- *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.
- *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.

Implementation of the product line selection criteria requires a configuration feature/option matrix that maps available structural design features/options against seismic withstand performance. This can be accomplished by characterizing the structural dynamic effect offered from each available configuration feature/option using analytical and/or empirical methods (finite element analysis and/or modal hammer survey). This structural demand matrix can also be used to determine test requirements for new product development activities by ranking seismic withstand performance against previously qualified configurations.

Model Building Code Provisions

The generic acceptance criterion for seismic qualification testing of nonstructural components, ICBO [12], was written to satisfy the requirements as specified in the 1997 and 2000 NEHRP provisions. The NEHRP provisions form the source document that most model building codes and standards have adopted, including the UBC, IBC, ASCE 7, NFPA 5000, and others. It should be noted that general commentary regarding the suitability of current code requirements for seismic qualification is beyond the scope of this paper.

Section 6 Architectural, Mechanical, and Electrical Components Design Requirements of the 1997 and 2000 NEHRP specifies the seismic design requirements for secondary systems and nonstructural building components. The lateral force requirement is defined by:

$$F_p = \frac{0.4\, a_p\, S_{DS}}{\left(\frac{R_p}{I_p}\right)} \left(1 + 2\frac{z}{h}\right) W_p\,, \tag{1a}$$

where:

- F_p Seismic design force centered at the component's center of gravity and distributed relative to component's mass distribution
- a_p Component amplification factor
- S_{DS} Design earthquake spectral response acceleration at short period
- R_p Component response modification factor
- I_p Component importance factor
- z Height in structure at point of attachment of component
- h Average roof height of structure relative to the base elevation
- W_p Component operating weight.

Additional stipulations are defined for allowable maximum and minimum values for F_p:

$$\textbf{Maximum} \quad F_p = 1.6\, S_{DS}\, I_p\, W_p \tag{1b}$$

$$\textbf{Minimum} \quad F_p = 0.3\, S_{DS}\, I_p\, W_p \tag{1c}$$

Close examination of equation 1a is needed to convert the lateral force requirements into shake-table test parameters. The height factor ratio (z / h) accounts for above grade-level equipment installations within the primary supporting structure and ranges from zero at grade-level to one at roof-level, essentially acting as a force increase factor to recognize building amplification as you move up within the primary structure. The component amplification factor, a_p, also acts as a force increase factor by accounting for probable amplification of response associated with the inherent flexibility of the nonstructural component, ranging from one for rigid components (no amplification) to two-and-a-half for flexible components (maximum amplification).

The site-specific ground spectral acceleration factor, S_{DS}, varies per geographic location (taken from the design value maps) and site soil conditions. The S_{DS} factor is used to define the general design earthquake response spectrum curve and is used to determine the design seismic forces for the primary building structure. Figure 1 shows the building design spectrum at the ground's surface contained in Section 4.1.2.6 General Procedure Response Spectrum of the 1997 and 2000 NEHRP. The S_{DS} factor ranges from relatively low values (0.18 g's in Florida) to high values (2.46 g's in New Madrid hazard area) depending on the seismicity of a given location.

The ratio of R_p over I_p (R_p / I_p) is considered to be a design reduction factor to account for inelastic response and represents the allowable inelastic energy absorption capacity of the equipment's force-resisting system. The component importance factor, I_p, represents the greater of the life-safety importance of the component and the hazard exposure importance of the structure. The I_p factor is used to reduce the permitted inelastic response. In other words, the higher the performance desired, the lesser the permitted inelastic response. The I_p factor is also used to indicate that verification of component operational functionality—at design earthquake levels—is required. Values for the (R_p / I_p) ratio range from 0.67 to 2.33 (while fixing I_p = 1.5). Hence, equation 1a defines the lateral force design requirement imposed on any nonstructural component for any given equipment location within a building structure and for any given building location in the United States.

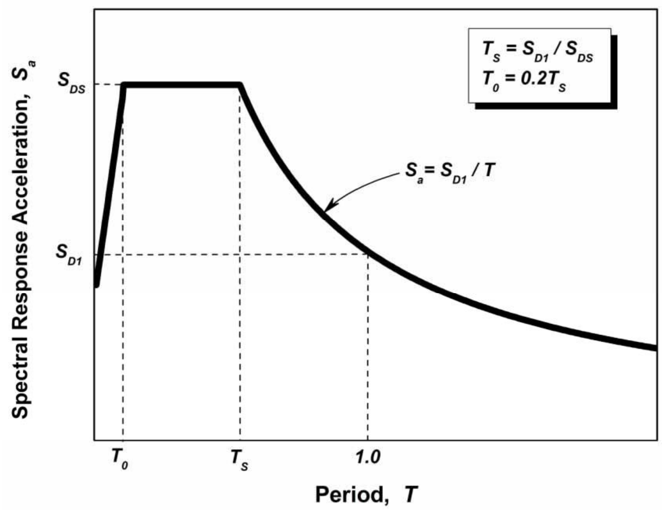

Figure 1. Figure 4.1.2.6 Design Response Spectrum, (figure reprinted from BSSC [8]).

Derivation of Seismic Qualification RRS

The goal of deriving the nonstructural seismic qualification RRS is to translate the building codes' requirements for nonstructural components into the necessary parameters compatible with shake-table testing. Typical response spectrum curves—plotted using a logarithmic scale—ramp up, remain flat, and then ramp down as illustrated in Figure 2. Correct determination of the A-B-C-D spectrum break points is the most critical step in relating lateral force code requirements to shake-table testing parameters. The shake-table RRS has its ordinate defined in terms of spectral response acceleration units (g's) and the abscissa in frequency units (Hz). It should be noted that for most mechanical and electrical equipment testing, it is common practice to use frequency units instead of period units. Throughout the remaining discussion in this paper natural frequency and period terms will be interchangeable with the understanding that frequency is simply the inverse of period.

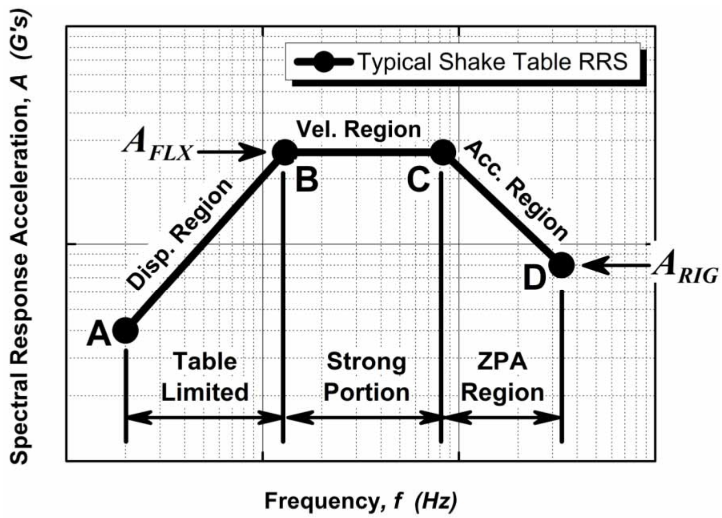

Figure 2. Typical shake-table required response spectrum curve plotted on logarithmic scale.

RRS Acceleration Values

In order to determine the nonstructural component's acceleration at point of attachment to the primary structure, the component weight is factored out of equation 1a resulting in the following formula for the NEHRP nonstructural component design lateral acceleration requirement:

$$\boldsymbol{A} \;=\; \frac{0.4\,\boldsymbol{a_p}\;\boldsymbol{S_{DS}}}{\left(\dfrac{\boldsymbol{R_p}}{\boldsymbol{I_p}}\right)}\left(1+2\,\frac{\boldsymbol{z}}{\boldsymbol{h}}\right). \tag{2}$$

As stated previously, the ratio (R_p / I_p) represents the allowable inelastic energy absorption capacity of the equipment's force-resisting system and is considered a design reduction factor. During the seismic simulation shake-table test the UUT component will respond to the excitation and inelastic behavior will naturally occur. Therefore the ratio (R_p / I_p) was set equal to one, which is indicative of an unreduced response. The authors have interpreted equation 2 to mean that the importance factor, I_p, does not increase the seismic test input motion but does effect the requirement for the UUT component to demonstrate operational functionality following seismic simulation testing and is used in AC156 to determine the post test UUT requirements for functionality compliance. The key point here is that the authors consider the shake-table input motions independent of the (R_p / I_p) ratio. For example, if a nonstructural component is ground supported (grade level installation), then the AC156 shake table input motion should equal the ground motions defined by code provisions for the base of a building. The ground motions are not increased by 1.5 because of the I_p designation for the component. However, what is expected with an I_p of 1.5 is essentially elastic response with verification of equipment functional performance immediately following the earthquake event. Conversely, with an importance factor set equal to one the expectation is inelastic response but overall structural stability and no expectation of component functionality. In addition, the authors do not consider that the ground motions should be reduced by the component's response modification factor, R_p.

The component amplification factor, a_p, was taken from the formal definition of flexible and rigid components, BSSC [1] and BSSC [2]. By definition, for fundamental frequencies less than 16.7 Hz the nonstructural component is considered flexible (maximum a_p value), which corresponds to the amplified portion of the RRS (segment B-C of Figure 2). For fundamental frequencies greater than 16.7 Hz the component is considered rigid (minimum a_p value), which corresponds to the zero period acceleration (point D of Figure 2). Hence, the RRS is constructed using two normalizing acceleration factors. The flexible acceleration factor (values for break points B and C of Figure 2) is defined by substituting (R_p / I_p) equal 1 and a_p equal 2.5 into equation 2, resulting in:

$$\boldsymbol{A_{FLX}} \;=\; \boldsymbol{S_{DS}}\left(1+2\,\frac{\boldsymbol{z}}{\boldsymbol{h}}\right), \tag{3a}$$

and the rigid acceleration factor (value for break point D of Figure 2) is defined by substituting (R_p / I_p) equal one and a_p equal one into equation 2, resulting in:

$$\boldsymbol{A_{RIG}} \;=\; 0.4\;\boldsymbol{S_{DS}}\left(1+2\,\frac{\boldsymbol{z}}{\boldsymbol{h}}\right), \tag{3b}$$

where A_{FLX} is limited to a maximum value of 1.6 times S_{DS}, in accordance with equation 1b. It is noted again that the I_p factor is not used to increase the maximum value of the shake-table input motion for reasons discussed earlier.

RRS Frequency Values

Spectral shape of the AC156 seismic qualification RRS follows the general shape depicted in Figure 2 and is constructed using the acceleration variables A_{FLX} and A_{RIG} (equations 3a and 3b) and the frequency variables (f_0, f_{FLX} and f_{RIG}) to define the RRS break points as shown in Figure 3.

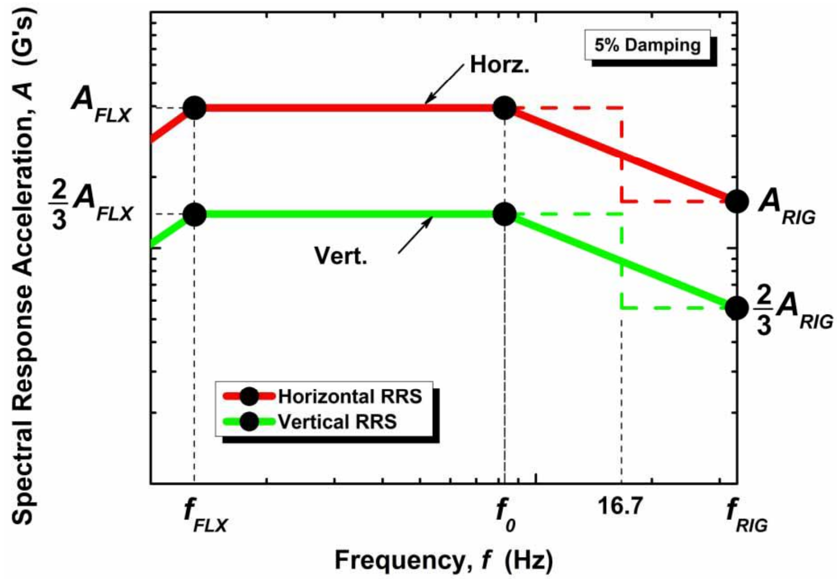

Figure 3. AC156 required response spectrum normalized for nonstructural components.

The frequency variables are directly related to the general design earthquake response spectrum curve used for design of the primary building structure as shown in Figure 1. The f_0 value corresponds to the inverse of the design response spectrum transition period T_0, from increasing acceleration to constant acceleration. Therefore, f_0 is defined as:

$$f_0 = \frac{1}{T_0} = \frac{1}{0.2\,T_S} = \frac{5\,S_{DS}}{S_{D1}} \tag{4a}$$

When soil properties are not known, Section 4.1.2.1 of the 1997 and 2000 NEHRP (Site Class Definitions) permits Site Class D to be assumed. In areas of high seismicity the ratio of S_{D1} / S_{DS} on Site Class B (soft rock) is approximately 0.4 and the ratio of S_{D1} / S_{DS} on Site Class D (moderately stiff soil) is approximately 0.6. Using the default options and substituting into equation 4a we obtain:

$$f_0 = \frac{5}{(0.6)} = 8.3 \ \textbf{Hz} \tag{4b}$$

Also in the Figure 3 AC156 spectrum, the frequency f_{FLX} corresponds approximately to the inverse of the design response spectrum transition period T_S, from constant acceleration to constant velocity. It should be noted at periods greater than T_S (where $T_S = S_{D1}$ / S_{DS}), the acceleration response of primary structures starts to reduce because the design ground motion acceleration response spectra beyond T_S reduces by the ratio of T_S / T (where T is the fundamental period of the primary structure). Since this reduction in the design forces for the primary structure is accounted for in the design force equations, it is justifiable to make a similar type of reduction in the design forces and in-structure test motion spectra of non-structural components. However, in observing the actual in-structure response spectra of acceleration recordings measured at the roof levels of buildings with a range of fundamental periods, this reduction in response typically begins at periods about 25% greater than T_S. Therefore, the authors have assumed the transition period, T_{FLX} ($1\ /\ f_{FLX}$), at the top of the primary structure at which test motion in-structure spectra begin reducing by a ratio of $T_S\ /\ T$ has been lengthened by 25% to account for this observation. At the ground level, the test motion in-structure spectra transition period matches the ground spectra. At relative elevations between the roof and the ground, linear interpolation is used to determine the transition period T_{FLX} ($1\ /\ f_{FLX}$). Therefore, f_{FLX} is defined as:

$$f_{FLX} = \frac{1}{T_S\left(1+0.25\dfrac{z}{h}\right)} = \frac{S_{DS}}{S_{D1}\left(1+0.25\dfrac{z}{h}\right)} \tag{5a}$$

Assuming a Site Class D default and substituting into equation 5a for the ratio of $S_{D1}\ /\ S_{DS}$, one obtains at the roof of the structure (where $z\ /\ h = 1.0$) the following for f_{FLX}:

$$f_{FLX} = \frac{1}{(0.6)(1+0.25)} = \frac{1}{(0.6)(1.25)} = 1.3\ \textbf{Hz} \tag{5b}$$

The f_{RIG} value is defined as the frequency associated with the zero period acceleration (break point D). NEHRP provisions define rigid components as having a fundamental frequency greater than 16.7 Hz. A value was selected for f_{RIG} to be at least one full octave greater than 16.7 Hz. Thus, f_{RIG} was set equal to 33.3 Hz. This cutoff frequency value is also consistent with other industry accepted test protocols, IEEE [9], IEEE [10], and Bellcore [11]. The values of f_0 equal to 8.3 Hz and f_{FLX} equal to 1.3 Hz and f_{RIG} equal to 33.3 Hz are currently included directly in AC156.

Two additional points should be noted about the Figure 3 AC156 seismic qualification RRS. First, between f_0 (8.3 Hz) and f_{RIG} (33.3 Hz) there is a ramping down of the spectra rather than a step function at 16.7 Hz (step function shown as dashed lines). The step function found in the code provisions is actually a simplification of the ramping portion of the design response spectrum (see Figure 1 between $T = 0$ and T_0). Second, the spectra are currently only valid for nonstructural building components with natural fundamental frequencies greater than f_{FLX} (1.3 Hz). For nonstructural components with fundamental frequencies less than f_{FLX} (1.3 Hz), site specific dynamic analyses are currently needed to develop suitable equipment qualification RRS and cannot be tested using AC156.

Vertical Requirements

Nonstructural building component earthquake effects are determined for combined horizontal and vertical loading. The required response spectrum for the horizontal direction is developed based on the normalized equipment RRS and the formula for total design horizontal force, F_p, as described above. The required response spectrum for the vertical direction is based on a simple assumption of two-thirds the ground level base acceleration, which is a common practice for defining vertical ground motion. It should be noted while explicit requirements for vertical ground motion are not currently specified in NEHRP provisions for building structures, it was considered prudent to include a vertical component in the shake-table testing protocol for nonstructural components. It is recommended that future research efforts be directed to better define the vertical nonstructural seismic requirements. The two-thirds assumption uses the same frequency break points as defined for the horizontal RRS. This assumption may not accurately reflect vertical experience data as noted in Papazoglou [13]. Both horizontal and vertical RRS are defined using a damping value equal to 5 percent of critical damping.

AC156 RRS Parameters When Building Characteristics are Known

The above formulation for development of a generic test spectra is based on not knowing anything about the building in which the nonstructural component is attached (other than the installation height). However, there are many occasions in which the building dynamic characteristics are known, and in those instances the horizontal force requirements may alternatively be defined utilizing the results of a dynamic analysis procedure for the seismic design of a specific building per Section 5.5 of 2000 NEHRP. The ground motion input for the dynamic analysis shall be consistent with response spectra constructed in accordance with Section 4.1, using R = 1.0. A result of the dynamic analysis procedure yields the following AC156 parameters for A_{FLX} and A_{RIG}:

$$\boldsymbol{A_{FLX}} = 2.5\, \boldsymbol{A_x}\, \boldsymbol{a_i} \tag{7a}$$

and

$$\boldsymbol{A_{RIG}} = 1.0\, \boldsymbol{A_x}\, \boldsymbol{a_i} \tag{7b}$$

where:

A_x Torsional amplification factor per Section 5.4.4.3 of the 2000 NEHRP

a_i Acceleration at level i obtained from the dynamic analysis procedure.

Development of the Seismic Simulation Waveform

To meet the AC156 required response spectra as defined above, the corresponding shake-table drive signals are derived using non-stationary broadband random excitations with energy content ranging from 1.3 to 33.3 Hz. The broadband shape of the AC156 RRS results from the generic approach that code provisions have taken regarding nonstructural requirements (e.g., any floor location within a building and any building location within the U.S.). Thus, the drive signal composition is multiple-frequency random excitations, the amplitudes of which are adjusted either manually or automatically based on a maximum one-third octave bandwidth resolution. The duration of the input motion is 30 seconds, with the non-stationary character being synthesized by a linear input signal build-hold-decay envelope of 5-20-5 seconds, respectively. Independent random signals that result from an aggregate of the maximum-one-third octave narrowband signals are used as the excitation to produce phase incoherent motions in the two principal horizontal and vertical axes of the shake-table. The AC156 requirement is to test in three orthogonal axes using either tri-axial, bi-axial, or uni-axial shake-tables. The use of bi-axial and uni-axial tables requires multiple stages with UUT rotation between stages such that all three axes have been tested.

In its present form, AC156 defines the shake-table requirement in terms of the normalized RRS as described above. Development of a suitable time history drive signal that satisfies AC156 spectral requirements is left to the test laboratory to accomplish prior to performing shake-table testing. The authors recognize that random multi-frequency time history waveforms may not resemble earthquake experience data, however the very nature of a broadband spectrum, necessitates the use of multi-frequency random input. Future research efforts are needed to better correlate multi-frequency random input with experience data to create hybrid waveforms that are compatible with broadband spectrum testing.

The test response spectrum (TRS) is computed using either justifiable analytical techniques or response spectrum analysis equipment using control accelerometers located at the UUT base. The TRS is calculated using a damping value equal to 5 percent of critical damping. The TRS must envelop the RRS based on the maximum-one-third octave bandwidth resolution over the frequency range from 1.3 to 33.3 Hz, or up to the limits of the shake-table control system. The amplitude of each maximum-one-third octave bandwidth is independently adjusted in each of the principal axes until the TRS envelops the RRS within the limitations of the test machine. The TRS should not exceed the RRS by more than 30 percent over the amplified frequency range. It is recommended that the TRS be computed with a maximum of one-sixth octave bandwidth resolution. Provisions are defined in AC156 to allow the TRS to dip below the RRS upon satisfying specific allowances.

Pass/Fail Acceptance Criterion

The obvious goal of performing seismic qualification testing is to demonstrate that the seismic capacity of a particular nonstructural component exceeds the seismic demand. In the past, determination of a successful test outcome has been difficult and almost entirely depends on subjective interpretation by the test laboratory. AC156 has addressed this issue by using the component importance factor to define minimum requirements for a passing test. The nonstructural component importance factor, I_p, represents the greater of the life-safety importance of the component and the hazard exposure importance of the structure, BSSC [1] and BSSC [2]. In AC156 this factor directly accounts for the functionality of the nonstructural building component under test. Essentially, there are two criteria used to determine test acceptance, one when I_p equals 1.0, and another when I_p equals 1.5:

I_p = 1.0 Equipment design must ensure that the anchored UUT will not leave its mounting and cause damage to other building components or injury to personnel during the seismic event. Structural integrity of the equipment attachment system shall be maintained. At the completion of the seismic simulation testing, the UUT does not pose a life safety hazard due to collapse or major subassemblies becoming separated, and materials deemed to be hazardous have not been released into the environment in quantities greater than the exempted amounts listed in the code. Structural damage, such as local yielding, to UUT force-resisting members is acceptable and structural members and joints comprising the UUT force-resisting system shall be allowed fractures and anomalies. Verification of post-test functional performance is not required.

I_p = 1.5 The equipment is deemed to be essential to the continued operation of a facility, and/or essential to maintaining critical life support systems, and/or contain materials deemed to be hazardous, to humans or the environment, in quantities greater than the exempted amounts listed in the code. Equipment design must ensure that the anchored UUT will not leave its mounting and cause damage to other building components or injury to personnel during the seismic event. Structural integrity of the equipment attachment system shall be maintained. After completion of the seismic simulation testing, the UUT shall satisfy all of the functional and operational tests specified by the manufacturer, and materials deemed to be hazardous shall not have been released into the environment in quantities greater than the exempted amounts listed in the code. In addition, at the completion of the seismic simulation testing, the UUT does not pose a life safety hazard due to collapse or major subassemblies becoming separated. Structural damage, such as local yielding, to UUT force-resisting members is acceptable and structural members and joints comprising the UUT force-resisting system shall be allowed fractures and anomalies. Verification of post-test equipment functionality is required.

CONCLUSIONS

Manufacturers of nonstructural equipment—using various different interpretations of model building code requirements—have pursued seismic qualification testing of nonstructural components for many years. Shake-table testing is the preferred industry approach for qualifying nonstructural equipment to meet the 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 shake-table testing RRS parameters. This situation results in multiple code interpretations and ultimately creates the occurrence of manufacturers claiming seismic qualification against building code requirements that were tested using vastly different shake-table RRS test levels.

Resolution of this inconsistency in code interpretation regarding qualification testing is addressed by generation of a generic test procedure that has been nationally endorsed by the ICC Evaluation Service organization. This test procedure document, ICBO [12], can be used to validate seismic withstand capacity for any nonstructural building component as defined by any model building code or standard that adopts the NEHRP provisions as the primary source document (which includes 2000 IBC, 1997 UBC, 2002 ASCE-7, 2003 NFPA 5000 and others). The development of the seismic qualification RRS is based upon the existing nonstructural lateral force procedure in conjunction with the building design response spectrum. 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 is 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 RRS for any nonstructural component for any given equipment location in a building and for any given building location in the United States.

This procedure is the first recognized qualification test protocol to address secondary system and nonstructural component requirements as defined by the primary model building codes being employed in the United States. The authors view this procedure as an initial attempt to define a practical seismic qualification standard that can be implemented in industry. It is recognized that future research efforts will be needed to "fine tune" this standard in the areas of vertical requirements, time history waveforms, and consideration for statistical approaches to nonstructural qualification using probability of failure measures. However, the primary goal of this paper is to help establish a standardized approach to seismic qualification testing such that subjective interpretations and non-uniform test methods can be eliminated, thus unambiguously satisfying the intent of model building code provisions for secondary systems and nonstructural building components that have fundamental frequencies greater than 1.3 Hz.

The final message to be communicated is about adopting the philosophy of seismic risk mitigation. General awareness of what is needed to lower the risk of experiencing nonstructural component failures following a seismic event is the first step. However, mitigating seismic risk and achieving the lowest possible risk associated with seismic performance of nonstructural components depends on the concept of shared responsibility between equipment operators, installers, and manufacturers. None of these parties on their own can lower the total risk, but when each party accepts responsibility for their portion, the combined risk ownership will ensure that the lowest possible risk is achieved. This concept is paramount when maximizing the probability of nonstructural component survival and functionality following an earthquake is a priority.

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