Dynamic Testing of Nonstructural Components and Equipment: Seismic Qualification and Determination of Functional Performance Limits

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ABSTRACT

Dynamic testing of nonstructural components, equipment and systems has been an effective method to satisfy seismic requirements found in model building codes used around the world. Testing is the only viable option when post–event, functional performance expectations are in place (e.g., essential equipment). Unfortunately, seismic qualification practices widely vary in industry, since correlation of the nonstructural lateral force requirements to parameters compatible with dynamic testing is not explicitly defined in code provisions. This paper presents key implementation issues necessary for conducting qualification testing in alignment with code intent as defined by code writing authorities responsible for developing the model building codes used in the United States. In addition, this paper expands on the idea that current-state qualification practice is not compatible with the desired-state goal of implementing performance-based seismic design (PBSD) approaches. PBSD is envisioned as the next-generation performance-based engineering procedures, where performance is expressed as the probable consequences of earthquake damage. A new approach to performance assessment for nonstructural components and systems will be required in which lower-level equipment subassemblies and components can be assessed independently and combined with other components to arrive at a top-level system fragility index. Composite fragility approaches will require industry acceptance prior to incorporation in the next generation building codes that adopt PBSD.

KEYWORDS: nonstructural, equipment, seismic qualification, fragility testing

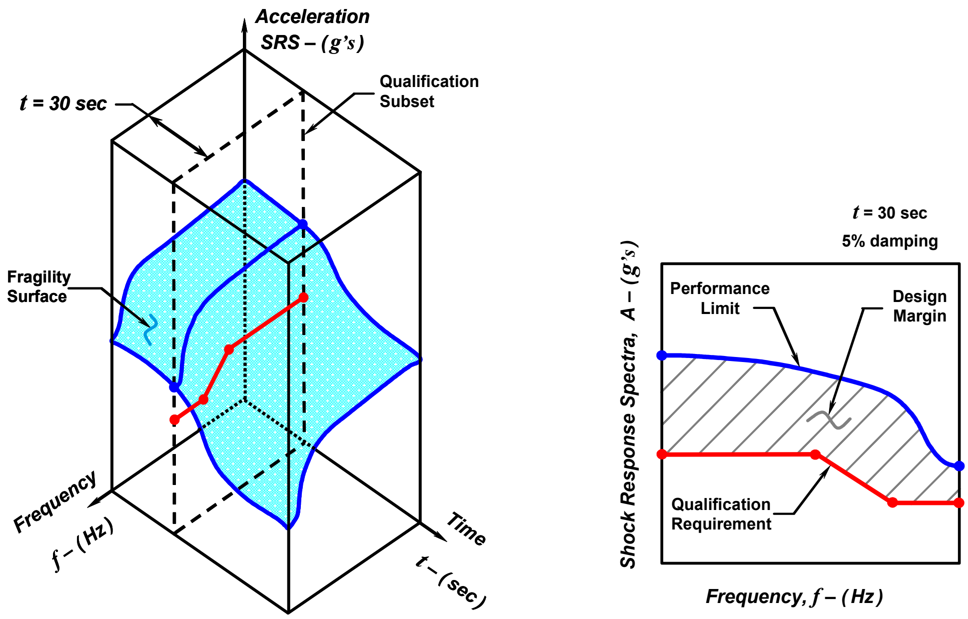
1. INTRODUCTION

The primary question that equipment manufacturers (OEMs—original equipment manufacturers) and suppliers of nonstructural components struggle with on a daily basis is: How are nonstructural equipment offerings gauged against anti-seismic requirements for compliance purposes? This is a critical question and is the issue most often mis-implemented in industry. Seismic compliance verification is a process that involves comparing the seismic capacity of equipment offerings to the specified demand requirement from a building code to verify that capacity exceeds demand for the nonstructural application. While the process of comparing equipment capacity to a specified demand level seems straightforward, it is fraught with opportunities for mistakes during implementation. What does equipment capacity actually mean? How is capacity determined? How can capacity be related to demand using comparable terms? Is equipment capacity the same as anchorage capacity? How does equipment capacity relate to system capacity? Does equipment capacity consider functional performance aspects? These questions can and do trip-up even the most astute OEM. Effectively answering these *seismic qualification* related questions is the focus of the first part of this paper.

Extending the concept of seismic qualification to address equipment fragility in the context of performance based seismic design (PBSD) approaches is another issue that needs exploring. PBSD is envisioned as the next-generation performance-based engineering procedures, where performance is expressed as the probable consequences of earthquake damage. Each damage state is expressed as a probability function, indicating the likelihood of the loss assessment based on the intensity of the earthquake ground shaking exposure. Nonstructural PBSD research efforts are being actively worked in the U.S. and future building codes will likely incorporate some form of PBSD. However, determination of PBSD implementation methods that can support industry deployment is not being actively researched. There is compelling need for evaluating nonstructural PBSD research activities in the context of implementation well before this research becomes codified in future model building code provisions. Examining the implementation aspects of fragility based anti-seismic procedures is the focus of the second part of this paper.

On the surface these two topics may seem very different and not subjects that can be combined and discussed in a single paper. However, if we step back and view these subjects from a big picture perspective there is a common thread that closely binds together both subjects. Both seismic qualification testing and fragility based testing are concerned with assessing a nonstructural component's performance under dynamic loading that is compatible with earthquake induced shaking environments. The determination of the entire performance continuum is the goal of PBSD fragility testing and seismic qualification testing is design assurance validation against a single point on the performance continuum. In fact, seismic qualification can be considered a snapshot of a specific point along the nonstructural component's performance continuum.

Before we can explore these topics in detail, we need to define the terms that are used. Nonstructural building components and equipment includes any piece of mechanical, electrical or electromechanical equipment and related systems, architectural elements and secondary building systems that are contained within a primary building structure. For purposes of this discussion, nonstructural components will be limited to mechanical, electrical or electromechanical equipment and will be referred to herein as equipment. The term performance can have many different meanings. Equipment performance is defined herein as the manner in which the equipment functions, operates, or behaves under environmental loading conditions that simulate earthquake shaking. A performance continuum is a theoretical surface relating performance anomalies (failures, malfunctions, and damage) to time duration, spectral acceleration, and frequency content. This surface defines the entire performance profile for the equipment item and is the ultimate measurement of the equipment's performance limits as a function of the three variables. The threshold performance limits of the equipment item establish the equipment's overall seismic withstand capacity. Seismic qualification relates to the performance continuum as shown in Figure 1. Qualification is a subset of the performance continuum where the time duration is set at a fixed value (30 seconds in this case) and the spectral acceleration magnitude is set at a value less than the performance limit. The difference between the performance limit and the qualification test level is called design margin.



(a) Performance continuum plot (b) Seismic qualification

Figure 1. Relationship between equipment performance continuum and seismic qualification.

The key point to be realized in Figure 1 is that a substantial leap will be required to move from today's current-state practice of conducting equipment seismic qualification to a future desired-state of mapping out equipment's overall performance continuum. And when viewing this from a pure implementation perspective, the required leap looks even more daunting. The authors believe that academic research plays a vital role in advancing global knowledge but that implementation plays the key role in protecting society from earthquake related hazards. Implementation is where the *rubber meets the road* and without effective implementation, earthquake protection of equipment will be a very bumpy ride indeed, with major gaps that remain unbridged. A good place to start this discovery is to uncover the current-state implementation challenges that exist in managing seismic qualification practices for equipment. Then, we will address the more complex challenges that will be encountered in the future as we move toward implementation of PBSD approaches.

2. IMPLEMENTATION OF EQUIPMENT SEISMIC QUALIFICATION

Many nations have well-defined building codes that have slowly evolved over the last half century with code changes being enacted on a regular basis. However, in the last ten years major code changes were adopted that fundamentally restructured the method of prescribing anti-seismic demand requirements. Previous to these changes, demands were typically specified by dividing up a country into several geographic zones, with each zone band having a uniform demand level (referred to as the zone system). The new paradigm for prescribing seismic demand incorporates a methodology based on probabilistic seismic hazard analysis (PSHA). PSHA forms the foundation of hazard maps used in modern building codes for the United States, Canada, and a growing list of other countries around the world. Building codes based on PSHA hazard maps are *site-specific* in nature and present a continuously variable anti-seismic demand requirement. The OEM needs to assess the entire range of demand levels and make informed decisions regarding the level of qualification that will be pursued for a given equipment offering. The simple fact is that maximum demand levels, as prescribed by the PSHA based hazard maps, are now impractical to easily satisfy. A good example of this can be seen by looking at the PSHA hazard maps for the United States. The maximum ground acceleration level now occurs in the central U.S., is directly linked to the New Madrid fault zone, and locally prescribes exceedingly high demand requirements. The key point here is that the OEM can no longer qualify equipment offerings to the maximum demand levels prescribed by building codes and must now pay attention to *site-specific* installation concerns. This is a new concept for the OEM to manage and it brings significant complications during order fulfillment.

To effectively implement seismic qualification practices, the OEM needs address the following issues related to equipment seismic requirements as defined by model building codes. Each of these areas will be discussed from the perspective of OEM implementation *best practices* to achieve equipment seismic qualification:
- Definition—to select the magnitude of the lateral force requirement to apply.
- Interpretation—to convert lateral force requirements into dynamic testing requirements based on code intent.
- Implementation—to execute equipment qualification testing programs.
- Verification—to verify that equipment capacity exceeds specified demand for application opportunities.

Requirement Definition—Present day model building code requirements for equipment are specified using prescriptive lateral force procedures. This implies that for any given equipment, the seismic requirement is prescribed by a force magnitude, which is simply an equivalent static acceleration coefficient multiplied by the component weight. Therefore, the seismic demand requirement for equipment is a static acceleration value that is dependent upon several design variables as specified in code provisions. The first issue at hand for the OEM is to decide on the magnitude of the design factors that influence the force equation. The site-specific ground acceleration factor has the greatest influence on the lateral force equation. Thus the OEM needs to look at the entire PSHA based hazard map that covers their prospective target market geography and assess the ground acceleration level that needs to be considered a minimum requirement. As stated above, the maximum levels will likely be difficult to satisfy, and thus a value less than the maximum is more practical and cost effective to meet. This ground acceleration assessment involves looking at the *hot spots* from the perspective of equipment application opportunities. If a localized *hot spot* covers geography that does not contain urban centers and is mostly rural, then the likelihood of receiving an equipment order in this area is remote. The goal of this assessment is to select a ground acceleration level that covers the overwhelming majority of population centers without fixating on selecting the maximum level. Chasing the maximum demand level from a qualification perspective can turn into an expensive and time consuming design activity without significant additional benefit.

The other design variable that influences the lateral force magnitude is the height factor. The force requirement at the building roof top is simply greater than the force requirement at the building foundation or grade level, due to building response amplification. However, in this case the OEM doesn't have much of an option. To limit all equipment application opportunities to those in which the equipment offering must be installed at grade level is not in the OEM's best interest. Thus, a roof level option needs to be selected. There may be a rare occurrence in which the OEM knows with certainty that the equipment is only installed on the grade level, but for the majority of OEMs, limiting equipment applications to grade level installations is not even considered.

Requirement Interpretation—The selection of a lateral force magnitude that makes good business sense to the OEM is only the first step. A task far more important than picking the requirement is interpreting the requirement. Modern building codes indicate that for compliance purposes the nonstructural seismic requirements can be satisfied by analysis, dynamic testing or use of experience data. The use of analysis is a seemingly attractive option, but it has some significant limitations in the OEM's ability to demonstrate compliance. The use of experience data has even more disadvantages and limitations than analytical methods. Thus, the most widely used method and most widely customer accepted method for design assurance validation against the code's nonstructural anti-seismic requirements is dynamic shake-table testing. This is especially true for equipment applications in which post-earthquake, performance expectations are in place (i.e., essential equipment). In addition, there is a growing North American marketplace interest in the OEM providing design assurance certification that seismic capacity exceeds demand based on the results of shake-table qualification testing, since this is the only practical way to verify equipment functionality after the seismic event. Therefore, from the OEM's perspective, the desire is to achieve seismic qualification via dynamic shake-table testing in order to satisfy the prescriptive lateral force procedures that are specified in the model building codes.

The fundamental prerequisite for effectively translating static loading requirements into a dynamic testing requirement is utilization of testing standards to ensure that uniform approaches are followed across industry. In the absence of standardized test procedures, OEM's must negotiate with test labs on a case-by-case basis to determine what the shake-table test protocol should be. This is not an optimal method because it leads to many different interpretations and approaches to satisfying code requirements and equipment qualification results will vary widely. Testing standards are routinely used across all industries to test products from concrete to aircraft and everything in-between. But, a standardized test procedure to perform seismic qualification testing in accordance with U.S. model building code seismic requirements was not available until recently.

In year 2000, the International Code Council's (ICC) Evaluation Services (ES) organization sponsored and accepted development of new acceptance criteria to qualify nonstructural equipment to building code seismic requirements. The result was AC156, "Acceptance Criteria for Seismic Qualification by Shake-Table Testing of Nonstructural Components and Systems." AC156 is the only seismic qualification test protocol that is fully correlated to the requirements specified in the International Building Code (IBC), which was based on the National Earthquake Hazard Reduction Program (NEHRP) provisions. In essence, AC156 provides the vehicle to transform lateral force requirements into dynamic testing requirements in accordance with the expectations of the code writers that were responsible for creating the NEHRP provisions (Gillengerten and Bachman, 2003; Gatscher, Caldwell, and Bachman, 2003). AC156 is currently the only nonstructural qualification test protocol directly supported by the U.S. NEHRP provisions.

Requirement Implementation—Once the OEM has selected the magnitude of the lateral force equation based on hazard map assessment and target market needs, they now have an accepted test protocol to convert the force requirements into equivalent shaker table requirements. All that is left for the OEM to do is to implement. The design drivers during product development come from satisfying the equipment's primary functional requirements. However, by including seismic compliance as a secondary functional requirement, design analysis can be conducted during the product development cycle using the seismic acceleration levels as input loading.

This type of design analysis is called comparative analysis; since multiple design candidates are compared to determine which candidate best fulfills the functional requirements. For example, perhaps four equipment structural design candidates have been developed and analyzed for seismic withstand resistance. The candidate that performs the best in resisting lateral accelerations and also satisfies manufacturability, serviceability and cost targets becomes the new equipment structural platform. The goal during conceptual design analysis for improving the equipment's seismic withstand resistance is to increase structural stiffness as much as possible without increasing base cost and without sacrificing the equipment's overall serviceability features. Most often these trade-offs pose challenging engineering decision points.

Compromises are required during any OEM product development activity, and thus the comparative analysis performed during concept development is not absolute validation that a design can pass a seismic qualification test. It provides engineering confidence that passing a shake-table test is likely, but seismic testing can have many unanticipated effects and equipment dynamic response cannot be predicted with certainty. Thus, the next step is for the OEM to conduct a seismic qualification testing program for the new equipment design. This entails many steps, but the qualification activity essentially breaks down to product line rationalization, contracting with a test lab to perform the testing, and finally conducting the test program.

The rationalization of a product line or selection of test configurations to cover the product line is often the most difficult step in the implementation process. This is especially true for equipment that are highly configurable in order to address a wide range of customer applications. Product line rationalization is part science and part marketing. Configuring the heaviest available product options with the highest center of gravity and smallest base footprint may not be the best choice. Marketing considerations are needed. For example, if this worst-case equipment configuration is not likely to be sold in high volume, then perhaps this most conservative selection should be reconsidered. Successfully passing seismic qualification testing is not a simple task and failures routinely result. Testing extreme configuration options could result in failure to meet even minimal demand levels. However, when the OEM performs pretest analysis to help with the selection process, a greater understanding of how the configuration will perform under testing conditions is gained. The disadvantage of not testing the worst-case configuration is that the OEM will have to employ an order fulfillment system that can preclude the sale of this worst-case configuration when seismic compliance is specified.

Once equipment test units have been properly configured and manufactured the test program can be executed. Depending on the complexity of the equipment offering, there could be as few as 2 to 4 test unit configurations or as many as 8 to 12 units necessary for qualification testing of the entire product line. Utilizing a testing protocol that has been specifically developed to satisfy model building code nonstructural seismic requirements is paramount. Without such a protocol in place, the OEM must negotiate with the test lab regarding code interpretation and the likelihood of arriving at a code interpretation that is harmonized with code expectations is remote. This point cannot be overstated. OEM participation in a costly and resource intensive activity such as seismic qualification testing that results in a capacity rating that cannot be justified to code authorities is to be avoided. By using a NEHRP approved test procedure (e.g., AC156) the actual qualification testing can be completed in less than two weeks. It is worth noting that the amount of preparation time and effort required prior to actual testing may greatly exceed test time – by up to a factor of five or more.

At this point of implementation the equipment platform has been shake-table tested and functional performance has been validated before and after shake-table testing. The equipment platform has been qualified to the nonstructural anti-seismic requirements of the applicable model building code. This includes the equipment's primary structural system, lateral force resisting members and internal subassemblies and components. However, this does not include the anchorage system. It is virtually impossible and is not economically justified for the OEM to test every possible anchorage system available in the marketplace (wedge, undercut, sleeve, shell, adhesive and various cast-in-place types). Thus qualification 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. In other words, the equipment is bolted to the shake-table using a steel test fixture and the required number of tie-down bolts and is not tested using concrete anchorage systems mounted to a concrete pad which is secured to a shake-table. Qualification testing of the anchorage system to determine anchorage capacity is the responsibility of concrete anchor manufacturers and not the responsibility of the OEM. These are two different capacities, one capacity for the nonstructural component and one capacity for the anchorage system. Both capacities must exceed the specified demand for a given equipment application. Proper specification of anchorage details is the responsibility of the building structural engineer of record.

Requirement Verification—Now that the OEM has designed, developed and seismically qualified the equipment offering, the qualification test data needs to be synthesized into a format that can be used for compliance verification purposes. Essentially, the qualification testing has established an equipment capacity upper limit for the equipment platform. This capacity rating is used during order fulfillment to verify that the capacity exceeds the demand for a given equipment application. Implementation of an automated capacity rating system that can be used by the OEM to deliver customer compliance certifications is desirable. This type of system requires inputting the equipment qualification test response spectrum data into a database that also contains the site specific ground acceleration demand levels from PSHA based hazard maps. The system performs a real-time seismic compliance verification check based on specifying a geographic location for the equipment installation. Thus for the equipment item, the OEM receives a request for bid proposal for supplying nonstructural equipment for a new essential facility. The OEM enters the provided building site address into their seismic compliance tool to verify that the equipment's seismic capacity exceeds the site specific demand requirement for the new building geographic location. The OEM then generates a site-specific seismic qualification certificate and attaches the compliance documentation as part of the OEM's bid specification.

Successful order fulfillment of equipment applications requires that the OEM understands the implementation needs for achieving seismic qualification in accordance with model building code requirements. This means that had the OEM not selected the right qualification level and/or not used a NEHRP approved qualification protocol, this hypothetical equipment order may have been installed without sufficient capacity and placed the OEM in a position of liability for non compliance. Requirements awareness, knowing what the current requirements are and knowing what is on the immediate horizon, is a necessary OEM practice. Requirements interpretation, knowing how to interpret in a manner that is aligned with code intent, is also a necessary OEM practice. And finally, implementing an effective OEM product development strategy that considers seismic compliance as a functional design requirement is essential to reduce engineering overhead and to ensure that seismic withstand resistance is a design driver that gets implemented during early product development.

3. IMPLEMENTATION OF EQUIPMENT FRAGILITY TESTING

The implementation practices for achieving seismic qualification, discussed above, may not sound overly complex. In fact, some may view these practices as common sense measures, but in reality very few OEMs have conducted rigorous qualification testing of equipment to satisfy the new PSHA based building codes (such as the IBC). This is due in most part to the building codes not explicitly specifying how to dynamically test equipment to satisfy the current lateral force requirement. This leaves the OEMs to implement the code's intent the best way they can, which all too often results in non-conservative, incorrect interpretations of the requirement. Even with approved test protocols such as AC156, all OEM confusion would be eliminated if the building codes explicitly specified how to convert static force requirements into dynamic testing requirements directly within the code provisions. However, for the time being this problem has been addressed by establishment of code approved test protocols. Next, attention needs to be focused on what is potentially on the horizon regarding treatment and implementation of PBSD methods.

As previously stated, PBSD is envisioned as the next-generation performance-based engineering procedures that are set to revolutionize the manner in which we think about seismic withstand capacity of equipment. PBSD employs fragility testing techniques that measure equipment performance in terms of fragility functions. Fragility functions are mathematical relationships used to assess the performance of the individual components, of systems incorporating these components, and of entire buildings containing these systems when they are subjected to loading caused by earthquake ground shaking. A fragility function indicates the probability that a component or system will experience damage at or in excess of a specific level, given that the component or system experiences a specific level of seismic demand. Fragilities are expressed as probability distributions, rather than deterministic relationships in order to account for the uncertainties inherent in the process of predicting damage as a function of demand. These uncertainties include such factors as the random nature of ground shaking and the resulting response of structures (i.e., building response and equipment response).

By examining fragility from an OEM perspective, the question becomes what is the probability that an equipment offering can demonstrate acceptable performance at varying levels of input demand? To answer this question the OEM must map-out the equipment's performance profile as illustrated in Figure 1a. Thus, the primary question becomes how does the OEM determine equipment's overall performance profile? There are currently two schools of thought on how best to accomplish this objective. The first approach is to treat equipment as *black box* building components. In other words, an equipment item is viewed from the outside as a self-contained *black box* whose internal composition is not examined when assessing its operational threshold limits while under vibration loading. This perspective requires fragility assessment to be performed at the highest or top level of equipment assembly which is the final in-service equipment condition. In theory, performing fragility assessments using top level equipment assemblies is a desirable goal. However, in practice this approach is rife with implementation problems that render it not only impractical but highly suspect for delivering incomplete information and thus yielding inaccurate risk assessment results.

The fundamental problem is that operational testing of top level equipment units, while under input vibration stimulus, requires that the test laboratory can replicate operating conditions that the building system would normally supply to equipment installations. For most equipment, these operating conditions would be difficult if not impossible to replicate in a test lab setting and would pose potentially dangerous conditions for a test lab to safely manage. For example, electrical distribution equipment require line side supply voltage and load side impedance elements to simulate the electrical distribution system parameters found in typical building applications. In fact, the high-power test equipment used by the OEM to validate electrical operational functionality is highly specialized and not transportable to a test lab facility. This reason alone makes top-level assembly testing of equipment impractical to accomplish. Another reason making this approach impractical to implement is that top-level equipment assemblies are inherently complex systems composed of many internal devices that do not support failure diagnosis at the top-level assembly. In other words, most equipment are not simple *black box* building components but are complex systems composed of smaller subassemblies that are functionally tested at a lower assembly level. Each lower-level component is tested separately to isolate the input/output parameters that are relevant for the component and to accommodate basic manufacturing practices. As lower-level components are assembled into the top-level equipment, many lower-level functional parameters are not available for fault diagnosis at the top-level, thus making performance assessments unmanageable when conducted during a top-level fragility assessment survey.

However, the reality of nonstructural equipment as assemblages of smaller components does lend itself to the second school of thought regarding fragility assessments. Not viewing equipment from the outside as *black box* building components, but viewing them from the inside as structural containers packaged with smaller subassembly equipment components provides a more useful approach to the problem. The idea is to decompose the equipment platform into constituent elements, such that fragility assessment can be performed on the individual parts, and then recombine the parts to arrive at a composite fragility representing the equipment system top-level assembly. This approach is analogous to determining the overall building structural fragility limit as a composite of the building's primary structural elements, which is the most promising solution currently being pursued by structures researchers.

The equipment decomposition process involves depicting the equipment as a structural system in which equipment subsystems are packaged and enclosed within the equipment's structural skeleton. The equipment platform's structural skeleton behaves like a frame that is mass loaded with distributed *black box* subsystems and attached to the building's primary support structure via an anchorage system. This perspective views the internal subsystem components and subassemblies as the individual *black boxes* needing fragility assessment. These *black box* equipment components are physically attached to the frame using mechanical attachments. In addition, there will typically be an electrical attachment of some kind from one *black box* to another *black box* or out to another equipment platform or out to an external power source. Thus the overall equipment platform can be decomposed into the following generalized constituent elements:

- *Equipment Force-resisting System*—defined as structural members or assemblies of members, including braces, frames, struts and attachments that transmit all loads between the equipment and the building structure. The force-resisting system supports the equipment's subassemblies and subsystem components and also transmits lateral forces and provides structural stability for the equipment platform in general.
- *Equipment Anchorage System*—defined as the primary attachment of the equipment's force-resisting system to the building structural system. The dynamic loading experienced by the equipment during the earthquake event must be reacted through the anchorage system and into the building structure.
- *Component*—defined as a logical sub-grouping of equipment functions typically organized and arranged as a physical devise, module or subassembly that can be detached from the equipment platform and can be mounted to a test fixture using the same mechanical and electrical interfaces and tested as a standalone unit.
- *Component Mechanical Interface*—defined as the mechanical interface between the component and structural frame. The mechanical interface could be mounting brackets, or mechanical fasteners or clips, or any method of attachment used to secure the component to the frame.
- *Component Electrical Interface*—defined as the electrical interface between the component and other components or between the component and the structural frame. The electrical interface could be a wired connection, or any method by which an electrical energy is sent from one point to the next.

Each of the constituent elements are assessed independently for determination of a fragility performance profile and then combined to arrive at the equipment's top-level fragility function. This type of *composite* approach requires characterization of the structural transmission paths (via the equipment force-resisting system) between components and anchorage to establish the dynamic interaction effects within the equipment platform. Rountree and Safford first introduced this composite fragility methodology in 1970 when the U.S. nuclear power industry was actively involved in fragility research. The fundamental advantage of this approach is that physically smaller and functionally less complex subassemblies are much easier and less costly to test and profile compared to testing top-level equipment units. Implementation of this approach or any other composite fragility-based testing technique that can support the needs of PBSD procedures will require research cooperation between industry and academia. PBSD procedures are likely many years away from being codified and incorporated into model building code provisions. However, the time is right to begin exploring implementation methods that can gain industry acceptance so that if and when building codes make the switch from a seismic qualification paradigm to a PBSD fragility-based paradigm, the nonstructural OEM industry will be capable and willing to implement the new approaches.

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