16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1895 (Abstract ID)

Registration Code: S-Y1463084779

Nonstructural Product Line Certification: The Evolution of Shake-Table Testing to Satisfy International Building Code Requirements

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Abstract

This paper highlights the evolution of shake-table testing methods to satisfy IBC (International Building Code) compliance requirements for seismic certification of essential building equipment. The IBC is the model building code used in the United States, and elsewhere, that is linked to the ASCE/SEI 7 design standard (Minimum Design Loads for Buildings and Other Structures). In 2000 an International Code Council Acceptance Criteria AC156 (Acceptance Criteria for Seismic Certification by Shake-Table Testing of Nonstructural Components) was developed to correlate nonstructural lateral force demands with response spectra test requirements. For the last eighteen years, AC156 has been used across industry as an accepted test protocol to certify essential equipment to IBC nonstructural requirements. AC156 has been an enormous success in establishing a uniform compliance rating for equipment seismic capacity. However, seismic certification in the United States has reached a regulatory maturity level that has outpaced industry's ability to maintain compliance when testing is conducted at the top-level of product assembly. Modern day mechanical and electrical equipment product lines will add and/or modify active subcomponents on a frequent basis. Retesting equipment to certify new or modified sub-components is simply cost prohibitive.

The next logical step in equipment seismic certification is to evolve an ability to establish product capacity ratings at lower levels of product assembly. What is needed is a generic methodology where the nonstructural test unit can be either a top-level building component / system, or can be lower-level product subsystems and subcomponents. The top-level products are referred to as "parent" product lines and the lower-level products are referred to as "child" product lines. The evolution of shake-table testing standards will need to include provisions to support testing of child products independent of the equipment parent they are contained. This would be a fundamental paradigm shift in nonstructural seismic certification. It is envisioned the long term ramification of this approach to equipment certification would be: increased number of products being tested, increased number of viable test labs to conduct testing, product testing performed upstream of the top-level equipment development activity, increased product resistance to earthquake loading, and a more cost effective certification strategy for industry implementation.

Nonstructural seismic certification is a validation process to ensure that the nonstructural product's capacity to resist motion and loading exceeds the motion and loading demand placed on it by the earthquake event. The nonstructural product represents a manufactured product line that encompasses a wide range of design variants within the product line family. Thus, the validation needs to be based on combining shake-table test results, from a subset of product samples (i.e., parent and child test units), with comparative assessment to the overall design variation. The introduction of a shake-table test standard which provides guidelines for establishing this certification process would be a major evolutionary step forward in increasing the confidence of compliance while reducing the single most significant barrier to code adoption and enforcement, the cost of implementation.

Keywords: nonstructural equipment testing; seismic certification; international building code compliance; subsystems and subcomponents

1. Background

Eighteen years ago, there was a need to establish seismic shake-table test spectra that is fully correlated with the nonstructural earthquake demand prescribed in model building codes used across North America. At that time, test laboratories established their own interpretation of code prescribed nonstructural demands and there was great inconsistency in test spectra from one test lab to the next [1]. As can be realized, this inconsistency in code interpretation created confusion for all of the stakeholders involved in earthquake protection activities. This was the motivation to create a single interpretation of nonstructural demands and resulted in establishing the first fully correlated test protocol in the United States, relating the code's lateral force demands to shake-table test spectra. AC156 was born in the year 2000 to address this key seismic testing need [2].

The establishment of a unified measuring stick for defining test spectra was a major milestone for seismic certification in North America, but it's not the only need. Since the creation of AC156, modern day manufacturing has made significant evolutionary changes, specific to the rapid incorporation of electronic and electromechanical systems into nonstructural product lines that typically did not include such devices at the time AC156 was first conceived. The manufacturing trend today is rapid inclusion of new electronics and related systems, with product update cycles about every 12-18 months. This implies that there is a new (or modified) device or electronic module added to a nonstructural product line every 12-18 months.

The compliance requirement for nonstructural certification is to validate both structural integrity and functional performance of the nonstructural test unit after being subjected to the prescribed test spectra demands. Today, seismic certification testing is performed at the top-level of product assembly. Thus, the expectation is that for every addition of a new (or modified) subcomponent device, seismic compliance testing needs to be conducted with a top-level (parent) test unit. When the subcomponent device cost is typically ten to fifty times less than the cost of the parent product test unit, it becomes a very impractical approach to certification when testing is required at the parent level of product assembly. Thus, today's need is to address testing nonstructural subsystems and subcomponents independent of the parent product to which they are part of.

The rest of this paper outlines a nonstructural testing strategy that supports testing subsystems and subcomponents independent of their parents. The certification process breaks down into two major tasks: (1) product line design assessment, which includes product mapping and rationalization and (2) product line certification assessment, which includes shake-table testing and final assessment. The nonstructural product represents a manufactured product line that encompasses a wide range of design variants within the product line family. Thus, the validation is based on combining shake-table test results, from a limited subset of product samples (parent and child), with comparative assessment to the overall design variation.

2. Product Line Design Assessment

In order to address independent testing of subcomponents, the establishment of a nonstructural product hierarchy is needed to breakdown the product system into three test unit types: (1) top-level mechanical and electrical building components and systems, (2) lower-level mechanical and electrical subsystems, and (3) lowest-level mechanical and electrical subcomponents. Figure 1 illustrates the generic hierarchy that is used to define the three categories of nonstructural product levels addressed in this paper. Thus, the nonstructural test unit (i.e., the UUT—unit under test) can be either a top-level building component or distribution system, or can be lower-level product subsystems and subcomponents. The top-level products are referred to as "parent" product lines and the lower-level products are referred to as "child" product lines.

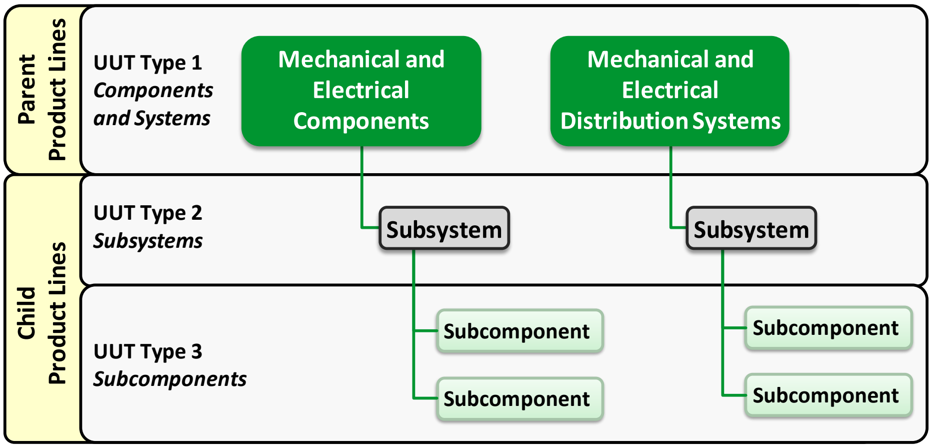


Fig. 1 – Generic nonstructural UUT product hierarchy.

2.1 Product Line Mapping

In order to establish certification of the parent product line, or to certify a portion of the parent product line, a description of the parent product line's design variability needs to be specified. The product line map serves to establish the scope of the certification program for the product line in question. Design variability is evaluated by considering two product line perspectives: (1) structural systems to resist earthquake loading and (2) operational systems to provide active functions.

The product line's force-resisting system (FRS) is the component's structural skeleton. Each parent component type will have a different type of FRS and will include structural members or assemblies of members (for example, frames, enclosures, pallets, struts, rods, panels, etc.). FRS assembly members can be joined together using mechanical fasteners or can be weldments. Monocoque construction techniques are also included as FRS types. The component FRS provides support for internal and external mounted subsystems and subcomponents. The FRS also provides overall structural stability for the nonstructural product platform. The FRS is the component's structural skeleton to resist all environmental and operating loads.

The product line's functional systems (subsystems and subcomponents) are the operating elements that transform an empty FRS skeleton into a functioning nonstructural building component or building distribution system. Subcomponents are packaged on or within the parent FRS and may be grouped together as a subsystem and mounted to the parent FRS or mounted as individual subcomponents.

Thus, the goal in product line mapping is to identify the parent product line's overall design variability by considering all FRS options that are applicable and considering all major subcomponents that are packaged as part of the parent product line. Major subcomponents are defined as any child subcomponents for which a subcomponent functional failure (structural, mechanical, thermal, electrical, and electromechanical) would result in a system failure to the essential building system in which the parent component is part of. The product line mapping process isolates the two product line perspectives of FRS options and major subcomponent family options.

2.1.1 FRS (Structural) Perspective

The first step in building the product line map, from a structural perspective, is to identify the various design features that will affect seismic withstand performance. Figure 2 displays the four aspects of FRS design options that need consideration for a given product line map.

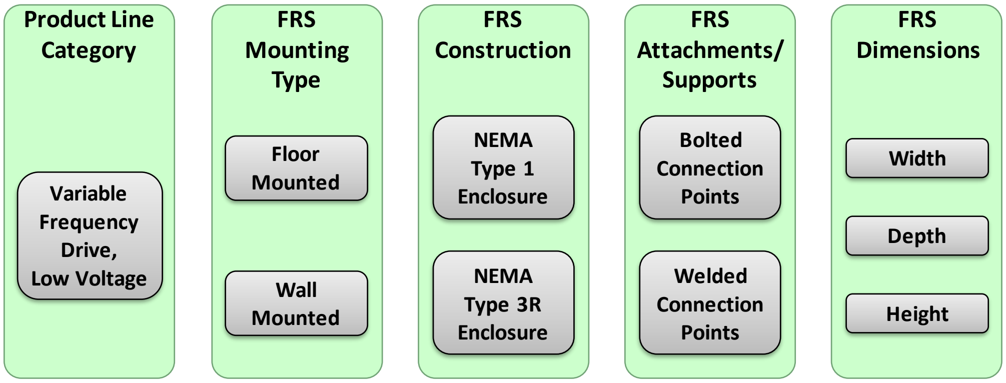


Fig. 2 – Primary FRS design features influencing seismic performance from available FRS options.

FRS Mounting Type – How the equipment FRS is mounted to the building structure has a fundamental impact on the seismic load path. Each FRS mounting type, that is a design option, establishes a unique certification level within the product line. For example, if both floor and wall mounted options are offered, then two certifications will be required.

FRS Construction – The design construction of a given product line FRS needs consideration. Design construction establishes how the primary FRS load path is designed to resist earthquake demands and includes consideration for alternate construction suppliers, designs and materials. For example, if the enclosure is constructed of folded carbon steel sheet metal members but also offers stainless steel, both options are mapped out.

FRS Attachments/Supports – FRS attachments/supports are the mechanical interface between the parent FRS and building structure at the connection points. A support is broadly defined as any structural member, brace, bracket, strut, etc. used to transfer loads from the parent FRS to building structure. An attachment is broadly defined as any mechanical fastener, bolt, screw, clip, etc. used to attach the parent FRS to a support or directly to the building structure. A weld can also be used as an attachment. The quantity, layout and orientation characteristics of FRS connection points (attachments/supports) needs to be considered.

FRS Dimensions – All FRS dimensional variances need consideration. FRS dimensions represent outline dimensional profiles for the parent product line.

The final step in building the FRS map is to layout the actual options, as related to the above criteria, from what can be configured within the constraints of the product line design space. Figure 3 displays an example product line FRS map based on the design space constraints of a low voltage, variable frequency drives product line.

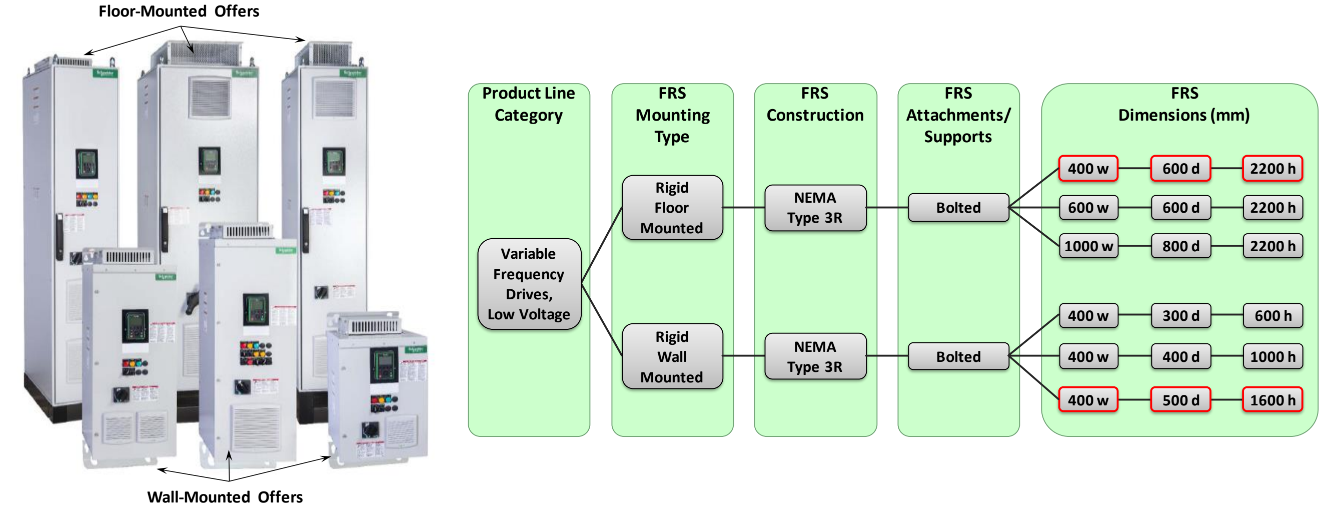


Fig. 3 – Variable frequency drives parent product line and map representing available FRS design features.

2.1.2 Subcomponent (Active Operation) Perspective

The last step in building the product line map is to consider major subcomponent families. Each family is identified and within each family, the range of design variability is specified by subcomponent performance characteristics. Performance characteristics are typically specific to subcomponent family types and will vary across different families. Figure 4 is an example of an electrical distribution circuit breaker subcomponent family map.

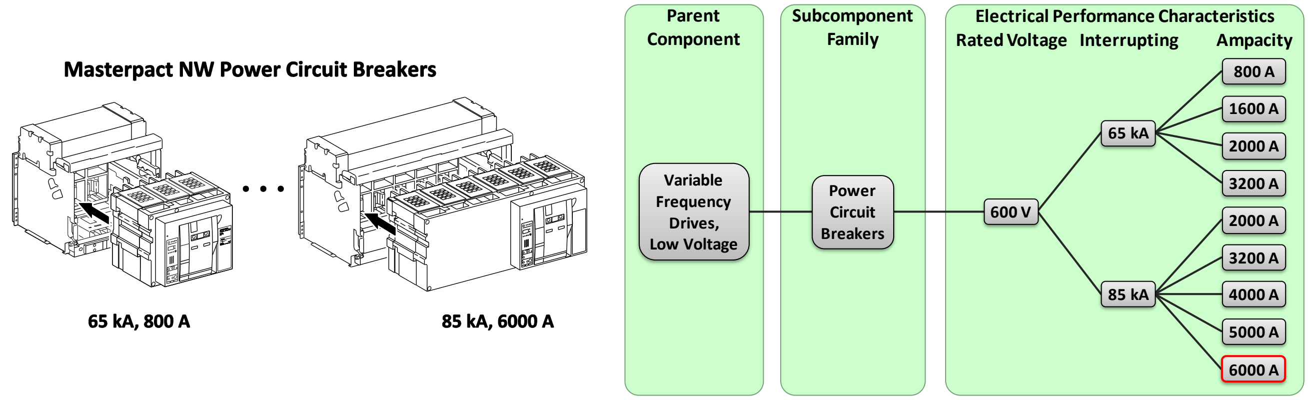


Fig. 4 – Power circuit breakers subcomponent family and map representing primary subcomponent electrical design features.

2.2 Product Line Rationalization

Product line certification involves testing a contrived and limited subset of UUTs that represent the worst case design configurations (i.e., least resistant designs) for the product line to withstand earthquake loading. Selecting the right subset of product configurations to test is a key element of the certification process. This step is often referred to as “product line rationalization.” Once the rationalized test candidates have been successfully tested, the remaining configurations (within the scope of the product line map) are certified based on extrapolation principles. Extrapolation is used to extend the certification across to the other family members within the product line being tested. The nonstructural product line is evaluated by making product design comparative assessments of both the product line’s force-resisting system and the major subcomponent families contained within the product line map.

2.2.1 Force-resisting System Criteria

The primary function of a product line’s FRS is to act as the product’s structural skeleton to resist all environmental and operating loads. Thus, the objective in selecting the right FRS design candidate to test is selecting a design variant that is most vulnerable to reacting earthquake ground motion while considering: FRS design features (as shown in Figure 2) and subcomponent packaging options that control mass density and center of mass. This implies that the right FRS design candidate to test is the one that exhibits the greatest mechanical joint stress under design earthquake ground motion loading conditions.

Within each FRS mounting type, structural evaluation of FRS design candidates requires comparative assessment to identify the FRS design candidate(s) that is most vulnerable to earthquake loading compared to the other FRS designs that are within the FRS mounting type. For example, Figure 3 identifies two mounting types, floor and wall mounts, and thus the goal is to determine the least resistant FRS design within each of the two mounting type options. The structural assessment must consider subcomponent packaging options that control mass density and center of mass for each FRS design member within the given FRS mount type. The philosophy of this approach is that if the most vulnerable FRS design (within the mount type) passes test, the remaining more earthquake resistant FRS designs will also likely pass test. The remaining FRS designs are certified by extrapolation based on the structural assessment. In Figure 3, the greatest joint stress in the FRS load path for the floor-mounted designs occurred in the smallest foot print option (400w by 600d) at maximum mass density and for the wall-mounted the greatest joint stress was exhibited in the largest unit (400w by 500d) at maximum mass. Joint stress is typically evaluated at key mechanical fasteners in the FRS load path to the building structure and used to compare across to the other foot print options.

2.2.2 Major Subcomponent Criteria

Subcomponents are the operating elements that transform an empty FRS skeleton into a functioning nonstructural building component or building distribution system. Subcomponents in themselves represent product lines that require certification. The complexity of a subcomponent product line will vary widely with many subcomponent product lines offering tens or hundreds or even thousands of design variants that need consideration during the rationalization process.

Within a given subcomponent family, there may be distinct design construction breakpoints that represent fundamental design differences that effects certification. Subcomponent design breakpoints are typically driven by certain threshold levels in performance characteristics between the family members and must be identified during the rationalization process. The same subcomponent family manufactured by different suppliers also constitutes a design breakpoint. Within each subcomponent design breakpoint, the subcomponent with the least resistant mechanical connection to the parent FRS is selected for testing. The philosophy of this approach is that the subcomponent's mechanical connection to the parent FRS is the most vulnerable element and is most likely to fail under earthquake loading. Thus, testing the unit that has the greatest FRS connection stress, and it passes, the remaining units will likely pass test. For example, in Figure 4 the 800A up to the 6000A (ampacity rating) circuit breakers represent similar breaker designs with the only difference being increasing physical size as the ampacity increases and thus one test unit is required from the family, the unit that has the greatest mechanical connection stress. In this example, it was the 6000A circuit breaker that exhibited the greatest FRS connection stress. It's worth noting, that in many instances the subcomponent that weighs the most is the one that exhibits maximum parent FRS connection stress (but not always). The remaining units are certified via extrapolation. Similarly to the FRS structural assessment, subcomponent connection stress is typically evaluated at the mechanical attachment fasteners to the FRS for comparison purposes to the other members in the family.

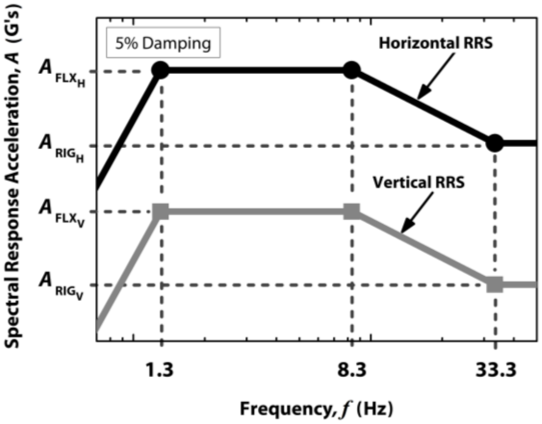
3. Certification Testing

Once product line mapping and rationalization is completed a test program can be conducted. This is where the concept of child testing becomes a fundamental need. Most electrical and mechanical equipment, that are designated seismic systems, contain many families of major subcomponents. For example, it's typical to have ten or more families that need consideration. This implies that at least ten subcomponents require testing, possibly more if there are more than one design breakpoint per family. In addition, there are the FRS design members that were identified during rationalization that need to be tested as well. Obviously, any parent FRS test candidate will be populated with as many subcomponent family test candidates as can be configured. However, the more likely scenario is that not all subcomponent test candidates can be configured into a single FRS design and will require multiple FRS configurations to cover subcomponent certification. Thus, the end result is having to test many parent FRS configurations to satisfy certification compliance requirements for validating equipment subcomponents.

Compounding this problem, is increasing industry pressure for reducing new product development time regarding subcomponent design activities. With new or modified subcomponent product development cycles every 12-18 months, the net byproduct is an endless cycle of retesting parent products that cost 10-50 times greater than the cost of the individual subcomponents needing certification. When an equipment supplier has multiple product lines requiring certification and each product line has multiple subcomponent families, the numbers add up quickly and renders the current certification process untenable. The need today is to certify major subcomponents independent of the parent.

3.1 Child UUT Test Spectra

As previously stated, AC156 is used for testing equipment to meet IBC compliance requirements. Figure 5 displays the AC156 test spectra for parent-level product testing. Testing the identified parent FRS design candidate(s) from section 2.2.1 requires using these input test spectra.



Horizontal RRS Parameters

$$A_{FLX_H} = S_{DS}\left(1+2\frac{z}{h}\right)$$

$$A_{FLX_H}\Big|_{Max} = 1.6\,S_{DS}$$

$$A_{RIG_H} = 0.4\,S_{DS}\left(1+2\frac{z}{h}\right)$$

Vertical RRS Parameters

$$A_{FLX_V} = \frac{2}{3}\,S_{DS}$$

$$A_{RIG_V} = \frac{4}{15}\,S_{DS}$$

Fig. 5 – AC156 nonstructural test spectra for equipment seismic certification.

The horizontal and vertical RRS (required response spectrum) parameters are correlated with IBC design requirements [2] and represent generic floor spectra inputs for any building location in the United States, and for any building type, and for any floor elevation within the building. What the AC156 test spectra does not represent, is the probable equipment FRS amplification associated with dynamic response. The option of testing nonstructural subsystems and subcomponents independently requires accounting for the dynamic response associated from the parent's force-resisting system.

The historical precedent for U.S. building codes, regarding nonstructural seismic design, is to treat equipment product platforms as either flexible or rigid oscillators, where the cutoff frequency is at 16.7 Hz (0.06 period) [3, 4]. An equipment item with a fundamental resonant frequency less than 16.7 Hz is considered flexible and an equipment item with a fundamental resonant frequency greater than or equal to 16.7 Hz is considered rigid. Fundamental resonance is defined as the lowest natural frequency of the parent system that is associated with maximum mass participation in each axis. This same flexible/rigid treatment can be directly used in defining test spectra requirements for child testing conducted independent of the parent product.

A parent FRS response factor, P_{FRS}, is needed to account for the probable dynamic response associated with different types of FRS mounting systems that are commonly found in nonstructural equipment applications. Table 1 identifies a set of generic options to use for the parent FRS response factor. The FRS response factors are applied independently to both horizontal and vertical axes of the UUT. This implies that if the parent product is flexible in horizontal axes but rigid in the vertical axis, different P_{FRS} factors are prescribed. It should be noted, the maximum response factor of 2.5 listed in Table 1 is equivalent to the maximum a_p factor (component amplification factor) used in the building code's nonstructural lateral force equation [4, 5].

Table 1 – Generic FRS response factors, P_{FRS}, for parent product lines

Parent Dynamic Response Category	**Parent FRS Mounting Type to Building Structure**	**Parent FRS Response Factor, P_{FRS}**
Flexible Mechanical and Electrical Components (Resonant Frequencies < 16.7 Hz)	Rigid FRS connection to floor with no top structural support/restraint added	2.5
	Rigid FRS connection to floor with top structural support/restraint added	1.75
	Rigid FRS connection to wall	1.5
Rigid Mechanical and Electrical Components (Resonant Frequencies ≥ 16.7 Hz)	Rigid FRS connection to floor with no top structural support/restraint added	1.25
	Rigid FRS connection to floor with top structural support/restraint added	1.25
	Rigid FRS connection to wall	1.25

The parent FRS response factors are used to amplify the AC156 test levels to account for FRS dynamic response when child testing is conducted independent from the parent. The required response spectrum, to be used for shake-table testing of child subsystems and subcomponents, applies the same spectrum break points (as shown in Figure 5) with the addition of the FRS response factor adjustment as shown below in Eq. (1) through Eq. (4).

$$A_{\mathrm{FLX\,H}} = S_{DS}\left(1+2\frac{z}{h}\right)P_{FRS}\,, \qquad A_{\mathrm{FLX\,H}}\Big|_{\mathrm{Max}} = 1.6\,S_{DS}\;P_{FRS} \tag{1}$$

$$A_{\mathrm{RIG\,H}} = 0.4\,S_{DS}\left(1+2\frac{z}{h}\right)P_{FRS} \tag{2}$$

$$A_{\mathrm{FLX\,V}} = \frac{2}{3}\,S_{DS}\;P_{FRS} \tag{3}$$

$$A_{\mathrm{RIG\,V}} = \frac{4}{15}\,S_{DS}\;P_{FRS} \tag{4}$$

3.2 Child UUT Shake-table Connections

Child test levels have now accounted for parent FRS dynamic effects. Equally important is accounting for the mechanical connection between the parent FRS and child subsystem or subcomponent when testing child UUTs independent of the parent. The weakest link in subsystem and subcomponent earthquake resistance is the mechanical connection interface at the point of attachment to the parent FRS. This mechanical connection interface must be represented when conducting child-level testing.

The selection of test candidates, from the subcomponent product maps, is based on determining the subcomponent with the least resistant mechanical connection to the parent FRS. The connection interface to the shake-table needs to include the necessary attachments and supports that are present in the parent-level product. The definition of attachments and supports was introduced in section 2.1.1, with respect to FRS connection to the building structure. Similarly, attachments and supports are used to connect subsystems and subcomponents to the parent FRS. The complexity of these child attachments and supports will likely vary greatly between subcomponent families, from simple connections using bolts and nuts to complex connections with nested brackets and bracing or even draw out type connections with rollers and rails. The obvious implication for highly complex child connections, is that it might be easier, and more cost effective, to test those configurations as a parent-level UUT. However, the majority of child connections will be relatively straightforward to replicate on the shake-table when testing child subsystems or subcomponents independent of the parent product they are attached.

A fundamental benefit of testing child UUTs independent of the parent, is the conservative nature of the resulting test setup. A good example of this conservatism can be found in floor mounted equipment. A flexible parent FRS shake-test will typically result in large deflections at resonant frequencies with inelastic responses. The major subcomponents, internally or externally packaged, will "ride along" with the parent FRS and will not attract the same amount of force as compared to being tested independently. Whereas a child UUT, mounted directly to a shake-table, will attract maximum force through the child's attachments and supports and thus will experience greater connection point stresses than it would experience in a flexible FRS parent test. With subcomponent connection points to the parent FRS being the weak link to resist earthquake demands, child-level testing will promote more robust connection point designs, resulting in improved earthquake resistance.

4. Certification Assessment

After successful completion of all certification test programs, the last step is to compile the product line's overall certification capacity. Certification assessment is the application of test data to determine a given product line's overall seismic certification capacity level. There are three types of assessments that can be made: (1) top-level parent product line testing, (2) lower-level child product lines tested independent of parents, and (3) lower-level child product lines tested in different parent product lines.

4.1 Parent FRS UUT Assessment

The product line rationalization step described in section 2.2 identifies which parent-level FRS test candidate(s) needs to be tested. Each parent UUT will have associated test response spectrum (TRS) analysis data taken during the shake-table test. The TRS of interest is the calculated response spectrum from the recorded shake-table control accelerometers, which is the input motion to the test unit. Each UUT will have three axes of TRS data; two horizontal axes (typically labeled UUT front-to-back and UUT side-to-side) and one UUT vertical axis. The assessment objective is to determine the least common denominator (i.e., minimum seismic capacity) from all three test axes. Figure 6 displays the process steps.

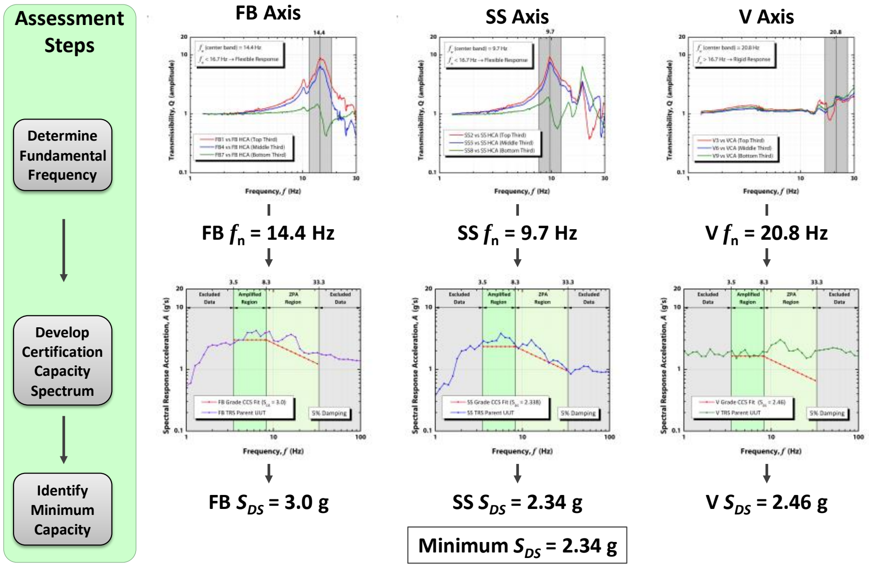


Fig. 6 – Parent FRS UUT seismic certification assessment.

A certification capacity spectrum (CCS) is established for each UUT principal axis, using the rules defined in AC156 [6]. The CCS starting frequency is dependent on the UUT's fundamental frequency in each axis and the CCS is developed to maximize the fit using the TRS data. The lowest certification spectrum, between the three axes, defines the seismic certification capacity for the top-level parent UUT. As can be observed in Figure 6, the parent UUT's horizontal axes represent a flexible response (f_n < 16.7 Hz) and behaves rigidly in the vertical direction ($f_n \geq 16.7$ Hz). The minimum certification capacity for the parent FRS UUT is $S_{DS} = 2.34$ g.

4.2 Child UUT Assessment

Each child UUT will also have associated TRS analysis data taken during a child-level shake-table test. The process for back calculating the child UUT's certification capacity is similar to that described for the parent UUT, except that the CCS starting frequency for child UUT assessment is dependent on the parent FRS fundamental frequencies. In addition, the child UUT capacity must be reduced (i.e., derated) by the applicable Table 1 P_{FRS} factors to account for probable parent FRS dynamic response. Figure 7 shows the steps for determining the certification capacity for a child UUT that will be considered in the overall certification of the parent product line.

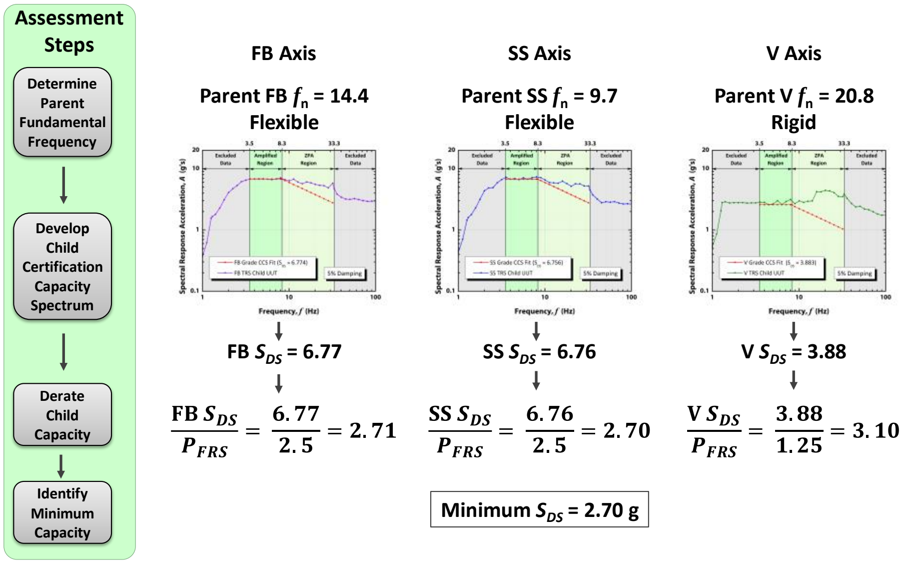


Fig. 7 – Child UUT seismic certification assessment.

In this example, the parent FRS is a floor mounted product line, thus a P_{FRS} factor of 2.5 is used for both horizontal axes (flexible response) and in the vertical axis a P_{FRS} factor of 1.25 is used (rigid response). One of the ramifications of testing child UUTs is the relatively high input spectral requirements needed to achieve capacity levels that are comparable to the parent after the derating reductions are applied.

4.3 Product Line Assessment

The final overall product line assessment is based on the minimum UUT assessment from all of the UUT data sources that are available. This includes the parent FRS UUT that represents the least resistant parent structural design and any child-level UUTs that were tested independent of the parent. In addition, subcomponent test data may be used from another parent product line that was previously tested and contained the same subcomponent as the product line under assessment. A common practice in equipment manufacturing is to package the same child product into multiple different parent product lines that are all made by the same equipment supplier. A good example of this can be found in electrical equipment. The same circuit breaker might be packaged into many different types of parent products (e.g., switchboard, switchgear, motor control center, etc.).

The major restriction for this type of child certification assessment is that the parents must all share a common FRS mounting type to the building structure. Floor mounted parents can be used together and wall mounted parents can be used together, but floor mounted parents cannot be used with wall mounted parents. This restriction is a byproduct of the seismic load path being dependent on how the parent FRS is attached to the building.

Figure 8 illustrates a final capacity assessment for a given product line. The product line elements highlighted in red were used to determine capacity. When viewed in this manner, it becomes evident which element of the product line is limiting the overall capacity. Increasing the certification level of the lowest element, will increase the certification of the parent product line. In many cases, a simple retest of a child subcomponent to higher test levels will directly improve the parent's overall certification capacity rating. In this example, the final product line capacity is S_{DS} = 1.98 g, with the limiting element being a major subcomponent (from UUT-2 source).

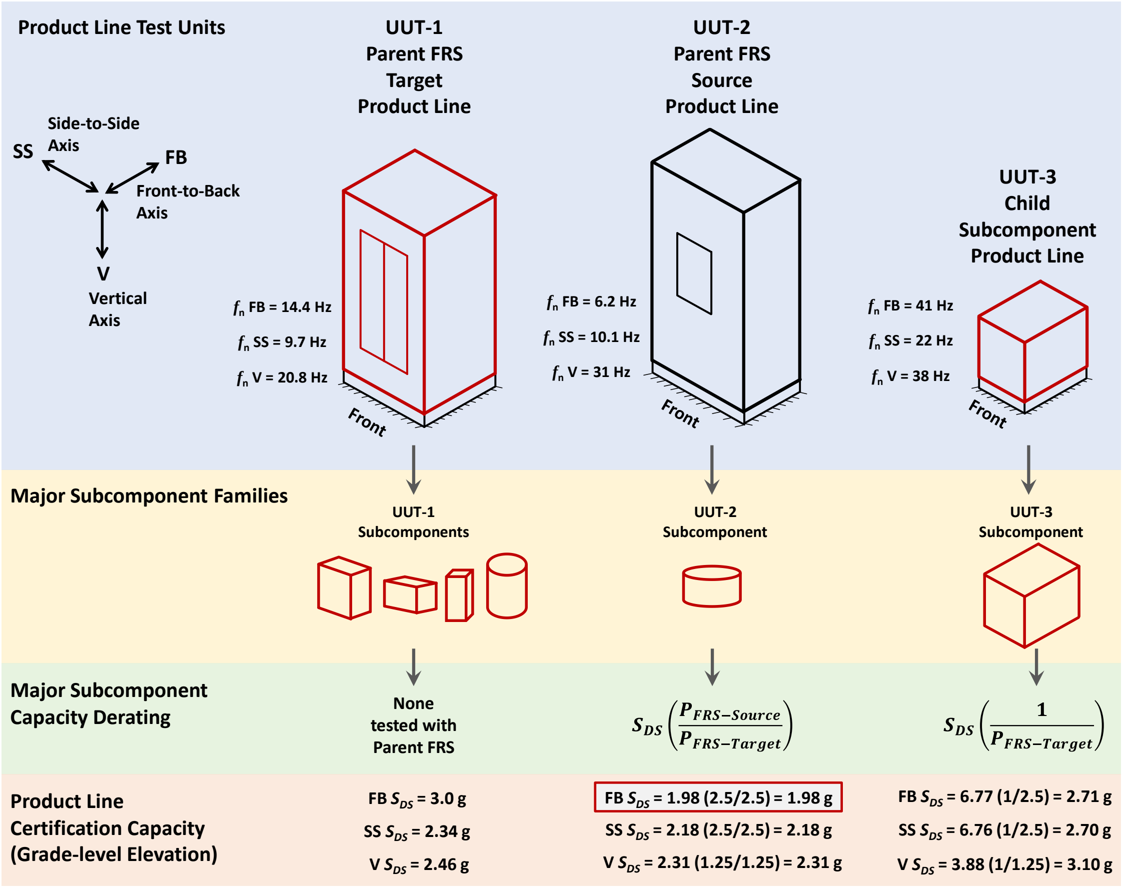


Fig. 8 – Product line seismic certification assessment.

5. Value Proposition

Economic reality must be a key ingredient in any engineering endeavor and earthquake protection is no different. The current state of nonstructural earthquake protection in the United States renders full compliance an impossible task based solely on the prohibitive cost of implementation. With the establishment of testing subcomponents and subsystems independent of the parent product line, a pathway to full compliance will be paved. The value proposition is compelling when seismic certification can be conducted at both parent and child-levels of product representation. The following summarizes the positive aspects of this new seismic conformance strategy.

- The total cost of certification will be reduced and spread across the supply chain thus eliminating the single greatest barrier to implementation we have today, high cost. Full compliance can be achieved when cost of compliance can be shared with a greater number of subcomponent suppliers.

- The total number of products that get tested will increase, resulting in improved overall nonstructural earthquake resistance. Today, the reality is that not all major subcomponent families are tested when testing is mandated at the parent level. The cost is prohibitive with this approach, and thus today, both equipment suppliers and code regulators are forced to circumvent the requirements.
- Independent child testing will result in more robust mechanical connection designs, which is the dominant failure mode for subcomponent packaging to the parent FRS. In addition, child testing will occur early during the subcomponent development cycle when product changes are easily made at less cost.
- With an increase in the number of subcomponents being tested, there will also be an increase in the number of test labs able to perform shake-table testing of "smaller and lighter" UUTs. Smaller electrohydraulic shake-tables (≈ 1m x 1m) are significantly less costly to install and maintain compared to the typical large scale shake-tables (≈ 4m x 4m). With more test labs available for testing the cost of testing will decrease.

6. Conclusions

Nonstructural earthquake protection in the United States has evolved over the last twenty years from simplistic anchor bolt calculations to extensive shake-table testing with active operation validation. However, regulatory enforcement has outpaced industry's ability to fully comply, specifically when compliance requires testing equipment at the top-level of product assembly. Today, it is not possible to fully comply because the cost is well beyond economic reality. The next evolutionary step in seismic certification is testing equipment subcomponents and subsystems independent from the parent product. This will provide the necessary pathway for equipment suppliers to implement a seismic conformance strategy that reduces certification cycle time, reduces total certification cost, and reduces the risk of noncompliance.

The seismic certification process involves product line mapping, rationalization, test programs and final assessment. The strategy outlined is this paper provides the needed details to support implementation of testing equipment subcomponents and subsystems while accounting for the parent's dynamic response and the mechanical connection to the parent FRS. The proposed parent FRS response factors are in full alignment with the current nonstructural amplification factors used in the code's lateral force equation. The authors envision this new approach to nonstructural seismic certification will result in overall improved nonstructural earthquake resistance while reducing the single most significant barrier to code adoption and enforcement, the cost of implementation.

7. References

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