the TRS touches the RRS. The corresponding S_{DS} value for the new RRS becomes the as-tested capacity rating that can be used for nonstructural certification purposes.

Figure 5B2-3(b) displays the adjusted RRS levels for each input direction. The adjustment of RRS levels to fit the TRS is performed in each axis. The final capacity for the test unit is the minimum adjusted RRS from the three input directions. In this example, the adjusted horizontal RRS level corresponds with $S_{DS} = 1.6$ and the adjusted vertical RRS level yields $S_{DS} = 2.055$. Thus, the as-tested nonstructural FRS capacity is $S_{DS} = 1.6$, which is the minimum of the three axes. The low-frequency cutoff shown in Fig. 5B2-3(b) is defined in AC156 and is dependent on the minimum FRS natural frequency (75% of the lowest natural frequency). In this example, the cutoff was set at 2.8 Hz. TRS points less than 2.8 Hz are ignored.

Functional Device

Functional device #1 [Fig. 5B2-2(a)] was qualified as part of the system-level testing with the same qualification parameters as shown for the FRS capacity. Thus, the capacity rating for device #1 is identical to the FRS capacity ($S_{DS} = 1.6$). However, the second functional device is a new product feature that has been recently incorporated into the nonstructural platform. The second functional device was tested as a standalone device and has a different capacity rating.

In this case, the transfer function between anchorage and location of device #2 needs to be determined. In other words, the amount of dynamic amplification that device #2 receives from the FRS needs to be accounted for during standalone testing. Then, upon completion of device #2 qualification testing, the device TRS is used to determine a capacity rating while accounting for the system transfer function. The as-tested capacity of device #2 is finally converted to an equivalent ground motion rating using AC156 formulation. The seismic capacity of device #2 is determined to be $S_{DS} = 1.51$ with $z/h = 1.0$.

The functional device capacity rating in this example is based on two different capacities. The rating for device #1 is based on dynamic testing of the top-level nonstructural assembly, and the rating for device #2 is based on standalone device testing using the response spectrum method (see Chapter 9 for details on conducting standalone device testing).

Attachments and Clearance Envelope

The three operational attachments (i.e., conduit) secured at the top of the equipment [Fig. 5B2-2(c)] provide a flexible connection to the FRS, and seismic capacity at the connection points is not a design factor if the necessary clearance is provided during installation. The necessary clearance can be validated by inspection of the nonstructural installation. At least 75 mm (3 in.) of FRS motion should be accommodated. This clearance is considered conservative and is loosely based on typical FRS displacements under seismic testing demands for flexible base-anchored equipment that are between 2 and 3 m ($\approx$ 7–10 ft) tall. The building design professional performs this visual inspection.

The isolation attachment is a spring and elastomeric snubber design [Fig. 5B2-2(b)] that inserts between the FRS and anchorage at eight locations along the base. Force demands calculated from the rigid-body anchorage calculation can be used to determine structural integrity of the base isolation frame, isolators, and welded connection between the FRS and the base isolation frame. For this example, the isolation design is specifically addressing earthquake demands. The intended isolation interaction is to attenuate seismic demands going into the equipment platform. Note that the code states that components mounted on vibration isolators shall have a bumper restraint or snubber in each horizontal direction. The design force shall be taken as $2F_p$ (Eq. 5B2-2) if the nominal clearance (air gap) between the equipment support frame and restraint is greater than 6.5 mm (0.25 in.). The building design professional is responsible for everything from the welded FRS connection to the base isolation frame itself, including isolators, down to the concrete anchors. The minimum seismic capacity of this base isolation system is determined to be $S_{DS} = 2.1$.

Combined System-Level Ratings

Table 5B2-1 summarizes the nonstructural capacity ratings for this example. Also shown in the table is the responsible stakeholder. As can be observed, the overall capacity for this nonstructural system ($S_{DS} = 1.43$) is based on the lowest capacity rating from the system elements. The anchorage displays the lowest-ranked capacity although overall, for this application, the nonstructural system-level capacity exceeds the project-specific demand ($1.43\ g > 1.187\ g$), resulting in positive compliance.

Another way to perceive this is to evaluate the potential limiting factors. This application can be installed in any location where the S_{DS} ground motion is less than 1.43 g (assuming equivalent concrete pad properties and height installation). Building site locations that exceed S_{DS} of 1.43 g will require either an increase in anchor bolt diameter or adding more anchor tie-down points. This will provide additional capacity until reaching S_{DS} demands of 1.51 g and greater. Once the ground motion intensity reaches this magnitude, the only way to show compliance is a retest of device #2 to higher qualification levels. It should be noted that the system capacity ratings are dependent on installation height. The capacity ratings increase if the application requires ground-level installation ($z/h = 0$).

The point of this example is to highlight the concept of combining individual nonstructural element capacities to determine a system-level capacity and highlight who is responsible from a qualification perspective. One of the benefits from this approach is immediate illumination of the system element that is limiting seismic compliance. It becomes obvious which system element needs improving to increase seismic withstand resistance. Design decisions to improve nonstructural seismic capacity become objective-based actions to improve the system's weakest link.

A secondary point from this example is to illustrate the highly variable nature of present-day qualification. The code's earthquake hazard maps present continuously variable demands that, in turn, create variable nonstructural capacities to satisfy building applications. Because capacity is a function of ground motion intensity (S_{DS}) and

Table 5B2-1. *Capacity Ratings for Nonstructural System Elements.*

Nonstructural System Element			Responsible Stakeholder	Seismic Capacity[a] S_{DS} (g)	Validation Method
Mechanical Subsystem	Force-Resisting Skeleton (FRS)		OEM	1.6	System-level testing performed in accordance with AC156 requirements using: $S_{DS} = 1.425$ $z/h = 1.0$ $I_p = 1.5$
	Attachments	Operational Attachment	Building Professional	N/A	Visual inspection performed at the nonstructural installation location to verify that flexible connection to FRS is adequate.
		Bracing Attachment	None	None	None
		Isolation Attachment	Building Professional	2.1	Rigid-body analysis performed in accordance with ASCE/SEI 7-10 requirements (snubber air gap < 0.25 in.) using: $S_{DS} = 1.187$ $a_p = 2.5$ $R_p = 1.5$ $z/h = 0.75$ $I_p = 1.5$
	Anchorage		Building Professional	**1.43**	Rigid-body analysis performed in accordance with ASCE/SEI 7-10 requirements using: $S_{DS} = 1.187$ $a_p = 2.5$ $R_p = 1.5$ $z/h = 0.75$ $I_p = 1.5$
Active Operation Subsystem	Functional Device #1		OEM	1.6	System-level testing performed in accordance with AC156 requirements using: $S_{DS} = 1.425$ $z/h = 1.0$ $I_p = 1.5$
	Functional Device #2		OEM	1.51	Standalone device testing performed by accounting for system transfer function between anchorage and device location.

[a]A seismic capacity rating $S_{DS} \geq 1.187$ structural application.

installation height ratio (*z/h)*, capacity can vary from application to application. This type of seismic qualification is a fundamental departure from the days when seismic demands were classified as one of four seismic zones.

In the past, standard OEM practice was to qualify nonstructural platforms to the maximum Zone IV demand level, and that was it. Today, the absolute worst-case floor motion, derived from IBC and ASCE/SEI 7-10 hazard maps, is too severe for most platforms to realistically meet. Qualification today involves strategically selecting floor motion demand levels that are less than worst-case maximums, based on the relative robustness of the product platform. Analytical methods can be used to help assess a platform's seismic robustness, as discussed in Chapter 6.

Each nonstructural platform will likely have different capacity ratings. This implies that nonstructural systems cannot be supplied without first assessing whether the capacity exceeds the project-specific application demand. This situation places the compliance verification burden directly on the design professional responsible for a given building application (i.e., the engineer of record). It is the nonstructural supplier's responsibility to clearly identify the equipment capacity rating (i.e., ground motion intensity and installation height ratio), so the engineer of record can evaluate the overall nonstructural system capacity.

5.3.1 Compliance Verification

It is apparent that the result from a systems design approach to seismic qualification is multiple capacity ratings for the various nonstructural system elements. After the qualification process is completed, each nonstructural platform will have different seismic capacity ratings based on the least capacity of the individual elements. In fact, each different functional device could have its own capacity rating. This by-product can create significant implementation issues for nonstructural OEMs that need to supply many different nonstructural platforms, with each platform offering multiple design configurations to support various building applications. Keeping track of all of the capacity ratings can be a logistics nightmare.

There are a couple of ways to handle this potential problem. One approach is to associate a seismic capacity rating to each nonstructural system element using factory-assigned metadata tags. A metadata tag, in this case, is the S_{DS} capacity magnitude assigned to a factory part number. When a nonstructural product application is fulfilled, the various elements that comprise the nonstructural system will dictate the overall capacity rating. Another way to approach this is to assign a seismic capacity rating tag to the top-level nonstructural part number, based on a worst-case assessment of functional device capacities.

In either case, the implementation requires using technology automation tools that can be incorporated into factory order systems. Manually evaluating every nonstructural product application for seismic compliance is highly inefficient and should be discouraged. Automation tools can be developed (i.e., software modules) that will save time, provide consistency across different platforms, and, most importantly, will avoid mistakes during compliance assessment.

Another advantage of incorporating seismic capacity ratings as metadata is the ability to visualize seismic compliance as a function of geography. Figure 5-5 shows the seismic compliance of two nonstructural product platforms as a function of U.S. geography. In the first example, the platform capacity is $S_{DS} = 0.73\,g$ and the second has a capacity set at $S_{DS} = 1.33\,g$. White areas on the map signify potential installation locations where the nonstructural capacity exceeds the required demand. Dark gray areas signify locations where the nonstructural platform does not meet demand requirements. As can be observed, the first platform [Fig. 5-5(a)] does not have enough capacity to satisfy most of the West Coast demand requirements. The second platform improves on the available locations in which capacity exceeds demand [Fig. 5-5(b)] but still cannot satisfy all of the West Coast demand requirements. Since both plots reflect a capacity rating at grade level ($z/h = 0$), applications that require above-grade installation would decrease the available locations even more for satisfying demand requirements (increase in dark gray areas).

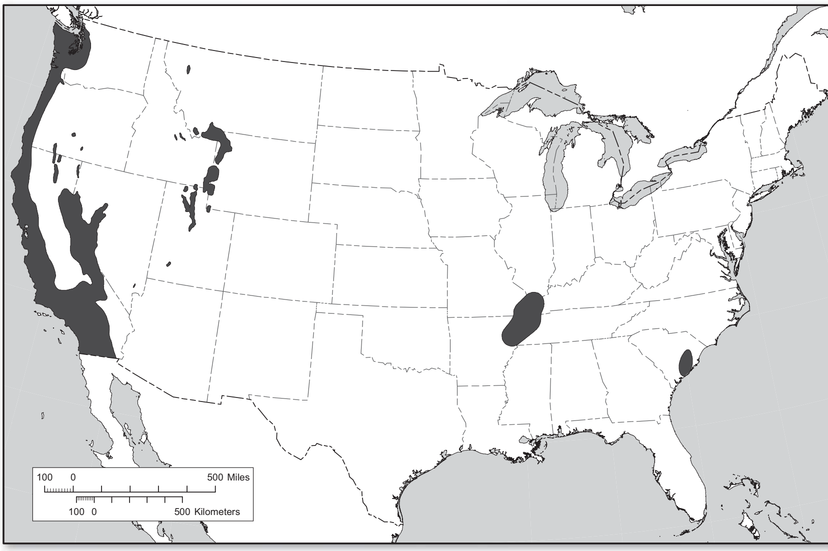
These graphical maps offer the OEM an immediate assessment of compliance status for given nonstructural offerings while also providing an objective tool to make decisions regarding future design changes. If a particular platform does not cover enough of the target market geography, then platform design modifications can be made to increase the platform's seismic withstand resistance. If the seismic capacity rating is assigned at the subsystem level, the maps can be used to isolate which of the nonstructural elements needs improving (i.e., which element is limiting the overall nonstructural capacity).

In addition, graphical compliance maps provide a tool to assess code changes made to the earthquake hazard maps. Since building codes are typically revised every 3 years (including hazard map revisions), any changes to the hazard maps can be visualized from the perspective of nonstructural compliance impact. Increases in ground motion intensity can potentially reduce the amount of geography that a nonstructural system can satisfy. Nonstructural systems that have lower capacity ratings are more susceptible to increases in the ground motion values prescribed in code hazard maps. Objective decisions can be made regarding nonstructural design changes and qualification retests when ground motion increases have eroded the amount of geography the nonstructural system can successfully meet.

This provides the greatest flexibility regarding nonstructural qualification. Ground motion magnitudes will fluctuate from code cycle to code cycle. However, this does not imply that nonstructural requalification is required with every change. Minor fluctuations in ground motion will have minimal impact on nonstructural compliance for most applications.

5.4 Seismic Qualification Summary

Nonstructural qualification is a validation process ensuring that the nonstructural system has greater capacity to resist motion and loading than the application demand as specified by building code seismic requirements. Each of the nonstructural system elements could have a different capacity rating based on using an accepted qualification method (i.e.,



(a)

(b)

Figure 5-5. *Nonstructural compliance shown as function of U.S. geography; dark gray areas represent locations in which the nonstructural item's capacity does not meet the required demand: (a) equipment platform with seismic capacity at* $S_{DS} = 0.73$ *g for grade-level installation; (b) equipment platform with seismic capacity at* $S_{DS} = 1.33$ *g for grade-level installation.*

analysis, testing, comparative experience, or combined methods). Multiple stakeholders are responsible for seismic compliance validation. No single stakeholder is responsible for qualifying the entire nonstructural system.

Seismic capacity ratings need to use a metric that is common to code-accepted compliance methods. The IBC and ASCE/SEI 7-10 ground motion spectral acceleration at short period, S_{DS}, is the appropriate common metric to use across the qualification methods. Presently, nonstructural dynamic testing and dynamic analysis must use an interpreted response spectrum that is consistent with code intent. The ICC Evaluation Service's AC156 is the only code-approved protocol to serve this purpose. We encourage code writers to incorporate a nonstructural response spectrum option directly into code provisions to eliminate the need for interpreted code requirements. This step will greatly minimize the existing implementation gaps with respect to nonstructural dynamic requirements.

Nonstructural compliance verification has become increasingly complex over the past decade. This is partially driven by the change in seismic hazard being prescribed by probabilistic ground motion maps and the abandoning of the old zone system. In addition, the expectation of postearthquake active operation for designated seismic systems now requires explicit demonstration of active performance following design-level earthquake demands. These code changes make compliance assessment a much greater challenge for OEMs and nonstructural suppliers. Nonstructural seismic qualification has evolved beyond simple anchor bolt calculations and now requires proactive measures by all stakeholders to get it right.

A product's seismic withstand resistance needs to be viewed as nonstructural design intent. This requires OEMs to adopt a coherent qualification strategy that becomes part of the product development process. The starting point for an effective strategy is requirements awareness—knowing what the nonstructural seismic requirements are for a given target market and how product offerings are gauged against the requirements for compliance purposes. The goal is to ensure that seismic withstand resistance is a design driver that gets implemented during early product development.

The cost of nonstructural seismic qualification should be viewed as a long-term investment. Model building codes have significantly evolved and will continue to evolve. The practice of establishing seismic compliance in the 21st century needs to evolve as well. The days of self-serving interpretation of the requirements or essentially ignoring the requirements completely have ended. New special enforcements demand a higher level of compliance with higher expectations for postearthquake performance. The next few chapters provide an updated look at using analysis, testing, comparative experience, and combined methods to establish nonstructural seismic compliance compatible with 21st-century building code expectations.

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Chapter 6

Analytical Methods

The capability of analysis tools available to engineers today is overwhelming. From graphical applications that embed closed formula equations to sophisticated finite element analysis (FEA), many types of analytical software are easily accessible to the modern-day design professional. However, deciding on the right tool and approach for the job at hand is not always a simple task. The explosion of computer processing capability has been a mixed blessing for design engineers. Finite element models (FEMs) are routinely solved that contain hundreds of thousands of degrees of freedom (DOF) and run on modest-sized personal computers. But do bigger models equate with increased accuracy? Does solving more complex models provide any insight into operational performance? Can simple hand calculations provide adequate information for the design professional to make good decisions? Can analysis be used to qualify nonstructural systems? These questions are explored here in the context of performing seismic analysis for nonstructural equipment and distribution systems. In addition, these questions are viewed from a perspective of satisfying building code requirements (IBC and ASCE/SEI 7-10) (ICC 2011; ASCE/SEI 2010) to achieve seismic compliance.

The goal of this chapter is to introduce a variety of analysis tools—in essence, to provide the design professional with a seismic analysis tool kit to draw upon. The analyses discussed are certainly not new but, in the context of their seismic application, they should help illuminate the complexities associated with nonstructural qualification. Our assumption here is that analysis application and results interpretation are more important than the specific software being used. There will be no discussion regarding which menu buttons to click for specific software programs. There are many commercially available FEA