Seismic Design of Nonbuilding Structures and Nonstructural Components

Part 2: Advanced Topics related to ASCE 7-16

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This article is the conclusion of a two-part series which discusses the seismic design provisions for nonbuilding structures found in Chapter 15 of ASCE 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures.* The previous article (Part 1, STRUCTURE, April 2017) provided an introduction to the seismic design of nonbuilding structures.

Several seismic related issues are unique to nonbuilding structures. This article covers the following advanced topics in the seismic design of nonbuilding structures:

- The determination of seismic forces on nonbuilding structures supported by other structures.
- The determination of seismic forces on common nonstructural components attached to nonbuilding structures.
- The interrelation and overlap between Chapter 13, *Seismic Design Requirements for Nonstructural Components*, and Chapter 15 of ASCE 7-16.
- Special considerations for the seismic design of tanks and vessels.

Nonbuilding Structures Supported by Other Structures

Section 15.3 of ASCE 7-16 provides requirements for the design of nonbuilding structures supported by other structures for seismic forces, and presents three possible scenarios:

- The nonbuilding structure weight is less than 25 percent of the combined weight of the nonbuilding structure and the supporting structure (15.3.1).
- The nonbuilding structure weight is greater than or equal to 25 percent of the combined weight of the nonbuilding structure and the supporting structure (15.3.2(1)) – rigid nonbuilding structure (T < 0.06 seconds).
- The nonbuilding structure weight is greater than or equal to 25 percent of the combined weight of the nonbuilding structure and the supporting structure (15.3.2(2)) – flexible nonbuilding structure ($T \geq$ 0.06 seconds).

Nonbuilding structures supported by other structures see amplified seismic forces in a similar manner as nonstructural components. To discuss the seismic design of nonbuilding structures supported by other structures, a review of the determination of seismic forces on nonstructural components is important.

Nonstructural Components

Section 13.3.1 of ASCE 7-16 specifies the use of Equation 13.3-1 (shown below) to determine the seismic design force on a nonstructural component.

$$F_p = \frac{0.4a_pS_{DS}W_p}{\left(\frac{R_p}{I_p}\right)}\left(1+2\,\frac{z}{h}\right) \qquad \text{Eqn. 13.3-1}$$

F_p shall not to be taken as less than:

$F_p = 0.3S_{DS}I_pW_p$

F_p is not required to be taken as greater than:

$F_p = 1.6S_{DS}I_pW_p$

where:

F_p = seismic design force

a_p = component amplification factor that varies from 1.0 (rigid component T_p < 0.06 seconds) to 2.5 (flexible component). T_p is the fundamental period of the component.

R_p = component response modification factor (same concept as R for structures)

I_p = component importance factor (1.0 or 1.5). I_p is not necessarily the same as the value of I_E for the supporting structure.

S_{DS} = short period spectral acceleration

W_p = component operating weight

z = height in structure of point of attachment of component with respect to the base.

h = average roof height of structure with respect to the base

The values of a_p and R_p are taken from Table 13.5-1 for architectural components or Table 13.6-1 for mechanical and electrical components.

Various terms in Equation 13.3-1 have significant physical meanings. The term $0.4a_pS_{DS}$ represents the peak ground acceleration when a_p equals 1.0 and the constant acceleration region of the response spectrum (plateau) when a_p equals 2.5. The term $(1 + 2z/h)$ represents an additional amplification of the ground motion acceleration due to the elevation of the point of attachment of the supporting structure.

25 Percent Limitation

Where the weight of the supported nonbuilding structure is less than 25 percent of the combined effective seismic weights of the nonbuilding structure and supporting structure, the design seismic forces of the supported nonbuilding structure are determined according to Chapter 13 where the values of R_p and a_p are determined per Section 13.1.5. Equation 13.3-1 is used to calculate the seismic force, F_p, on the supported nonbuilding structure. The supporting structure is designed to the requirements of Chapter 12, *Seismic Design Requirements for Building Structures*, or Section 15.5, *Nonbuilding Structures Similar to Buildings*, as appropriate, with the weight of the supported nonbuilding structure considered in the determination of the effective seismic weight, *W*. Section 15.3 represents a clear dividing line between Chapter 13 and Chapter 15 where the nonbuilding structure is supported by another structure.

More than 25 Percent with *Rigid Nonbuilding Structure*

Where the fundamental period of the supported nonbuilding structure, *T*, is less than 0.06 seconds, the supported nonbuilding structure is considered to be a rigid element. In this case, the supporting structure is designed to the requirements of Chapter 12 or Section 15.5 as appropriate, and the *R*-value of the combined system is permitted to be taken as the *R*-value of the supporting structural system. The supported nonbuilding structure is simply taken as another mass in the design of the supporting structure. This procedure is similar to that used for the case where the supported nonbuilding structure is less than 25 percent of the combined mass.

The supported nonbuilding structure and its attachments are designed for the forces determined using the procedures of Chapter 13, where the value of R_p is taken as equal to the *R*-value of the nonbuilding structure as outlined in Table 15.4-2, and a_p shall be taken as 1.0.

It is important to note that very few supported nonbuilding structures qualify as rigid elements. There is a great temptation to assume that the supported nonbuilding structure is rigid due to the resulting ease of calculation and lower loads. The period of the supported nonbuilding structure must be honestly evaluated, taking into account such items as fluid-structure interaction and the flexibility of the supporting floor beams. Procedures for taking fluid-structure interaction into account can be found in TID-7024 (1963).

More than 25 Percent with *Flexible Nonbuilding Structure*

Where the fundamental period of the supported nonbuilding structure, *T*, is greater than or equal to 0.06 seconds, the supported nonbuilding structure is considered to be a flexible element. In this case, the nonbuilding structure and supporting structure are modeled together in a combined model with appropriate stiffness and effective seismic weight distributions. The combined structure is designed to Section 15.5, with the *R*-value of the combined system taken as the lesser *R*-value of the nonbuilding structure or the supporting structure.

The supported nonbuilding structure and its attachments are designed for the forces determined for the supported nonbuilding structure in the combined analysis. A flexible nonbuilding structure supported by another structure is by far the most common situation. Because the combined structure is designed using the lesser *R*-value of the supported nonbuilding structure or the supporting structure, the use of a high *R*-value structural system (e.g. special concentrically braced frame) offers no economic advantage. Of course, a high *R*-value structural system may always be used to provide better performance.

The use of a combined model requires that the structural engineer designing the supporting structure work in close collaboration with the manufacturer of the supported nonbuilding structure. The combined model does not have to be complex. An example of this type of combined model can be found in Appendix 4.G of ASCE *Guidelines for Seismic Evaluation and Design of Petrochemical Facilities* (2011).

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Common Nonstructural Components Attached to Nonbuilding Structures

Table 13.6-1 (Mechanical and Electrical Components) and Table 13.5-1 (Architectural Components) contain the basic seismic parameters (a_p and R_p) for many common nonstructural components. Occasionally, the engineer will run into cases where specific values for the components are not listed. In this case, it is best to use "*other mechanical or electrical components*" from Table 13.6-1 or, in the case of an architectural component, use values from "*other rigid components*" or "*other flexible components*" from Table 13.5-1.

For mechanical or electrical components not listed in Table 13.6-1, the category of "*other mechanical or electrical components*" provides a simple, although conservative, solution by using a_p of 1.0 and R_p of 1.5. Engineers often try to use values for components in Table 13.6-1 that they feel are similar to their component. The engineer takes on some risk in using this approach because the descriptions of the components in Table 13.6-1 are not very detailed. An example can be seen in trying to choose values for a *fin fan*. A *fin fan* is a type of air cooler with integral support legs that is often supported on pipe racks. The values listed for fans in Table 13.6-1 (a_p = 2.5 and R_p = 6) are not intended for *fin fans* with integral support legs (these values do apply where *fin fans* are not supported on integral support legs). *Fin fans* with integral support legs have been added to Table 13.6-1 (a_p = 2.5 and R_p = 3) in ASCE 7-16. It was necessary to specifically add an entry, with significantly reduced values, for *fin fans* with integral support legs to ASCE 7-16 due to the fans' poor performance in seismic events, such as the February 27, 2010, Chile earthquake (Soules, Bachman, and Silva, 2016). When in doubt, and when you cannot match your component to an exact description in Table 13.6-1, you should select the "*other mechanical or electrical components*" category.

For architectural components not listed in Table 13.5-1, the multiple choices provided under "*other rigid components*" or "*other flexible components*" require engineering judgment. The engineer must first decide if the component is rigid or flexible. This decision should be based on an approximate natural period, T_p, for the component. The engineer must then decide if the elements and attachments of the component are high-deformability, limited-deformability, or low-deformability. Section 11.2 provides definitions of high-, limited-, and low-deformability regarding the ratio of the ultimate deformation to the limit deformation. These definitions, while precise, are not straightforward to apply. Fortunately, the commentary to Chapter 13 provides some guidance. For example, the commentary notes that high-deformability materials are materials such as steel or copper that can accommodate relative displacements inelastically if the connections also provide high-deformability. Therefore, the types of connections used are critical in the classification process. As an example, steel walkways and steel platforms are commonly attached to nonbuilding structures in industrial facilities. While the steel walkways and platforms are constructed of a high-deformability material, the connections often are not seismically detailed and frequently include short attachment columns with limited ability to absorb inelastic deformations. Most configurations would also qualify as flexible. Therefore, a reasonable recommendation for values of a_p and R_p for steel walkways and platforms are a_p = 2.5 and R_p = 2.5, which corresponds to "*other flexible components*" and "*limited-deformability elements and attachments*."

Chapter 13 or Chapter 15?

As described earlier, ASCE 7-16 Section 15.3 provides a clear delineation between Chapter 13 and Chapter 15 for nonstructural components and nonbuilding structures supported by other structures, based on the weight of the supported nonstructural component or nonbuilding structure. Unfortunately, the same cannot be said of certain nonstructural components and nonbuilding structures supported at grade and common to both chapters. The following recommendations attempt to address this lack of clear delineation between Chapter 13 and Chapter 15.

The most informative reference for deciding whether to use Chapter 13 or Chapter 15 is *Nonstructural Component or Nonbuilding Structure?* (Bachman and Dowty, 2008). This resource identifies the common components covered by both Chapter 13 and Chapter 15 as:

- Billboards and Signs
- Bins
- Chimneys
- Conveyors
- Cooling Towers
- Stacks
- Tanks
- Towers
- Vessels

Bachman and Dowty also suggest three ways to differentiate between nonstructural components and nonbuilding structures:

- Size – nonstructural components are small, usually less than 10 feet in height
- Construction – nonstructural components are typically shop fabricated
- Function – nonstructural components are primarily designed for functionality while nonbuilding structures are primarily designed to maintain structural stability

Tanks and Vessels

Tanks and vessels are *nonbuilding structures not similar to buildings*. As such, they exhibit a very different dynamic response than building structures. There are four special considerations for tanks and vessels:

1) The importance of anchor rod stretch.
2) The importance of providing seismic freeboard.
3) The importance of providing piping flexibility.
4) Special design requirements for vessel support skirts.

Anchor Rod Stretch

Many nonbuilding structures rely on the ductile behavior of anchor bolts to justify the *R*-value assigned to the structure. Anchor bolts used for tanks and vessels must stretch under seismic loads to provide the required ductility. Section 15.4.9 provides a consistent treatment of anchorage on nonbuilding structures. Anchors must be designed to be governed by the tensile strength of a ductile steel element. Post-installed anchors in concrete or masonry must be pre-qualified for seismic applications.

Section 15.7.3 is intended to ensure that anchor attachments are designed such that the anchor will yield (stretch) before the anchor attachment to the structure fails. Under Section 15.7.3, connections, excluding anchors (bolts or rods) embedded in concrete, must be designed to develop Ω_0 times the calculated connection design force.

Section 15.7.5 requires anchorage to meet the requirements of Section 15.4.9, whereby the anchor embedment into the concrete must be designed to develop the tensile strength of the anchor. The anchor must have a minimum gauge length (stretch) of eight diameters.

The load combinations with overstrength of Section 12.4.3 are not to be used to size the anchor bolts for tanks, or horizontal and vertical vessels. Oversized anchors are not able to stretch and, therefore, do not provide the required ductility.

Seismic Freeboard

The impact of a sloshing wave on the tank roof or forcing the floating roof into a fixed roof is a continuing source of seismic damage to ground supported storage tanks. Occasionally, external floating roofs are forced outside of the tank shell by the sloshing wave and end up landing on the shell or having the seal catch the shell. Loss of a floating roof in any of these cases often results in a fire. This damage can be eliminated by providing sufficient seismic freeboard.

Piping Flexibility

The lack of flexibility in piping connections to tanks is a continuing source of seismic damage to ground supported storage tanks. Therefore, ASCE 7 requires piping systems connected to tanks and vessels to be flexible enough to take specified displacements as noted in Table 15.7-1. The piping must be able to accommodate these movements at allowable stress levels.

The piping must also be able to accommodate the amplified movements (C_d times the values in the tables) without rupturing. Experience shows that systems with little or no flexibility fail in large seismic events and systems with flexibility built-in perform well.

Vessel Support Skirts

Skirt supported vessels fail in buckling, which is not a ductile failure mode. Therefore, a more conservative design approach is required. To prevent collapse, ASCE 7 Section 15.7.10 and Table 15.4-2 require skirt supported vessels to be checked for seismic loads based on R/I = 1.0 if the structure falls in Risk Category IV or if an R-value of 3.0 is used in the design of the vessel. The R/I = 1.0 check will typically govern the design of the skirt over using loads determined with an R-factor of 3 in a moderate to high area of seismic activity. The foundation and anchorage are not required to be designed for the R/I = 1.0 load.

Conclusion

This article provides an overview of some advanced topics encountered in the design of nonbuilding structures and nonstructural components. Key takeaways from this article include:

- Seismic forces on nonbuilding structures supported by other structures are determined by the size and stiffness of the supported nonbuilding structure.
- The choice of design coefficients for nonstructural components is a function of the deformability of the element and its connection.
- The applicability of Chapter 13 or Chapter 15 can be determined based on the size, construction, and function of the component or nonbuilding structure.
- The performance of tanks and vessels in a seismic event depends heavily on the anchorage details used, the use of seismic freeboard, the use of flexible piping connections, and the proper design of skirt supports.▪

The online version of this article contains detailed references. Please visit **www.STRUCTUREmag.org**.