Structural Design

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Seismic Design of Nonbuilding Structures

Introduction to Designing with ASCE 7-16

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The title of ASCE 7-16 is *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. This article is the first in a series intended as an introduction to the seismic design of the "other structures," commonly known as nonbuilding structures.

Types of Nonbuilding Structures

Nonbuilding structures are divided into two different categories for seismic design – *similar to buildings* and *not similar to buildings*.

Nonbuilding structures similar to buildings are designed and constructed with structural systems similar to buildings. Nonbuilding structures similar to buildings also have a dynamic response similar to buildings. A typical nonbuilding structure similar to a building is shown in *Figure 1*, a pipe rack that uses ordinary moment frames and ordinary braced frames to resist seismic forces.

ASCE 7-16, Section 15.5, provides specific requirements for certain nonbuilding structures similar to buildings:

- Pipe Racks (15.5.2)
- Storage Racks (15.5.3)
- Electrical Power Generating Facilities (15.5.4)
- Structural Towers for Tanks and Vessels (15.5.5)
- Piers and Wharves (15.5.6)

Additionally, Section 11.1.3 allows industrial buildings to be treated as nonbuilding structures in certain situations for the purpose of seismic design. Many industrial buildings have geometries and framing systems that are different from the typical occupied structures covered by Chapter 12. The limited occupancy of these buildings reduces the hazard associated with their performance in seismic events. Therefore, when the occupancy is limited to maintenance and monitoring operations, these structures may be designed in accordance with the provisions of Section 15.5 for nonbuilding structures similar to buildings. Examples of such structures include boiler buildings, aircraft hangars, steel mills, aluminum smelting facilities, and other automated manufacturing facilities.

Nonbuilding structures not similar to buildings are designed and constructed with structural systems very different from those used in buildings. Nonbuilding structures *not* similar to buildings also have dynamic response not similar to buildings.

A typical nonbuilding structure *not* similar to a building is shown in *Figure 2*, an elevated water tank that is a shell structure transferring forces through membrane action. Sections 15.6 and 15.7 provide specific requirements for certain nonbuilding structures *not* similar to buildings:

Figure 1. A nonbuilding structure similar to a building.

Figure 2. Nonbuilding structure not similar to a building.

- Earth Retaining Structures (15.6.1)
- Stacks and Chimneys (15.6.2)
- Amusement Structures (15.6.3)
- Special Hydraulic Structures (15.6.4)
- Secondary Containment Systems (15.6.5)
- Telecommunication Towers (15.6.6)
- Steel Tubular Support Structures for Onshore Wind Turbine Generator Systems (15.6.7)
- Ground-Supported Cantilever Walls or Fences (15.6.8)
- Tanks and Vessels (15.7)

Different Treatment of Nonbuilding Structures for Seismic Design

The primary differences between buildings and nonbuilding structures are in the occupancy of the structures and the structural systems used. As mentioned above, the limited occupancy of these nonbuilding structures reduces the hazard associated with their performance in seismic events. Nonbuilding structures are designed for higher seismic forces because nonbuilding structures do not incorporate elements that increase damping and ductility typically found in buildings (floors, diaphragms, non-structural elements). For the same reason, Section 15.4.4 allows the fundamental period of nonbuilding structures to be calculated using the structural properties and deformation characteristics of the structural system of the nonbuilding structure without the restrictions and limits of Section 12.8.2.

Determination of Basic Seismic Parameters

The seismic parameters used for the design of nonbuilding structures are the same as those used for the design of buildings with a few exceptions, as noted in the subsequent sections. These seismic parameters are discussed below.

Return Period, Risk, and MCE_R

ASCE 7-16 uses risk-targeted Maximum Credible Earthquake (MCE_R) ground motions. The MCE_R ground motions use the different shapes of hazard curves to adjust the uniform hazard ground motions (2-percent-in-50-years) such that they are expected to result in a uniform annual frequency of collapse, or risk level when used in design. The risk level targeted in ASCE 7-16 corresponds (approximately) to 1 percent probability of collapse in 50 years. The design ground motion contained in ASCE 7-16 is taken as two-thirds of the MCE_R ground motion.

Map Values S_s, S_1, and T_L

S_s represents the mapped MCE_R, 5 percent damped, spectral response acceleration at short periods (constant acceleration portion of response spectrum). S_1 represents the mapped MCE_R, 5 percent damped, spectral response acceleration at a period of 1 second (constant velocity portion of response spectrum). T_L represents the long-period transition period that separates the constant velocity portion of the response spectrum from the constant displacement portion of the response spectrum. T_L varies from 4 seconds to 16 seconds. T_L has little effect on the design of building structures but has a major effect on certain types of *nonbuilding structures not similar to buildings*. T_L has a significant impact on the magnitude of the convective force and sloshing wave height in aboveground liquid storage tanks.

Soil Types

Soil conditions can amplify the seismic ground motion. ASCE 7-16 defines six different soil types (A-F). If the soil type is unknown, soil type D must be assumed (ASCE 7 Section 11.4.2) with a minimum value of F_a equal to1.2. Soil type F requires a site-specific evaluation. A site-specific response analysis is required in the following situations:

- Structures on Site Class E sites with S_S greater than or equal to 1.0
- Structures on Site Class D and E sites with S_1 greater than or equal to 0.2

To account for the different soil types, the MCE_R ground accelerations S_S and S_1 are modified by F_a and F_v respectively. Values of F_a and F_v are found in Tables 11.4-1 and 11.4-2.

S_{DS}, S_{D1}, and the Design Response Spectrum

The design response spectrum is defined by S_{DS} and S_{D1} and is based on 5% damping. Liquid has a much lower damping resulting in higher seismic forces. For most nonbuilding structures, the application of S_{DS} and S_{D1} is identical to that for buildings. Above ground liquid storage tanks are an exception to this statement. For the convective (sloshing) component in above ground liquid storage tanks, the response spectrum values for the constant velocity region and the constant displacement region are multiplied by 1.5 to convert the values to 0.5% damping.

Risk Category

The Risk Category for a nonbuilding structure is defined in Section 1.5 and Table 1.5-1 of ASCE 7-16. Unlike the majority of buildings, most petrochemical structures will fall in Risk Category III or IV based on the Material Safety Data Sheet (MSDS) of the products stored, unless the hazard assessment provisions of Section 1.5.3 are used to justify a reduced risk category. Many petrochemical structures store large quantities of hazardous materials, thereby requiring a more conservative design approach. The Risk Category affects the importance factor used for the design of the structure, as well as some design and detailing requirements. Table 1.5-2 is used to determine the Importance Factor (IE) value based on Risk Category. The Importance Factor (I_E) is used to adjust the level of structural reliability of a nonbuilding structure to be consistent with the classification listed in Table 1.5-1.

Seismic Design Category

In ASCE 7-16, the Seismic Design Category (SDC) is a function of Risk Category and soil modified seismic risk in the form of S_{DS} and S_{D1} and is determined from Tables 11.6-1 and 11.6-2. For a given nonbuilding structure, SDC is determined twice – first as a function of S_{DS} and a second time as a function of S_{D1}. The more severe category will govern. SDC triggers special detailing requirements, especially for foundations. ASCE 7-16 contains an exception to the determination of SDC. This exception allows SDC to be determined from ASCE 7-16 Table 11.6-1 only if the structure is governed by S_{DS} and meets the criteria in Section 11.6. This exception can be applied to *nonbuilding structures similar to buildings* but *not* to *nonbuilding structures not similar to buildings*.

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R, Ω_o, and C_d

Values of R, Ω_o, and C_d are located in Table 12.2-1 for building structures, Table 15.4-1 for *nonbuilding structures similar to buildings*, and Table 15.4-2 for *nonbuilding structures not similar to buildings*. Chapter 15 Section 15.4.1 allows systems from either Table 12.2-1 or 15.4-1 to be chosen for *nonbuilding structures similar to buildings*.

Response Modification Factor (R)

The Response Modification Factor represents the inherent overstrength and global ductility capacity of structural components. Design seismic loads are reduced by R. This reduced design strength level results in nonlinear behavior and energy absorption at displacements in excess of initial yield. In other words, damage (but not collapse) is allowed.

Many nonbuilding structures are designed using allowable stress design (ASD) base methods. In many ASD based reference standards, R_W is used instead of R. In these cases, $R_W = 1.4R$.

Overstrength Factor (Ω_o)

The seismic load effect with the overstrength factor is intended to address those situations where the failure of an isolated, individual, brittle element can result in the loss of a complete seismic-force-resisting system or instability and collapse. A special seismic load combination (seismic load effect including overstrength factor) is specified in ASCE 7-16 Section 12.4.3. Numerous documents such as 2016 IBC, ASCE 7-16, 2016 AISC Seismic Provisions, and ACI 318-14 define elements that must be designed for the special seismic load combination. The elements requiring design using the special seismic load combination in buildings also must be designed using the special seismic load combinations for *nonbuilding structures similar to buildings*. As an example, the struts connecting the transverse moment frames in a pipe rack act as collectors and must be designed for the special seismic load combinations. For *nonbuilding structures not similar to buildings*, very few elements (e.g. anchor attachment to shells of tanks and vessels) require the use of the overstrength factor in their design.

Deflection Amplification Factor (C_d)

The elastic deformations calculated under the reduced design forces (1/R) are then amplified by the deflection amplification factor, C_d, to estimate the expected deformations likely to be experienced in response to the design ground motion. Please note that the "reduced design forces" are at a "strength" level. As mentioned above, many *nonbuilding structures not similar to buildings* are designed using ASD methods. Therefore, any elastic deformations based on ASD level loads must be increased by a factor of 1.4 in addition to C_d.

Redundancy Factor (ρ)

The Redundancy Factor is a factor intended to penalize structures with little redundancy (lack of multiple load paths) in their lateral force-resisting systems. Rules and exceptions are found in Section 12.3.4. The value of ρ is either 1.0 or 1.3. The value of ρ is always 1.0 for structures in SDC B and C and other structures as defined in 12.3.4.1. For a typical pipe rack, ρ is usually 1.0 or 1.3 in the longitudinal direction (braced frame) and 1.3 in the transverse (moment frame) direction in SDC D through F. The Redundancy Factor is set equal to 1.0 for *nonbuilding structures not similar to buildings* per the exception listed in ASCE 7-16 Sections 15.6 and 12.3.4.1.

Trade-off between Ductility and Strength

In Table 15.4-1, selected *nonbuilding structures similar to buildings* using "ordinary" structural systems are provided an option where both lower R-values and less restrictive height limitations are allowed. This option permits "ordinary" structural systems that have performed well in past earthquakes to be constructed with fewer restrictions in Seismic Design Categories D, E, and F –provided seismic detailing is used and design force levels are considerably higher. The R-value/ductility trade-off recognizes that the size of some nonbuilding structures is determined by factors other than traditional loadings and result in structures that are much stronger than required for seismic loadings. Therefore, the structure's ductility demand is much lower than a corresponding building. The R-value/ductility trade-off also attempts to obtain the same structural performance at the increased heights. The user will find that the option of reduced R-value/less-restricted-height will prove to be the economical choice in most situations due to the relative cost of materials and construction labor. It must be emphasized that the R-value/ductility trade-off of Table 15.4-1 only applies to *nonbuilding structures similar to buildings* and cannot be applied to buildings.

Use of Reference Documents

Reference Documents are industry standards (such as API 650 – *Welded Steel Tanks for Oil Storage*) for different nonbuilding structures that have been accepted by ASCE 7 as modified by the provisions of Chapter 15. Reference Documents as used by Chapter 15 do not include material standards such as AISC 341 or ACI 318. Some of the Reference Documents listed throughout Chapter 15 of ASCE 7 have well-defined seismic design procedures. For some of these Reference Documents, ASCE 7 provides "bridging" equations which modify the procedure provided in the Reference Document. These modifications bring the Reference Document up to the same force and displacement level used by ASCE 7. The hierarchy of Reference Documents relative to other codes and standards is not understood by many engineers. The order of precedence is the adopted building code (IBC), then ASCE 7, and finally the reference document (e.g. API 650).

Conclusion

This article has provided an introduction to the seismic design of nonbuilding structures to ASCE 7-16. Although there are some exceptions as noted above, most of the core concepts used in the seismic design of buildings apply to nonbuilding structures as well. Key takeaways from this article are:

- Nonbuilding structures are divided into two different categories for seismic design – *similar to buildings* and *not similar to buildings*.
- Nonbuilding structures are treated differently than buildings in seismic design because of the lack of human occupancy and because nonbuilding structures do not incorporate elements that increase damping and ductility (floors, diaphragms, non-structural elements) typically found in buildings.
- The presence of liquid in many nonbuilding structures requires the modification of the ground motions used for design.
- The trade-off between ductility and strength is unique to the seismic design of *nonbuilding structures similar to buildings*.
- Many nonbuilding structures rely on the use of Reference Documents for their seismic design.

A follow-up article will cover advanced topics in ASCE 7-16 seismic design of nonbuilding structures and nonstructural components.■