This month's Steel Interchange is adapted from Section 2 of AISC's *Facts for Steel Buildings #3– Earthquakes and Seismic Design*. The full publication and other installments on fire and blast in the *Facts for Steel Buildings* series are available for free at **www.aisc.org/facts**.

steel interchange

What are a structure's important dynamic properties?

The amount and way that a structure deforms in an earthquake, termed its response, are a function of the strength and dynamic properties of the ground shaking, as well as those of the structure itself. The principal dynamic properties of importance to structural earthquake response are the structure's modal properties and its damping.

What is an acceleration response spectrum?

An acceleration response spectrum is a plot of the maximum acceleration $x(T)$ that single-degree-of-freedom structures having different periods, T, would experience when subjected to a specific earthquake ground motion. This plot is constructed by performing response history analyses for a series of structures, each having a different period, T, obtaining the maximum acceleration of each structure from the analysis, and plotting this as a function of T. Linear acceleration response spectra are most common and are obtained by performing linear response history analysis. Figure 1 shows a typical linear acceleration response spectrum obtained from a record of the 1940 Imperial Valley earthquake.

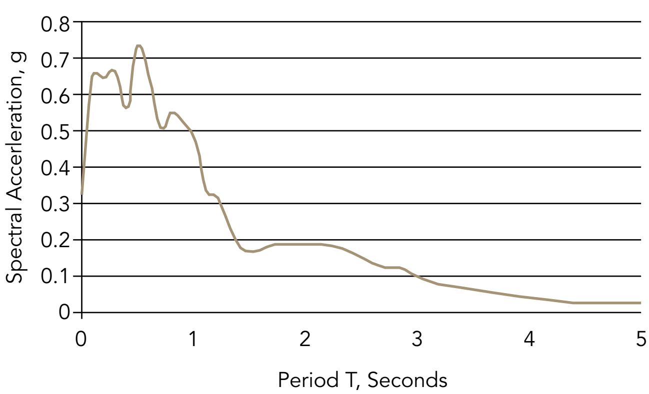

Figure 1. Linear acceleration response spectrum, 1940 El Centro, 180° component, 5% damping.

Although the response spectra obtained from each earthquake record will be different, spectra obtained from earthquakes having similar magnitudes on sites with similar characteristics tend to have common characteristics. This has permitted the building codes to adopt standard response spectra that incorporate these characteristics and which envelop spectra that would be anticipated at a building site during a design earthquake. The response spectra contained in the building code are called smoothed design spectra because the peaks and valleys that are common in the spectrum obtained from any single record are averaged out to form smooth functional forms that generally envelope the real spectra.

What is inelastic response?

Inelastic response occurs when the amplitude of earthquake shaking is strong enough to cause forces in a structure that exceed the strength of any of the structure's elements or connections. When this occurs, the structure may experience a variety of behaviors. If the elements that are strained beyond their elastic strength limit are brittle, they will tend to break and lose the ability to resist any further load. This type of behavior is typified by a steel tension member that is stretched such that the force in the brace exceeds the ultimate strength of its end connections, or by an unreinforced concrete element that is strained beyond its cracking strength. If the element is ductile, it may exhibit plastic behavior, being able to maintain its yield strength as it is strained beyond its elastic limit. This type of behavior is typified by properly braced, compact section beams in moment frames; by the cores of buckling-restrained braces; and by the shear links in eccentrically braced frames. Even elements that are ductile and capable of exhibiting significant post-yielding deformation without failure will eventually break and lose load-carrying capacity due to low-cycle fatigue if plastically strained over a number of cycles.

Modern structural analysis software provides the capability to analyze structures at deformation levels that exceed their elastic limit. In order to do this, these programs require input on the hysteretic (nonlinear force vs. deformation) properties of the deforming elements.

What is ductility?

Ductility is the property possessed by some structural elements, and structures composed of such elements, that enables them to sustain load-carrying capability when strained beyond their elastic limit. For structures that have well-defined yield and ultimate deformation capacities, such as those depicted in Figures 2 and 3, ductility, μ, is defined by the following Equation.

$$\mu = \frac{\delta_u}{\delta_y}$$

In this equation, δ_u and δ_y are the displacements at which failure and yielding, respectively, initiate.

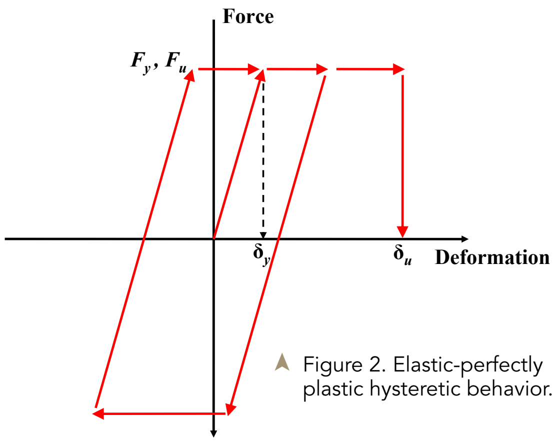

Figure 2. Elastic-perfectly plastic hysteretic behavior.

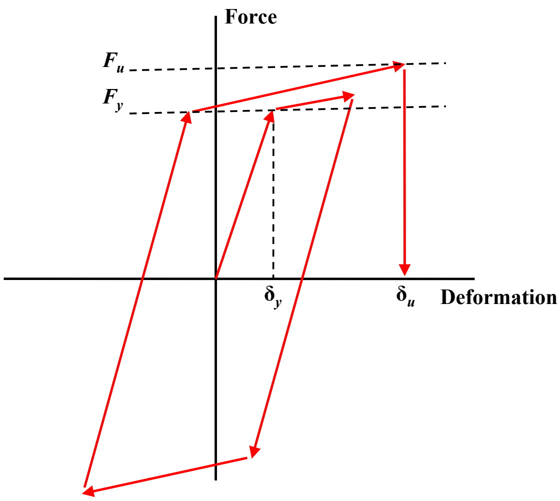

Figure 3. Elastic-plastic strain hardening behavior.

Ductility is an important parameter for seismic resistance because it enables the design of structures that do not have adequate strength to resist strong earthquake shaking elastically to still survive such shaking through inelastic response. Structures that do not have ductility will fail when they are subjected to ground motion that deforms them beyond their elastic limit. Most of the design criteria contained in AISC 341 for design of the various types of steel and composite structures are intended to ensure that these structures will have sufficient ductility, enabling their design for forces that are substantially less than required to resist design ground motions elastically.

How does inelastic response affect a structure?

One of the principal benefits of inelastic response is that it limits the amount of force that is induced in the structure by the ground shaking. For example, if a structure has hysteretic characteristics similar to the elastic-plastic hysteretic behavior shown in Figure 2, no matter how far earthquake shaking deforms the structure it will never experience more force than F_y. If a structure is properly designed, this effect makes it possible to place ductile elements at key locations in the seismic load resisting system that will yield and protect other elements that are not ductile from being overstressed. This is a key strategy in design of structures for seismic resistance—sometimes called capacity design because elements in the structure that are not ductile are designed with sufficient capacity to resist the forces that will occur after the ductile elements yield.

Inelastic response also affects the amount of deformation a structure will experience in an earthquake. When a structure responds inelastically to earthquake shaking, a number of things can happen. If the structure is ductile, it will continue to provide resistance after deforming beyond its yield point. However, its instantaneous stiffness will reduce, lengthening its effective periods of vibration and changing its mode shapes. In addition, as the structure strains inelastically, it will begin to dissipate a portion of the energy imparted on it by the earthquake in the form of strain energy.

The reduction in stiffness and period lengthening that accompanies ductile behavior tends to increase the amount of displacement the structure will experience as it is pushed by earthquake forces. At the same time, the inelastic strain energy that the structure dissipates acts as a form of damping and tends to reduce the amount of deformation induced by the shaking. Exactly how each of these behaviors will affect a specific structure depends on the initial dynamic characteristics of the structure and the dynamic characteristics of the ground motion. However, there are some general observations that can be made about the effect of inelastic response on the amount of deformation a structure will experience.

These effects tend to be different for structures having relatively long periods of vibration than for structures with short periods of vibration. For the purpose of this discussion, structures having a first mode period of vibration of one second or more can be considered long-period structures. Structures having first mode periods of 0.5 seconds or less may be considered short-period structures. Structures with fundamental periods between 0.5 seconds and one second may behave either as short- or long-period structures, depending on the dynamic characteristics of the ground shaking.

In general, the displacement experienced by long-period structures that undergo inelastic response will be about the same as if the structure had remained elastic. This behavior was first noted by Newmark and Hall (1982) and is sometimes called the "equal displacement" rule.

Short-period structures behave in a different manner. When short-period structures yield, they tend to experience larger displacement than they would have if they remained elastic. If the hysteretic behavior of a short-period structure is such that it experiences pinching, this tends to increase the displacements even more.

Inelastic strength degradation tends to further increase inelastic displacement, both for short- and long-period structures. Strain hardening tends to reduce these displacements.

Regardless of whether a structure is brittle or ductile, or has short or long period, inelastic behavior will always result in structural damage. In steel structures, this damage will take the form of yielding, buckling and fracturing. Depending on the severity of this damage, it may or may not be necessary to repair the structure after the earthquake.

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