CHAPTER 4
BUILDINGS, STRUCTURES, AND NONSTRUCTURAL COMPONENTS

The NEHRP Recommended Seismic Provisions includes seismic design and construction requirements for a wide range of buildings and structures and their nonstructural components. This chapter presents an overview of those different types of buildings, structures, and nonstructural components.

4.1 Buildings

Generally, a building can be defined as an enclosed structure intended for human occupancy. However, a building includes the structure itself and nonstructural components (e.g., cladding, roofing, interior walls and ceilings, HVAC systems, electrical systems) permanently attached to and supported by the structure. The scope of the Provisions provides recommended seismic design criteria for all buildings except detached one- and two-family dwellings located in zones of relatively low seismic activity and agricultural structures (e.g., barns and storage sheds) that are only intended to have incidental human occupancy. The Provisions also specifies seismic design criteria for nonstructural components in buildings that can be subjected to intense levels of ground shaking.

4.1.1 Structural Systems

Over many years, engineers have observed that some structural systems perform better in earthquakes than others. Based on these observations, the Provisions design criteria for building structures are based on the structural system used. Structural systems are categorized based on the material of construction (e.g., concrete, masonry, steel, or wood), by the way in which lateral forces induced by earthquake shaking are resisted by the structure (e.g., by walls or frames), and by the relative quality of seismic-resistant design and detailing provided.

The Provisions recognizes six broad categories of structural system:

- Bearing wall systems,
- Building frame systems,
- Moment-resisting frame systems,
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- Dual systems,
- Cantilever column systems, and
- Systems not specifically designed for seismic resistance.

In bearing wall systems, structural walls located throughout the structure provide the primary vertical support for the building’s weight and that of its contents as well as the building’s lateral resistance. Bearing wall buildings are commonly used for residential construction, warehouses, and low-rise commercial buildings of concrete, masonry, and wood construction. Figures 21, 22, and 23 show typical bearing wall buildings.

Figure 21  Wood studs and structural panel sheathing of typical wood frame bearing wall construction.

Figure 22  Typical low-rise concrete bearing wall building.
Building frames are a common structural system for buildings constructed of structural steel and concrete. In building frame structures, the building’s weight is typically carried by vertical elements called columns and horizontal elements called beams. Lateral resistance is provided either by diagonal steel members (termed braces) that extend between the beams and columns to provide horizontal rigidity or by concrete, masonry, or timber shear walls that provide lateral resistance but do not carry the structure’s weight. In some building frame structures, the diagonal braces or walls form an inherent and evident part of the building design as is the case for the high-rise building in San Francisco shown in Figure 24. In most buildings, the braces or walls may be hidden behind exterior cladding or interior partitions.
Moment-resisting frame systems are commonly used for both structural steel and reinforced concrete construction. In this form of construction, the horizontal beams and vertical columns provide both support for the structure’s weight and the strength and stiffness needed to resist lateral forces. Stiffness and strength are achieved through the use of rigid connections between the beams and columns that prevent these elements from rotating relative to one another. Although somewhat more expensive to construct than bearing wall and braced frame structural systems, moment-resisting frame systems are popular because they do not require braced frames or structural walls, therefore permitting large open spaces and facades with many unobstructed window openings. Figure 25 shows a steel moment-resisting frame building under construction.

Dual systems, an economical alternative to moment-resisting frames, are commonly used for tall buildings. Dual system structures feature a combination of moment-resisting frames and concrete, masonry, or steel walls or steel braced
frames. The moment-resisting frames provide vertical support for the structure’s weight and a portion of the structure’s lateral resistance while most of the lateral resistance is provided either by concrete, masonry, or steel walls or by steel braced frames. Some dual systems are also called frame-shear wall interactive systems.

Cantilever column systems are sometimes used for single-story structures or in the top story of multistory structures. In these structures, the columns cantilever upward from their base where they are restrained from rotation. The columns provide both vertical support of the building’s weight and lateral resistance to earthquake forces. Structures using this system have performed poorly in past earthquakes and severe restrictions are placed on its use in zones of high seismic activity.

In regions of relatively low seismic risk, the *NEHRP Recommended Seismic Provisions* permits the design and construction of structural steel buildings that do not specifically conform to any of the above system types. These buildings are referred to as “structures not specifically detailed for seismic resistance.”
In addition to these basic structural systems and the primary materials of construction, the *Provisions* also categorizes structural systems based on the quality and extent of seismic-resistant detailing used in a structure’s design. Systems that employ extensive measures to provide for superior seismic resistance are termed “special” systems while systems that do not have such extensive design features are typically called “ordinary” systems. The *Provisions* also includes design rules for structural systems intended to provide seismic resistance that is superior to that of “ordinary” systems but not as good as that of “special” systems; these systems are called “intermediate” systems.

### 4.1.2 Nonstructural Components

In addition to the structural framing and the floor and roof systems, buildings include many components and systems that are not structural in nature but that can be damaged by earthquake effects. The types of nonstructural components covered by the *NEHRP Recommended Seismic Provisions* include:

- Architectural features such as exterior cladding and glazing, ornamentation, ceilings, interior partitions, and stairs;
- Mechanical components and systems including air conditioning equipment, ducts, elevators, escalators, pumps, and emergency generators;
- Electrical components including transformers, switchgear, motor control centers, lighting, and raceways;
- Fire protection systems including piping and tanks; and
- Plumbing systems and components including piping, fixtures, and equipment.

The design and construction requirements contained in the *Provisions* are intended to ensure that most of these components are adequately attached to the supporting structure so that earthquake shaking does not cause them to topple or fall, injuring building occupants or obstructing exit paths. For those pieces of equipment and components that must function to provide for the safety of building occupants (e.g., emergency lighting and fire suppression systems), the *Provisions* provides design criteria intended to ensure that these systems and components will function after an earthquake. The *Provisions* also includes recommendations intended to ensure that nonstructural components critical to the operability of essential facilities such as hospitals can operate following strong earthquake shaking.
4.2 Nonbuilding Structures

The NEHRP Recommended Seismic Provisions also includes seismic design criteria for many structures that are not considered to be buildings. These structures are called nonbuilding structures and include:

- Storage tanks, pressure vessels, and pipe supports such as those commonly found in petroleum refineries and chemical plants (Figure 26);
- Water towers;
- Chimneys and smokestacks;
- Steel storage racks (Figure 27);
- Piers and wharves;
- Amusement structures including roller coasters; and
- Electrical transmission towers.

Some nonbuilding structures, however, are not covered by the design recommendations contained in the Provisions because they are of a highly specialized nature and industry groups that focus on the design and construction of these structures have developed specific criteria for their design. Some such structures are highway and railroad bridges, nuclear power plants, hydroelectric dams, and offshore petroleum production platforms.

Figure 26 Structures commonly found in petroleum refineries and chemical plants.
Just as it does for buildings, the *NEHRP Recommended Seismic Provisions* classifies nonbuilding structures based on the structural system that provides earthquake resistance. Some nonbuilding structures use structural systems commonly found in buildings such as braced frames and moment frames. These structures are identified as nonbuilding structures with a structural system similar to buildings, and the design requirements for these structures are essentially identical to those for building structures. Other nonbuilding structures are called nonbuilding structures with structural systems not similar to buildings, and the *Provisions* contains special design requirements that are unique to the particular characteristics of these structures.
4.3 Protective Systems

Most of the seismic-resistant structural systems used in both buildings and nonbuilding structures are variations of systems that were traditionally used in structures not designed for earthquake resistance. Over the years, engineers and researchers improved the earthquake resistance of these traditional systems by observing their behavior in laboratory tests and actual earthquakes and incrementally refining the design criteria to achieve better performance. Nevertheless, these systems are still designed with the intent that they will sustain damage when subjected to design-level or more severe earthquake effects.

Beginning in the 1970s, engineers and researchers began to develop systems and technologies capable of responding to earthquake ground shaking without sustaining damage and thereby protecting the building or structure. The NEHRP Recommended Seismic Provisions presently includes design criteria for two such technologies – seismic isolation and energy dissipation systems.

Seismic isolation systems consist of specially designed bearing elements that are typically placed between a structure and its foundation (Figure 28). Two types of bearing are commonly used – one is composed of layers of natural or synthetic rubber material bonded to thin steel plates in a multilevel sandwich form and the second consists of specially shaped steel elements coated with a low-friction material. Both types of bearings are capable of accommodating large lateral displacements while transmitting relatively small forces into the structure above. When these isolation systems are placed in a structure, they effectively “isolate” the building from ground shaking so that, when an earthquake occurs, the building experiences only a small fraction of the forces that would affect it if it were rigidly attached to its foundations.

Energy dissipation systems are composed of structural elements capable of dissipating large amounts of earthquake energy without experiencing damage, much like the shock absorbers placed in the suspensions of automobiles. Energy dissipation systems usually are placed in a structure as part of a diagonal bracing system. Several types of energy dissipation system are available today including hydraulic dampers, friction dampers, wall dampers, tuned mass dampers, and hysteretic dampers.

Hydraulic dampers are very similar to automotive shock absorbers. They consist of a double acting hydraulic cylinder that dissipates energy by moving a piston device through a viscous fluid that is contained within an enclosed cylinder. Friction dampers are essentially structural braces that are spliced to the structure using slotted holes and high-strength bolts with a tactile material on the mating surfaces of the connection. When the braces are subjected to tension or com-
pression forces, they slip at the splice connection and dissipate energy through friction. Wall dampers are a form of viscous damper that consists of vertical plates arranged in a sandwich configuration with a highly viscous material. One set of plates is attached to one level of a structure and another set to the adjacent level. When the structure displaces laterally in response to earthquake shaking, the plates shear the viscous material and dissipate energy. Hysteretic dampers dissipate energy by yielding specially shaped structural elements that are placed in series with conventional wall or brace elements. Tuned mass dampers consist of a large mass on a spring-like device. When they are mounted on a structure, the lateral displacement of the structure excites the mass, which then begins to move and dissipate significant portions of the earthquake’s energy, protecting the structure in the process.

Although seismic isolation and energy dissipation systems have been available for more than 20 years, their use in new buildings has been confined primarily to very important structures that must remain functional after a strong earthquake and to buildings housing valuable contents such as museums or data centers. This is because their use adds to the construction cost for a structure and most owners have not viewed the additional protection provided by these technologies as worth the additional cost.

Figure 28  The San Bernardino County Justice Center in California was one of the first base-isolated buildings in the United States.

### 4.4 Existing Buildings and Structures

The *NEHRP Recommended Seismic Provisions* primarily addresses the design of new buildings and structures. However, the most significant seismic risks in the United States today are associated with existing buildings and structures designed and constructed prior to the adoption and enforcement of current seismic design requirements in building codes. It is possible to upgrade these existing hazard-
ous structures so that they will perform better in future earthquakes and some communities in the United States have adopted ordinances that require seismic upgrades of the most hazardous types of existing building.

Chapter 34 of the *International Building Code* and Appendix 11B of the ASCE/SEI 7 standard include requirements aimed at improving the seismic resistance of existing structures, typically as part of a significant expansion, repair, or alteration of the building. These requirements are intended to prevent existing buildings from being made more hazardous than they already are (by either reducing their current strength or adding mass to them) and to trigger a seismic upgrade of these buildings when their expected useful life is extended by a major renovation project.

When a structurally dependent addition to an existing building is proposed, Appendix 11B of ASCE/SEI 7 requires that the entire structure, including the original building and the addition, be brought into compliance with the seismic requirements for new construction. The upgrade requirement is waived if it can be demonstrated that the addition does not increase the seismic forces on any existing element by more than 10 percent unless these elements have the capacity to resist the additional forces and that the addition in no way reduces the seismic resistance of the structure below that required for a new structure.

The ASCE/SEI 7 standard contains similar requirements for building alterations such as cutting new door openings into walls, cutting new stairway openings in floors, or relocating braces within a structure. Such alterations trigger a requirement to bring the entire structure into conformance with the seismic requirements for new buildings unless the alteration does not increase the seismic force on any element by more than 10 percent, the seismic resistance of the structure is not reduced, the forces imposed on existing elements do not exceed their capacity, new elements are detailed and connected to the structure in accordance with the requirements for new structures, and a structural irregularity is not created or made more severe.

Both ASCE/SEI 7 and the *International Building Code* require a seismic upgrade of an existing structure when an occupancy change will result in a higher risk to the public. An example of such an occupancy change would be the conversion of a normally unoccupied warehouse building into condominiums or an emergency shelter intended to provide living space for the public after a disaster. Further discussion of occupancies and the design requirements associated with them is contained in the next chapter.

Although both ASCE/SEI 7 and the *International Building Code* require that existing buildings and structures be upgraded to comply with the requirements for
new structures under some circumstances, it often is impractical and technically
impossible to do this for many structures because they are constructed of systems
and materials that are on longer permitted by the building codes and for which
suitable design criteria are no longer available. In order to obtain literal compli-
ance with the requirements to upgrade such structures, it would be necessary to
demolish the nonconforming elements and replace them with new conforming
construction, which is seldom economically practical. Recognizing this, FEMA
has developed a series of publications specifically intended to help engineers iden-
tify the likely performance of existing nonconforming buildings and design effective
means of upgrading these structures. Several of these publications have since
evolved into national consensus standards issued by the American Society of Civil
Engineers and they are widely accepted by building officials as suitable alternatives
to the requirements of the building code for existing structures.

One such standard, ASCE/SEI 31-02, Seismic Evaluation of Existing Buildings, is
based on FEMA 310 and employs a tiered methodology that enables engineers to
determine whether buildings are capable of meeting either life safety or immedi-
ate occupancy performance objectives. The lowest tier of evaluation provides a
simple checklist to assist the engineer in identifying deficiencies that are known to
have caused poor performance in buildings in past earthquakes. Higher tier evalu-
ations utilize progressively more complex analytical procedures to quantitatively
evaluate an existing building’s probable performance.

ASCE/SEI 41-06, Seismic Rehabilitation of Existing Buildings, is based on sev-
eral FEMA publications (notably, FEMA 273/274 and FEMA 356) and provides
design criteria for the seismic upgrading of existing buildings to meet alternative
performance criteria ranging from a reduction of collapse risk to the capability to
survive design-level earthquakes and remain functional. FEMA 547, Techniques
for the Seismic Rehabilitation of Existing Buildings, is an important companion
document to ASCE/SEI 41-06; it provides engineers with alternative structural
techniques that can be used to effectively upgrade existing buildings.

Many jurisdictions have adopted ordinances that require owners of some types
of buildings known to be particularly hazardous to perform seismic upgrades of
these structures. The targets of such ordinances include unreinforced masonry
buildings, older precast concrete tiltup buildings, and wood frame buildings with
weak first stories or inadequately attached to their foundations. Some of these
ordinances adopt technical provisions contained in the International Existing
Buildings Code produced by the International Code Council as a companion pub-
lication to the IBC. Other ordinances permit the use of the ASCE 41 procedures or
specify other acceptable procedures developed for that particular community.
Owners often elect to undertake upgrades of buildings independent of requirements contained in the building codes or locally adopted ordinances. These upgrades may range from incremental projects that address specific building deficiencies to complete upgrades intended to provide performance equivalent or superior to that anticipated by the building code for new construction. The *International Building Code* includes permissive language that enables such upgrades so long as the engineer designing the upgrade can demonstrate that the proposed changes do not create new seismic deficiencies or exacerbate existing seismic deficiencies. FEMA 390 through 400 suggest some ways to incrementally improve a building’s seismic performance and FEMA 420 is an engineering guide for use with those publications.