THE REGULATION OF SEISMIC DESIGN 6

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6.1 INTRODUCTION

This chapter presents an overview of the development of seismic design codes in the United States. It includes a discussion of concepts underlying performance-based seismic design and addresses how seismic provisions in current model building codes can inform architectural design decisions.

Readers can find an explanation of the basis for hazard maps that are used to define code-specified design earthquake parameters in Chapter 2. Chapter 3 discusses the seismic zonation principles used to generate seismic design regulations that restrict property use or require site-specific design approaches. Chapter 5 explains how building codes classify building configurations for seismic design purposes. Chapter 8 discusses the regulatory environment for seismic-design involving existing buildings.

Although building codes have evolved substantially in the last hundred years, they still reflect history in the way that they are organized and used. Code sections that originated as fire mitigation measures precede the sections containing the structural provisions that include seismic design requirements. Sections pertaining to modern building systems, such as plumbing and electrical systems, are published as separate volumes. In conventional building design practice, architects take primary responsibility for addressing fire-related provisions. Although the use of fire-resistive design consultants is becoming common in certain kinds of institutional and commercial building designs, architects using these consultants will still develop initial conceptual designs in accordance with the principles that underlie fire-resistive code measures.

The same is not commonly true in seismic design. Although building configuration and other design features, determined by the architect, are known to impact the structural and nonstructural performance of buildings in earthquakes, architects do not usually consult the sections of the code where the seismic design requirements are addressed. Codes governing seismic design were established in the second half of the twentieth century, primarily by structural engineers, and reflect the increasing specialization and disciplinary division between architectural and engineering practice. Few architects practicing today take responsibility for structural aspects of seismic design, and many consult with engineers on the design of nonstructural architectural elements that are regulated by seismic code provisions. However, architects routinely make design decisions that impact the use and interpretation of seismic design codes.

6.2 EARTHQUAKES AND CODE ACTION

Historically, seismic design provisions were added to codes in response to the lessons learned from earthquake damage. Although the evolution of technical understanding of building performance has guided the development of these provisions, code action has been driven primarily by political rather than technical advances. Communities with well-developed political mechanisms for addressing public safety have tended to pioneer code developments, but the long periods between damaging earthquakes have made it easy for communities to forget to follow through with efforts begun in the aftermath of disasters. In addition, the political and technical complexities inherent in extracting lessons from earthquakes have made it difficult to achieve consensus on appropriate code measures.

6.2.1 Early 20th Century

Despite the destruction of 27,000 buildings and fatalities estimated by the USGS (United States Geological Survey) and others to be between 700 and 2,100, the 1906 San Francisco earthquake did not stimulate an explicit code response. A wind-load requirement was implemented and was assumed to be sufficient to resist earthquake forces. Post-earthquake investigators reported that 80% to 95% of damage in the most affected

Figure 6-1: San Francisco 1906, fire and earthquake damage.

SOURCE: KARL V. STEINBRUGGE COLLECTION AT NISEE. PHOTOGRAPHER: ARNOLD GENTHE.

areas of the city was caused by fire, with only 5% to 20% of the damage caused by shaking; the event was interpreted as a great fire rather than a great earthquake (Figure 6-1).

Differences in building performance based on construction, configuration, and soils conditions were observed during and after the earthquake, but there was no systematic investigation of the performance of anti-seismic systems voluntarily implemented by engineers in the last four decades of the 19th century, or of the code requirement implemented in 1901 to provide bond iron through the wythes of brick walls. Performance observations of selected steel-frame and concrete structures were used to justify the removal of some code restrictions concerning building height. In the aftermath of the San Francisco earthquake, engineers' awareness of seismic risk increased, resulting in voluntary efforts at seismic-resistant design, but codes did not specifically direct the design community to address earthquake related hazards.

Figure 6-2: Santa Barbara, 1925, typical failure of brick walls and timber interior.

SOURCE: KARL V. STEINBRUGGE COLLECTION AT NISEE; PHOTOGRAPHER: UNKNOWN.

6.2.2 The 1920s and the First Seismic Code

By the 1920s, the mechanisms for implementing seismic regulations for buildings in California were in place. The professional dialog about earthquake design had become more public since 1906, and post-earthquake investigators who examined field conditions after the 1925 Santa Barbara Earthquake called for code action (Figure 6-2).

In 1927, the Pacific Coast Building Officials Conference (precursor to ICBO, the International Conference of Building Officials) included an appendix of optional seismic design provisions in the first edition of the *Uniform Building Code* (UBC). A lateral load requirement was set at 7.5% of the building weight with an increase to 10% for sites with soft soils. This established the first version of the **equivalent lateral force procedure** still used in seismic codes today (Box 1). At the same time, some California cities began to adopt mandatory seismic design provisions in response to advocacy from citizens.

In the late 1920s the Structural Engineers Association of California (SEAOC) formed to address concerns about access to technical information and professional practice issues. For the next several decades, SEAOC's volunteer efforts would yield significant contributions to California codes and ultimately assume a leading role in the development of U.S. seismic codes.

6.2.3 Mid-Century Codes and the Introduction of Statewide Regulations

A large number of school buildings constructed of unreinforced masonry were severely damaged in the 1933 Long Beach earthquake (Figure 6-3). A public outcry for safer schools resulted in intense efforts by California legislators to quickly enact legislation requiring seismic design provisions. The Field Act of 1933 transferred the responsibility for approving plans and supervising construction of public schools to the State Division of

Figure 6-3: Long Beach, 1933, Alexander Hamilton Junior High School.

SOURCE: KARL V. STEINBRUGGE COLLECTION AT NISEE; PHOTOGRAPHER: UNKNOWN.

Box 1 The Equivalent Lateral Force Procedure

The Equivalent Lateral Force Procedure simplifies the dynamic effects of earthquakes by using a static model. Historically, the procedure was used for the design of all structures, but the current codes restrict its application to small buildings of regular configuration and larger buildings of limited height constructed with flexible diaphragms that are not considered to be essential or hazardous to the public.

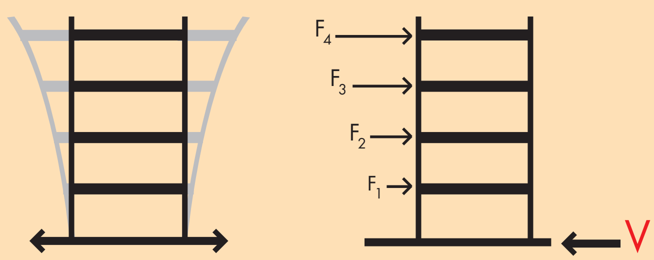
$$V = C_S W$$

where

$$C_S = \frac{S_{DS}}{\left[\frac{R}{I_E}\right]}$$

- seismic base factor (V)
- building weight including permanent and long term contents (W)
- an attenuation parameter that varies according to soil conditions and the structures fundamental period (S_{DS})
- a response modification factor that reflects the structural behavior of the seismic force resisting system (R)
- importance factor based on building use (I_E)

In an earthquake, buildings experience ground motion that causes high accelerations and proportionately large internal forces in the building structure for short durations. In the equivalent lateral force procedure, static loads with a lesser magnitude than the actual earthquke forces are applied. This relies on the ability structures have to withstand larger forces for short periods of time and allows for a less conservative, more affordable seismic design. The seismic base shear V was specified as a given percentage of the building weight. The value is determined by combining factors representing properties of the structure, soil, and use of the building.



The tendency for the building to sway from side to side in response to ground motion produces greater accelerations in the upper parts of the building. This back and forth motion is called the fundamental mode, which dominates the response of most regular building structures.
To model this effect statically, the equivalent lateral force procedure redistributes the load applied to the buildings floors to account for their distance from the base.

Architecture. It included lateral force requirements that varied according to the type of structural system. In the same year, the Riley Act created a mandatory seismic design coefficient for all buildings in the State of California and prevented construction of new unreinforced masonry buildings. The provisions of the Field and Riley Acts were developed in a simple form for implementation and did not reflect the latest developments in engineering understanding. It was not until 1943 that the Los Angeles Building Code adopted the first provisions in the United States that accounted for building height and flexibility.

The Long Beach earthquake provided the stimulus for state-mandated seismic design provisions that began the process of coalescing independent local efforts and assuring that minimum standards were enforced throughout California. However, the seismic provisions of the UBC did not become the standard in California until 1960. Before that time, many local jurisdictions added their own seismic design provisions to the Riley Act requirements.

In the late 1940s SEAOC responded to the inadequacy of seismic design codes by embarking upon work that would form the basis for the first edition of the *Recommended Lateral Force Requirements and Commentary*, also known as the SEAOC Blue Book. These recommended seismic design provisions for new buildings were included in the 1961 UBC. The Blue Book, published from 1959 through 1999, continued to evolve with major re-evaluations after significant earthquakes.

After 1960, the development of seismic design codes typically began with provision proposals initiated by the Blue Book that were later incorporated into the UBC. New systems, such as ductile moment frames, were incorporated into the code incrementally as they came into use. Inclusion of similar provisions in the other model codes in the United States followed the UBC's lead but occurred somewhat later. The UBC, used most extensively in the west, initiated national trends in earthquake-resistant code requirements.

The 1971 San Fernando earthquake occurred less than a decade after the extensively studied 1964 Alaska earthquake, and confirmed findings of greater-than-expected damage to engineered buildings meeting code provisions (Figure 6-4). Extensive data on the performance of newer building systems was collected. Observations stimulated research on the influence of reinforcement patterns on the strength and deformation

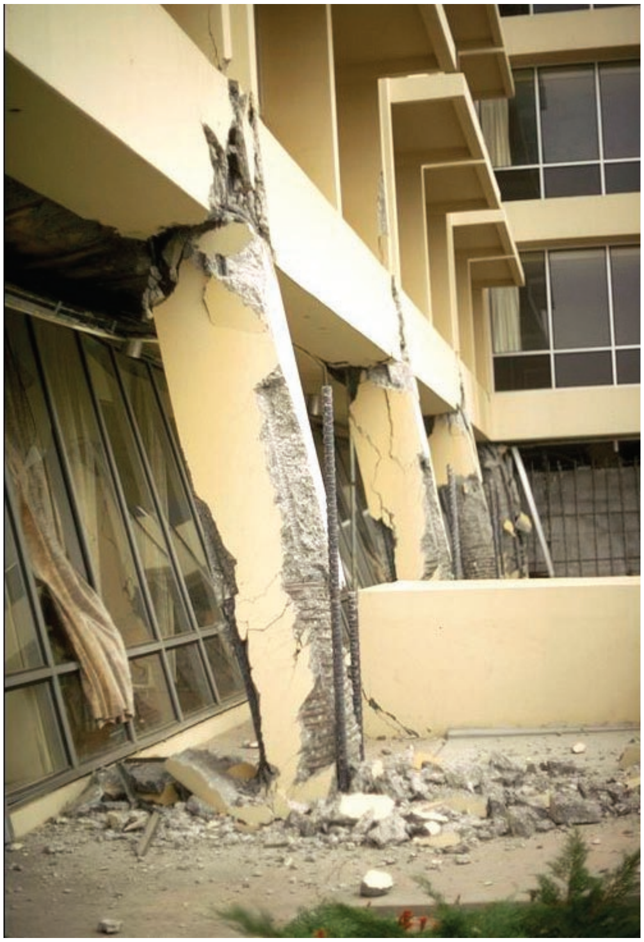


Figure 6-4: Sylmar, 1971, Damage to engineered building at Olive View Medical Center.

SOURCE: KARL V. STEINBRUGGE COLLECTION AT NISEE; PHOTOGRAPHER: KARL V. STEINBRUGG.

of concrete structural components. Evidence for the effects of building configuration and relative stiffness of structural elements as well as the performance of structural connections spurred revisions to code requirements.

Although the 1976 UBC increased building strength requirements and adopted the concept of increasing strength according to occupancy type, design forces remained only a fraction of the actual forces experienced by buildings during ground shaking (Figure 6-5). As discussed in chapter 4, building codes permit designs for less-than-expected earthquake forces to facilitate relatively simple linear analysis and design procedures because such designs, when coupled with detailing requirements also stipulated in codes, have proven successful in past earthquakes. In 1973, in an effort to assist the application of current technological develop-

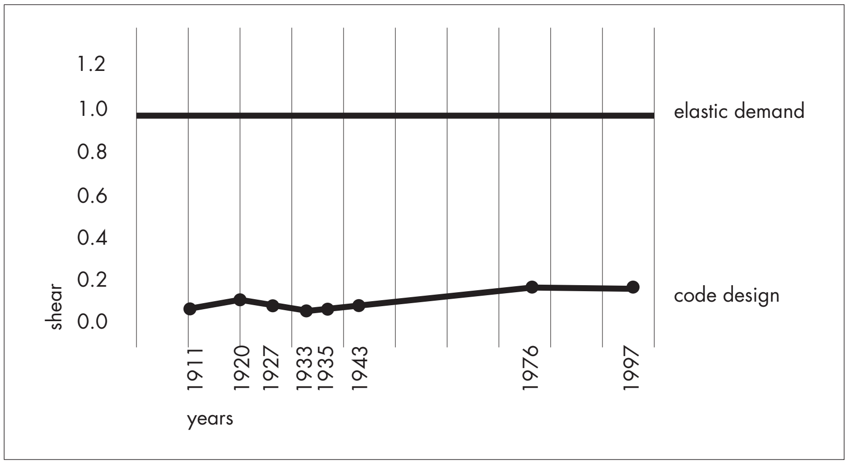


Figure 6-5: Graph comparing actual elastic demand with code-mandated design forces.

SOURCE: HOLMES, W., THE HISTORY OF U.S. SEISMIC CODE DEVELOPMENT, PUBLISHED IN THE *EERI GOLDEN ANNIVERSARY VOLUME 1948-1998*, EARTHQUAKE ENGINEERING RESEARCH INSTITUTE, OAKLAND, CALIFORNIA, 1998).

ments to structural engineering practice, SEAOC established the Applied Technology Council (ATC) to translate engineering research into usable design information.

In the aftermath of earthquakes of the 1960s and 70s, the need for more stringent building standards at the state level was recognized. The California Hospital Act, passed soon after the San Fernando earthquake, mandated more stringent building standards, plan checking, and inspection for hospitals under the direction of the Office of Statewide Health Planning and Development, with the intent of improving patient protection and maintaining building use through the regulation of non-structural as well as structural design.

6.2.4 Late 20th Century: the Move toward New Model Building Codes

By the mid 1970s, the need for federal seismic design standards, coupled with the structural engineering profession's interest in significantly updating code content and streamlining its organization, shifted code development from regional to national efforts. A series of projects to develop national guidelines for seismic design began in the mid'70s. This effort provided the groundwork that led to the publication: ATC-3-

06, *Tentative Provisions for the Development of Seismic Regulations for Buildings.* In 1977, the U.S. Congress passed the National Earthquake Hazards Reduction Act. In the following year, FEMA established the National Earthquake Hazard Reduction Program (NEHRP) and the Building Seismic Safety Council (BSSC) to develop the first nationally applicable seismic design guidelines for new buildings.

A major milestone was reached in 1985 when FEMA published the first version of the NEHRP *Recommended Provisions for Seismic Regulations of Buildings and Other Structures.* The *Provisions* were originally conceived to be a resource document, rather than a code, but the format and language of the *Provisions* conform to conventional code language. The NEHRP Provisions had major national influence, and both the BOCA (Building Officials Code Administrators) *National Code* and the SBCCI (Southern Building Code Congress International) *Standard Code* adopted requirements based on the NEHRP *Provisions* in 1991 and 1992 respectively. The seismic provisions of current building codes are largely based on the NEHRP *Provisions*, supplemented by industry materials association standards. A significant difference between the NEHRP *Provisions*

Figure 6-6: San Francisco, 1989, elevated highway support bents, an example of failure of engineered structures.

SOURCE: EERI ANNOTATED SLIDE COLLECTION

and earlier model codes was the introduction of provisions that related design forces to the characteristics of the ground motion of the site. This part of the *Provisions* required designers to consider dynamic effects and resulted in larger than previously considered forces and building deformations for some kinds of structures. Most important architecturally was the inclusion of regulations that identified building configuration as a factor in determining acceptable engineering analysis methods and selecting structural systems.

The extent of damage to buildings and the larger-than-expected economic losses caused by the 1989 Loma Prieta earthquake galvanized the need for public involvement in identifying acceptable building performance (Figure 6-6). After Loma Prieta, many building owners discovered that they misunderstood the protection provided by the codes and had made investment decisions based on unrealistic expectations about building performance and the likelihood of damaging earthquakes. A post-earthquake economic recession in Northern California alerted government officials to the potential economic cost of large earthquakes. The insurance industry responded with a lack of confidence in the insurability of the building stock. For those concerned with economic impacts, the life safety intent of building codes was no longer a sufficient standard. People who made decisions that affected their communities' seismic risk needed to better understand the relationship between code compliance and building performance. At the same time, engineers were developing methods for predicting building performance with greater accuracy. The combined effect of these developments stimulated an increased interest in performance-based codes and design guidelines.

Figure 6-7: Northridge, 1994 Failure of a welded steel connection.

SOURCE: EERI ANNOTATED SLIDE COLLECTION

The 1994 Northridge earthquake surprised the engineering community by severely damaging several recently constructed steel moment frame buildings (Figure 6-7). It confirmed the need for experimental research as part of the code development process. It also reinforced many of the lessons learned by the public in Loma Prieta. Damage patterns in Northridge revealed

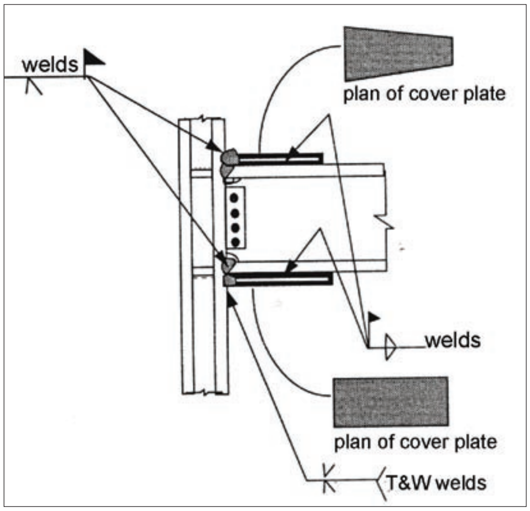


Figure 6-8: Example of a pre-qualified steel moment beam-column connection developed in the aftermath of the Northridge earthquake

SOURCE: SAC JOINT VENTURE, INTERIM GUIDLINES, REPORT # SAC -95-02 FEMA, WASHINGTON, DC.

the uncertainties associated with earthquakes, and provided examples of how buildings designed to resist the larger equivalent lateral forces required by more recent codes do not always perform better than older buildings. Ductile moment-resisting connections used in steel frames showed unexpected failures due to the complex behavior of welded beam-column connections.

In the aftermath of the Northridge earthquake, FEMA sponsored an extensive study of the steel moment connection problem. SAC, a joint venture of SEAOC, ATC and CUREE (Consortium of Universities for Research in Earthquake Engineering) conducted the work and produced a series of publications containing guidelines for engineering practice. The guidelines introduced pre-qualified connection designs and more explicit requirements for substantiating proposed designs with experimental research. The need for analytical techniques that could predict performance more accurately was identified. Many of the recommendations were later incorporated into building codes (Figure 6-8).

After the Loma Prieta and Northridge earthquakes, disaster-stricken communities raised questions about the nature of code protection, and design professionals began to question their own performance expectations for buildings designed to meet code requirements. Government agencies and representatives at the local, state, and national levels became concerned with the potential economic cost of large earthquakes. At the same time, innovative structural systems designed to improve performance, such as seismic isolation, became more commonly used.

In this climate, U.S. model code associations, the ICBO, the SBCCI , and BOCA, joined to form the International Code Council (ICC). By the year 2000, the UBC and NEHRP seismic design provisions were merged in the first edition of the *International Building Code* (IBC). Shortly after, NFPA (National Fire Protection Association) undertook a building code development process that produced the *NFPA 5000 Building Code* with seismic design requirements also based on the NEHRP *Provisions*. As local jurisdictions adopt these new model codes design teams, working on projects in regions with lower levels of seismicity, have been required to address more stringent seismic design regulations than has been the case in the past, particularly on sites with less than optimal soils conditions. NEHRP requires site-specific soil data in order to determine the seismic design category of a building. According to NEHRP, a building project in Atlanta on soft soil may be required to have the same level of seismic design as a building in California. More extensive geotechnical investigations of the building site can be used to determine the appropriate code-defined soil classification and provide the design team with critical information that will affect seismic design requirements specified by the code.

In the 1990s, FEMA sponsored the development of guidelines for the seismic evaluation and rehabilitation of existing buildings that introduced methods that would inform the future conceptual basis of codes for new buildings. Nonlinear analysis, an analytical method that integrates the deformation of a structure into the analysis of a structural design, was identified as an essential tool for some seismic design applications and the concept of performance goals was introduced. This work produced several publications that have had a significant impact on code development: FEMA 273, NEHRP *Guidelines of the Seismic Rehabilitation of Buildings*, supplemented by FEMA 274, a Commentary, and FEMA 276, Example Applications. FEMA 356, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* converted the guidelines into code language. They are discussed in Chapter 8. Many of FEMA's seismic evaluation and rehabilitation concepts have been adopted in the *International Existing Building Code.*

By the end of the decade, engineering organizations put forward several proposals for code action that called for a more unified, performance-based approach to the regulation of seismic design for new buildings. (See section 6.4 for a discussion of performance-based seismic design.) The SEAOC *Vision 2000: Performance-Based Seismic Engineering of Buildings* called for a code development project that would create a more coherent rationale for seismic code provisions, drawing upon new analytical methods and incorporating an approach that incorporates performance predictions into the design process. The Earthquake Engineering Research Center (EERC) summarized the issues surrounding building performance in FEMA 283, *Performance-Based Seismic Design of Buildings: an Action Plan for Future Studies*. The Earthquake Engineering Research Institute (EERI) produced FEMA 349, *Action Plan for Performance-Based Seismic Design*, and FEMA has now contracted for the development of performance-based seismic design guidelines.

6.2.5 Current Status of Seismic Code Development

The introduction of *IBC* and *NFPA 5000* has assisted the move toward standardizing seismic code regulations in the U.S., but design professionals express concern that the pace of code developments has not kept up with the profession's needs. Debates about the value of simplicity versus the value of reliability continue. Critics argue that codes have become unnecessarily complex and fail to communicate the intent behind code provisions. There is concern that code procedures can be overly restrictive in ways that discourage sound design strategies. There is also concern that, in some cases, designs that "meet the code" may be inadequate. These issues are being aired and addressed in the dialog that surrounds the code revision process and in the work currently underway to develop methods of performance-based design.

6.3 CODE INTENT

6.3.1 The Purpose of Earthquake Code Provisions

The IBC's stated purpose is:

> "to establish the minimum requirements to safeguard the public health, safety and general welfare through structural strength, means of egress, facilities, stability, sanitation, adequate light and ventilation, energy conservation and safety to life and property from fire and other hazards attributed to the built environment and to provide safety to fire fighters and emergency responders during emergency operations. "

The primary intent of all seismic code provisions is to protect the life safety of building occupants and the general public through the prevention of structural collapse and nonstructural life-threatening hazards during an earthquake. However, it is generally acknowledged that seismic code provisions are also intended to control the severity of damage in small or moderate earthquakes. In large earthquakes, damage is expected; engineers rely on the mechanisms provided by damage to contribute to a structure's damping capacity. The SEAOC *Blue Book* states that code-designed buildings should be able to:

1. Resist a minor level of earthquake ground motion without damage;

2. Resist a moderate level of earthquake ground motion without structural damage, but possibly experience some nonstructural damage;

3. Resist a major level of earthquake ground motion having an intensity equal to the strongest either experienced or forecast for the building site, without collapse, but possibly with some structural as well as nonstructural damage.

Codes also recognize that some structures are more important to protect than others. The NEHRP *Provisions* stated purpose is:

1. To provide minimum design criteria for structures appropriate to their primary function and use, considering the need to protect the health, safety, and welfare of the general public by minimizing the earthquake-related risk to life, and

2. To improve the capability of essential facilities and structures containing substantial quantities of hazardous materials to function during and after design earthquakes.

6.3.2 Conflicts Between Intent, Expectations, and Performance

Codes do not explicitly address economic intent. Members of the general public who believe earthquake-resistant design should provide them with usable buildings after an earthquake often misunderstand the term "meets code." Design professionals are responsible to convey seismic design performance expectations to decision makers. Clear communication between engineers and building owners is important and the architect's role as a facilitator of the dialog between owners, and members of the design team is critical to promoting a shared understanding that can form the basis for appropriate design decisions. This communication is complicated by the indirect and somewhat unpredictable relationship between code compliance and building performance. The NEHRP *Provisions* state:

> "The actual ability to accomplish these goals depends upon a number of factors including the structural framing type, configuration, materials, and as-built details of construction."

Local site factors and the variations that can occur with different combinations of structural systems and materials, construction methods and building configuration cause differences in building performance. Factors influencing performance can be subtle and the cause of damage difficult to determine. Earthquakes have produced different damage patterns in apparently identical adjacent buildings. The professional judgment of the design team, the extent of code compliance, and level of plan review also affect building damage. For example, school buildings constructed under the quality control regulations of the Field Act have consistently outperformed other buildings designed to meet similar code provisions.

Given the complexity of building performance in earthquakes, it is readily apparent that many past code "improvements" which increased the lateral base shear (and therefore the strength of buildings to resist a static lateral load) did not have a directly proportional effect on building performance. There are too many other factors involved. Although more sophisticated analysis methods can produce better performance predictions, seismic performance of buildings can be more accurately expressed as a probabilistic rather than as an absolute phenomenon. For example, in a Modified Mercalli level IX earthquake (defined in Chapter 2), it is expected that less than one percent of the midrise concrete shear-wall buildings designed to meet the seismic code minimums of the 1991 UBC will collapse. Five percent of them will experience extensive structural and nonstructural damage, and thirty percent will experience moderate (primarily nonstructural) damage. Seventy percent will have minor or no damage. At present, performance data from real earthquakes or analysis results is not extensive enough to generate reliable probabilistic scenarios for all of the existing and commonly designed combinations of building configurations and structural systems. However, as this information becomes available, it is likely to be reflected in future codes.

Codes are put forward as minimum standards, but it is common practice for designers and owners to aim to meet rather than exceed code minimums as way to control project costs. As owners have become more aware of the limitations of seismic codes, there is greater interest in electing to build to higher standards. This is particularly true for corporate and institutional building owners who self-insure or include risk management and loss projections in their planning process. As owners raise concerns about acceptable levels of risk, there is an increased need to be able to predict building performance and relate that performance to design standards.

6.4 PERFORMANCE BASED SEISMIC DESIGN

6.4.1 Prescriptive Design, Performance Design, and the Code

Performance-based design is fundamentally different from prescriptive design. Prescriptive codes describe what to do—the goal is to achieve a particular design outcome that meets the intent of the code. For example, Table 2305.3.3 of the IBC states that the maximum aspect ratio (height to length) for shear walls sheathed with particleboard is 3.5:1. The intent behind this provision is to insure adequate sheathing of elements used as shear walls and to prevent unrealistically high tie-downs from overturning moments. In contrast, a performance approach for the same structure would describe the intent of the code in a way that allows the designer to decide how the intent is met. In the case of the wood frame building above, the code might stipulate that the lateral movement, or drift, of each floor with respect to the floor below may not exceed 2.5% of the floor-to-floor height. It is then up to the designer to decide how to achieve this outcome. If the designer chooses to use shear walls that are more slender than prescribed by the code, then the designer will need to demonstrate, using a rational basis acceptable to the building official, that the slender shear walls, as well as the rest of the structure, will meet performance requirements.

The distinction between performance and prescriptive methods is complicated by the fact that performance can be a relative concept. For example, a designer studying a concrete-frame building with shear walls could view the maximum story drift permitted by codes for this structural system as a prescriptive requirement. The reason the code limits drift is to prevent the negative consequences of large lateral movements. These include p-delta effects that compromise column integrity, and the concentrated stresses at connections, and higher levels of nonstructural damage caused by excessive movements of the structural frame. If a designer can address these issues through a performance-based approach, the drift need not be limited.

Prescriptive code provisions have some advantages. They have been shown to be reliable for meeting life safety objectives in the U.S. The performance of school buildings in recent California earthquakes substantiates this. They can be applied consistently even in cases where design judgment is difficult or where the designer or building official is inexperienced with alternative design methods. But prescriptive codes do not readily support innovative or alternative approaches to seismic design that provide equal or better building performance.

6.4.2 Definitions of Performance-Based Seismic Design

The term "performance based seismic design", as currently used, has multiple definitions. It is used to refer to a design approach that meets the life safety and building performance intents of the code, while providing designers and building officials with a more systematic way to get at the alternative design option currently available in codes. In this regard, performance-based seismic design facilitates innovation and makes it easier for designers to propose new building systems not covered by existing code provisions or to extend the use of existing systems beyond code limitations. For example, a designer may propose to use a given structural system for a building that is taller than code permits for that system. The designer would provide the building official with a performance-based rationale that shows how the design will meet the intent behind the code's height limit.

Performance-based design is also used to refer to a design approach that identifies and selects a performance level from several performance options. The current version of the IBC can be called performance-based because it incorporates distinctions between performance goals for different building uses. But the term is more commonly used when referring to performance options that exceed code minimums or in cases when buildings are expected to remain operational after a disaster.

From a technical perspective, performance-based design has a different definition. It is a design approach that provides designers with tools to achieve specific performance objectives such that the probable performance of a structure could be reliably predicted. Current codes do not aim to do this. Their goal is to achieve a minimum standard, based on life safety, for most structures and an immediate post-earthquake occupancy standard for facilities essential for post-earthquake recovery. Code requirements have evolved over time to insure that a reasonable effort has been made to meet the minimum standard, but they do not yield performance predictions. The expected performance level of a building that meets current seismic codes is highly variable and undefined by the code. However, the seismic engineering community is now exploring code development options that create a more explicit link between design approach and code content.

6.4.3 Implementing Performance-Based Seismic Design

At the present time, code development efforts related to seismic design are focusing on incorporating performance-based design concepts. It is proposed that future codes would establish frameworks that would assist designers as they provide building owners with a clear choice between a minimum standard and specified higher performance levels. This work includes an effort to translate recent advances in engineering understanding of building performance in past earthquakes, laboratory tests, and structural analysis methods to design guidelines. FEMA, seeking to improve code reliability and facilitate design to higher standards, is funding a longer term effort to develop performance-based design guidelines as initially outlined in FEMA 349. The project scope includes the development of structural, nonstructural, and risk management guidelines supported by a development plan and a stakeholder's guide.

The shift to a performance-based seismic design code will have other broader impacts on building design practice. Although architects are generally not concerned with the details of applying the seismic code and routinely delegate this aspect of code compliance to the structural engineer, a performance-based seismic code will involve the architect more directly in the seismic design process. Architects working with such a code must become very familiar with the definition of performance levels, and the economic implications of the choice of level. Seismic design concerns are also likely to figure more explicitly in the pre-design phase of the architectural design process when project objectives are identified, which often takes place before the involvement of the structural engineer. In the traditional role of coordinator of the design team and primary contact for the client, the architect will facilitate the dialog surrounding performance-based seismic design decisions. As the primary deliverer of information to the client, the architect will need to include more extensive discussions of technical and economic aspects of seismic design than are presently necessary with a single standard code. In projects with alternative administrative structures, such as design-build, architects will experience increased interaction related to seismic design decisions.

As performance-based seismic design methods come into use, the technical challenges inherent in devising structures for architectural schemes that require structural irregularities may increase. As discussed in Chapter 5, buildings with regular configurations perform more predictably than those with irregular configurations. Engineers attempting to meet performance levels specified in a code may become more reluctant to provide performance assurances for irregular structures proposed by the architect. The pressure to predict performance accurately could result in an overly conservative approach to building configuration. Communication and creative collaboration between the architect and the engineer will become more critical, particularly during the initial conceptual phases of the building design process.

The shift to a performance-based approach will also impact the format, enforcement, and implementation of codes. Current codes do not specify design methods or imply a design philosophy. They presume that designers will determine the design approach. A performance-based code suggests that the criteria associated with performance objectives would emerge from an articulated conceptual framework for seismic design. The format of codes would reflect that framework. Enforcing a code that specifies multiple levels of design and performance would require a more complex procedure than currently used. Implementation of a performance-based seismic design code suggests a departure from the traditional evolutionary model of code development to a redesign of the code document. This process would require the support of elected officials and the public. Its success will depend upon increased public understanding of the behavior of structures in earthquakes, the limitations of current codes, and the rationale behind a performance-based approach.

A performance-based seismic design code format could provide a unified basis for comparison of design alternatives that give decision makers a consistent means of quantifying risk. That basis will enable design professionals to respond to the needs of all decision makers and stakeholders concerned with seismic design, including owners, lenders, insurers, tenants, and communities at large. Performance-based design methods are already being used for this purpose, but a code-specified framework could assist decision makers who wish to compare design alternatives and project types.

The need for simplified methods for lower risk building project types will remain, and performance-based seismic design would ultimately provide a basis for the development of new prescriptive code requirements. These requirements would be as simple or simpler to apply as current code provisions, but would have a unified conceptual basis that would provide more predictable performance outcomes. It would be easier for designers to relate code provisions to code intent and eliminate some of the obstacles to seismic design innovation. It would also allow designers to combine performance-based and prescriptive methods in a more consistent manner.

6.5 SEISMIC DESIGN PROVISIONS

6.5.1 Code-Defined Parameters

Seismic design provisions vary in complexity, depending upon the risk associated with the project type. As building risk increases and structural design demands become greater, code provisions expand to include a greater number of parameters that support more sophisticated analytical techniques. Table 6.1 illustrates how these code-defined parameters can be influenced by architectural design decisions, thereby impacting seismic design requirements.

Table 6-1: The effects of architectural design decisions on code parameters and code-mandated design requirements

IBC SEISMIC DESIGN PARAMETERS	ARCHITECTURAL DESIGN DECISIONS	SEISMIC DESIGN REQUIREMENTS
Ground motion accelerations	Site selection at the national and regional scale	Affects design earthquake forces
Site classes (soils properties) combined with ground motion accelerations to determine a site coefficient	-Site selection at regional and local levels -Placement of the building on a particular site	-Failure-prone soils require site-specific geotechnical investigation -Site coefficient affects design earthquake forces -Soils properties affect building response to ground motion
Fundamental period of the structure	-Building height -Selection of structural system	-Affects design earthquake forces -Affects building response to ground motion
Seismic use groups and occupancy importance factors	Assignment of program spaces to buildings	-Affects eligibility for simplified analysis methods - Triggers need to meet more stringent code requirements
Seismic design category that relates structure importance to design accelerations	Site selection for particular building uses	Used to identify appropriate code procedures
Building configuration classification	-Building size -Footprint geometry and massing -Organization of interior spaces -Structural framing patterns	Used to modify the analysis procedures specified by the code and can trigger more extensive analysis requirements
Response modification factor, system over strength factor, deflection amplification factor, redundancy coefficient	-Type of lateral load resisting system -Materials of construction of the lateral load resisting system	-Affects design earthquake forces -Affects building response to earthquake forces

6.5.2 Performance Levels

In performance-based seismic design, a decision-making team that includes designers as well as stakeholders makes choices between alternate performance levels. To do this, the team must consider the appropriate level of seismic hazard to which the building should be designed as well as the acceptable risk that would guide building performance expectations. Implicit in this process is an evaluation of costs and benefits. Performance levels must be articulated qualitatively and technically. Qualitative performance objectives are stated according to the needs of stakeholders. These objectives include life safety, ability to use a building for shelter after an event, ability to continue to produce services or income at the site after an event, and the costs associated with repair, loss of use, and loss of contents.

Technical performance levels translate qualitative performance levels into damage states expected for structural and nonstructural systems. As defined in Table 6-2, the SEAOC *Vision 2000* document proposes four qualitative performance levels. Figure 6-9 shows how the NEHRP *Provisions* relate these performance levels to probabilistic seismic hazard levels and occupancy categories called Seismic Use Groups (SUG). SUGs classify structures according to risk and importance. SUG I is the category

Table 6-2: SEAOC *Vision 2000* Qualitative Performance Levels

Fully operational	Continuous service. Negligible structural and nonstructural damage.
Operational	Most operations and functions can resume immediately. Structure safe for occupancy. Essential operations protected, non-essential operations disrupted. Repair required to restore some non-essential services. Damage is light.
Life Safety	Damage is moderate, but structure remains stable. Selected building systems, features, or contents may be protected from damage. Life safety is generally protected. Building may be evacuated following earthquake. Repair possible, but may be economically impractical.
Near Collapse	Damage severe, but structural collapse prevented. Nonstructural elements may fall. Repair generally not possible.

SOURCE: SEAOC VISION 2000 REPORT

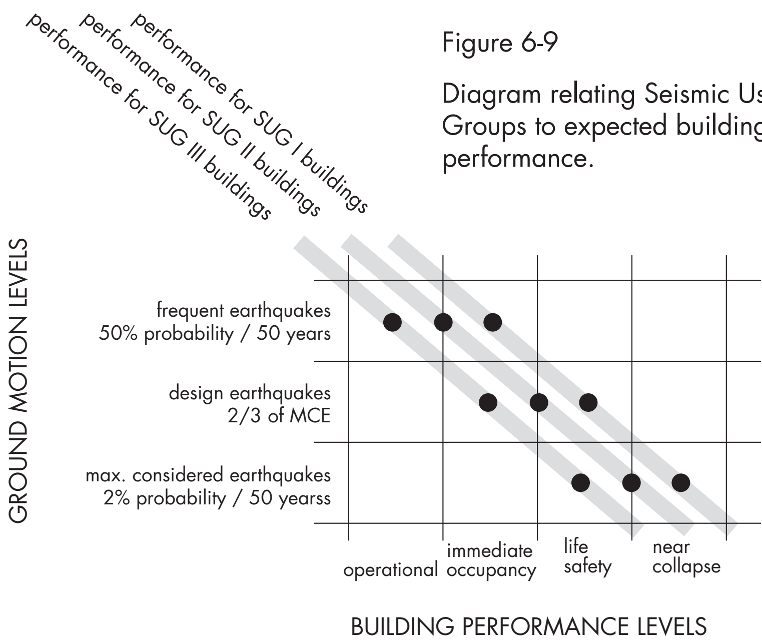


Figure 6-9

Diagram relating Seismic Use Groups to expected building performance.

SOURCE: FEMA 450 PART 2, *COMMENTARY ON THE 2003 NEHRP RECOMMENDED PROVISIONS FOR NEW BUILDINGS AND OTHER STRUCTURES,*

assigned to most structures. SUG II structures have high-occupancy levels with restricted egress. SUG III structures are essential facilities for post-earthquake recovery or facilities that contain hazardous materials. The performance criteria for each group is progressively more stringent.

6.5.3 Performance-Based Seismic Engineering

The technical definition of a performance level must specify building performance in terms that can be verified by an analysis of the proposed building design. As the design team responds to the specific needs of individual stakeholders, multiple performance objectives will be identified, and multiple technical parameters will be used to establish acceptance criteria. The identification and implementation of technical performance criteria requires the ability to predict, with reasonable reliability, the behavior of a building subject to an earthquake hazard. Recent advances in analytical tools and computational capabilities have advanced the art of earthquake performance prediction and made the development of performance-based approaches to engineering design more possible now than in the recent past.

Seismic engineering analysis is the art of translating understandings of seismic hazards into predictions of building behavior in a way that can inform building design. It is used in the conceptual design phase to evaluate alternative structural systems and configurations, in the schematic design phase to refine the layout of the selected structural system, and in the design development phase to determine the details of construction. Throughout the design process, engineering analysis is used to verify that the proposed design will perform at an acceptable level and satisfy building code requirements. Engineers select analysis methods based on the type of structural behavior being examined and the need for information about that behavior. Simple methods can be useful for conceptual design even when complex methods are required for design development. In a given building design project, multiple analysis methods will be used to verify design decisions that range from the selection of a structural system to the selection of a bolt diameter.

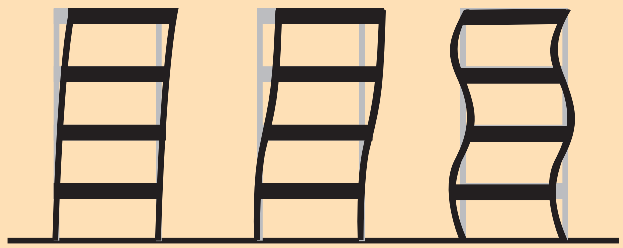
In performance-based seismic engineering practice, performance implications of some design decisions have to be predicted with a greater degree of accuracy than others. Designers aim to use the simplest, most cost-effective method appropriate for the design task at hand. It takes a combination of theoretical knowledge and engineering judgment to select appropriate analytical methods. Routine design of small regular buildings of conventional construction can be accomplished with simple analytical methods, whereas large, irregular buildings are likely to require a more complex analysis. Designers will sometimes choose to use more than one analysis method as a way to examine different aspects of a structure's behavior. Although the code does not specify approaches to seismic design, it does restrict the use of certain analytical methods to insure that they are used appropriately. From an architect's perspective, this means that some combinations of building parameters will require more costly engineering analysis methods.

6.5.4 Engineering Analysis Methods

Seismic analysis methods can be divided into two groups—linear procedures and nonlinear procedures. Linear procedures are by far the most common and are used in the majority of seismic design applications for new buildings. The term "linear" refers to the assumption that there is a constant proportional relationship between structural deformation and the forces causing it. Engineers are familiar with linear analysis because it is the same as used for analysis of beams, girders, and columns for gravity systems. Most prefer linear seismic design for the same reason. However,

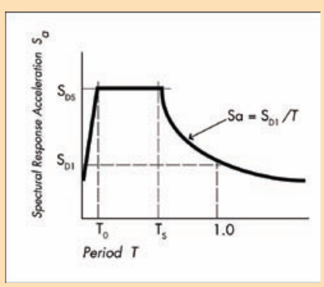
Box 2. Linear Dynamic Analysis

A linear dynamic analysis is useful for evaluating irregular or dynamically complex buildings. An irregular building is defined as having a distribution of mass or stiffness of the structure that is nonuniform and is often created in buildings that that have complex space planning requirements or asymmetrical configurations. Dynamic complexity is common in flexible structural systems. Flexibility is greatly influenced by the selection of structural system and building height. Flexible buildings tend to have a significant response to higher mode shapes. Mode shapes are movement patterns that occur naturally in structures that have been set in motion by ground shaking. The diagram below compares the shapes of the first three modes.



first or fundamental mode   second mode   third mode

Designers use linear dynamic analysis to determine the degree of influence each mode shape will have on a structure's performance. The importance of higher modes depends on the relationship between the fundamental mode of the structure and the dynamic-ground shaking characteristics of the site. Designers express mode shape influence in terms of the percent of building mass assigned to a particular mode. If the building mass vibrates primarily in the first or fundamental mode, a static analysis is permitted by the code. Although linear dynamic analysis methods are becoming routine in engineering practice, they are more complicated because they require detailed information about ground motion. When linear dynamic analysis is used to meet code requirements or check code conformance, the structure-ground shaking interaction is usually modeled using a response spectrum. The IBC code includes design response spectra, a procedure for developing a design structure curve based on the general design response spectrum show below.



design response spectrum

An alternative and significantly more complex method for modeling ground shaking, called a time history analysis, examines modal response using actual ground motion data. The code requires that time history analyses consider several different ground motion records to insure that the structure response is sufficiently representative to account for future unknown ground motion patterns.

the linear forces used and building deformations are not those expected in an earthquake and have been somewhat arbitrarily developed to result in buildings that are adequately resistant to life-threatening earthquake damage. A nonlinear approach adds another layer of analytic complexity. It takes into account the changing stiffness of various elements and the overall structure during the shaking. Structural elements are designed by examining deformations rather than forces. Although nonlinear analysis can be used to design new buildings, it is more commonly used to predict seismic response for evaluation and retrofit of existing structures.

Linear analysis can be static or dynamic. The IBC's equivalent lateral force procedure, shown in Box 1, is a simple version of a linear static analysis. A linear static procedure is well suited to buildings with regular configurations that have a response to ground motion that is dominated by the back and forth swaying of a structure called the fundamental mode. Linear models can also be dynamic. The dynamic version of a linear model, shown in Box 2, is known as a modal analysis. It is based on an idealized site response spectrum and takes into account motions that are influenced by higher mode shapes providing more information about a building's behavior under seismic loads. Because it is linear, the displacements expected under different modes can be added together to identify critical design behaviors. A modal analysis is frequently used to create a more accurate picture of how irregular structures would perform. Seismic codes allow and, in some cases, require designers to substitute a modal analysis for static methods.

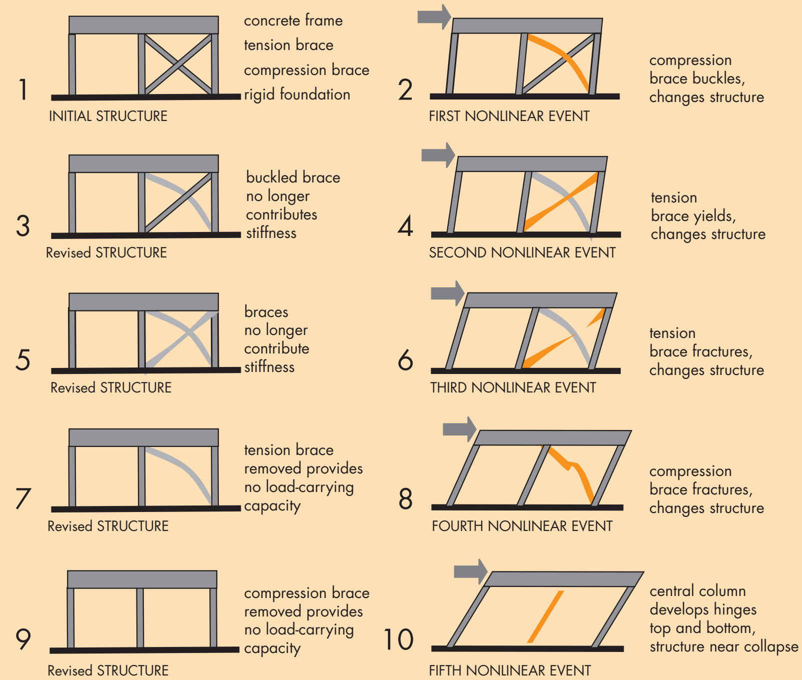
Nonlinear analysis methods can also be static or dynamic. The "push-over" analysis shown in Box 3 is a static nonlinear analysis technique that offers the potential for increased accuracy at the expense of increased complexity. It requires multiple iterations of a static analysis that can account for the effects of yielding elements and help designers visualize how building behavior transforms as damage states progress. It is often used to identify and control the weak links that initiate structural failure mechanisms.

A nonlinear dynamic analysis or time history analysis is the most sophisticated and time-consuming method requiring a detailed knowledge of building properties and ground motions. It is relatively new to design practice and is used in the research and experimental stages of design applications. The IBC accepts this analysis procedure, provided that a design review is performed by an independent team of qualified design professionals.

Box 3. Nonlinear Static "Pushover" Analysis

A pushover analysis is a nonlinear static method that accounts for the way structures redesign themselves during earthquakes. As individual components of a structure yield or fail, the earthquake forces on the building are shifted to other components. A pushover analysis simulates this phenomenon by applying loads until the weak link in the structure is found and then revising the model to incorporate the changes in the structure caused by the weak link. A second iteration is then performed to study how the loads are redistributed in the structure. The structure is "pushed" again until the second weak link is discovered. This process continues until the yield pattern for the whole structure under seismic loading is identified.

A pushover analysis is only useful for evaluating nonlinear structures for which the fundamental mode dominates and is not suitable for certain irregular or dynamically complex structures. These would need to be designed using a nonlinear dynamic method. Some building structures are inherently linear because they lack redundancy or exhibit brittle modes of failure. These structures can be modeled sufficiently accurately using linear analysis methods. A sequence of nonlinear events used in a pushover analysis is shown below for a single-story, two-bay reinforced concrete frame with one bay of steel cross bracing. The sequence is shown numbered in the figure.



In current engineering practice, pushover analysis is more commonly used to evaluate the seismic capacity of existing structures and appears in several recent guidelines for seismic design concerning existing buildings. It can also be a useful design tool for the performance-based design of new buildings that rely on ductility or redundancies to resist earthquake forces.

To implement this method reliably, designers must be able to make a sufficiently accurate model that will reflect inelastic properties and potential deformation mechanisms of the structure. This requires a more sophisticated understanding of the structure's behavior than linear methods. Nonlinear analysis results produce more data and can be difficult to interpret. The current IBC code treats nonlinear analysis as an alternate method, but nonlinear approaches are likely to become integrated into the code as the code evolves in the future.

ADAPTED FROM A PRESENTATION MADE BY RON HAMBURGER AT EARTHQUAKE ANALYSIS METHODS: PREDICTING BUILDING BEHAVIOR, A FEMA-SPONSORED EERI TECHNICAL SEMINAR, 1999.

In general, nonlinear methods are not useful if the intent of the design is to verify compliance with minimum code provisions. Nonlinear methods generate a significantly greater quantity of analytical results that require substantially more engineering effort to produce and interpret. These methods are more appropriately used to determine estimates of performance with higher reliability than standard code expectation or to analyze the combined effects of new retrofit components and existing systems. If the intent of the analysis is to verify code compliance, linear analysis methods will suffice. Future codes are likely to include explicit guidelines for the use of nonlinear methods as they become a more routine part of conventional engineering practice.

6.6 NONSTRUCTURAL CODES

The IBC 2003 seismic code deals with the problem of reducing damage to nonstructural components in two ways. The first is to impose limits on the horizontal drift or deflection of the main structure. This is because nonstructural damage (such as glass breakage or fracturing of piping) may occur because the building structure is too flexible, causing racking in wall panels, partitions, and glazing framing. Flexible structures are economical because the code allows for considerably reduced forces to be used in the design; however, this approach solves the structural problem at the expense of the nonstructural components. Although this approach can still be used, the imposition of drift limits ensures that the flexibility of the structure will not be such that excessive nonstructural damage results.

The second approach is to assign force values based on acceleration to the critical nonstructural components and their connections to ensure that they will be strong enough to resist seismic accelerations in their own right or as the result of attachment to the structure. The analysis procedure is similar to, although less complex than, the procedure for determining the equivalent lateral force on the main structure. Modifications to the basic F=Ma equation include coefficients for importance, component amplification, component response modification, and the height of the component within the structure. All these modifiers increase the design forces relative to the spectral accelerations derived from the hazard maps.

In a way similar to that used to determine the forces on the main structure, the required performance characteristics for nonstructural components are related to three different Seismic Use Groups based on the use and occupancy of the building.

Several exemptions are made in the IBC seismic code:

1. All components in Seismic Design Category A structures are exempt because of the lower seismic effects on these items.

2. All architectural components (except parapets supported by bearing or shear walls) in Seismic Design Category B structures are exempt if they have an importance factor of 1.00, which indicates that they are not a life safety threat. (The importance factor is a 1.5 multiplier for components that are needed to function after the earthquake for life safety, that contain hazardous contents, or are large storage racks open to the public.). The importance factor is selected by the engineer, based on criteri in the code and consultation with the building official.

3. Mechanical and electrical components, Seismic Design Category B.

4. Mechanical and electrical components, Seismic Design Category C when the components importance factor is 1.00.

5. All Mechanical and electrical components in all seismic design categories that weigh less than 400 pounds, are mounted 4 ft. or less above the floor, have an importance factor of 1.00, are not critical to the continued operation of the building, and include flexible connections between the components and associated ductwork, piping and conduit.

6. Mechanical and electrical components in Seismic Design Categories C, D and F that weigh 20 pounds or less, the importance factor is 1.00, and flexible connections are provided.

Of all the elements of the building envelope, heavy precast concrete wall cladding panels attached to steel or reinforced concrete-frame structures require the most design and construction attention to ensure seismic safety. These typically span from floor-to-floor: horizontal drift or deformation of the building structural frame can create considerable racking forces in panels that are rigidly attached at top and bottom, resulting in damage or possible drop-off. Therefore, the attachment of these panels must permit differential movement of the floors without transmitting racking forces to the panels. This is achieved by special detailing of the connection of panels to structure.

Seismic codes require that heavy panels accommodate movement either by sliding or ductile connections. In high seismic zones sliding connections are rarely used, because of the possibility of incorrect adjustments when bolts are used, jamming or binding due to unwanted materials left after installation, and jamming due to geometrical change of the structural frame under horizontal forces.

The need for disassociating the heavy panel from the frame has a major impact on connection detailing. As a result, a connection commonly termed “push-pull” has been developed, primarily in California, which provides, if properly engineered and installed, a simple and reliable method of de-coupling the panel from the structure. The generic connection method consists of supporting the panel by fixed bearing connections to a structural element at one floor to accommodate the gravity loads, and using ductile “tie-back” connections to a structural element at an adjoining floor (Figure 6-10).

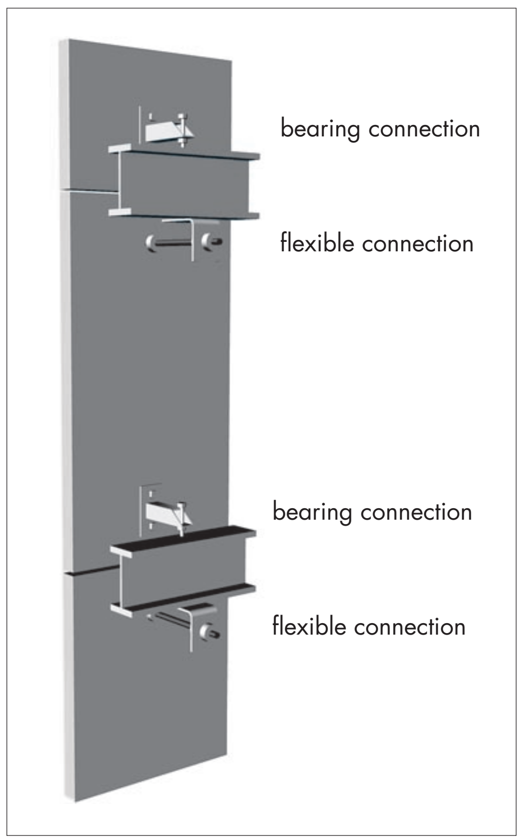


Figure 6-10

Typical floor-to-floor push-pull panel connections. Each beam has a bearing connection at the bottom of a panel and a flexible, or tie-back, connection for the panel below.

Recent developments in nonstructural seismic codes include a performance-based design approach, comparable to that used for structural design. This approach was first defined in the NEHRP *Guidelines for the Seismic Rehabilitation of Buildings* (FEMA 273,274) and subsequently in FEMA 356, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*. This will be replaced in 2006 by a new ASCE standard, ASCE 41.

6.7 CONCLUSION

The continually transforming content of seismic design codes reflects the evolution of design practice as it takes place in changing technical and political contexts. As the shift to a performance-based approach takes place, designers are raising questions about possible impacts on design practice. How will a performance-based seismic code affect professional liability? How will it affect the cost of professional design services? Will it be particularly difficult or expensive for small firms or inexperienced owners to implement? Will it really help designers manage uncertainty? Without real data on real buildings in real earthquakes to confirm our performance predictions, how confident can we be that our performance-based design methods work?

As the dialog surrounding building code development continues, new insights are emerging, particularly the recognition that this process needs the attention of all stakeholders concerned with the built environment. For architects, the new codes and the performance-based concepts behind them will require greater involvement in seismic design decisions. As architects help owners investigate the feasibility of proposed building projects and lead their clients through the design process, they will need to be aware of the interaction between design decisions and seismic design regulations.

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