Performance-Based Earthquake Design of Buildings and Structures

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Credit: 2 PDH

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PERFORMANCE-BASED ENGINEERING: AN EMERGING CONCEPT IN SEISMIC DESIGN 4

Performance-based seismic design, the focus of this chapter, is a relatively new concept that reflects a natural evolution in engineering design practice. It is based on investigations of building performance in past earthquakes and laboratory research, and is enabled by improvements in analytical tools and computational capabilities. Performance-based seismic design concepts have been made possible by the collective intellect of an interested profession and significant financial resources provided in large part by the federally funded National Earthquake Hazards Reduction Program.

To introduce the subject, we begin with a description of the process by which seismic codes are developed and implemented (Section 4.1), followed by a discussion of the expected performance of new buildings designed in accordance with current seismic codes (Section 4.2). Interestingly enough, as discussed in Section 4.3, currently applied concepts in performance-based seismic design were developed for the rehabilitation of existing buildings, as opposed to the design of new buildings. These concepts, however, apply equally well to new buildings, and model codes for new building seismic design are beginning to adopt and adapt the performance-based concepts created for seismic rehabilitation of existing buildings. As described in Section 4.4, work is also underway to develop next-generation performance-based seismic design guidelines for new and existing buildings.

4.1 SEISMIC DESIGN PROVISIONS IN BUILDING CODES

Building design codes for cities, states, or other jurisdictions throughout the United States are typically based on the adoption and occasional modification of a model building code. Up until the mid-1990s, there were three primary model building code organizations: Building Officials and Code Administrators International, Inc. (BOCA), International Conference of Building Officials (ICBO), and Southern Building Code Congress International, Inc. (SBCCI). In 1994, these three organizations united to found the International Code Council (ICC), a nonprofit organization dedicated to developing a single set of comprehensive and coordinated national model construction codes. The first code published by ICC was the *2000 International Building Code* (IBC; ICC, 2000).

Building code adoption is a complicated process, especially in regions with significant exposure to natural hazards such as earthquake, wind, or flood. In some earthquake-prone regions of the United States, the seismic design provisions outlined in the 2000 IBC have not been adopted. Instead, the provisions of the *Uniform Building Code* (UBC), the model building code published by IBCO from 1949 through 1997 (ICBO, 1997), are still used. The seismic provisions in the UBC are based primarily on the provisions contained in the Structural Engineers Association of California (SEAOC) *Recommended Lateral Force Requirements and Commentary*, known as the *Blue Book* and published from 1959 through 1999 (SEAOC, 1999). In addition, the 1997 UBC relies on the provisions contained in the 1994 edition of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings* (BSSC, 1995), while the 2000 IBC relies on the more recent 1997 edition of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* (BSSC, 1998).

The *NEHRP Provisions* have been published regularly since the National Earthquake Hazards Reduction Program (NEHRP) was created in 1978 as a response to Congress passing P.L. 95-124, the Earthquake Hazards Reduction Act of 1977. The Federal Emergency Management Agency (FEMA) was mandated to implement P.L. 95-124 and NEHRP, and the Building Seismic Safety Council (BSSC) was formed to provide a broad consensus mechanism for regularly updating the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings* (hereinafter referred to as the *NEHRP Recommended Provisions),* first published in 1978 by the Applied Technology Council as *Tentative Provisions for the Development of Seismic Regulations for Buildings*, (ATC-03 Report; ATC, 1978). The most recent version of the *NEHRP Recommended Provisions* is the 2000 edition (BSSC, 2001) and a 2003 edition is currently in development, as discussed later in this chapter.

The remainder of this chapter explores seismic design issues related to current building codes, specifically the intent of current codes with respect to the performance of structural and nonstructural building systems. The current codes include the 2000 IBC and the 1997 UBC (and the *NEHRP Recommended Provisions* and SEAOC *Blue Book* on which they rely), as these are most commonly used, although it should be noted that a few jurisdictions have adopted the recently published National Fire Protection Agency (NFPA) 5000 *Building Construction and Safety Code* (NFPA, 2003) in conjunction with the American Society of Civil Engineers (ASCE, 2002) ASCE 7-02 publication, *Minimum Design Loads for Buildings and Other Structures*, for earthquake loading requirements.

Performance-based engineering, an emerging design tool for managing seismic risk, and the impact that the emergence of performance-based design strategies will have on future buildings and their seismic performance, discussed later in this chapter.

4.2 EXPECTED PERFORMANCE WHEN DESIGNING TO CURRENT CODES

The basic intent of current seismic design provisions is best summarized by the SEAOC *Recommended Lateral Force Requirements and Commentary* (SEAOC, 1999), which states:

> These Requirements provide minimum standards for use in building design regulation to maintain public safety in the extreme ground shaking likely to occur during an earthquake. These Requirements are primarily intended to safeguard against major failures and loss of life, not to limit damage, maintain functions, or provide for easy repair.

DESIGN CONSIDERATION

Current seismic design codes are essentially aimed at the preservation of life and safety for the benefit of the community.

In other words, current seismic design codes are essentially aimed at the preservation of life and safety for the benefit of the community. The recommended provisions express expectations and provide no guarantees; they assume that there may be damage to a building as a result of an earthquake. For example, the SEAOC *Recommended Lateral Force Requirements and Commentary* includes a general set of performance statements to qualify the nature of expected damage, as follows:

> Structures designed in accordance with these recommendations should, in general, be able to:
>
> - Resist a minor level of earthquake ground motion without damage
> - Resist a moderate level of earthquake ground motion without structural damage, but possibly experience some nonstructural damage.
> - 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.
>
> It is expected that structural damage, even in a major design level earthquake, will be limited to a repairable level for most structures that meet these Requirements. In some instances, damage may not be economical to repair. The level of damage depends upon a

number of factors, including the intensity and duration of ground shaking, structure configuration, type of lateral force resisting system, materials used in the construction, and construction workmanship.

> **DESIGN CONSIDERATION**
>
> Codes do not provide the designer with the difference in performance between different structural systems.

Designers use codes as a resource, as they provide minimum acceptable consensus standards. Codes provide no guidance on the selection of materials and systems, rather only criteria for their use once selected. Codes also do not provide the designer with the difference in performance between systems; for example, the difference between the stiffness of shear walls and frames and the importance of this characteristic for the overall seismic performance of the building. Lastly, codes do not discuss that the use of some structural systems will result in more nonstructural damage than others, even though the structural systems perform equally well in resisting the earthquake forces. The following sub-sections describe the expected performance of structural and nonstructural components, respectively.

Expected Performance of Structural Components

> **DESIGN CONSIDERATION**
>
> Current seismic design provisions for non-essential facilities are intended to provide resistance to collapse in a major earthquake (typically the design ground motion). Resistance to collapse means that the structure may have lost a substantial amount of its original lateral stiffness and strength, but the gravity-load-bearing elements still function and provide some margin of safety against collapse.

As mentioned earlier, current seismic design provisions for non-essential facilities are intended to provide life safety, i.e., no damage in a minor earthquake, limited structural damage in a moderate earthquake, and resistance to collapse in a major earthquake (typically the design ground motion). Resistance to collapse means that the structure may have lost a substantial amount of its original lateral stiffness and strength, but the gravity-load-bearing elements still function and provide some margin of safety against collapse. The structure may have permanent lateral offset and some elements of the seismic-force resisting system may exhibit substantial cracking, spalling, yielding, buckling, and localized failure. Following a major earthquake, the structure is not safe for continued occupancy until repairs are done. Shaking associated with strong aftershocks could threaten the stability of the structure. Repair to a structure in this state is expected to be feasible, however it may not be economically attractive to do so. Section 4.3 includes further discussion of the seismic behavior of specific structural systems in the context of describing performance-based design objectives.

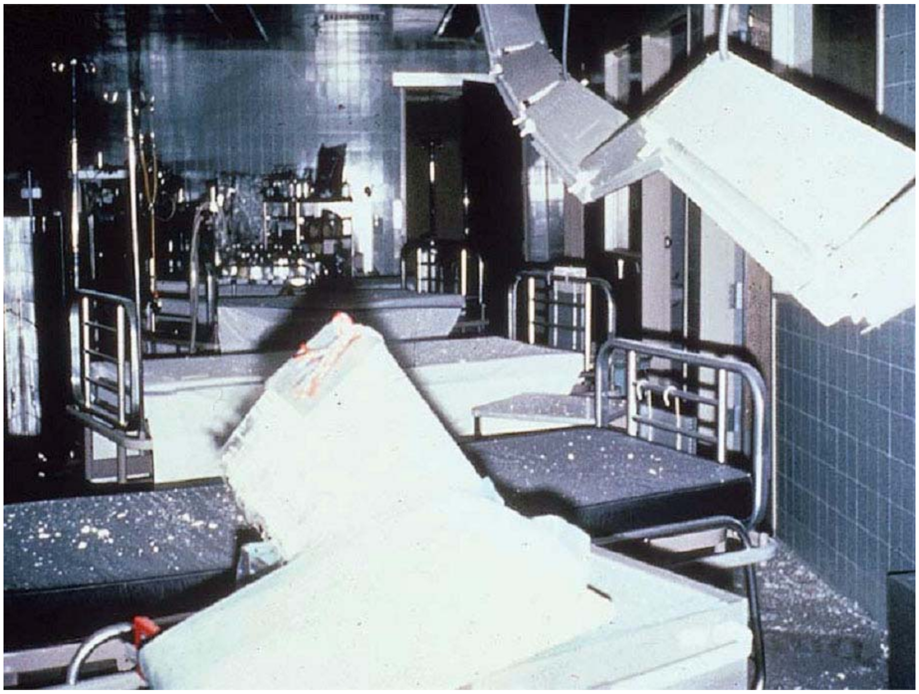


Figure 4-1 Photo of lights set into a fixed ceiling system that shook loose during an earthquake and are hanging from their conduits. (ATC-20 Training Slide Set photo)

Expected Performance of Nonstructural Components

While current seismic design provisions provide minimum structural performance standards in terms of resistance to collapse, they typically do not address performance of nonstructural components, such as room partitions, filing cabinets and book cases, hung lighting and ceilings, entryway canopies, and stairwells; nor do they address performance of mechanical, electrical, or plumbing systems including fire sprinklers, heating and air conditioning equipment or ductwork, and electrical panels or transformers. The vast majority of damage and resulting loss of building functionality during recent damaging earthquakes has been the result of damage to nonstructural components and systems (Figure 4-1). Many building owners have been surprised when a building withstands the effects of a moderate earthquake from a structural perspective, but is still rendered inoperable from a nonstructural standpoint.

DESIGN CONSIDERATION

While current seismic design provisions provide minimum structural performance standards in terms of resistance to collapse, they typically do not address performance of nonstructural components.

Current seismic design provisions typically require that nonstructural components be secured so as to not present a falling hazard; however, these components can still be severely damaged such that they can not function. Loss of electric power, breaks in water supply and sewer out-

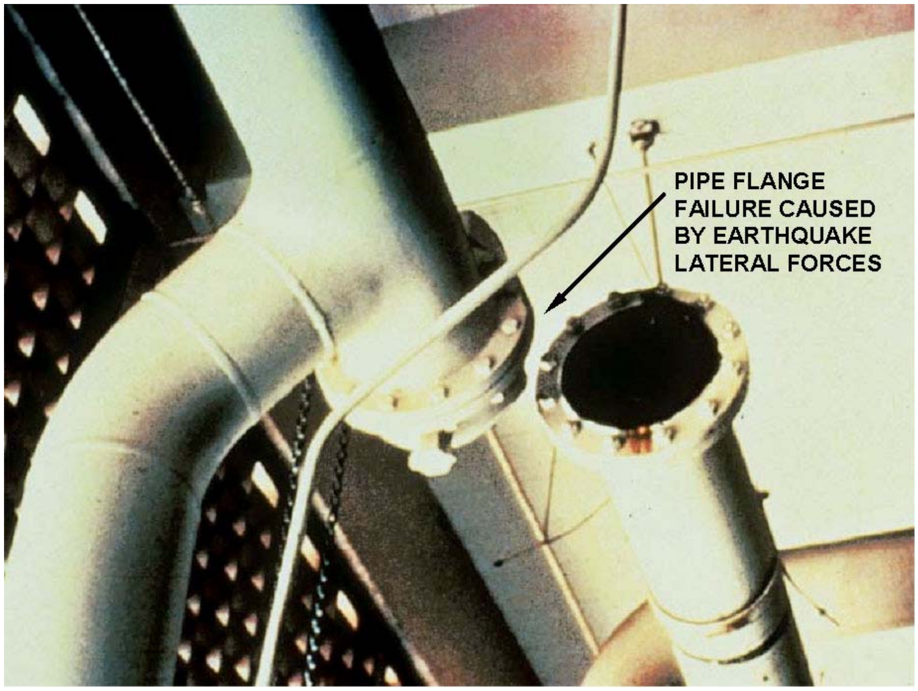


Figure 4-2 Photo of pipe flange failure caused by earthquake lateral forces. (ATC-20 Training Slide Set photo)

flow lines (see Figure 4-2), or non-functioning heating or air conditioning will render a building unusable by tenants. Breaks in fire sprinklers will cause flooding within all or part of a building, soaked carpets and walls, inundated files and records, and electrical shorts or failures in electrical equipment and computers. Other examples of nonstructural damage that can be expected in a code-compliant building subjected to strong ground shaking include extensive cracking in cladding, glazing, partitions, and chimneys; broken light fixtures; racked doors; and dropped ceiling tiles. Section 4.3 includes further discussion of the seismic behavior of specific nonstructural systems in the context of describing performance-based design objectives.

4.3 CURRENT SPECIFICATIONS FOR PERFORMANCE-BASED SEISMIC DESIGN

DESIGN CONSIDERATION

The primary function of performance-based seismic design is the ability to achieve, through analytical means, a building design that will reliably perform in a prescribed manner under one or more seismic hazard conditions.

As described earlier, an important yet emerging concept in the successful implementation of seismic risk management strategies is the application of performance-based seismic design approaches. The primary function of performance-based seismic design is the ability to achieve, through analytical means, a building design that will reliably perform in a prescribed manner under one or more seismic hazard conditions. The fact that alternative levels of building performance are being defined and can be chosen as performance objectives is a relatively new development in seismic design. Some of its origins lie in studies of building performance during recent earthquakes, in which owners of buildings that suffered hundreds of thousands of dollars in damage were surprised to learn that the buildings met the intent of the life-safety provisions of the seismic code under which they were designed, since no one was killed or seriously injured. Out of these experiences came the realization that design professionals need to be more explicit about what "design to code" represents and what seismic design in general can and can not accomplish. At the same time, studies of damaged buildings, together with laboratory research and computer analyses, have led to a much more sophisticated understanding of building response under the range of earthquake ground motion that can be expected to occur.

This section describes some of the key concepts of performance-based seismic design. These concepts have emerged from a series of studies, funded by FEMA, that focused on the development of performance-based seismic design guidelines for existing buildings. The first study, published in the FEMA 237 report, *Seismic Rehabilitation of Buildings – Phase I: Issues Identification and Resolution* (ATC, 1992), identified and resolved a wide variety of scope, format, socio-economic, and detailed technical issues that needed to be considered during the subsequent development of practical guidelines for the seismic rehabilitation of buildings. During that initial study, the concept of performance goals was introduced, effectively commencing the move toward performance-based seismic design. The follow-on study, an $8-million FEMA-funded effort carried out jointly by the Applied Technology Council, the Building Seismic Safety Council, and the American Society of Civil Engineers, resulted in the formulation of detailed guidelines, written for practicing structural engineers and building officials, that specify the means to use performance-based design concepts to rehabilitate existing buildings to improve their seismic resistance. The final set of products of that effort consists of three documents: FEMA 273, NEHRP *Guidelines for the Seismic Rehabilitation of Buildings* (ATC/BSSC, 1997a); FEMA 274, *NEHRP Commentary for the Guidelines for Seismic Rehabilitation of Buildings* (ATC/BSSC, 1997b); and FEMA 276, *Example Applications of the NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (ATC, 1997). In order to speed the implementation of the FEMA 273 *Guidelines* in structural engineering practice, the *Guidelines* were converted, with funding from FEMA, to a *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (FEMA 356) by the American Society of Civil Engineers

(ASCE, 2000). The conversion process maintained the performance levels and performance descriptions, as described below, and other concepts developed for the FEMA 273 *Guidelines*.

Midway through the long-term FEMA effort to develop the FEMA 273 *Guidelines* and FEMA 356 *Prestandard*, the Structural Engineers Association of California (SEAOC) developed *Vision 2000, Performance Based Seismic Engineering of Buildings*, which describes a framework for performance based seismic design of new buildings. At about the same time, the Applied Technology Council developed the ATC-40 report, *Seismic Evaluation and Rehabilitation of Concrete Buildings* (ATC, 1996b), a detailed procedures manual for the seismic evaluation and rehabilitation of concrete buildings using performance-based seismic design concepts. All of the documents described above are important, state-of-the-art resources for the structural engineering community.

RESOURCES

Engineering Applications for Performance-Based Seismic Design

- ATC-40, *Seismic Evaluation and Retrofit of Concrete Buildings*, Applied Technology Council, 1996b.
- FEMA-273, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, (ATC/BSSC, 1997a).
- FEMA-274, *Commentary on NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, (ATC/BSSC, 1997b).
- FEMA-356, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (ASCE, 2000).
- SEAOC, *Vision 2000: Performance Based Seismic Engineering of Buildings*, Structural Engineers Association of California, 1995.

The application of performance-based seismic design can be highly technical, and requires that the design engineer have a good understanding of seismic hazards, and the dynamic and inelastic behavior of buildings and materials. Unlike the application of building codes, performance-based seismic design is not typically prescriptive in nature, and often requires significantly more detailed building analysis than might otherwise be required. However, as discussed earlier, the advantages of performance-based seismic design in the development of an overall risk management plan is usually worth the extra effort spent by the design team. It is the challenge of the design team to convey this level of importance to the owner and the owner's representatives.

Building Performance Objectives

A fundamental concept behind the implementation of performance-based seismic design is the development of a consensus set of performance objectives. The performance objectives describe the intended performance of the building (e.g., in terms of life safety, levels of acceptable damage, and post-earthquake functionality) when subjected to an earthquake hazard of a defined intensity (e.g., a maximum credible event or an event with a certain return period). As earthquake intensity increases, building performance generally decreases. The goal of specifying a performance objective is to achieve a reliable estimate of

DEFINITION

def-ə-

Building Performance Objective
Intended performance level in combination with a specified seismic shaking level.

Table 4-1 Performance Objectives (Adapted from FEMA 356 (ASCE, 2000))

		Target Building Performance Levels*			
		Operational Performance Level (1-A)	Immediate Occupancy Performance Level (1-B)	Life Safety Performance Level (3-C)	Collapse Prevention Performance Level (5-E)
Earthquake Hazard Level (ground motions having a specified probability of being exceeded in a 50-year period)	50%/50 year	a	b	c	d
	20%/50 year	e	f	g	h
	BSE-1 (10%/50 year)	i	j	k	l
	BSE-2 (2%/50 year)	m	n	o	p

*Alpha-numeric identifiers in parentheses defined in Table 4-2

Notes:
1. Each cell in the above matrix represents a discrete Rehabilitation Objective
2. Three specific Rehabilitation Objectives are defined in FEMA 356:
   Basic Safety Objective = cells k + p
   Enhanced Objectives = cells k + p + any of a, e, i, b, f, j, or n
   Limited Objectives = cell k alone, or cell p alone
   Limited Objectives = cells c, g, d, h, l

performance under one or more earthquake hazard scenarios. A representation of different performance objectives is shown in Table 4-1, which is taken from FEMA 356 *Prestandard and Commentary for Seismic Rehabilitation of Buildings* ((ASCE, 2000), a prestandard for performance-based seismic rehabilitation of existing buildings. Although FEMA 356 pertains to seismic rehabilitation, the same concepts apply to new design.

As shown in Table 4-1, FEMA 356 defines two basic earthquake hazard levels – Basic Safety Earthquake 1 (BSE-1, corresponding to 475-year return period event, or ground motions having a 10% probability of being exceeded in 50 years) and Basic Safety Earthquake 2 (BSE-2 corresponding to 2475-year return period event, or ground motions having a 2% probability of being exceeded in 50 years). The Basic Safety Objective (BSO) is then defined as meeting the target building performance level of Life Safety for BSE-1, and the target building performance level of Collapse Prevention for BSE-2 (cells k and p in Table 4-1). FEMA 356 states,

> The BSO is intended to approximate the earthquake risk to life safety traditionally considered acceptable in the United States.

Buildings meeting the BSO are expected to experience little damage from relatively frequent, moderate earthquakes, but significantly more damage and potential economic loss from the most severe and infrequent earthquakes that could affect them.

Performance objectives higher than the BSO are defined as Enhanced Objectives, which are achieved by designing for target building performance levels greater than those of the BSO at either the BSE-1 or BSE-2 hazard levels or by designing for the target building performance levels of the BSO using an earthquake hazard level that exceeds either the BSE-1 or BSE-2 (see Table 4-1 notes). The possible combinations of target building performance and earthquake hazard level corresponding to design for an enhanced performance objective are limitless – the goal is simply to provide building performance better than that intended by the BSO and mandated in most current design codes.

Note also that certain cells of the matrix (Table 4-1) are referred to as Limited Objectives. While this lower performance objective may be applicable to certain partial or reduced seismic rehabilitation designs, it does not apply to new design as it falls below current code standards.

Building Performance Levels

Building performance can be described qualitatively in terms of the:

- safety afforded building occupants, during and after an earthquake.
- cost and feasibility of restoring the building to pre-earthquake conditions.
- length of time the building is removed from service to conduct repairs.
- economic, architectural, or historic impacts on the community at large.

These performance characteristics will be directly related to the extent of damage sustained by the building during a damaging earthquake. As shown in Table 4-1, FEMA 356 defines four basic Target Building Performance Levels, which differ only slightly in terminology from the four levels described in FEMA 369, *The 2000 NEHRP Recommended Provisions for New Buildings and Other Structures, Part 2: Commentary* (BSSC, 2001). These performance levels, illustrated graphically in Figure 4-3, are:

- **Operational Level:** The lowest level of overall damage to the building. The structure will retain nearly all of its pre-earthquake strength and stiffness. Expected damage includes minor cracking

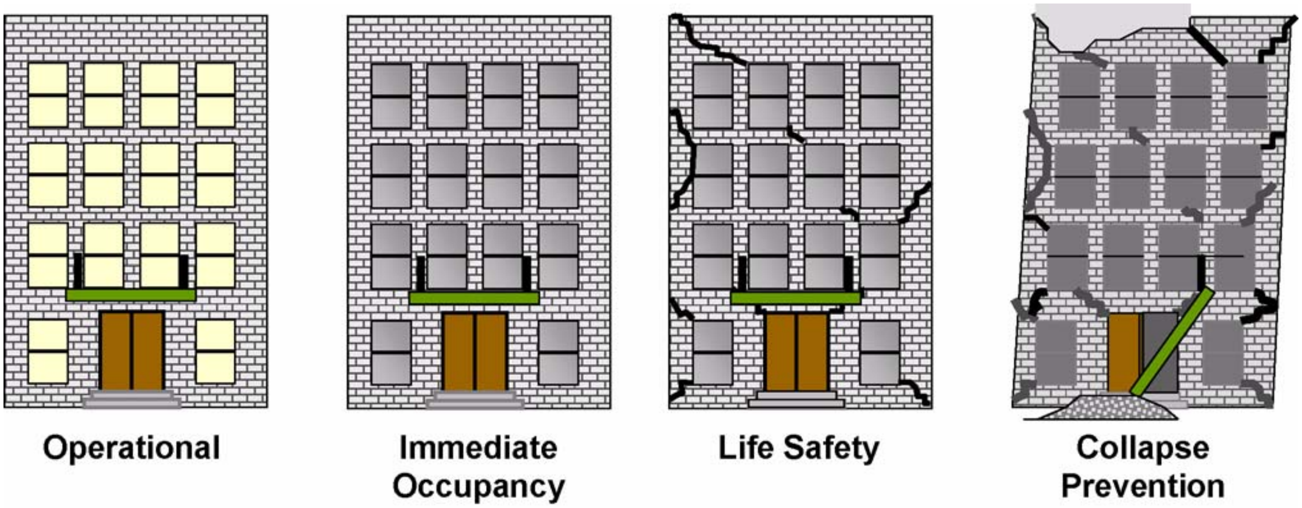


Figure 4-3 Graphic illustration of Operational, Immediate Occupancy, Life-Safety, and Collapse Prevention Performance Levels. (Courtesy of R. Hamburger)

of facades, partitions, and ceilings, as well as structural elements. All mechanical, electrical, plumbing, and other systems necessary for normal operation of the buildings are expected to be functional, possibly from standby sources. Negligible damage to nonstructural components is expected. Under very low levels of earthquake ground motion, most buildings should be able to meet or exceed this performance level. Typically, however, it will not be economically practical to design for this level of performance under severe levels of ground shaking, except for buildings that house essential services.

- **Immediate Occupancy Level:** Overall damage to the building is light. Damage to the structural systems is similar to the Operational Performance Level; however, somewhat more damage to nonstructural systems is expected. Nonstructural components such as cladding and ceilings, and mechanical and electrical components remain secured; however, repair and cleanup may be needed. It is expected that utilities necessary for normal function of all systems will not be available, although those necessary for life safety systems would be provided. Many building owners may wish to achieve this level of performance when the building is subjected to moderate levels of earthquake ground motion. In addition, some owners may desire such performance for very important buildings, under severe levels of earthquake ground shaking. This level provides most of the protection obtained under the Operational Building Performance Level, without the associated cost of providing standby utilities and performing rigorous seismic qualification to validate equipment performance.

- **Life Safety Level:** Structural and nonstructural damage is significant. The building may lose a substantial amount of its pre-earthquake lateral strength and stiffness, but the gravity-load-bearing elements function. Out-of-plane wall failures and tipping of parapets are not expected, but there will be some permanent drift and select elements of the lateral-force resisting system may have substantial cracking, spalling, yielding, and buckling. Nonstructural components are secured and not presenting a falling hazard, but many architectural, mechanical, and electrical systems are damaged. The building may not be safe for continued occupancy until repairs are done. Repair of the structure is feasible, but it may not be economically attractive to do so. This performance level is generally the basis for the intent of code compliance.

> DESIGN CONSIDERATION
>
> Buildings designed to meet the life safety performance level may not be safe for continued occupancy (after the occurrence of a design level earthquake) until repairs are done.

- **Collapse Prevention Level** or **Near Collapse Level:** The structure sustains severe damage. The lateral-force resisting system loses most of its pre-earthquake strength and stiffness. Load-bearing columns and walls function, but the building is near collapse. Substantial degradation of structural elements occurs, including extensive cracking and spalling of masonry and concrete elements, and buckling and fracture of steel elements. Infills and unbraced parapets may fail and exits may be blocked. The building has large permanent drifts. Nonstructural components experience substantial damage and may be falling hazards. The building is unsafe for occupancy. Repair and restoration is probably not practically achievable. This building performance level has been selected as the basis for mandatory seismic rehabilitation ordinances enacted by some municipalities, as it results in mitigation of the most severe life-safety hazards at relatively low cost.

Building performance levels typically comprise a structural performance level that describes the limiting damage state of the structural systems, plus a nonstructural performance level that describes the limiting damage state of the nonstructural systems and components. Table 4-2, from FEMA 356, illustrates this concept. A Target Building Performance Level is designated by the number corresponding to the Structural Performance Level (identified as S-1 through S-6) and the letter corresponding to the Nonstructural Performance Level (identified as N-A through N-E). Note that in Tables 4-1 and 4-2, the four Target Building Performance Levels discussed above are each designated as follows.

Table 4-2 Target Building Performance Levels and Ranges (ASCE, 2000)

Nonstructural Performance Levels	Structural Performance Levels and Ranges					
	S-1 Immediate Occupancy	S-2 Damage Control Range	S-3 Life Safety	S-4 Limited Safety Range	S-5 Collapse Prevention	S-6 Not Considered
N-A Operational	Operational (1-A)	2-A	NR[1]	NR[1]	NR[1]	NR[1]
N-B Immediate Occupancy	Immediate Occupancy (1-B)	2-B	3-B	NR[1]	NR[1]	NR[1]
N-C Life Safety	1-C	2-C	Life Safety (3-C)	4-C	5-C	6-C
N-D Hazards Reduced	NR[1]	2-D	3-D	4-D	5-D	6-D
N-E Not Considered	NR[1]	NR[1]	NR[1]	4-E	Collapse Prevention (5-E)	NR[1]

Notes:
1. NR = Not Recommended

- **Operational Level** (1-A): Immediate Occupancy Structural Performance Level (S-1) plus Operational Nonstructural Performance Level (N-A).
- **Immediate Occupancy Level** (1-B): Immediate Occupancy Structural Performance Level (S-1) plus Immediate Occupancy Nonstructural Performance Level (N-B).
- **Life Safety Level** (3-C): Life Safety Structural Performance Level (S-3) plus Life Safety Nonstructural Performance Level (N-C).
- **Collapse Prevention Level** (5-E): Collapse Prevention Structural Performance Level (S-5) plus Not Considered Nonstructural Performance Level (N-E).

Note also that in Table 4-2, there are several combinations of structural and nonstructural performance levels that are not recommended for rehabilitation; the same lack of recommendation applies to new design. The six structural performance levels and five nonstructural performance levels are described in the following subsections.

Structural Performance Levels

For the rehabilitation of existing buildings, the Structural Performance Levels most commonly used are the Immediate Occupancy Level, the

Life Safety Level, and the Collapse Prevention Level (S-1, S-3, and S-5, respectively, in Table 4-2). These levels are discrete points on a continuous scale describing the building's expected performance or, alternatively, how much damage, economic loss, and disruption may occur following the design earthquake. Intermediate levels are often used to assist in quantifying the continuous scale. For example, Table 4-2 lists Structural Performance Levels of Damage Control Range (S-2), Limited Safety Range (S-4), and Not Considered (S-6).

Structural Performance Levels relate to the limiting damage states for common elements of the building's lateral force resisting systems. Table 4-3 and Table 4-4, taken from FEMA 356, provide descriptions of the damage associated with the three Structural Performance Levels of Collapse Prevention, Life Safety, and Immediate Occupancy for specific types of horizontal (Table 4-3) and vertical (Table 4-4) structural elements and systems.

Nonstructural Performance Levels

The four Nonstructural Performance Levels most commonly used are the Operational Level, the Immediate Occupancy Level, the Life Safety Level, and the Hazards Reduced Level (N-A, N-B, N-C, and N-D, respectively, in Table 4-2). Table 4-2 also includes the additional performance level of Not Considered (N-E). Nonstructural components addressed

Table 4-3 Structural Performance Levels and Damage—Horizontal Elements (From FEMA 356)

Element	Performance Levels		
	Collapse Prevention	Life Safety	Immediate Occupancy
Metal Deck Diaphragms	Large distortion with buckling of some units and tearing of many welds and seam attachments.	Some localized failure of welded connections of deck to framing and between panels. Minor local buckling of deck.	Connections between deck units and framing intact. Minor distortions.
Wood Diaphragms	Large permanent distortion with partial withdrawal of nails and extensive splitting of elements.	Some splitting at connections. Loosening of sheathing. Observable withdrawal of fasteners. Splitting of framing and sheathing.	No observable loosening or withdrawal of fasteners. No splitting of sheathing or framing.
Concrete Diaphragms	Extensive crushing and observable offset across many cracks.	Extensive cracking (< 1/4" width). Local crushing and spalling.	Distributed hairline cracking. Some minor cracks of larger size (< 1/8″ width).
Precast Diaphragms	Connections between units fail. Units shift relative to each other. Crushing and spalling at joints.	Extensive cracking (< 1/4″ width). Local crushing and spalling.	Some minor cracking along joints.

Table 4-4 Structural Performance Levels and Damage[1]—Vertical Elements (from FEMA 356)

Elements	Type	Structural Performance Levels		
		Collapse Prevention	Life Safety	Immediate Occupancy
Concrete Frames	Primary	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Extensive damage to beams. Spalling of cover and shear cracking (< 1/8" width) for ductile columns. Minor spalling in nonductile columns. Joint cracks < 1/8" wide.	Minor hairline cracking. Limited yielding possible at a few locations. No crushing (strains below 0.003).
	Secondary	Extensive spalling in columns (limited shortening) and beams. Severe joint damage. Some reinforcing buckled.	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Minor spalling in a few places in ductile columns and beams. Flexural cracking in beams and columns. Shear cracking in joints < 1/16" width.
	Drift[2]	4% transient or permanent	2% transient; 1% permanent	1% transient; negligible permanent
Steel Moment Frames	Primary	Extensive distortion of beams and column panels. Many fractures at moment connections, but shear connections remain intact.	Hinges form. Local buckling of some beam elements. Severe joint distortion; isolated moment connection fractures, but shear connections remain intact. A few elements may experience partial fracture.	Minor local yielding at a few places. No fractures. Minor buckling or observable permanent distortion of members.
	Secondary	Same as primary.	Extensive distortion of beams and column panels. Many fractures at moment connections, but shear connections remain intact.	Same as primary.
	Drift[2]	5% transient or permanent	2.5% transient; 1% permanent	0.7% transient; negligible permanent
Braced Steel Frames	Primary	Extensive yielding and buckling of braces. Many braces and their connections may fail.	Many braces yield or buckle but do not totally fail. Many connections may fail.	Minor yielding or buckling of braces.
	Secondary	Same as primary.	Same as primary.	Same as primary.
	Drift[2]	2% transient or permanent	1.5% transient; 0.5% permanent	0.5% transient; negligible permanent

Table 4-4 Structural Performance Levels and Damage[1]—Vertical Elements (from FEMA 356) (Continued)

Concrete Walls	Primary	Major flexural and shear cracks and voids. Sliding at joints. Extensive crushing and buckling of reinforcement. Failure around openings. Severe boundary element damage. Coupling beams shattered and virtually disintegrated.	Some boundary element distress, including limited buckling of reinforcement. Some sliding at joints. Damage around openings. Some crushing and flexural cracking. Coupling beams: extensive shear and flexural cracks; some crushing, but concrete generally remains in place.	Minor hairline cracking of walls, < 1/16" wide. Coupling beams experience cracking < 1/8" width.
	Secondary	Panels shattered and virtually disintegrated.	Major flexural and shear cracks. Sliding at joints. Extensive crushing. Failure around openings. Severe boundary element damage. Coupling beams shattered and virtually disintegrated.	Minor hairline cracking of walls. Some evidence of sliding at construction joints. Coupling beams experience cracks < 1/8" width. Minor spalling.
	Drift[2]	2% transient or permanent	1% transient; 0.5% permanent	0.5% transient; negligible permanent
Unreinforced Masonry Infill Walls[3]	Primary	Extensive cracking and crushing; portions of face course shed.	Extensive cracking and some crushing but wall remains in place. No falling units. Extensive crushing and spalling of veneers at corners of openings.	Minor (<1/8" width) cracking of masonry infills and veneers. Minor spalling in veneers at a few corner openings.
	Secondary	Extensive crushing and shattering; some walls dislodge.	Same as primary.	Same as primary.
	Drift[2]	0.6% transient or permanent	0.5% transient; 0.3% permanent	0.1% transient; negligible permanent
Unreinforced Masonry (Noninfill) Walls	Primary	Extensive cracking; face course and veneer may peel off. Noticeable in- plane and out-of-plane offsets.	Extensive cracking. Noticeable in-plane offsets of masonry and minor out-of-plane offsets.	Minor (< 1/8" width) cracking of veneers. Minor spalling in veneers at a few corner openings. No observable out-of- plane offsets.
	Secondary	Nonbearing panels dislodge.	Same as primary.	Same as primary.
	Drift[2]	1% transient or permanent	0.6% transient; 0.6% permanent	0.3% transient; 0.3% permanent

Table 4-4 Structural Performance Levels and Damage[1]—Vertical Elements (from FEMA 356) (Continued)

Reinforced Masonry Walls	Primary	Crushing; extensive cracking. Damage around openings and at corners. Some fallen units.	Extensive cracking (< 1/4") distributed throughout wall. Some isolated crushing.	Minor (< 1/8" width) cracking. No out-of-plane offsets.
	Secondary	Panels shattered and virtually disintegrated.	Crushing; extensive cracking; damage around openings and at corners; some fallen units.	Same as primary.
	Drift[2]	1.5% transient or permanent	0.6% transient; 0.6% permanent	0.2% transient; 0.2% permanent
Wood Stud Walls	Primary	Connections loose. Nails partially withdrawn. Some splitting of members and panels. Veneers dislodged.	Moderate loosening of connections and minor splitting of members.	Distributed minor hairline cracking of gypsum and plaster veneers.
	Secondary	Sheathing sheared off. Let-in braces fractured and buckled. Framing split and fractured.	Connections loose. Nails partially withdrawn. Some splitting of members and panels.	Same as primary.
	Drift[2]	3% transient or permanent	2% transient; 1% permanent	1% transient; 0.25% permanent
Precast Concrete Connections	Primary	Some connection failures but no elements dislodged.	Local crushing and spalling at connections, but no gross failure of connections.	Minor working at connections; cracks < 1/16" width at connections.
	Secondary	Same as primary.	Some connection failures but no elements dislodged.	Minor crushing and spalling at connections.
Foundations	General	Major settlement and tilting.	Total settlements < 6" and differential settlements < 1/2" in 30 ft.	Minor settlement and negligible tilting.

Notes:

1. The damage states indicated in this table are provided to allow an understanding of the severity of damage that may be sustained by various structural elements when present in structures meeting the definitions of the Structural Performance Levels. These damage states are not intended for use in post- earthquake evaluation of damage nor for judging the safety of, or required level of repair to, a structure following an earthquake.
2. The drift values, differential settlements, and similar quantities indicated in these tables are not intended to be used as acceptance criteria for evaluating the acceptability of a rehabilitation design in accordance with the analysis procedures provided in these Guidelines; rather, they are indicative of the range of drift that typical structures containing the indicated structural elements may undergo when responding within the various performance levels. Drift control of a rehabilitated structure may often be governed by the requirements to protect nonstructural components. Acceptable levels of foundation settlement or movement are highly dependent on the construction of the superstructure. The values indicated are intended to be qualitative descriptions of the approximate behavior of structures meeting the indicated levels.
3. For limiting damage to frame elements of infilled frames, refer to the rows for concrete or steel frames.

by these performance levels include architectural components (e.g., partitions, exterior cladding, and ceilings) and mechanical and electrical components (e.g., HVAC systems, plumbing, fire suppression systems, and lighting). Occupant contents and furnishings (such as inventory and computers) are often included as well.

Nonstructural Performance Levels relate to the limiting damage states for common elements of the building's architectural features, utility systems, and contents and other equipment. Tables 4-5, 4-6, and 4-7 taken from FEMA 356, provide descriptions of the damage associated with the four Nonstructural Performance Levels of Hazards Reduced, Life Safety, Immediate Occupancy, and Operational for specific types of architectural components (Table 4-5); mechanical, electrical, and plumbing system components (Table 4-6); and contents (Table 4-7).

4.4 IMPACT OF PERFORMANCE-BASED STRATEGIES ON FUTURE DESIGN CODES

While current design codes explicitly require life safety design for only a single level of ground motion, it is expected that future design codes will provide engineers with the necessary guidelines to design and construct buildings that meet a number of performance criteria when subjected to earthquake ground motion of differing severity. The current (2000) version of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* (BSSC, 2001) has initiated a move towards incorporating performance-based strategies through the use of three "Seismic Use Groups." These groups are categorized based on the occupancy of the structures and the relative consequences of earthquake-induced damage to the structures as follows:

- Group III structures are essential facilities required for postearthquake recovery, and those structures that contain significant amounts of hazardous materials. An example is a medical facility with emergency treatment facilities.
- Group II structures are those having a large number of occupants and those where the occupants ability to exit is restrained. An example is an elementary school.
- Group I structures are all other structures, basically those with a lesser life hazard only insofar as there is expected to be fewer occupants in the structures and the structures are lower and/or smaller. An example is a low-rise commercial office building.

The *2000 NEHRP Recommended Provisions for Seismic Regulations of New Buildings and Other Structures* specify progressively more conservative

Table 4-5 Nonstructural Performance Levels and Damage—Architectural Components (from FEMA 356)

Component	Nonstructural Performance Levels			
	Hazards Reduced Level	Life Safety	Immediate Occupancy	Operational
Cladding	Severe damage to connections and cladding. Many panels loosened.	Severe distortion in connections. Distributed cracking, bending, crushing, and spalling of cladding elements. Some fracturing of cladding, but panels do not fall.	Connections yield; minor cracks (< 1/16" width) or bending in cladding.	Connections yield; minor cracks (< 1/16" width) or bending in cladding.
Glazing	General shattered glass and distorted frames. Widespread falling hazards.	Extensive cracked glass; little broken glass.	Some cracked panes; none broken.	Some cracked panes; none broken
Partitions	Severe racking and damage in many cases.	Distributed damage; some severe cracking, crushing, and racking in some areas.	Cracking to about 1/16" width at openings. Minor crushing and cracking at corners.	Cracking to about 1/16" width at openings. Minor crushing and cracking at corners.
Ceilings	Most ceilings damaged. Light suspended ceilings dropped. Severe cracking in hard ceilings.	Extensive damage. Dropped suspended ceiling tiles. Moderate cracking in hard ceilings.	Minor damage. Some suspended ceiling tiles disrupted. A few panels dropped. Minor cracking in hard ceilings.	Generally negligible damage. Isolated suspended panel dislocations, or cracks in hard ceilings.
Parapets and Ornamentation	Extensive damage; some fall in nonoccupied areas.	Extensive damage; some falling in nonoccupied areas.	Minor damage.	Minor damage.
Canopies & Marquees	Extensive distortion.	Moderate distortion.	Minor damage.	Minor damage.
Chimneys & Stacks	Extensive damage. No collapse.	Extensive damage. No collapse.	Minor cracking.	Negligible damage.
Stairs & Fire Escapes	Extensive racking. Loss of use.	Some racking and cracking of slabs, usable.	Minor damage.	Negligible damage.
Light Fixtures	Extensive damage. Falling hazards occur.	Many broken light fixtures. Falling hazards generally avoided in heavier fixtures (> 20 pounds).	Minor damage. Some pendant lights broken.	Negligible damage.
Doors	Distributed damage. Many racked and jammed doors.	Distributed damage. Some racked and jammed doors.	Minor damage. Doors operable.	Minor damage. Doors operable.

Table 4-6 Nonstructural Performance Levels and Damage—Mechanical, Electrical, and Plumbing Systems/Components (from FEMA 356)

System/ Component	Nonstructural Performance Levels			
	Hazards Reduced	Life Safety	Immediate Occupancy	Operational
Elevators	Elevators out of service; counterweights off rails.	Elevators out of service; counterweights do not dislodge.	Elevators operable; can be started when power available.	Elevators operate.
HVAC Equipment	Most units do not operate; many slide or overturn; some suspended units fall.	Units shift on supports, rupturing attached ducting, piping, and conduit, but do not fall.	Units are secure and most operate if power and other required utilities are available.	Units are secure and operate; emergency power and other utilities provided, if required.
Ducts	Ducts break loose of equipment and louvers; some supports fail; some ducts fall.	Minor damage at joints of sections and attachment to equipment; some supports damaged, but ducts do not fall.	Minor damage at joints, but ducts remain serviceable.	Negligible damage.
Piping	Some lines rupture. Some supports fail. Some piping falls.	Minor damage at joints, with some leakage. Some supports damaged, but systems remain suspended.	Minor leaks develop at a few joints.	Negligible damage.
Fire Sprinkler Systems	Many sprinkler heads damaged by collapsing ceilings. Leaks develop at couplings. Some branch lines fail.	Some sprinkler heads damaged by swaying ceilings. Leaks develop at some couplings.	Minor leakage at a few heads or pipe joints. System remains operable.	Negligible damage.
Fire Alarm Systems	Ceiling mounted sensors damaged. System nonfunctional.	May not function.	System is functional.	System is functional.
Emergency Lighting	Some lights fall. Power may not be available.	System is functional.	System is functional.	System is functional.
Electrical Distribution Equipment	Units slide and/or overturn, rupturing attached conduit. Uninterruptable Power Source systems fail. Diesel generators do not start.	Units shift on supports and may not operate. Generators provided for emergency power start; utility service lost.	Units are secure and generally operable. Emergency generators start, but may not be adequate to service all power requirements.	Units are functional. Emergency power is provided, as needed.
Plumbing	Some fixtures broken; lines broken; mains disrupted at source.	Some fixtures broken, lines broken; mains disrupted at source.	Fixtures and lines serviceable; however, utility service may not be available.	System is functional. On-site water supply provided, if required.

Table 4-7 Nonstructural Performance Levels and Damage—Contents (from FEMA 356)

Contents Type	Nonstructural Performance Levels			
	Hazards Reduced	Life Safety	Immediate Occupancy	Operational
Computer Systems	Units roll and overturn, disconnect cables. Raised access floors collapse.	Units shift and may disconnect cables, but do not overturn. Power not available.	Units secure and remain connected. Power may not be available to operate, and minor internal damage may occur.	Units undamaged and operable; power available.
Manufacturing Equipment	Units slide and overturn; utilities disconnected. Heavy units require reconnection and realignment. Sensitive equipment may not be functional.	Units slide, but do not overturn; utilities not available; some realignment required to operate.	Units secure, and most operable if power and utilities available.	Units secure and operable; power and utilities available.
Desktop Equipment	Units slide off desks.	Some equipment slides off desks.	Some equipment slides off desks.	Equipment secured to desks and operable.
File Cabinets	Cabinets overturn and spill contents.	Drawers slide open; cabinets tip.	Drawers slide open, but cabinets do not tip.	Drawers slide open, but cabinets do not tip.
Book Shelves	Shelves overturn and spill contents.	Books slide off shelves.	Books slide on shelves.	Books remain on shelves.
Hazardous Materials	Severe damage; no large quantity of material released.	Minor damage; occasional materials spilled; gaseous materials contained.	Negligible damage; materials contained.	Negligible damage; materials contained.
Art Objects	Objects damaged by falling, water, dust.	Objects damaged by falling, water, dust.	Some objects may be damaged by falling.	Objects undamaged.

strength, drift control, system selection, and detailing requirements for structures contained in the three groups, in order to attain minimum levels of earthquake performance suitable to the individual occupancies. The design criteria for each group are intended to produce specific types of performance in design earthquake events, based on the importance of reducing structural damage and improving life safety. Figure 4-4, taken from the *Commentary to the 2000 NEHRP Provisions*, illustrates this concept.

Next-Generation Performance-Based Seismic Design Guidelines

Incorporation of performance-based engineering concepts in future design codes will also be aided by a major effort recently initiated by the Applied Technology Council (ATC) with funding from the Federal Emergency Management Agency (FEMA). The project, known as

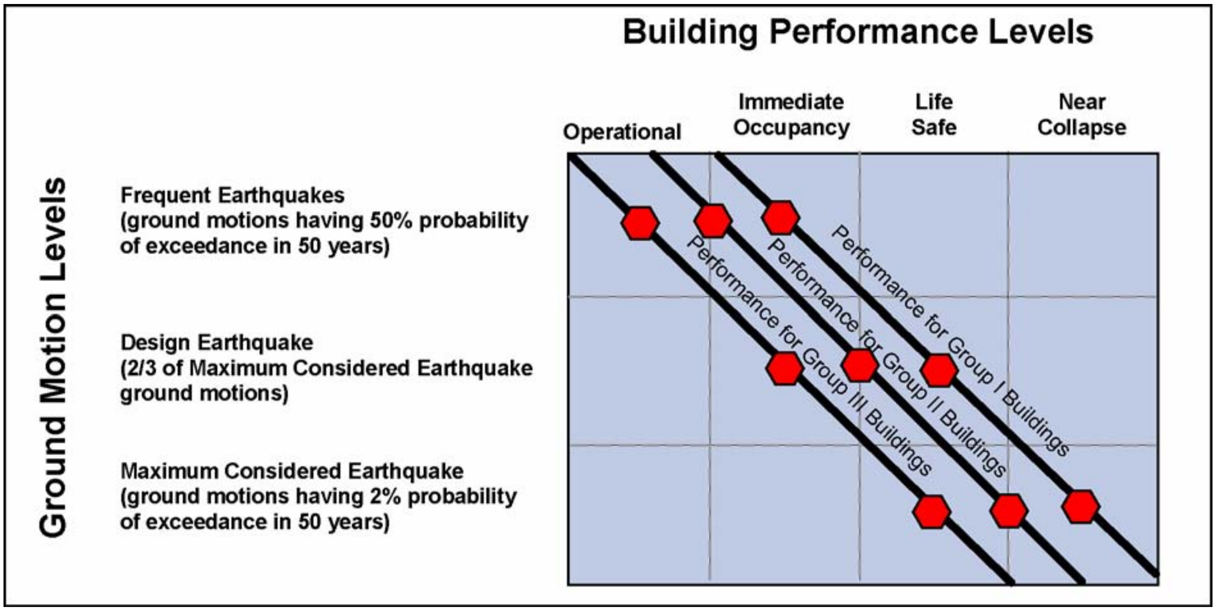
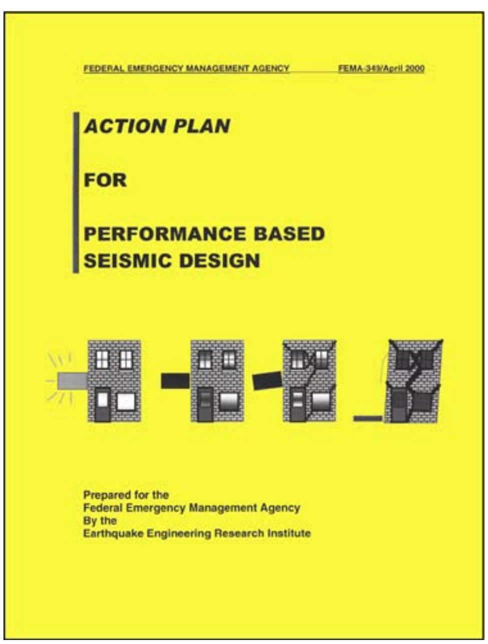


Figure 4-4 Expected building performance. (from BSSC, 2001)

ATC-58, Development of Performance-Based Seismic Design Guidelines, is currently in Phase I, Project Initiation and Performance Characterization. FEMA has provided funding for Phase I of a planned multi-year program to develop the guidelines, following the general approach outlined in FEMA 349, *Action Plan for Performance Based Seismic Design* (EERI, 2000). It is expected that the successful development of the guidelines will require a multi-year effort entailing financial and technical participation from the four NEHRP agencies as well as private industry.



FEMA 349 identifies six products essential to the creation and implementation of comprehensive, acceptable Performance-Based Seismic Design Guidelines:

1. A *Program Management Plan* that incorporates a broadly based oversight group to shepherd and promote the development of the Guidelines (over an extended period of time, say up to 10 years), and an education and implementation strategy to facilitate the use of the Guidelines.
2. *Structural Performance Products* that characterize building performance, specify how to evaluate a building's performance capability for a specified level of seismic hazard and with a defined reliability or level of confidence, and provide guidance on how to design a structure to provide desired performance (with defined reliability).

3. *Nonstructural Performance Products* that provide engineers with the capability to evaluate and design nonstructural components, such as partitions, piping, HVAC (heating, ventilation, and air conditioning) equipment, with the goal of ensuring that such components will provide desired performance (with defined reliability).
4. *Risk Management Products* that provide methodologies for calculating the benefits of designing to various performance objectives and to make rational economic choices about the levels of performance desired, the levels of confidence desired, and the comparative costs to reach those levels.
5. *Performance-Based Seismic Design Guidelines* that provide methodology and criteria for design professionals, material suppliers, and equipment manufacturers to implement performance-based design procedures.
6. A *Stakeholders Guide* that explains performance-based seismic design to nontechnical audiences, including building owners, managers, and lending institutions.

4.5 GUIDANCE FOR DESIGN PROFESSIONALS

It is clear that performance-based strategies will be included in future seismic design codes. Regardless of when this actually occurs, design professionals can utilize the information in this document, as well as those referenced below, to provide owners and managers with a much clearer picture of what may be expected in terms of damage, downtime, and occupant safety for a given building under various intensities of ground motion.

When communicating with building owner representatives during the development of seismic performance criteria for a new building, it would be useful to:

1. Explain the concepts of performance-based seismic design using the concepts and materials provided in this document and the references cited.
2. Help the owner to determine if a performance level higher than life safety is needed for the design earthquake; if so, use these materials and the references cited to assist the owner in developing a design that would be accepted by the governing regulatory agency (e.g., local building department).

4.6 REFERENCES AND FURTHER READING

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