Fire Protection Handbook

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SECTION 1

Chapter 1

Challenges to Safety in the Built Environment

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Chapter Contents

Defining the Challenges to Safety
Relevant Major Societal Trends
Major Databases
Overview of Types of Peril Causing Harm
Fire, Burns, and Electric Shock
Falls
Natural Disasters
Fatalities Involving Hazardous Environments

Key Terms

all-hazard education, built environment, Consumer Product Safety Commission (CPSC), hazard, International Classification of Diseases (ICD), *Remembering When,* risk, *Risk Watch*®

We expect a great deal of our built environments. We expect that they protect us from hazards arising from objects we bring into the environments and from the components of the structure itself. We expect that our built environment itself will not be harmful and will provide a protective envelope to shield us from harm arising outside the built environment. We expect it to keep us secure and comfortable and to provide conveniences for the time we spend in it. We expect a lot from our built environments in addition to functionality, usability, attractive appearance, affordability of construction and operation, and a host of other nonsafety goals and objectives.

The first step in evaluating the challenges to safety in the built environment is to classify the types of harm encountered. This chapter examines several perils causing harm to people and property in the built environment.

See also, Section 1, Chapter 7, "Protecting Against Extreme Events"; and Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection."

DEFINING THE CHALLENGES TO SAFETY

Any harm that occurs inside a built environment could theoretically have been prevented or mitigated, at least in some very small way, by some feasible modification to the built environment. However, that definition of challenges to safety is far too sweeping to be useful. A built-in visual and motion building monitoring system might provide enough surveillance to reduce the fraction of heart attacks or strokes that prove fatal by detecting collapse or other actions indicating a person in distress, but if our purpose is to track the effectiveness of our current typical code and design choices, it would not be helpful to have tracking statistics dominated by the large number of heart attacks simply because it is technically feasible to build a structure that would help on some of them.

Any harm that occurs as a direct result of some failure in the built environment under conditions anticipated by the code is the type of event that should be tallied as an indicator of performance. However, that definition of challenges to safety is far too narrow to capture what good design can accomplish in the way of preventing or reducing harm. The narrow definition is more appropriate for assigning legal liability than for evaluating overall effectiveness and impact.

Also of concern is any harm that occurs as a result of conditions that were not anticipated by the code but that should have been, and would have been, anticipated with better information or better understanding of the factors driving perilous events and the performance of the built environment to challenges those events represent. The sometimes delicate and emotional debate if the codes should consider and provide design criterion for hostile acts or terrorism is a relatively new and highly complex subject. These events are neither predictable nor quantifiable. Although databases of such events exist, there is no return interval or probabilistic data to support a hard and fast design approach that could realistically be included in our design codes and standards to address these events. See also Section 1, Chapter 7, "Protecting Against Extreme Events."

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General crime deterrence and security measures, such as those covered by NFPA 730, *Guide for Premises Security,* do have a place in the types of harmful hazards that our codes and standards should address.

Options for Data

Natural disasters—including major wildfires but excluding other major fires—involve probabilistically occurring natural hazard–event triggers, whose probabilities vary by location (e.g., coastal location) and by characteristics (e.g., soil conditions) that themselves vary by location. Therefore, risk assessment for the hazards can be set up using risk maps for the triggering events, and codes can control design choices by specifying building performance in response to specified severities of these triggering events (analogous to fire scenarios used in performance-based design). The actual data on these natural disasters—and the losses they cause, which reflect both the event of severity and the building performance in resisting damage from the event—are what we track in order to gain insight into both the challenges to buildings and the performance of different building materials and designs in response to those challenges.

In the area of fire safety, the instances of harm occur in well-defined incidents, most of which lead to an encounter with an official body (e.g., a fire department) and the creation of an official record (e.g., incident report). These reported incidents are represented by the large or small samples of incidents captured by one or another international database. At least in the United States, these databases provide a baseline for surveillance of the magnitude of the harm proper design is intended to prevent or reduce. These databases provide information on the size of the problem, answering many, but far from all, of the questions we have about the effect of design choices and code language on resulting harm.

It is true that the database encompasses instances in which other parties are far more responsible than the builders and managers of built environments for the harm, instances that could not have been prevented or mitigated by even the most expansive, and often times expensive, of design standards. Nevertheless, the overall database can be used to identify candidate areas for targeted safety improvement, to estimate the magnitude of improved safety achievable by proposed design changes, and to monitor the changes in loss magnitudes associated with the implementation of design changes.

The databases available for monitoring, tracking, and surveillance of other types of harm within the built environment are not so well developed, except for major natural disasters, which are sufficiently few in number that they can be individually documented in great detail. For other instances of harm that do not involve fire or a natural disaster, there is less ability to develop statistics by type of harm and physical object creating the hazard (and thereby distinguishing between those that are part of the built environment and those that are not).

A notable exception may be criminal activity for which there are police crime and arrest databases. Deterrent systems comprised of metal detectors, screening processes, limited access doors, and overall procedural policies are examples of design changes to a built environment that could address this type of challenge.

Data are needed that can support a comprehensive analysis of all forms of harm associated with built environments, leading to a more focused analysis of options for action to address that harm and supported after actions are taken by follow-up monitoring of the impact of those actions in practice. This sequence corresponds to what is sometimes called program analysis and, after actions have been taken, program evaluation. Engineers and economists both apply risk assessment, which includes these steps as well, even though risk has different meanings to both.

Questions Involved in Safety Decisions

Conducting analysis in support of safety decisions requires detailed answers to a series of questions pertaining to the overall risk. Discussion of the following questions is the starting point for analysis.

- *Is this a significant risk?* Use readily available data to conduct a primary risk estimate. In this first triage phase, risks are identified and justifications are made as to whether or not the risk needs further examination.
- *What are the risk details?* Describe the circumstances of all probable scenarios of the risk, so an understanding of an overall developmental process of the risk can be created. During this process of risk factor identification, the potential impact of candidate strategies is determined. In this second triage phase, risks are deemed to be significant or not.
- *What are the best ways for dealing with this risk?* Identify candidate strategies, considering one or more options within each of several general approaches, such as prevention, mitigation, and separation. The options may be interventions, programs, or risk control techniques. In this treatment selection phase, a risk is considered and one or more ways are selected to address it. The risk is judged to be significant enough to focus on and conventional enough to change.
- *What is the best way to implement the strategy?* In this service delivery strategy phase, the cost-effectiveness of implementing one or more strategies that show promise is addressed.

The goal of this chapter is to provide readily available information that bears on the first question of establishing whether a risk is significant but not much on the subsequent questions. This chapter represents more of a starting point than a full overview of the challenges to safety in the built environment. A structure will be provided, and details will be filled in to the extent possible. It is the authors' intention that this starting point will be a first step in the development of more complete databases, providing answers to a wider range of safety questions about the built environment.

RELEVANT MAJOR SOCIETAL TRENDS

Growth in Older Population

For every form of fatal injury in a built environment, except for poisonings by solids or liquids and unintentional firearms injuries, older adults are at higher risk.[1] This part of the population is also the fastest-growing segment of the population, not only in the United States but also throughout the economically developed world.[2]

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The United States has a death rate (8.3 per 1000 population) that is lower than its birthrate (14.1 per 1000 population). Annual population growth from 2000 to 2005 was 1.03 percent, and older adults defined as age 65 and older represent 12.4 percent of the total population. The United States must deal with both a need for more buildings to house a growing population and a need to remake the building stock to address the special needs of a rapidly growing older population.

Growth in High-Risk Areas

The U.S. population has been growing specifically in those regions where the likelihood of certain natural disasters is higher. Although population growth in coastal communities nationwide has actually been slower than in the rest of the country,[2] the state of Florida ranked third highest in number of people added in the 1990s, and Florida has by far the highest frequency of hurricane incidence of any state.[2,3] The geography of Florida is such that even population increases away from the coast can add to the people likely to be affected by hurricane-force winds and rain. The state that added the largest number of people was California, which also has by far the most people living in areas of frequent seismic activity.[2,3]

Whether growth in high-risk areas is disproportionately large or only proportional to growth elsewhere, it means the same perilous event will cause more deaths and damage more value in property, unless the increased exposure has been offset by improvements in protection.

MAJOR DATABASES

Even though 90 to 95 percent of all unwanted fires are unreported to fire departments, the ones that are reported number nearly 2 million a year, and they represent most of the deaths and property damage.[4] For every other type of harm, there is no analogous database with comparable breadth of scope and detail.

Major individual incidents, involving multiple deaths or millions of dollars of loss, are more likely to be extensively documented, and the more severe the harm caused by an incident, the more likely it is that a case study report on the incident will be published. It is, therefore, possible to develop lists and pattern analyses of these incidents. However, these large incidents generally account for only a small fraction of total harm to people, either by deaths or by nonfatal injuries. Such large incidents may account for a large share of damage to property, but for many forms of harm, like fire, they do not.

Database of Death Certificates

The national database of death certificates provides useful details on deaths due to injury.[5] The International Classification of Diseases (ICD) is designed for the classification of morbidity and mortality information for statistical purposes and for indexing of hospital records by disease and operations for data storage and retrieval.[5] The ICD has been revised approximately every 10 years since 1900 in order to reflect changes in understanding of disease mechanisms and in disease terminology.[5]

ICD-9 and ICD-10 were used to compile data tables for this chapter. However, although the traditional ICD structure has been retained, an alphanumeric coding scheme (ICD-10) replaces the previous numeric one (ICD-9).[5] This does provide a larger coding frame to leave room for future revision, but some categories of the previous edition have been left out of the latest revision. The data tables in the chapter will represent those changes.

Illnesses are generally not coded to indicate the involvement of or relevance of components of the built environment. This is an important gap, because it means we cannot really isolate and identify relevant illnesses, such as waterborne illness due to backflow or cross-connections in a plumbing system, Legionnaire's disease due to cultivating of bacteria or viruses in poorly designed or poorly operating air-circulation systems, and the kind of airborne illnesses associated with indoor air pollution. However, the statistics presented in this chapter will focus on fatal and nonfatal injuries, not illnesses.

The database of death certificates codes unintentional injuries as V01–X89, Y85–Y86. Deaths in which the injury was intentional (e.g., homicide, suicide) or where it the intent was unknown (codes X60–Y89) are largely excluded from the chapter. Deaths involving transportation or vehicles (codes V01–V99, Y85) are excluded from this chapter as being outside the definition of the built environment. Also excluded are injuries arising from medical problems (e.g., poisonings by drugs, medical malpractice), as these (codes X40–X49, Y4–Y84, Y88.0–Y88.3) are also deemed to be outside the definition of the built environment. Finally, statistics presented in the chapter exclude unintentional firearm injuries (codes X93–X95), radiation (codes W88–W91), and overexertion (codes X50–X57).

Databases on Injuries and Property Damage

Nonfatal injuries are not routinely captured, but there are three exceptions (in addition to the injury component of the fire incident databases). Occupational injuries are captured by the U.S. Department of Labor if they meet a severity threshold.[6] Injuries involving a trip to the hospital emergency room and associated with a consumer product are reported in a U.S. Consumer Product Safety Commission database.[7] (Recent changes mean that all emergency room injuries will be captured in the near future.) And the injuries people suffer that go unreported to any medical or other entity are tracked through an in-home sample survey as part of the National Health Interview Survey.[8] The database on occupational injuries uses approximately the same structure as the death certificate codes with additional detail in some places.

Apart from any natural disasters and fires, property damage is tracked only by the insurance industry and, for storms, by the National Weather Service.[9,10] Their published information has some useful detail, and it is possible that their unpublished coded data will in time permit more detailed analysis.

Influence of Major Incidents

Many issues in building codes and other codes for the built environment have historically been addressed not on the basis of number, rates, or percentages of fires or statistically derived indicators such as risk values, but rather on the basis of individual major incidents that indicate a specific type of hazard or

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type of built-environment performance problem not previously encountered. For example, the Northridge earthquake of 1994 showed some problems with brittle fracture of structural steel that, although not necessarily significant in the loss in that incident, were nevertheless unexpected, leading to new research and code-change proposals. For this reason, this chapter includes not only statistics but also lists of deadliest or costliest incidents, where such lists are meaningful and potentially useful. There is an extended discussion in Section 2, Chapter 1, "Physics and Chemistry of Fire," of the past century of progress in fire safety, by major occupancy type, in which trigger events were often individual fires but progress could be measured statistically.

OVERVIEW OF TYPES OF PERIL CAUSING HARM

Table 1.1.1 provides a first-level classification of types of peril causing harm to people (deaths, injuries, and illnesses) and to property (including potential business interruption or other interference with mission continuity), cultural or historical value damage, and environmental damage. Direct and indirect perils causing harm are both of interest. Fire, burns, and electric shock; falls; natural disasters; water or storms; and harmful environments are the main types of peril causing harm in the built environment.

Fire is as a rapid, persistent, chemical reaction that releases heat and light.[11] In the built environment, fire is combined with explosions, electric shock, scalds, and other types of burns. The majority of harm to property by fire is from thermal or corrosive effects.

Falls are the most common type of peril causing harm in the built environment and include injuries caused by the fall and injuries due to objects falling on other people. Types of falls in the built environment include the following:

- Falls from or on stairs and steps
- Falls from or on ladders or scaffolding
- Falls out of structures
- Falls from one level to another
- Falling objects

Falling objects may be a direct result of structural collapse caused by another type of peril harming the built environment.

TABLE 1.1.1 Typology of Types of Peril Causing Harm to People and Property in the Built Environment

Peril Causing Harm	*Harm to People*	*Harm to Property**
Fire, burns, and electrical shock	Burns from fire, hot surfaces, steam, or other hot objects Electrical shock Injury from structural failure resulting from fire Explosions Injury from inhaled toxic products Injury from oxygen deprivation resulting from fire	Direct harm from thermal or corrosive effects of fire Damage from structural failure resulting from fire
Falls	Injuries due to fall Injuries due to objects falling on people	Structural collapse
Natural disasters (e.g., earthquakes, landslides, hurricanes, tornadoes)	Injury from structural failure resulting from natural disaster Fire injuries Injuries due to falling objects or objects in motion Fall injuries Postevent harmful environment (e.g., disease, exposure) Postevent electrical shock	Damage from structural failure resulting from natural disaster Fire Wind and water damage
Water (e.g., floods, storms)	Injuries due to falling objects or objects in motion Drowning Postevent electrical shock Postevent harmful environment	Damage due to wind, water, or storm loads (e.g., snow or hail) Flooding Water damage
Harmful environment	Poisoning by solid, liquid, or gas Mechanical suffocation Water-borne or airborne disease Adverse health effects of excessive heat or cold, insufficient or poor lighting, excessive noise or vibration, or radiation exposure (e.g., radon)	Corrosive or other damaging effects of moisture Damage due to heat or cold Damage due to noise or vibration Radiation damage

Note: The categories in this table are not taken from any published source and are not in general use. They are proposed only as a basis for organizing the material in this chapter. Some performance issues for the built environment are excluded from this typology, including all issues of amenities and issues of access, such as those addressed by the Americans with Disabilities Act (ADA). Vehicles and outdoor settings not involving structures are excluded from consideration here, even though most of those environments can be regarded as built.

*Includes business interruption, other functionality damage, and damage to heritage.

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Natural disasters are created by natural processes and as disasters effect society and the built environment. Earthquakes, hurricanes, and tornadoes all contribute to structural damage and may produce serious types of harm such as fire, electric shock, and fall injuries, all of which can be fatal.

Water from storms and floods has the potential to create major property losses, although most of the deaths in this category are not associated with catastrophic events.

A harmful environment refers to an environment in which people are exposed to harmful substances, such as airborne disease and poisonous gases. The built environment serves as a barrier to protect people from harm. Like people, it is susceptible to any type of peril causing harm. Harmful environments can exist alone or as the result of another type of peril. Sick building syndrome, which can result from mold or release of volatile organic compounds (VOCs) from synthetic materials, may cause illness in some occupants.

The degree of harm depends on exposure and the relative vulnerability of the built environment to a particular peril. Both exposure and vulnerability depend considerably on the location chosen for the structure. Soil type, rainfall, geography, and wind speed are examples of factors contributing to the degree of harm on the built environment.

FIRE, BURNS, AND ELECTRIC SHOCK

This chapter will provide a few fire statistics in context with other hazards, with nonfire-thermal-related injuries addressed at greater length, because the fire loss experience including magnitudes, trends, and patterns is extensively discussed in Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection."

Fire Losses and Injuries

Tables 1.1.2 and 1.1.3 provide overviews of U.S. fire deaths and related property damage, respectively. Table 1.1.2 compares fire deaths as estimated by the NFPA survey with those recorded by the primary fire-related X-codes in the national death certificate database. Table 1.1.3 excludes transportation and vehicle-related fires, which is why those statistics track more closely with NFPA survey data on structure fires alone and are also provided in Table 1.1.2. Death certificate counts from these X-codes can also exclude some incendiary fire deaths but should do so only if the fatal injury was itself known to have been intended, in which case it qualifies as a homicide or suicide and is classified there for primary categorization. It appears that few such fire deaths are so classified.

The NFPA survey can miss deaths occurring outside a reported fire. Clothing ignitions are the classic example, but the death certificate database tracks clothing ignition deaths separately, and such deaths total less than 200 per year, some of which will be reported to fire departments. The NFPA survey is also subject to some sampling variation. The estimate of total fire deaths, for example, is subject to a 95 percent confidence interval of plus or minus just under 400 deaths, which is a more typical difference between the structure fire death estimate and the death certificate tally.

TABLE 1.1.2 Tracking U.S. Fire Deaths Based on NFPA Survey

Year	*Total*	*Structure Fire Only*	*Based on Death Certificate Coding X00–X09 Only*
1993	4,635	3,980	3,914
1994	4,275	3,590	3,999
1995	4,585	3,985	3,768
1996	4,990	4,220	3,748
1997	4,050	3,510	3,502
1998	4,035	3,420	3,263
1999	3,570	3,040	3,348
2000	4,045	3,535	3,377
2001*	6,196	5,671	3,309
2002	3,380	2,775	3,159

*2,451 of these deaths occurred due to the events of 9/11/01.

Source: NFPA survey, National Safety Council (NSC), and National Center for Health Statistics (NCHS) Vital Statistics System provided data for the number of deaths.

TABLE 1.1.3 Tracking U.S. Property Loss to Fire

Year	*Based on NFPA Survey (in Billions of Dollars)*	*Estimated by Insurance Services Office (in Billions of Dollars)*
1993	8.546	11.331
1994	8.151	12.778
1995	8.918	11.887
1996	9.406	12.544
1997	8.525	12.940
1998	8.629	11.510
1999	10.024	12.428
2000	11.207	13.457
2001	44.023	17.118
2002	10.337	17.586

Note: NFPA survey figures are estimates by fire officers, sometimes with the benefit of information on insurance estimates. ISO estimates include actual home insurance claims and estimates and losses in uninsured or underinsured properties.

Sources: NFPA survey; Insurance Information Institute, *The I.I.I. Insurance Fact Book 2006,* New York: Insurance Information Institute, 2006.

Similarly, there are a number of possible reasons for the modest but growing gap between the NFPA estimates of direct property damage and the Insurance Services Office estimates of fire loss, as shown in Table 1.1.3. The insurance industry estimate may include indirect losses (e.g., reimbursement for temporary housing or business interruption) and may overadjust for losses in uninsured or underinsured properties. The fire department–based NFPA estimate will miss losses in unreported fires even if they result in insurance claims. The insurance industry estimate is a mix of detailed observations by highly trained loss appraisers and self-reported losses as adjusted in response

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to comments from appraisers who have not personally observed the fire scene. It is hard to say whether such estimates will be higher or lower, more or less accurate, than estimates by fire officers, who lack the same loss-estimation training but sometimes have access to insurance appraisals of the same fires and experience in other occupations, which give them the insight into what things cost.

Although the NFPA survey estimates are the best measures of fire loss, when fire is considered by itself, the available statistics on other hazards and types of harm are most comparable to the death certificate data and the insurance industry estimates for fire.

Burns and Electric Shock

Table 1.1.4 provides available information on total U.S. burn injuries, based on in-home surveys conducted by the U.S. Department of Health and Human Services. The samples are sufficiently small that the estimates of burn injuries are subject to considerable uncertainty. (For example, the estimate of a quarter million bed-disabling burn injuries per year in or during 1980 to 1981 is subject to relative error of more than 30%.) This uncertainty is also the reason why published analyses of the survey data do not always address burns and, when they do, use 2- or 3-year averages to reduce error to an acceptable level. The principal finding of Table 1.1.4 is that total U.S. burn injuries declined from roughly 2 million in 1980 to 1981 (and for at least two decades) to roughly 1 million in 1991 to 1993.

Table 1.1.5 provides a 10-year trend on pressure vessel explosions. Explosions involving pressurized tires, pipes, or hoses make up the largest share of fatal injuries, whereas boiler injuries make up the smallest share. Note that gas cylinders are a category under pressure vessels. This can point to a rough separation of natural gas (excluding pressure vessels) and LP-gas (gas cylinder explosion), although each of these is part of a category that can include other various situations and gases. Within the "explosion of other specified pressurized device" there is a roughly even split that tilts somewhat toward the unknowns.

Table 1.1.6 provides a 10-year trend on deaths due to injuries from hot objects. Figure 1.1.1 indicates 67 percent of those fatal injuries involve hot tap water, drinks, food, fats, or cooking oil, whereas 22 percent of those fatal injuries are caused by steam or other hot liquid or vapor. Figure 1.1.2 provides an overview of the death rates per million population by age-group for deaths due to injury by steam or other hot liquid or vapor. These rates are a measure of the differences in risk of death from this type of harm for different age-groups. As with fire deaths, the very young and older adults are the two high-risk age-groups, but unlike fire, the very young are not that much more at risk

TABLE 1.1.4 U.S. Burn Injuries Based on Responses to National Health Interview (In-Home) Survey

Measure	*1980–1981*	*1985–1987*	*1991–1993*
Burn injuries (per year)	2,130,000	1,735,000	1,129,000
Burn injuries per 100 population (per year)	1.0	0.7	0.4
Medically attended burn injuries	1,615,000	1,614,000	1,073,000
Restricted-activity burn injuries	1,213,000	810,000	445,000
Bed-disability burn injuries	244,000*	399,000	124,000
Average number of days of restricted activity per restricted-activity burn injury	6.1	8.8	NA
Average number of days of bed disability per bed-disability burn injury	5.7	8.1	NA

*Relative standard error of estimate exceeds 30 percent.
NA = Not available or not yet available.

Sources: *Types of Injuries and Impairments Due to Injuries—United States,* Series 10, No. 159, 1986; *Types of Injuries by Selected Characteristics, 1985–87,* Series 10, No. 175, 1990; and advance data from John Gary Collins, U.S. Department of Health and Human Services, author of all analyses shown here.

TABLE 1.1.5 Unintentional Injury Deaths Due to Explosion of Pressure Vessel, Deaths Coded on U.S. Death Certificates

Year	*Total Explosion of Pressure Vessels*	*Explosion of Boiler*	*Explosion of Gas Cylinder*	*Explosion of Pressurized Tire, Pipe, or Hose*	*Explosion of Other Specified Pressurized Device*
1994	30	2	10	15	3
1995	36	2	11	16	7
1996	27	3	6	16	2
1997	33	5	11	15	2
1998	31	2	5	22	2
1999	33	6	6	14	7
2000	30	3	8	12	7
2001	38	1	14	12	11
2002	27	5	9	10	3

Source: CDC/NCHS website, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm.

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TABLE 1.1.6 Unintentional Injury Deaths Involving Contact with Hot Objects or Substances, 1993–2002

Year	*Total*
1993	130
1994	107
1995	97
1996	104
1997	111
1998	108
1999	123
2000	110
2001	114
2002	102

Note: Involved corrosive substances and steam. Data prior to 1999 listed as Death Certificate Code E924. Post-1999 data listed as Death Certificate Codes X10–X19.

Sources: National Safety Council, *Accident Facts* and *Injury Facts,* Itasca, IL: National Safety Council, 1992–2006; 2002 data from CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

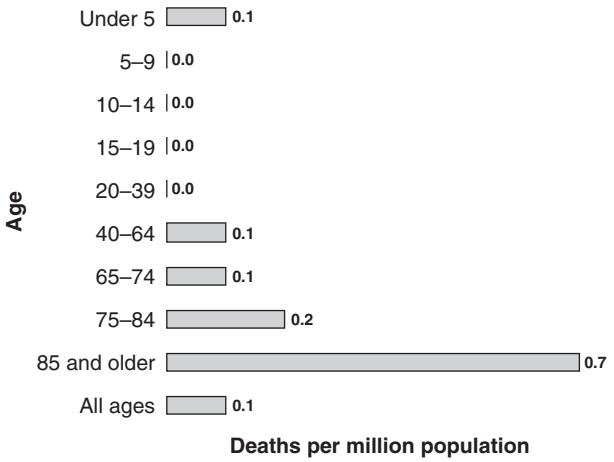

FIGURE 1.1.2 Deaths Due to Steam or Other Hot Liquid or Vapor, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

than the all-ages average, and the older adults have risks much higher than those for the very young.

Table 1.1.7 provides a 10-year trend for the available components of deaths due to unintentional injury by electrical current. The largest share of fatal injuries due to electrical current falls into the "other or unknown" category. This table reflects the revision of the ICD. Home equipment, industrial equipment, and generating plants or distribution categories were discontinued in the tenth revision. However, data from 1999 to 2002 also demonstrate that the largest share of fatal injuries falls into the "other specified" category.

According to data prior to 1999, injuries involving home or industrial equipment have been declining substantially. Those involving generating plants or distribution equipment have not. As a result, deaths from electric current associated with generating plants or distribution now routinely outnumber those associated with home equipment by a large margin.

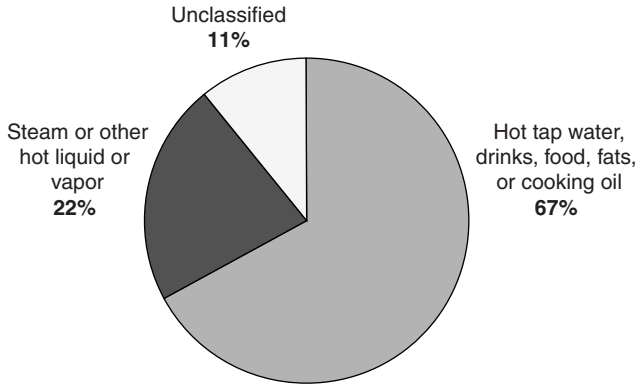

FIGURE 1.1.1 Deaths Due to Hot Object, by Type of Object, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

FALLS

Falling People

Falls account for by far the largest number of fatal injuries among all the types of injuries that can occur in the built environment. Table 1.1.8 provides 10 years of data pertaining to deaths due to falls for the major types of falls. The "other or unknown-type" category contains the largest share of deaths, whereas the category for falls on the same level from collision, pushing, or shoving has the smallest share of deaths. Nearly half of these types of falls occur in sports and the rest involve other or unknown-type activities.

Falls from or on Stairs or Steps. Note that deaths due to falls from or on stairs or steps—the major category of falls most clearly linked to the design of the built environment—have been increasing over the period analyzed and are up by about 20 percent in the most recent decade analyzed. This is a larger increase than can be explained by the growth in total population, but it might be better explained by an age-adjusted analysis, which would factor in not only the growth in the total population but also the growth in the older-adult share of the population.

Figure 1.1.3 provides an overview of deaths per million population, by age, for fatal falls from or on stairs or steps. The risk is negligible for children, even children under age 5, but rises rapidly among older adults. Half of all deaths from falls from or on stairs or steps are people age 75 and older. This risk for adults age 85 or older is roughly 14 times the all-ages risk and 65 times the risk for younger adults.

Falls from or on Ladders or Scaffolding. Table 1.1.9 shows the total number of falls on or from ladders or scaffolding, as

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TABLE 1.1.7 Unintentional Injury Deaths by Electrical Current, Deaths Coded on U.S. Death Certificates

Year	Lightning*	Total Electric Current	Home Equipment	Industrial Equipment	Generating Plants or Distribution	Other or Unknown
1993	57	548	82	46	142	278
1994	84	561	84	42	144	291
1995	76	559	88	26	158	287
1996	63	482	66	15	135	266
1997	68	488	53	27	139	269
1998	63	548	59	27	144	318

Year	Lightning*	Total Electric Current	Electric Transmission Lines	Other Specified
1999	64	437	127	310
2000	50	395	99	296
2001	44	405	83	326
2002	66	431	109	322

*Not included in total.

Source: John R. Hall, Jr., *Burns and Toxic Gases in Non-Fire Situations,* National Fire Protection Association, 2005; National Safety Council, *Injury Facts,* 2005–2006 edition, Itasca, IL: National Safety Council, 2006.

TABLE 1.1.8 Unintentional Injury Deaths Due to Falls, Deaths Coded on U.S. Death Certificates

Year	Total	Falls on or from Stairs or Steps	Falls on or from Ladders and Scaffolding	Falls from out of Building or Structure	Falls into Holes or Other Openings in Surface	Other Falls from One Level to Another	Falls on Same Level from Slipping, Tripping, or Stumbling	Falls on Same Level from Collision, Pushing, or Shoving	Other Unknown-Type Falls
1993	13,141	1,087	301	509	107	1,156	520	9	9,452
1994	13,450	1,163	327	477	93	1,066	600	4	9,920
1995	13,986	1,241	352	467	94	1,145	491	8	10,188
1996	14,986	1,239	369	444	88	1,129	688	3	11,026
1997	15,447	1,295	368	549	70	1,106	726	4	11,329
1998	16,274	1,389	352	550	95	1,187	740	6	11,955
1999	11,331	1,421	375	550	NA	552	611	15	7,807
2000	10,419	1,307	412	506	NA	476	565	7	7,146
2001	11,322	1,462	439	580	NA	595	564	22	7,660
2002	11,382	1,598	406	557	NA	509	646	12	7,654

Source: National Safety Council, *Injury Facts* and *Accident Facts,* Itasca, IL: National Safety Council, 1992–2002; 2002 statistics from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

well as both components. Falls on or from ladders contains the largest share of fatal injuries. Falls involving ladders dominate by 4 to 1. Figure 1.1.4 provides an overview of deaths per million population for fatal falls from or onto ladders, by age of victim. The risk is highest by far for older adults. A majority (55%) of the deaths are adults age 65 or older.

Falls out of Structures. Figure 1.1.5 provides an overview of deaths per million population for fatal falls out of a building or structure, by age of victim. There has been considerable publicity surrounding preschool children falling out of buildings, resulting in a recent push for bars on windows, which, if installed incorrectly, can become a deadly barrier preventing safe escape from a fire in the building. However, as with every type of fatal fall examined so far, the higher risks are faced by older adults. The risk for adults age 85 and over is five times the all-ages risk.

Falls from One Level to Another. Table 1.1.10 provides a breakdown of the different types of fatal falls from one level to another. Falls from playground equipment are a negligible share of the total. Falls from cliffs are an important component

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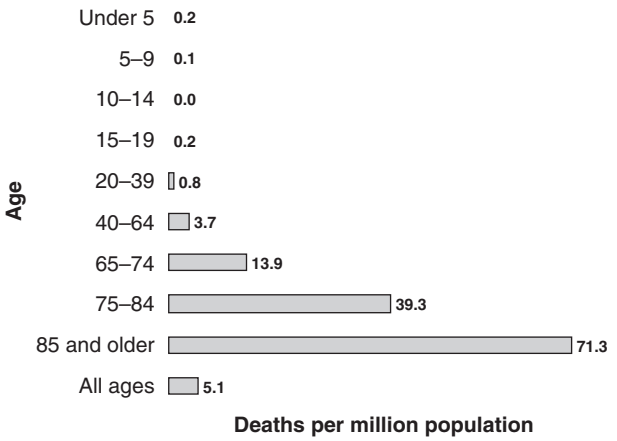

FIGURE 1.1.3 Deaths Due to Falls on or from Stairs or Steps, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

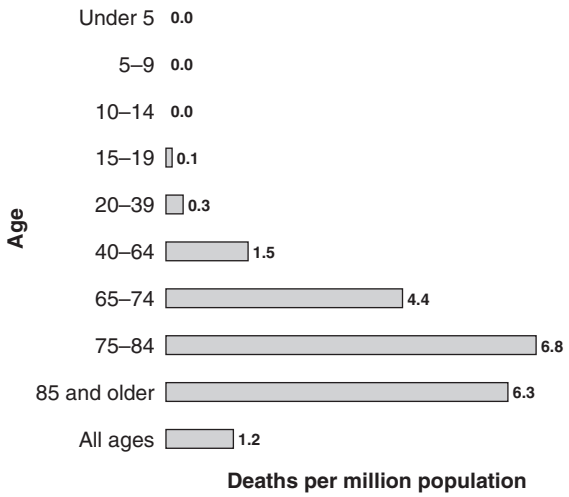

FIGURE 1.1.4 Deaths Due to Falls on or from Ladders, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

but one that has been declining sharply. Falls from chairs or beds compose the largest share of fatal falls from one level to another, and those deaths have not been declining.

Figure 1.1.6 shows that differences in this risk by age are the largest yet seen in this chapter. Adults age 85 or older have more than 30 times the all-ages risk of suffering a fatal fall from a chair or bed. This age group accounted for roughly half (49%) of all deaths from this type of fall. Young children have a higher risk than older children but much less risk than older adults.

The category of "other" falls from one level to another shows a very different profile than that for falls from chairs and beds. The age profile more closely resembles that for deaths due to falls involving cliffs, which means it would be inappropriate and possibly misleading to treat these underspecified falls as if they were similar to falls from chairs and beds. The age profile for these falls looks more like one might expect from falls off roofs, but it seems unlikely that this specific scenario would account for such a large death toll.

Nonfatal Falls. Table 1.1.11 illustrates the number of nonfatal falls based on responses to the government's in-home survey of health problems. The nonfatal fall injuries in Table 1.1.11 outnumber the fatal fall injuries in Table 1.1.8 by nearly a thousand to one. The relative importance of various types of falls is different, reflecting in part the fact that some types of falls—for example, from stairs or steps, or out of a building structure—are more likely to be fatal than some other types of falls.

TABLE 1.1.9 Unintentional Injury Deaths Due to Falls from Ladders Versus Scaffolding, Deaths Coded on U.S. Death Certificates

Year	*Total Falls on or from Ladders or Scaffolding*	*Falls on or from Ladders*	*Falls on or from Scaffolding*
1994	327	268	59
1995	352	294	58
1996	369	299	70
1997	368	301	67
1998	352	284	68
1999	375	320	55
2000	412	355	57
2001	439	376	63
2002	406	360	46

Sources: National Safety Council, *Accident Facts* and *Injury Facts,* 1992–2004 editions, Itasca, IL: National Safety Council, 1992–2004; 2002 data from CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

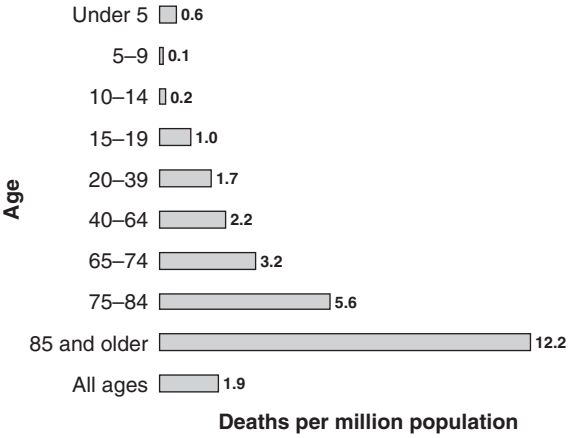

FIGURE 1.1.5 Deaths Due to Falls out of Building or Structure, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

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TABLE 1.1.10 Unintentional Injury Deaths Due to Fall from One Level to Another, Deaths Coded on U.S. Death Certificates

Year	*Total Other Falls from One Level to Another*	*Falls from Playground Equipment*	*Falls from Cliffs*	*Falls from Chairs or Beds*	*Other Falls from One Level to Another*
1994	1066	4	107	429	526
1995	1145	2	113	516	514
1996	1129	3	91	485	550
1997	1106	6	64	501	535
1998	887	2	63	208	614
1999	1617	4	83	978	552
2000	1170	0	82	612	476
2001	1358	4	62	697	595
2002	1344	3	80	752	509

Sources: National Safety Council, *Accident Facts* and *Injury Facts,* 1992–2004 editions, Itasca, IL: National Safety Council, 1992–2004; 2002 data from CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

International Perspective on Falls. Table 1.1.12 illustrates the unintentional injury death rates due to falls at the international level. The table shows the averages of available 2000–2002 fatal fall rates for different countries. Unlike the case with fire deaths, the U.S. rate of fall deaths per million population is one of the lowest; Argentina has the lowest rate among all the countries listed.

An analysis of the international differences would need to begin with an examination of differences in age distributions, which could make a large difference in light of the enormous differences in risk of death from falls among age groups. Also, it would be useful to know how much variation in heights of surfaces normally encountered by people exists from place to place. Certainly, high-rise buildings are more common in some countries than others, but it is unlikely that this is a major factor in the overall statistics. Other differences, such as the average heights of beds or sleeping surfaces (e.g., futons), might exist, however, and might be important. Differences in contributing risk factors, such as the use of alcohol, could be important. And the possibility of differences in definitions used in practice or in data collection should also be considered.

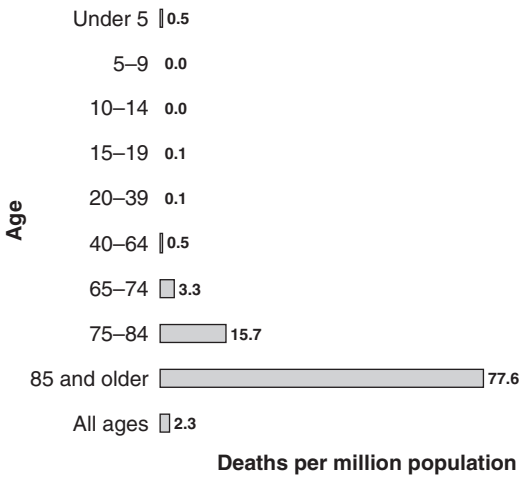

FIGURE 1.1.6 Deaths from Falls from Chairs or Beds, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

Falling Objects

Deaths due to falling objects are the kinds of deaths that might include a significant share that can be related to the design and operating decisions of the built environment. Unfortunately, the coding provides no details on the kinds of falling objects involved. Whatever the objects may be, the toll from objects has

TABLE 1.1.11 U.S. Nonfatal Fall Injuries Based on Responses to National Health Interview (In-Home) Survey

Type of Fall	*Estimated 1997 Injuries*
Total fall episodes	11,306,000
Total types of falls mentioned*	12,285,000
Onto floor or level ground	4,158,000
From or onto stairs or steps	1,296,000
From or onto curb or sidewalk	1,162,000
From or onto chair, bed, sofa, or other furniture	807,000
From or onto playground equipment	493,000
From ladder or scaffolding	447,000
Into hole or other opening	382,000
From or onto escalator, building or other structure, tree, toilet, bathtub, or pool	610,000
Unreported type	2,793,000
Refused to give type or did not know	135,000

Note: Sum may not equal total because of rounding error.
*More fall types are mentioned than there were fall episodes because respondents could specify up to two types.
Source: Centers for Disease Control and Prevention report, *Injury and Poisoning Episodes and Conditions: National Health Survey, 1997,* Series 10, No. 202, Table 3, p. 19, July 2000.

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TABLE 1.1.12 Rates per Thousand Population of Unintentional Injury Deaths Due to Falls (Average of Latest Available 2000–2002 Rates)

Country	*Average Death Rate Due to Falls*
North America	
Canada	51
United States	47
Mexico	23
South America	
Chile	19
Argentina	8
Asia/Pacific	
New Zealand	65
Japan	50
Australia	32
Europe	
Hungary	312
Finland	216
Norway	195
Italy	183
Czech Republic	178
Slovenia	149
Croatia	139
Austria	121
Russia	104
Ireland	98
Poland	97
France	90
Sweden	61
Portugal	60
Netherlands	55
United Kingdom	55
Greece	53
Spain	37
Bulgaria	36

Note: Listings are limited to countries with the latest rates available (2000–2002).

Source: National Safety Council, *Injury Facts,* 2005–2006 edition, Itasca, IL: National Safety Council, 2006.

shown little decline. Table 1.1.13 illustrates the number of fatal injuries caused by falling objects.

Striking or Being Struck by Falling Objects

Within the category of people striking against or being struck by objects, it is possible to distinguish deaths due to people striking other people in a crowd, as in a hurried or rushed evacuation or when a crowd presses someone against a stationary barrier. Instances that might fit within this category might also be coded somewhere else. A good example would be a crowd-crushing situation that would be considered not to fit the "struck by" label.

Table 1.1.14 provides a breakdown of 2004 occupational injuries and illnesses by event or exposure, overall and for each of three groups of objects that are entirely or mostly recognizable as components of the built environment—floors, walkways, and ground surfaces; furniture and fixtures; and machinery.

TABLE 1.1.13 Other Deaths Due to Objects in Motion, Deaths Coded on U.S. Death Certificates

Year	*Due to Cataclysmic Earth Movement or Eruption*	*Struck by Falling Object*	*Struck by People or Against Object*
1993	17	714	187
1994	46	739	207
1995	25	656	198
1996	42	732	171
1997	20	727	247
1998	24	723	336
1999	46	701	131
2000	36	712	146
2001	28	707	135
2002	31	721	127

Sources: National Safety Council, *Injury Facts* and *Accident Facts,* 1992–2004 editions, Itasca, IL: National Safety Council, 1992–2004; 2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

NATURAL DISASTERS

Earthquakes

An earthquake is the vibration of the Earth's surface by the rapid release of energy. Most earthquakes are caused by slippage along a geologic fault in the Earth's crust.[12] The energy released during an earthquake is measured by the Richter scale (Table 1.1.15). Each unit of Richter magnitude equates to roughly a 32-fold energy increase. With each increase in magnitude comes the increased probability for loss of life and property damage. Earthquakes include many of the deadliest and costliest incidents in history.[13] Approximately 6200 earthquakes detectable by human beings occur every year.

Deadliest U.S. Earthquakes. Table 1.1.16 lists the 10 deadliest U.S. earthquakes of all time, leading with the 1906 San Francisco earthquake, which caused the costliest U.S. fire of all time. Six out of the 10 earthquakes occurred in California, and two others were offshore earthquakes near Alaska that produced tsunamis that resulted in the deaths of many. Since earthquakes have the ability to produce major postevent disasters such as fire, tsunamis, flooding, and landslides, these events could be listed as a multiperil incident. Reliable death tolls are hard to come by for older events, and property loss totals are even rarer, regardless of reliability. Therefore, it is possible that some of these incidents do not belong on the lists and other events, no longer even cited in general references, do belong.

Table 1.1.17 lists the 10 deadliest world earthquakes of all time, with the top earthquake occurring in China. This earthquake resulted in 830,000 estimated deaths and is possibly the greatest natural disaster of all time. The following earthquakes are estimated to have resulted in over 100,000 deaths each.

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TABLE 1.1.14 Nonfatal Private-Industry Occupational Injuries or Illnesses Involving Days Away from Work, by Event or Exposure, and by Selected Objects Providing Source of Injury or Illness

	2004 Injuries and Illness per 10,000 Full-Time Workers			
Event or Exposure	*Total*	*Floors, Walkways, or Ground Surfaces*	*Furniture or Fixtures*	*Machinery*
Contact with objects or equipment	**37.6**	**0.8**	**2.2**	**6.2**
Struck against object	9.4	0.6	1.0	1.5
Falling object	6.9	0	0.7	0.4
Flying object	2.1	0	0	0.1
Swinging or slipping object	6.4	—	0.1	0.3
Rolling or sliding object	0.6	0	0	0.2
Unclassified or unknown type	0.8	—	—	0.1
Caught in or compressed by equipment or objects	6.2	0	0.2	3.1
Caught in or crushed in collapsing materials	0	0	—	—
Excavation or cave-in	0	0	—	—
Collapsing structure	0	—	—	—
Unclassified or unknown type	0.4	—	0	0.1
Rubbed or abraded by friction or pressure	1.7	0.1	0	0
Rubbed, abraded, or jarred by vibration	0.2	0	0	0.1
Unclassified or unknown type	0	—	—	—
Falls	**28.7**	**24.8**	**0.5**	**0.3**
Fall to lower level	9.0	7.9	0	0
Down stairs or steps	2.1	2.0	—	—
From floor, deck, or ground level	0.5	0.4	—	—
Through existing floor opening	0.1	0.1	—	—
Through floor surface	0.1	0.1	—	—
From loading dock	0.1	0.1	—	—
From ground level to lower level	0.1	0.1	—	—
Unclassified or unknown type	0.3	0.2	0	—
From ladder	2.5	2.1	—	0
From piled or stacked material	0.1	0.1	—	—
From roof	0.3	0.2	—	—
Through existing roof opening	0	0	—	—
Through roof surface	0	0	—	—
Through skylight	0	—	—	—
From roof edge	0.1	0.1	—	—
Unclassified or unknown type	0.1	0.1	—	—
From scaffold or staging	0.4	0.3	—	—
From building girders or other structural steel	0	0	—	—
From nonmoving vehicle	1.7	1.5	0	0
Jump to lower level	0.6	0.5	0	0
Fall on same level	18.7	16.2	0.4	0.3
To floor, walkway, or other surface	15.8	15.8	—	—
Onto or against objects	2.4	0	0.4	0.3
Unspecified or unknown type	0.3	0.2	0	0
Bodily reaction or exertion	**57.4**	**0.6**	**2.2**	**2.1**
Bodily reaction—slip, trip, or loss of balance without fall	4.2	0.3	0	0
Exposure to harmful substances or environments	**5.9**	**—**	**0**	**0.4**
Contact with electrical current	0.3	—	0	0.1
Of appliance, tool, or other equipment	0.1	—	0	0.1
Of wiring transformer or other electrical distribution equipment	0.1	—	—	—
Of overhead power lines	0	—	—	—
Of underground or buried power lines	—	—	—	—
From lightning	0	—	—	—
Unspecified or unknown type	0	—	—	—
Contact with temperature extremes	2.1	—	0	0.3
Hot objects	1.9	—	0	0.3

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TABLE 1.1.14 Continued

Event or Exposure	2004 Injuries and Illness per 10,000 Full-Time Workers			
	Total	*Floors, Walkways, or Ground Surfaces*	*Furniture or Fixtures*	*Machinery*
Exposure to air pressure changes	0	—	—	—
Exposure to caustic, noxious, or allergenic substances	3.0	—	0	0
Exposure to noise	0	—	—	—
Exposure to radiation	0.2	—	—	0
Welding light	0.2	—	—	0
Unclassified or unknown type	—	—	—	—
Exposure to traumatic or stressful event	0.2	—	—	—
Unclassified or unknown type	—	—	—	—
Transportation incidents	**7.1**	**0**	**—**	**0.2**
Fires or explosions	**0.3**	**—**	**0**	**0**
Assault or violent act	**2.8**	**0**	**0**	**—**
Unclassified or unknown type	**1.5**	**0**	**0**	**0**

Note: Sums may not equal totals due to rounding error.
Source: Table R36, Case and Demographic Resources Tables, from http://www.osha.gov/oshstats.

TABLE 1.1.15 Richter Scale Magnitude

Richter Magnitudes	*Effects*	*Estimated Number per Year*
<2.0	Generally felt but not recorded	600,000
2.0–2.9	Potentially perceptible	300,000
3.0–3.9	Felt by some	49,000
4.0–4.9	Felt by most	6,200
5.0–5.9	Damaging shocks	800
6.0–6.9	Destructive in populous regions	266
7.0–7.9	Major earthquakes; inflict serious damage	18
8.0 and above	Great earthquakes; destroy entire communities	1.4

Source: Edward J. Tarbuck and Frederick K. Lutgens, *Earth Science,* eleventh edition. Upper Saddle River, NJ: Pearson Education Inc., 2006.

Costliest U.S. Earthquakes. Table 1.1.18 lists the 10 costliest U.S. earthquakes of all time, based on adjustment to 2004 dollars. The 1994 Northridge, California, earthquake and the 1989 Loma Prieta earthquake lead the list by a substantial margin, with the 1964 Anchorage, Alaska, earthquake ranking third. All but one of the costliest earthquakes occurred in California.

Landslides

Landslides are the downslope movement of rock and soil under the influence of gravity.[12] All material resting on a slope is considered to have an angle of repose, that is, an angle at which the material will remain stable.[13] Gravity is the controlling force of landslides, but several factors play an important role in creating downslope movement.

Factors Triggering Landslides. Landslides are sometimes triggered when periods of heavy rains or periods of snowmelt saturate surface materials. Oversteepening of slopes is another important trigger of landslides, whereas removal of vegetation allows for the enhancement of landslides. If the slopes are steep and water is plentiful, a landslide can easily occur.[12] Landslides commonly occur in connection with other major natural disasters such as earthquakes, wildfires, and floods.[14]

Landslides constitute a major geologic hazard because they cause $1–$2 billion in damages and more than 25 fatalities each year.[14] Landslides pose serious threats to the built environment in many parts of the country. Expansion of urban and recreational developments into hillside areas results in increasing numbers of residential and commercial properties in danger of landslides.

Deadliest Landslides Worldwide. Table 1.1.19 lists the 10 deadliest landslides of all time, six of which were caused by an earthquake. The most recent major landslide occurred in 1990 in Iran. A magnitude 7.7 earthquake shook the nation, triggering major landslides that claimed the lives of over 40,000 people. Two of the landslides making the list were triggered by consecutive days of torrential rains.

Hurricanes, Cyclones, and Tornadoes

A hurricane is a tropical cyclonic storm having winds in excess of 74 miles per hour. Hurricanes most often develop in late summer when water temperatures have reached 80°F or higher and, thus, are able to provide the necessary heat and moisture to the air. Based on the study of past hurricanes, the Saffir-Simpson

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TABLE 1.1.16 Deadliest U.S. Earthquakes of All Time

Location	Richter Scale Magnitude	Year	Estimated Deaths	Comments
1. San Francisco, CA	7.7	1906	~3000	Fires caused extensive damage and deaths
2. Unimak Island, AK	8.1	1946	165	Tsunami: 159 Hawaii, 5 Alaska, 1 California
3. Prince William Sound, AK	9.2	1964	131	Tsunami: 98 Alaska, 11 California, 1 Oregon
4. Long Beach, CA	6.2	1933	115	Property damage estimated at $40 million
5. Ka'u District, Island of Hawaii	7.9	1868	77	Tsunami, landslide; largest earthquake in HI
6. San Fernando, CA	6.6	1971	65	Property damage estimated at $505 million
7. Loma Prieta, CA	6.9	1989	63	Estimated $6 billion in property damage
8. Northridge, CA	6.8	1994	61	Damages in excess of $40 billion
9. Charleston, SC	6.6	1886	60	Greatest historical earthquake in eastern United States
10. San Juan Capistrano, CA	7.5	1812	40	Damage estimate unknown

Sources: United States Geological Survey, Earthquake Hazards Program, http://www.usgs.gov; Frederick K. Lutgens and E. J. Tarbuck, *Earth Science,* eleventh edition, Upper Saddle River, NJ: Pearson Prentice Hall, 2006; "Earthquakes," *The 2006 World Almanac and Book of Facts,* New York: World Almanac Education Group, Inc., 2006.

TABLE 1.1.17 World's Deadliest Earthquakes on Record

Location	Richter Scale Magnitude	Year	Estimated Deaths	Comments
1. Shensi, China	~8.0	1556	830,000	Possibly the greatest natural disaster
2. Sumatra, Indonesia	9.0	2004	283,106	Deaths from earthquake and tsunami
3. Tangshan, China	7.5	1976	255,000	Deaths estimated as high as 655,000
4. Aleppo, Syria	NA	1138	230,000	
5. Damghan, Iran	NA	856	200,000	
6. Nan-shan, China	7.9	1927	200,000	Large fractures in the Earth's surface
7. Gansu, China	8.6	1920	200,000	Major fractures in surface; mudslides
8. Ardabil, Iran	NA	893	150,000	
9. Kanto, Japan	8.3	1923	143,000	Fire caused extensive destruction
10. USSR	7.3	1948	110,000	

NA = Not available.

Sources: United States Geological Survey, Earthquake Hazards Program, http://www.usgs.gov; Frederick K. Lutgens and E. J. Tarbuck, *Earth Science,* eleventh edition, Upper Saddle River, NJ: Pearson Prentice Hall, 2006; "Earthquakes," *The 2006 World Almanac and Book of Facts,* New York: World Almanac Education Group, Inc., 2006.

scale (Table 1.1.20) was established to rank the relative intensities of hurricanes. Predictions of hurricane severity and damage are expressed in terms of this scale.[12]

Deadliest U.S. Hurricanes. Table 1.1.21 lists the 10 deadliest U.S. hurricanes of all time. Eight of the deadliest hurricanes occurred before the convention of assigning names to hurricanes that began after World War II. Poor record keeping prior to the twentieth century and the fact that some hurricanes wiped out all life on isolated or island communities may mean that some hurricanes with true death tolls high enough to justify inclusion are not recognized as such. This also explains the considerable variation in estimated death tolls for some of these storms from one source to another.

The most recent hurricane to appear on the list of the 10 deadliest is Hurricane Katrina in 2005. Hurricane Katrina struck the Gulf Coast as a strong category 3 hurricane, resulting in severe storm surge damage along the Louisiana, Mississippi, and Alabama coasts and extensive wind damage. Secondary events, including severe urban flooding as a result of failure of parts of the levee system in New Orleans, resulted in over 1300 deaths.[15]

Deadliest Cyclones Worldwide. A *cyclone* (the term includes hurricanes and typhoons) is a low-pressure center characterized by a counterclockwise flow of air in the Northern Hemisphere (and a clockwise flow in the Southern Hemisphere). The terms *hurricane* and *typhoon* are regional names, with hurricane being the common choice for cyclones east of North and Central America.[12] Table 1.1.22 lists the five deadliest cyclones of all time. Four of the five occurred on the Indian subcontinent, and the deadliest one of all—the 1970 cyclone in what was then

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TABLE 1.1.18 Costliest U.S. Earthquakes of All Time

Location	Magnitude	Year	Estimated Total Property Damage (in Billions of Dollars)	
			Year of Occurrence	*In 2004*
1. Northridge, CA	6.7	1994	13.00–20.00	17.00–25.00
2. Loma Prieta, CA (San Francisco Bay Area)	6.9	1989	7.00	10.70
3. Anchorage, AK (tsunami damage)	9.2	1964	0.50	3.10
4. San Fernando, CA	6.5	1971	0.60	3.10
5. Southern California (primarily in Los Angeles)	5.9	1987	0.40	0.60
6. Southern California (Landers, Big Bear)	7.6	1992	0.09	0.10
7. Northern California coast	7.1	1992	0.07	0.09
8. Kern County, CA	7.5	1952	0.06	0.43
9. Long Beach, CA	6.3	1993	0.04	0.58
10. Central California (Coalinga)	6.4	1983	0.03	0.06

Source: Insurance Information Institute, *The I.I.I. Insurance Fact Book 2006,* New York: Insurance Information Institute, 2006.

TABLE 1.1.19 World's Deadliest Landslides

Rank	*Location*	*Year*	*Estimated Number of Deaths*	*Precipitating Event*
1	Kansu, China	1920	180,000	Earthquake
2	Western Iran	1990	45,000–50,000	Earthquake
3	Khait, Tadzhikistan	1949	12,000	Earthquake
4	Minatitlan, Mexico	1959	5,000	Earthquake
5	Belluno, Italy	1963	4,000	Earthquake
6	Huascaran, Peru	1962	3,500	
7	Chiavenna, Italy	1618	2,420	
8	Bihar, India	1968	1,000	Heavy rains
9	Chungar, Peru	1971	400–600	Earthquake
10	Rio de Janeiro, Brazil	1966	550	Heavy rains

Sources: James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992; United States Geological Survey Natural Hazards Support System, http://nhss.cr.usgs.gov.

TABLE 1.1.20 Saffir-Simpson Hurricane Scale

Category	*Central Pressure (millibars)*	*Winds (mph)*	*Storm Surge (ft)*	*Damage*
1	≥980	74–95	4–5	Minimal
2	965–979	96–110	6–8	Moderate
3	945–964	111–130	9–12	Extensive
4	920–944	131–155	13–18	Extreme
5	<920	>155	>18	Catastrophic

Sources: Edward J. Tarbuck and Frederick K. Lutgens, *Earth Science,* eleventh edition, Upper Saddle River, NJ: Pearson Education Inc., 2006; U.S. National Weather Service website, http://www.nhc.noaa.gov/aboutsshs.shtml.

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TABLE 1.1.21 Deadliest U.S. Hurricanes of All Time

Rank	Hurricane	Year	Category	Estimated Deaths
1	Texas (Galveston)	1900	4	8000
2	Florida (Lake Okeechobee)	1928	4	2500
3	St. Jo, Florida	1841	NA	4000
4	Katrina	2005	3	1300+*
5	Louisiana (Cheniere Caminanda)	1893	4	1000–1400
6	South Carolina/Georgia (Sea Islands)	1893	3	1000–2000
7	Georgia/South Carolina	1881	2	700
8	Florida Keys	1935	5	408
9	Louisiana, Last Island	1856	4	400
10	Audrey	1957	4	390

*Estimated deaths as of 10/05.
NA = Not available.

Sources:
1. James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979.
2. Eric S. Blake et al., 2005, "The Deadliest, Costliest, and Most Intense United States Tropical Cyclones From 1851 to 2004 (and Other Frequently Requested Facts)," NOAA, Technical Memorandum, NWS TPC-4, 48 pp.
3. Lee Davis, *Natural Disasters,* New York: Facts on File, 1992.
4. Tom Ross and Neal Lott, *Billion Dollar U.S. Weather Disasters, 1980–2005,* NOAA, National Climatic Data Center Fact Sheet, 2006, http://www.ncdc.noaa.gov/oa/reports/billionz.html.
5. "Hurricanes," *The 2006 World Almanac and Book of Facts,* New York: World Almanac Education Group, Inc., 2006.

TABLE 1.1.22 World's Deadliest Cyclones of All Time (Includes Hurricanes and Typhoons)

Rank	Storm	Year	Estimated Deaths
1	East Pakistan*	1970	200,000–1,000,000
2A	Bengal, India	1737	300,000
2B	Haiphong, Vietnam	1881	300,000
4	Bangladesh	1991	139,000
5A	Bengal, India	1876	100,000+
5B	Bombay, India	1882	100,000+

*The lack of timely, substantial relief from the government led to the breakaway creation of Bangladesh.

Sources: National Safety Council, *Injury Facts 2000,* Itasca, IL: National Safety Council, 2000; *World Almanac 2006,* New York: World Almanac Education Group, Inc., 2006; James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992.

East Pakistan—triggered the most extreme response to ineffective emergency response in world history, namely, the creation of the breakaway nation of Bangladesh.

Costliest U.S. Hurricanes. Table 1.1.23 lists the 10 costliest U.S. hurricanes of all time. The list is comprised mainly of hurricanes from 2004 and 2005. The 2004 Atlantic hurricane season caused an estimated $22.9 billion in insured losses according to ISO's Property Claim Services unit, the highest amount ever recorded in a single year up to the 2005 season.[9] The 2005 hurricane season was the worst on record, with 26 named storms, 14 of which became hurricanes and more than $46 billion in insured losses, resulting in a record high.[9] The season produced Katrina in August, the most costly hurricane in U.S. history. The losses from Hurricane Katrina doubled the losses of Hurricane Andrew in 1992.

Tornadoes. A tornado is a small, very intensive cyclonic storm with exceedingly high winds. Tornadoes form in association with severe thunderstorms that produce high winds, heavy rainfall, and hail. Their sporadic nature and violent winds cause many deaths each year. One commonly used guide to measure tornado intensity is the Fujita intensity scale (Table 1.1.24). Because tornado winds cannot be directly measured, a rating on the Fujita scale is determined by assessing the worst damage produced by a storm.[12]

Table 1.1.25 lists the number of tornadoes and associated deaths for the past 10 years. Table 1.1.26 lists the 10 deadliest U.S. tornado incidents of all time and in a contiguous region. The three single-tornado incidents on the list all occurred in the nineteenth century.

Tornado incidents rarely produce combined property losses in excess of $1 billion and, possibly for that reason, there were not enough tornado incidents with documented high property losses to justify preparing a list of the 10 costliest tornado incidents.

Water or Storms

Deaths in the water certainly occur as a consequence of a natural disaster. However, most of the deaths in the water or storms group do not involve catastrophic events. They involve drownings or submersions in more everyday situations, typically associated with swimming or diving. Table 1.1.27 provides an overview of these water- and storm-related fatal injuries.

Drownings in bathtubs come closest to involving design options for the built environment. Figure 1.1.7 shows that this

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TABLE 1.1.23 Costliest U.S. Hurricanes of All Time

Rank	Hurricane	Category	Location	Year	Estimated Loss (in Billions of Dollars) In Year of Occurrence	Estimated Loss (in Billions of Dollars) In 2004
1	Katrina	3	AL, FL, GA, LA, MS, TN	2005	34.40	34.40*
2	Andrew	4	FL, LA, MS	1992	15.50	20.87
3	Charley	4	FL, NC, SC	2004	7.48	7.48
4	Ivan	3	AL, FL, GA, +12 other states	2004	7.11	7.11
5	Hugo	4	U.S Virgin Islands, PR, 4 states	1989	4.20	6.40
6	Wilma	3	FL	2005	6.10	6.10*
7	Rita	3	Gulf Coast	2005	4.70	4.70*
8	Frances	2	FL, GA, SC, NC, NY	2004	4.60	4.60
9	Jeanne	3	PR, FL, PA, GA, SC, NY	2004	3.66	3.66
10	Georges	2	U.S Virgin Islands, PR, 4 states	1998	2.90	3.36

*Expressed in 2005 dollars.

Sources:
1. Insurance Information Institute, *The I.I.I. Insurance Fact Book 2006,* New York: Insurance Information Institute, 2006.
2. Eric S. Blake et al., 2005, "The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2004 (And Other Frequently Requested Facts)," NOAA, *Technical Memorandum,* NWS TPC-4, 48 pp.
3. Tom Ross and Neal Lott, *Billion Dollar U.S. Weather Disasters, 1980–2005,* NOAA, National Climatic Data Center Fact Sheet, 2006, http://www.ncdc.noaa.gov/oa/reports/billionz.html.

risk targets the very young and very old, much as fire does. Children under age 5 have roughly three times the all-ages risk, a higher relative risk than the same age children have for death from fire. Older adults show a lower relative risk for drowning in bathtubs than they do for death from fire.

Storms

Types of Storms. Storm data collected by the National Weather Service[10] show significant annual averages of damage (including both property and crop damage) in 2000 to 2004 from three types of storms:

- *Hail storms* average $0.97 billion per year
- *Thunderstorms (including wind)* average $0.33 billion per year
- *Winter storms* average $0.52 billion per year

TABLE 1.1.24 Fujita Intensity Scale

Scale	Wind Speed (mph)	Damage
F0	<72	Light damage
F1	72–112	Moderate damage
F2	113–157	Considerable damage
F3	158–206	Severe damage
F4	207–260	Devastating damage
F5	>260	Incredible damage

Source: Edward J. Tarbuck and Frederick K. Lutgens, *Earth Science,* eleventh edition, Upper Saddle River, NJ: Pearson Education Inc., 2006.

Four other types of storms or storm effects—lightning, coastal storms, tsunamis, and ice storms—are not shown in the preceding list because each type averages much less damage per year in 2000 to 2004 than do the listed types. Clearly, this will not be true of 2005, when losses from the December Asian tsunami are included.

TABLE 1.1.25 Tornadoes and Deaths Due to Tornadoes in the United States

Year	Number of Tornadoes	Deaths
1989	856	50
1990	1133	53
1991	1132	39
1992	1297	39
1993	1173	33
1994	1082	69
1995	1234	30
1996	1173	25
1997	1148	67
1998	1424	130
1999	1345	94
2000	1071	40
2001	1216	40
2002	941	55
2003	1376	54
2004	1819	36

Source: U.S. National Weather Service, as cited in Insurance Information Institute, *The I.I.I. Insurance Fact Book 2006,* New York: Insurance Information Institute, 2006.

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TABLE 1.1.26 Deadliest Tornado Incidents of All Time

Rank	*Location*	*Number of Tornadoes*	*Dates*	*Estimated Deaths*
1	Southeastern United States	60+	February 19, 1884	800+
2	Illinois, Indiana, and Missouri	8	March 18, 1925	606
3	South Carolina	1	September 10, 1811	500+
4	Alabama, Arkansas, Georgia, Mississippi, North Carolina, and Tennessee	3+	April 4–7, 1936	402
5	Mississippi	1	May 7, 1840	317
6	Alabama, Georgia, Kentucky, Ohio, and Tennessee	148	April 3–4, 1974	307
7	Missouri	1	May 27, 1896	306
8	Illinois, Indiana, Michigan, Ohio, and Wisconsin	37–40	April 11, 1965	272
9	Alabama	20	March 21, 1932	268
10	Arkansas, Missouri, and Tennessee	31	March 21–22, 1952	229

Sources: National Safety Council, *Injury Facts 2000,* Itasca, IL: National Safety Council, 2000; *World Almanac Book of Facts 2006,* New York: World Almanac Education Group, Inc., 2006; James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992; National Oceanic and Atmospheric Administration, Storm Prediction Center, "The 25 Deadliest U.S. Tornadoes," http://www.spc.noaa.gov/faq/tornado/killers.html.

Winter Storms. Available references do not cite a sufficient number of very costly individual winter storms, ice storms, hail, storms, or freezes to generate comparable lists. It also is not clear how much of the reported loss for such storms is relevant to such an assessments of impact on the built environment. For example, crop damage and snow removal costs would not be relevant to such an assessment. Damage due to snow loading is not separately tabulated in any published data, which would be the most relevant form of damage.

It can be noted that the highest U.S. property loss discovered for a winter storm was the 1993 blizzard dubbed the "Storm of the Century," with losses estimated at $3 to $6 billion, including $1.75 billion in insured loss. In the 1990s, however, at least three European winter storms, code named Daria, Lothar, and Vivian, each accounted for at least $4 billion in insured losses. The Storm of the Century also would rank second on a list of the 10 deadliest U.S. winter storms, accounting for an estimated 200 to 270 deaths, second only to an 1888 storm in the Northeast, in which 400 to 800 people were estimated to have died. A 1956 winter storm in Europe had the highest worldwide death toll identified at 1000 killed.

TABLE 1.1.27 Deaths Due to Drownings, Submersions, Storms, or Floods, Deaths Coded on U.S. Death Certificates

Year	*Cataclysmic Storms or Floods**	*Total Drownings and Submersions*	*Drownings in Bathtubs*	*Other or Unknown Type Drowning During Sport or Recreation*	*Drowning or Submersion Including Swimming or Diving Not for Sport or Recreation*
1993	96	3807	306	858	2643
1994	107	3404	301	694	2409
1995	74	3790	281	822	2687
1996	93	3488	330	645	2513
1997	136	3561	329	648	2584
1998	204	3964	337	685	2942
1999	144	3499	290	1467	1742
2000	54	3458	317	1439	1702
2001	89	3250	291	1309	1650
2002	72	3416	321	1134	1961

Note: Excluded from the table are water transport accidents, suicides, homicides, and incidents where it could not be determined whether injury was intentional or unintentional.
*Not included in total drownings and submersions.

Sources: National Safety Council, *Injury Facts and Accident Facts,* Itasca, IL: National Safety Council, 2004; 2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

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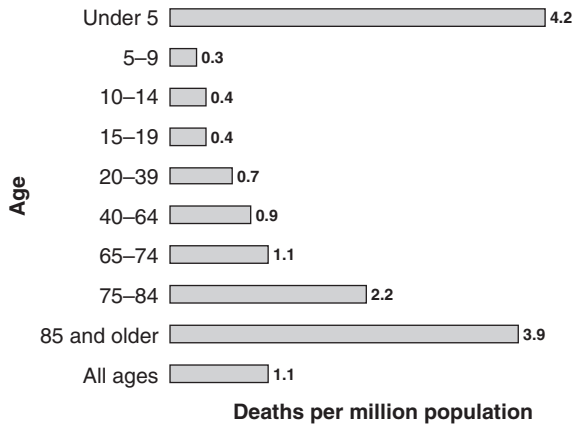

FIGURE 1.1.7 Deaths Due to Drowning in Bathtub, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

Estimating Property Loss from Natural Disasters

Table 1.1.28 represents an attempt to estimate property loss not limited to catastrophes for major sources of such loss. The table is limited to insured loss and to loss covered under homeowner policies. The table combines published data on shares of premium dollars that go toward compensation for losses with published data on the share of losses accounted for by each of several major hazard groups.

The fire and lightning losses in Table 1.1.28 should be comparable to NFPA statistics on property damage to in-home fires, and, in fact, the figures are reasonably close. This encourages optimism that the figures on wind and hail and on water damage and freezing are also comparable.

TABLE 1.1.28 Estimated Insured Property Damage Under Homeowners Multiple-Peril Policies

	Estimated Loss (in Billions of Dollars)		
Year	*Fire, Lightning, and Debris Removal*	*Wind and Hail*	*Water Damage and Freezing*
1994	5.2	2.0	4.7
1995	5.9	4.0	2.9
1996	5.4	5.0	3.6
1997	6.7	3.2	3.1
1998	6.5	6.3	3.3
1999	7.2	5.6	4.4
2000	9.1	4.5	4.9
2001	8.3	5.8	5.9
2002	8.4	5.3	5.6
2003	8.3	6.6	5.7
2004	6.2	13.4	4.6

Source: *The I.I.I. Insurance Fact Book 2003–2006,* New York: Insurance Information Institute, 2003–2006.

It has already been noted that fire losses in individual large loss fires do not dominate total property losses due to fire. In the majority of the years shown in Table 1.1.28, losses due to hurricanes—the large-loss windstorms—would dominate total property damage due to wind and hail. However, losses due to major flood events do not appear to dominate the total water damage and freezing values. In any event, most home insurance policies exclude damage due to major floods from coverage, which is why the Federal Emergency Management Agency's National Flood Insurance Program (NFIP) was created. The plumbing failures and ordinary rainstorms that probably account for most or all of the loss under water damage and freezing should constitute challenges that design for the built environment is meant to address.

Floods

Deadliest U.S. Floods. Table 1.1.29 lists the 10 deadliest U.S. floods of all time. The well-known Johnstown, Pennsylvania, flood of 1889 has by far the highest death toll on the list. The most recent flood to appear on the list was the 1972 Rapid City, South Dakota, flash flood. Like the classic Johnstown flood, a dam collapse was a critical event in the large loss. The other floods primarily involved rising waters swollen by rain and are more in keeping with the use of flood plain maps as a device for quantifying risk by location. Half of the floods on this list involved locations in the Mississippi River valley.

Deadliest Floods Worldwide. Table 1.1.30 lists the five deadliest floods of all time worldwide. All of them occurred in China. Two of the incidents, occurring three centuries apart, were initiated or worsened by deliberate acts in a wartime setting. One involved the destruction of river dikes by rebels, and the other involved flooding crops already ravaged by destruction by troops. In general, lists in this handbook of deadliest or costliest incidents exclude wartime incidents, which would account for many of the deadliest fires and avalanches* of all time, to name just two examples. The exception is made here only because there are so few incidents known to involve death tolls on the scale of incidents in Table 1.1.26 that the alternative to including these incidents would have been to shorten or exclude this list.

Costliest U.S. Floods. Table 1.1.31 lists the 10 costliest U.S. floods of all time. Even though all loss figures have been adjusted for inflation, half of the listed floods are from the last decade of the twentieth century. The costliest incident of all resulted in as much loss as the next two costliest floods combined. Four of the 10 floods involved the Mississippi River valley. The last three floods on the list were due in whole or in part to rivers swollen by melting snow, a scenario that did not contribute to any of the 10 deadliest floods.

Table 1.1.32 provides an overview of death tolls and losses from U.S. floods for the five most recent years available based on the storm data tracking done by the National Weather Service of the U.S. National Oceanic and Atmospheric Administration.

*An avalanche is a type of landslide distinguished by usually rapid movement of a newly detached segment of earth.[12] This definition is useful for *Fire Protection Handbook* Section 3, Chapter 1, "An Overview of the Fire Problem and Fire Protection."

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TABLE 1.1.29 Deadliest U.S. Floods of All Time

Rank	*Flood*	*Year*	*Estimated Deaths*
1	Johnstown, PA South Fork dam collapsed	1889	2209
2	Scioto, Mad, Miami, and Muskingum River Valleys, OH, IN, and IL Rain-swollen waters bridged levees	1913	732
3	San Fransicquito Canyon, CA St. Francis dam collapsed	1928	450
4	Ohio and Mississippi River Valleys Rain-swollen waters bridged levees	1937	380
5	Willow Creek, OR Flash flood due to fast, heavy storm	1903	325
6	Mississippi River Valley Rain-swollen waters bridged levees	1927	313
7	Rapid City, SD Flash flood due to heavy rain and dam collapse	1972	236
8	Mississippi River Valley Rain- and snow-melt-swollen waters flooded banks	1874	200–300
9	Mississippi River Valley Snow-melt-swollen waters bridged levees	1912	200–250
10	Kansas City, MO, and Lower Mississippi, Missouri, Kansas and Des Moines River Valleys Rain-swollen waters flooded banks	1903	200

Sources: National Safety Council, *Injury Facts 2000,* Itasca, IL: National Safety Council, 2000; *World Almanac Book of Facts 2006,* New York: World Almanac Education Group, Inc., 2006; James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992.

Flash floods always dominate river floods as causes of death and in most years also dominate as causes of property loss, but the damage caused by river floods in the exceptional years is more than enough to dominate multiyear statistics.

FATALITIES INVOLVING HAZARDOUS ENVIRONMENTS

The broader notion of a hazardous environment is that, as people move about within the built environment, they are exposed in some manner to hazards with the potential to cause harm. An atmosphere contaminated by deadly carbon monoxide is an obvious example. Most other examples of hazardous environments involve hazards that are less pervasive and more avoidable.

Carbon Monoxide and Other Poisonings by Gases and Vapors

Table 1.1.33 gives a 10-year overview of trends in poisonings by gases and vapors. The two major components are motor vehicle exhaust gas and other utility gas or carbon monoxide.

TABLE 1.1.30 World's Deadliest Floods of All Time

Rank	*Flood*	*Year*	*Estimated Deaths*
1	Huang He (Yellow) River, China	1931	3,700,000
2	Huang He (Yellow) River, China	1887	900,000
3	Kaifeng, China Dikes were destroyed by rebels	1642	300,000
4	Northern China Crops flooded and also destroyed by government, causing famine	1939	200,000
5	Chang Jiang (Yangtze) River	1911	100,000–200,000

Sources: National Safety Council, *Injury Facts 2000,* Itasca, IL: National Safety Council, 2000; *World Almanac Book of Facts 2006,* New York: World Almanac Education Group, Inc., 2006; James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992.

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TABLE 1.1.31 Costliest U.S. Floods of All Time

Rank	Flood	Year	Estimated Loss (in Billions of Dollars)	
			In Year of Occurrence	*In 2005*
1	Mississippi River Valley Rain-swollen waters bridged levees	1993	15.0–20.0	20.3–27.0
2	Connecticut River Valley Rain-swollen waters were due to Hurricanes Connie and Rita, but without storm surge or wind factors	1955	1.8	13.1
3	Kansas River Basin Rain-swollen waters bridged levees	1951	1.0+	7.5
4	Mississippi and Missouri River Valleys	1947	0.85	7.4
5	Texas, Oklahoma, Louisiana, and Mississippi Flooding with hail and tornadoes caused damage	1995	5.0–6.0	6.4–7.7
6	Willow Creek, OR Flash flood due to fast, heavy storm	1903	0.25–0.33	1.8–2.3
7	Mississippi River Valley Rain-swollen waters flooded banks	1937	0.30+	4.1
8	California Flooding was due to snow melt after blizzard	1996	3.0	3.1
9	Northeast to Mid-Atlantic United States Flooding was due to snow melt after blizzard	1996	3.0	3.1
10	Northwestern United States Snow melt and heavy rain led to flooding	1996–1997	2.0–3.0	2.43–3.65

Sources: National Safety Council, *Injury Facts 2000,* Itasca, IL: National Safety Council, 2000; *World Almanac Book of Facts 2006,* New York: World Almanac Education Group, Inc., 2006; James Cornell, *The Great International Disaster Book,* New York: Pocket Books, 1979; Lee Davis, *Natural Disasters,* New York: Facts on File, 1992.

Table 1.1.34 provides a five-year trend overview of the latter, for which half the deaths are attributed to carbon monoxide with no other details reported. The two largest components with details known are LP-gas from portable containers, for which deaths appear to be declining, and carbon monoxide from incomplete combustion of domestic fuels, for which no clear trend is apparent.

Tables 1.1.35 and 1.1.36 provide eight-year trends of deaths from carbon monoxide associated with unvented releases from heating and cooking equipment, respectively. Gas-fueled heating equipment dominates these figures, particularly in recent years. Deaths from carbon monoxide from charcoal grills include, and are probably dominated by, deaths from improper indoor use of these grills.

TABLE 1.1.32 Losses Due to Floods According to Storm Data Compiled by U.S. National Weather Service

Year	Deaths				Property Damage (in Billions of Dollars)				
	Total	*Flash Floods*	*River Floods*	*Small Stream or Urban Flood*	*Total*	*Flash Floods*	*River Floods*	*Small Stream or Urban Flood*	*Combined Crop Damage*
1996	131	94	31	6	3.5	1.1	1.0	0.0	0.4
1997	118	86	29	3	7.0	0.9	6.0	0.0	0.1
1998	136	118	14	4	2.6	0.9	1.4	0.0	0.3
1999	68	60	5	3	1.8	1.2	0.2	0.0	0.4
2000	38	30	3	5	1.5	0.8	0.5	0.0	0.2
2001	48	35	11	12	2.6	0.9	0.4	0.0	1.3
2002	49	38	7	4	1.3	0.3	0.3	0.0	0.7
2003	86	67	18	1	5.2	2.1	0.4	0.0	2.7
2004	82	58	24	0	3.7	0.9	0.8	0.0	2.0

Note: Sums may not equal totals because of rounding error.

Source: U.S. National Weather Service Summary of Natural Hazard Statistics for 2000–2004 in the United States.

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TABLE 1.1.33 Non-Fire Unintentional Injury Deaths Due to Poisoning by Gases and Vapors, Coded on U.S. Death Certificates

Year	*Total*	*Gas from Pipeline*	*Motor Vehicle Exhaust Gas*	*Other Utility Gas or Carbon Monoxide*	*Other*
1993	660	14	245	290	111
1994	685	24	246	307	108
1995	611	27	234	272	78
1996	638	23	219	283	113
1997	576	13	208	251	104
1998	546	15	190	254	87
1999	597 (63)*	—	—	—	—
2000	631 (38)*	—	—	—	—
2001	656 (63)*	—	—	—	—
2002	691 (51)*	—	—	—	—

*Only deaths due to organic solvents and hydrocarbons and their vapors are reported separately after 1998. Their totals are shown in parentheses.

Sources: National Safety Council, *Injury Facts* and *Accident Facts,* Itasca, IL: National Safety Council, 2005–2006; 2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm; John R. Hall, Jr., *Burns and Toxic Gases in Non-Fire Situations,* National Fire Protection Association, 2005.

TABLE 1.1.34 Non-Fire Unintentional Injury Deaths Due to Utility Gas or Carbon Monoxide, Excluding Motor Vehicle Exhaust Gas and Gas from Pipeline, Deaths Coded on U.S. Death Certificates

Year	*Total*	*LP-Gas from Mobile Container*	*Carbon Other and Unspecified Utility Gas*	*Monoxide from Incomplete Combustion of Domestic Fuels*	*Other Carbon Monoxide*	*Unknown Type Carbon Monoxide*
1994	307	59	11	59	25	153
1995	272	57	13	44	18	140
1996	283	57	18	52	10	146
1997	251	39	25	50	14	123
1998	254	37	11	60	18	128

Source: Statistics from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

TABLE 1.1.35 Unintentional Injury Non-Fire Deaths Due to Carbon Monoxide, by Type of Heating Device, 1993–2002

Year	*Central Heating Unit (Furnace) Natural-Gas-Fueled*	*Water Heater Gas-Fueled*	*Space Heater or Furnace LP-Gas-Fueled*	*Any Device Liquid-Fueled*[a]	*Any Device Solid-Fueled*[b]
1993	43	11	83	15	10
1994	64	7	93	12	8
1995	55	5	90	7	8
1996	35	8	99	21	10
1997	61	8	55	12	6
1998	63	8	54	5	5
1999	21	1	25	2	0
2000	41	3	32	6	2
2001	32	0	29	6	6
2002	22	1	50	4	5

Notes: Statistics shown here include proportional allocation of deaths and injuries involving gas-fueled heating equipment with unknown type of equipment for 1993–1997. These allocations do not appear in the source reports.

[a]Principally oil-fueled furnaces and portable kerosene heaters.

[b]Includes coal-fueled furnaces, wood stoves, and fireplaces.

Sources: John R. Hall, Jr., *Burns and Toxic Gases in Non-Fire Situations,* National Fire Protection Association, 2005; 2002 data taken from Debra S. Ascone and Natalie Marcy, *Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products, 2002 Annual Estimates,* July 2005, Table 1. Statistics no longer reported separately for liquid-fueled or solid-fueled heating devices.

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TABLE 1.1.36 Unintentional Injury Non-Fire Deaths Due to Carbon Monoxide, by Type of Cooking Device, 1993–2002

Year	*Range, Stove, or Oven Gas-Fueled*	*Grill Charcoal*
1993	6	27
1994	9	15
1995	5	14
1996	15	19
1997	5	23
1998	3	16
1999	6	17
2000	11	8
2001	10	12
2002	3	10

Sources: John R. Hall, Jr., *Burns and Toxic Gases in Non-Fire Situations,* National Fire Protection Association, 2005; 2002 data taken from Debra S. Ascone and Natalie Marcy, *Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products, 2002 Annual Estimates,* July 2005, Table 1.

Carbon Monoxide Detectors. In 2002, 29 percent of households had at least one carbon monoxide detector. As had happened at this point per home smoke alarms, usage is higher for affluent households (34% of households with annual incomes of at least $50,000). Unlike smoke alarms, carbon monoxide detectors have been adopted in single-family dwellings (35%) far more than in apartments (17%), modular or manufactured homes (16%), and duplexes and townhouses (21%). Interestingly, carbon monoxide detectors are far more common in houses that use some type of fuel for central heating (38% for gas, 29% for fuel oil) than in homes that use electric power for central heating (13%). It appears that homes with significant potential sources of unvented carbon monoxide are understandably more motivated to obtain carbon monoxide detectors.[16]

For context, Table 1.1.37 provides statistics on suicide deaths due to gas or vapor and on related deaths when it was not determined whether the death was intentional or not. Suicides are far more numerous than unintentional injury deaths by the same mechanism of gas or vapor. Note that all these death tolls have been declining significantly with the possible exception of suicide by gas or vapor other than motor vehicle exhaust.

Poisonings

Table 1.1.38 provides a 10-year overview of other hazardous environment deaths involving specific objects. The first three columns are for poisonings by various solids or liquids. Cleaners and paints are shown separately because that category includes substances that might be encountered in components of the built environment. Fumes from cleaners and flaked-off lead paint are examples. Corrosives and caustics are shown separately because they also have the potential, although probably less than with cleaners and paints, to be encountered after application of substances to components of the built environment.

More often, these substances cause fatal poisonings because they are accessed in stored form and then ingested. The

TABLE 1.1.37 Deaths Due to Poisoning by Gases and Vapors, 1993–2002

Year	*Unintentional Injury**	*Intentional Injury (Homicide or Suicide)**	*Undetermined Whether Unintentional or Deliberate**
1993	660	2092	107
1994	685	2044	84
1995	611	2095	107
1996	638	2007	118
1997	576	1918	77
1998	546	1726	82
1999	597 (63)	1618 (64)	89 (9)
2000	631 (38)	1521 (65)	87 (12)
2001	656 (63)	1519 (61)	89 (10)
2002	691 (51)	1485 (51)	85 (14)

Notes: Prior to 1999, suicides were distinguished by motor vehicle exhaust versus other gas. In the early 1980s, motor vehicle exhaust suicides outnumbered suicides by other gases by nearly 5 to 1. In the late 1990s, the ratio had declined to only 3 to 1.

*Beginning in 1999, only organic solvents and halogenated hydrocarbons and their vapors are distinguishable, and their totals are shown in parentheses.

Sources: John R. Hall, Jr., *Burns and Toxic Gases in Non-Fire Situations,* National Fire Protection Association, 2005; National Safety Council, *Injury Facts and Accident Facts,* Itasca, IL: National Safety Council, 2005–2006; 2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

separately listed cleaners, paints, corrosives, and caustics are a very small part of the overall category of poisonings by solids and liquids, as the third column demonstrates. Most of this category consists of alcohol products.

Machinery and Instruments

The fourth column of Table 1.1.38 tabulates deaths occurring when someone is caught in or between two objects. The fifth tabulates deaths involving machinery, more than half of which involve agricultural machinery, pointing to the high risks involved in farming. The sixth column tabulates deaths caused by cutting or piercing instruments and objects.

Almost none of the deaths shown in Table 1.1.38 can be said to arise from hazards of the built environment. However, there may be significant indirect effects. Specifically, the design of the built environment may make access to hazardous products, by small children or other people with reduced capacity to make sound risk judgments, more or less difficult. The design, through ergonomics or a lack thereof, may make interaction with machinery or other large objects more or less likely to cause injury. More likely, Table 1.1.38 is relevant in setting priorities and tracking progress for more general safety programs as opposed to choices involving the built environment.

Suffocation

The same is true of Table 1.1.39, which provides a 10-year overview of deaths due to suffocation or inhaling foreign objects.

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TABLE 1.1.38 Other Hazardous Environment Deaths, Deaths Coded on U.S. Death Certificates

Year	*Poisoning by Cleaner or Paint*	*Poisoning by Corrosive or Caustic*	*Other and Unknown-Type Poisoning by Solids or Liquids*[a]	*Caught in or Between Objects*	*Caused by Machinery*[b]	*Caused by Cutting or Piercing Instrument or Object*
1993	21	13	461	91	999	108
1994	13	14	454	83	970	103
1995	10	10	441	90	986	118
1996	10	9	422	71	926	97
1997	14	8	466	85	1055	104
1998	10	5	402	118	1018	121
1999[c]	—	—	—	74	622	93
2000	—	—	—	85	676	84
2001	—	—	—	85	648	116
2002	—	—	—	109	652	115

Note: The ICD is revised periodically, and these revisions can affect the classifications of death certificate code categories. The tenth revision completely revised the categories effective with 1999 data.
[a]Includes alcohol or petroleum products, agricultural products, chemical or pharmaceutical products, and foods or plants. Alcohol products dominate.
[b]Majority of deaths caused by machinery are specifically caused by agricultural machinery.
[c]Categories with dashes were discontinued after 1998.
Source: National Safety Council, *Injury Facts,* Itasca, IL: National Safety Council, 2002–2006; 1999–2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

Only mechanical suffocation has identified components that could relate to the built environment, and they are shown in detail in the 4-year overview of Table 1.1.40.

Suffocation in a bed or cradle accounts for hundreds of deaths annually, and a bed is a sufficiently large piece of furniture that it can be treated as part of the specification of a built environment, even though codes for the built environment rarely set requirements for contents and furnishings, particularly in private homes, which is where most of the suffocation deaths in beds and cradles probably occur. Nevertheless, Figure 1.1.8 provides an overview of differences in risk of such suffocation by age of victim. Crib deaths of very young children clearly dominate.

Excessive Temperatures

Deaths due to excessive heat and cold vary considerably from year to year. Death certificate data from 1993 to 2002 in Table 1.1.41 show that, in most years, cold is the dominant killer. Storm data for 2000 to 2004, collected by the National Weather Service, shows just the opposite, with excessive heat the leading killer in four of the five years, usually by a wide margin. When

TABLE 1.1.39 Deaths Due to Suffocation or Foreign Objects, Deaths Coded on U.S. Death Certificates

Year	*Total Suffocation or Foreign Object*	*Suffocation or Respiratory Tract Obstruction Due to Food*	*Suffocation or Respiratory Tract Obstruction Due to Object Other Than Food*	*Mechanical and Other Types of Suffocation*	*Foreign Body Entering Other Bodily Orifice*
1994	4161	1110	1955	1078	18
1995	4274	1088	2097	1062	27
1996	4338	1126	2080	1114	18
1997	4437	1095	2180	1145	17
1998	4608	1147	2368	1070	23
1999	4572	640	2828	1085	19
2000	4896	744	3187	934	31
2001	4813	742	3021	1021	29
2002	4863	819	2940	1085	19

Source: CDC/NCHS website, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm.

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TABLE 1.1.40 Deaths Due to Mechanical Suffocation, Deaths Coded on U.S. Death Certificates

Year	*Mechanical and Other Types of Suffocation*	*Accidental Suffocation and Strangulation in Bed*	*Confined or Trapped in a Low-Oxygen Environment*	*Due to Cave-In, Falling Earth, and Other Substances*	*Other Specified Threats to Breathing*	*Unknown Threats to Breathing*
1994	1078	227	9	58	375	359
1995	1062	207	14	59	406	339
1996	1114	219	15	57	436	347
1997	1145	236	21	54	451	339
1998	1070	247	13	55	400	328
1999	1552	509	19	57	203	764
2000	1002	327	15	64	195	401
2001	1091	456	20	56	210	349
2002	1092	509	19	57	203	304

Sources: National Safety Council, *Injury Facts* and *Accident Facts,* Itasca, IL: National Safety Council, 1992–2000; 1999–2002 data from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

detailed circumstances are known and reported, most of the death certificate excessive temperature deaths are specifically attributed to weather as the cause of the extreme temperatures.

Excessive heat or cold, as a cause of death that can be essentially eliminated by a properly designed and operated building, provides the connection to the built environment, although mostly indirectly. Homelessness creates exposure to these potentially lethal conditions, as does the absence of effective and affordable climate control, principally heat for the winter. These problems are not really problems in the design of the building—although the cost of heating and the extent of natural cooling can vary considerably as a function of design—but are always problems arising from our efforts to live in environments of our own making.

Figure 1.1.9 provides a breakdown of deaths due to hunger, thirst, exposure, or neglect. Nearly half involve exposure to harsh weather, so they belong with the deaths shown on Table 1.1.41 as due to excessive heat or excessive cold.

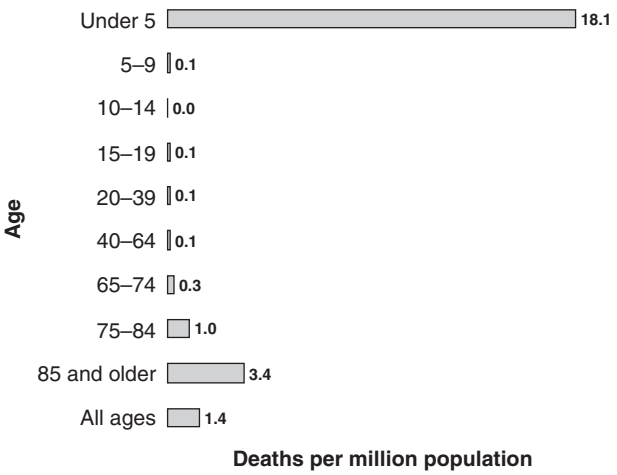

FIGURE 1.1.8 Deaths Due to Suffocation in Bed or Cradle, by Age, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

SUMMARY

If we are guided by the relative magnitude of real harm done to real people—either direct harm to people or damage to their property—then the statistics presented here would appear to give us five priority areas for future attention, aimed at improved safety:

- Fire, burns, or shock because of harm to both people and property
- Falls because of harm to people

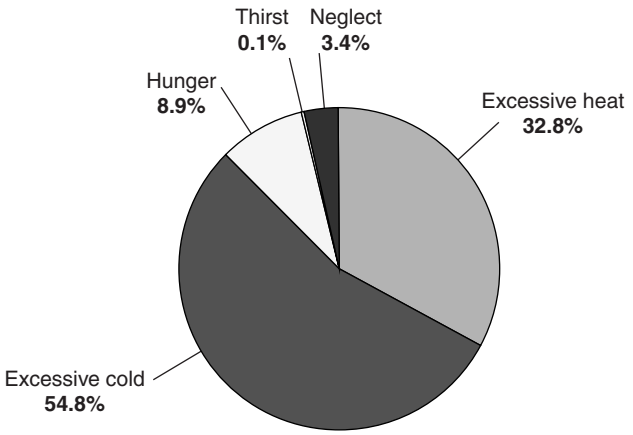

FIGURE 1.1.9 Deaths Due to Hunger, Thirst, Excessive Heat or Cold, or Neglect, by Cause, 1999–2002 (Source: CDC/NCHS, National Vital Statistics System, Mortality, http://www.cdc.gov/nchs/datawh/statab/unpubd/mortabs/gmwki10.htm)

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TABLE 1.1.41 Deaths Due to Natural or Environmental Factors, Excluding Lightning, Storms, Floods, Earth Movement, or Eruption, Deaths Coded on U.S. Death Certificates

Year	*Excessive Heat*	*Excessive Cold*	*Hunger, Thirst, Exposure, or Neglect*	*Animal or Plant*	*Other Natural Environmental Factor**
1993	299	641	243	176	13
1994	221	633	221	152	10
1995	716	553	203	159	15
1996	249	685	224	175	19
1997	182	501	224	170	25
1998	375	420	252	157	26
1999	594	598	170	223	22
2000	301	742	172	223	12
2001	300	599	128	176	13
2002	350	646	117	194	13

*Specifically, these were due to high, low, or changing air pressure; travel; or motion.

Source: National Safety Council, *Injury Facts and Accident Facts,* Itasca, IL: National Safety Council, 1992–2002; 2002 statistics from the CDC/NCHS website, http://www.cdc.gov/ncipc/osp/data.htm.

- Natural disasters because of harm to both people and property
- Water or storms because of harm to property more than people
- Harmful environment because of harm to people

Except for natural disasters, these priority areas primarily center around harm occurring in homes—dwellings, duplexes, manufactured homes, and apartments—which are traditionally the places where strict control by codes stops. Even if you allow for the fact that more time is spent at home than anywhere else, the risks from falls, fires, and water are higher at home than elsewhere. In terms of the first triage question—is this a big enough problem to worry about?—the answer for these four is yes. The next question asked how much of a difference can be made through changes in your built environments. To answer that question, it helps to distinguish among the five types in terms of the relative safety focus each has received in recent decades.

Fire has been the primary focus of NFPA for more than a century. Natural disasters are the focus of emergency managers at all levels of government and have been a focus of much of the insurance industry for some time. Water damage due to plumbing problems has been a focus of plumbing codes for some time.

Falls are the odd group in that they so clearly dominate any characterization of deaths in the built environment but have never been the primary focus of any major national organization or governmental agency.

Fatal falls can be made less likely through three distinct elements of design in the built environment. First, a variety of design decisions can make footing either more or less precarious. The dimensions of steps and stairs have long been controlled through codes, but there are other design elements, such as flooring angles, that may not have received much attention. Illumination levels at walking surfaces can also influence the safe use of the stairs. Also, the "slipperiness" or slip resistance of various surfaces, ranging from the aptly named "throw rug" or highly polished wood floor at one extreme to thick carpet or grooved concrete at the other extreme, has a bearing on the probability that a fall will occur.

Second, there is the effect of the surface's ability to absorb the impact of a fall without causing harm, or at least not fatal harm. Different flooring products certainly vary in this regard, but there is also a potential influence from lower walls, hard corners, protruding sharp or hard edges, and so forth.

Finally, there is the presence or absence, effectiveness or ineffectiveness, of physical aids to stabilization, such as handrails. These are all the design elements that compensate for the dangers created by walking surfaces or that permit an incipient fall to be interrupted or minimized on impact.

With so many opportunities to intervene via design in the number one cause of unintentional injury and deaths in the built environment, it is remarkable that falls have not emerged previously as a point of focus. The broad interception of the goals of NFPA *101®*, *Life Safety Code®*, has provided a limited basis for focus on falls by some of the technical committee volunteers working with NFPA. More recently, the U.S. Centers for Disease Control and Prevention has identified falls by older adults as a priority focus for its work, and NFPA's Center for High Risk Outreach has given preventative education regarding falls in the *Remembering When* program. Falls among children age 14 and under are one of the risk areas addressed in NFPA's school-based injury prevention program, *Risk Watch®*. Notwithstanding these serious and worthwhile programs, there is still a niche to be filled in focusing on code provisions to shape design of the built environment to reduce fatal falls.

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on safety challenges in the built environment discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following document.)*

NFPA 730, *Guide for Premises Security*

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SECTION 1

Chapter 2

Fundamentals of Structurally Safe Building Design

Revised by
Bonnie E. Manley

Chapter Contents

Challenges to the Built Environment
Design Loads and Forces
Basic Building Systems and Components
Fundamental Design Concepts
Basic Design Methodology

Key Terms

building code, building envelope, built environment, dead load, design load, earthquake force, horizontal load, live load, load and resistance factor design, load-path concept, occupancy type, overstress, performance level, performance-based design, snow and ice load, stress design, structural integrity, structural system, vertical load, wind force

Engineers sometimes joke that structural design is "the art of molding materials we do not wholly understand, into shapes we cannot precisely analyze, to withstand forces we cannot really assess, in such a way that the community at large has no reason to suspect the extent of our ignorance." Although overstated, this saying contains truth. The structure design and construction process contains many inherent uncertainties.

Despite these uncertainties, it is possible to provide relatively uniform levels of safety and reliability by starting with a design that meets the basic requirements of the adopted building code and then ensuring that, as it is built, the structure conforms to the approved design documents—the plans and specifications. For help, owners, architects, engineers, building officials, and contractors turn to the building code, not only to help define their roles, but also to provide the minimum standards for design and construction quality.

From a structural standpoint, today's model building codes scope the general building requirements for given occupancies, including such items as height and area limitations, construction types, basic building configurations, and construction techniques. Additionally, the building codes adopt, by reference, design load standards that define the minimum permissible strengths to resist floor loads and other unique environmental forces due to wind, snow, water, and earthquakes. Material design standards, which also tend to be adopted by reference in the building codes, define material strengths, properties, and specific design methods that can be used by engineers with reasonable safety. Some minimum standards for construction quality are also specified in the building codes. For the purposes of this chapter, the many codes and standards that affect the structural design and construction of buildings are collectively referred to as "building codes." This collection of codes and myriad referenced standards work to provide a safe, functional, and appealing structure at the end of the design and construction process.

Operating within this environment of codes and standards, the structural engineer must optimize the design in such a manner that the building provides acceptable levels of safety and serviceability while being economical to construct. One approach to "optimum" building design says that if a structure is loaded to the slightest fraction beyond its strength limit, all elements should simultaneously fail and the entire structure collapse. This approach is seldom used. Instead, most structures are designed such that if they are overloaded, they are able to deform and give some warning to occupants prior to failure, so that evacuation and perhaps shoring can occur.

See also Section 1, Chapter 1, "Challenges to Safety in the Built Environment"; Section 1, Chapter 3, "Codes and Standards for the Built Environment"; and Section 1, Chapter 4, "Legal Issues for the Designer and Enforcer."

CHALLENGES TO THE BUILT ENVIRONMENT

The total complex of houses, factories, offices, schools, and so on in which we live and work is referred to as the "built environment." Each year, lives and property are lost due to building

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failures. Mostly, hurricanes or other high winds, earthquakes, floods, and other dramatic events precipitate these building failures. Much less often, failures are precipitated by minor events or even ordinary loads and conditions due to inadequate design and construction, lack of proper code enforcement, simple neglect, or decay. Although building codes are intended to protect lives, clearly there are instances where they have not done so. Problems occur for both existing buildings and new construction.

Existing Buildings

Modern construction materials are very different from those used in the past. In some respects they are better, and in others, worse. However, the methods and details that are used to combine these materials into finished buildings have improved significantly with time. Building codes and construction methods change with time, incorporating new materials and methods of construction and "lessons learned" from various failures induced by disasters such as fires, earthquakes, and hurricanes. Because of continual improvements in building codes, most buildings designed and constructed today are considered safer and more reliable than buildings that were designed using older building codes. Building loss investigations, the ability to do more analysis, and widespread use of various hazard simulation models—all benefit the design and construction process.

In most communities, new building construction in any year represents less than 2 percent of the total number of buildings.* There are two exceptions to this general rule. The first is a new, fast growth/development community. The second involves massive rebuilding efforts following a natural disaster or postwar period. Consider the status of many communities in Louisiana, Mississippi, and Alabama that had a high percentage of their commercial and residential structures destroyed beyond repair as a result of Hurricane Katrina in August 2005. Jurisdictions that had little or no significant construction since the 1970s are now undergoing a tremendous rebuilding effort.

However, given the general 2 percent rate of new buildings, at any one time at least 50 percent of the building population is likely to be more than 30 years in age. For many communities, this percentage is actually much greater. Because of continual improvements in building codes and building technology, older buildings designed to the standards and codes of 30 or more years ago are by some measures considered unsafe in comparison to current standards. Therefore, it is likely that every community contains a significant number of buildings that could be unsafe if exposed to major events that newly constructed buildings could better survive.

Existing buildings are typically replaced only when either a better financial use is found for the property or because the physical condition of the building becomes so poor as to preclude further use. Once a building is constructed, and an occupancy permit issued, building codes contain few restrictions on the building's continued use. In general, the following apply:

- The owner is required to meet certain zoning restrictions in terms of types of use or contents.
- Major additions, alterations, or changes in use may trigger improvements to meet newer building codes. However, these requirements may be circumvented by physical separation of the new and existing construction or by other negotiated means.
- If the local building official becomes aware of an obviously unsafe condition, the official has the power to condemn a building. However, such actions are quite rare and typically occur only after a damaging event or failure.
- Some codes, like NFPA *101*®, *Life Safety Code*®, and some regulations, like the Americans with Disabilities Act, impose requirements on existing buildings, and some of these provide for enforcement of retroactive requirements, regardless of whether any other work efforts are undertaken.

As a result, many existing buildings contain latent risks due to deterioration, owner-initiated changes that were not done in accordance with the permitting process, deferred maintenance, or basic details of construction that would not be found in newer construction.

New Buildings

Every building is unique in some ways and without prototype. To be safe and serviceable, it is vital that the construction be in accordance with the approved design documents. This requires that all parties involved in the construction process—code developers, owners, architects, the insurance community, engineers, code officials, and contractors—each exercise the skill and responsibility necessary to make certain that their part of the project is done in conformance with the intended requirements, while still meeting the limitations of project schedules and budgets.

A common challenge to this process is communication—for contractors and building officials to be able to correctly interpret the architect's and engineer's intent from their drawings and specifications, and for the architects and engineers to be able to interpret the intent of code developers from the building codes.

Another challenge of new construction is for engineers and code developers to predict the types and magnitudes of forces and events that a building may experience during its existence, and to define design loading conditions within building codes that are sufficient to withstand those conditions, without undue financial penalties. Ongoing debate—since 2001—involves the need to carefully analyze the design assumptions as they may relate to certain extreme events, most notably terrorism and hostile acts. The cadre of codes and standards simply cannot strive for "more" safety or "ultimate" safety, but rather they need to provide an "appropriate" level of safety.

DESIGN LOADS AND FORCES

Basic Types of Loads and Forces

Building codes define the following basic types of loads and forces as a basis for structural design. These loads and forces include the following:

*The conservative estimate of 2 percent is based on assessor's data for the county of Orange, California, an area of high growth. The annual development in Orange County between 1972 and 1994 added an average of 3 percent annually to the cumulative number of developed parcels.

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- Dead load
- Live load
- Snow and ice loads
- Wind forces
- Earthquake forces

Dead Load. Dead load is the weight of the building itself. It includes the weight of all permanent fixed items, such as floor framing, walls, ceilings, roofing, and major fixed service equipment, but excludes loads from variable items, such as furnishings, people, traffic, and equipment, that change constantly throughout the building's life. Dead load is the easiest to predict and can be known with the most certainty, although there can still be some variation between dead load estimated by the engineer and the actual as-constructed weight.

Live Load. Live load is the weight of items such as furnishings, people, traffic, and equipment related to the use or occupancy of the building. This weight is generally known with little certainty, as it can vary over time. Building codes include tables of minimum required design live loads for various occupancy types, which are sometimes posted on signs within buildings. These design live loads represent reasonable maximum bounds on the amount of weight from these variable items that may be placed on a floor or roof during its life. It is extremely unlikely, except in certain types of occupancies such as warehouses, that all areas of floors and roofs would simultaneously be loaded to the design levels at the same time. Hence, building codes include "live load reduction factors" that account for the low likelihood of simultaneous heavy loading of large portions of the building and allow the design load to be reduced for building elements that support larger areas. Thus, an individual floor beam might be designed to support a larger floor load (on a pounds per square foot basis) than a column that supports many beams.

Snow and Ice Loads. Snow and ice loads are the design weights required by building codes to be considered for accumulation of snow and ice. Building codes define snow load in terms of "ground snow loads" that represent a weight of snow having a 2 percent annual probability of being exceeded (50 year mean recurrence)[1]—that is, such heavy loads are anticipated to occur only every 50 years or so. The building codes include maps that specify minimum design snow loads for various regions of the country. However, snow depths can be highly variable, particularly within mountainous regions, where local building officials often specify "standard" ground snow loads within their jurisdictions that are different from those indicated in the maps.

The ground snow load, contained on building code maps and enforced by building officials, is not the same load that is actually used to design buildings. Design snow loads are calculated based on the ground snow load, but require modifications to account for the effects of roof slope, thermal conditions (heated versus unheated), wind conditions that can cause snow to drift across roofs, and building shape or geometry conditions, which may cause drifts or snowfalls from adjacent higher roofs to accumulate. Design load standards are used to translate the basic ground snow loads into specific design weights that vary over the roof surface.

Wind Forces. Design wind forces are determined using horizontal wind pressures associated with a design wind velocity that is specified for a location. Just as with snow loads, building codes include maps of design wind velocity values for most areas (Figures 1.2.1 through 1.2.4). However, these maps exclude some "special wind regions" in which local terrain conditions produce occasional high wind conditions. In those areas, the building official is required to specify the design wind velocity.

Prior to 1998, the commonly accepted definition of design wind velocity was based on the "fastest-mile" wind speed, which was the wind speed based on the time required for a mile-long sample of air to pass a fixed point. Around 1998, U.S. building codes redefined the design wind velocity as the mean wind speed averaged over 3 seconds, measured at 33 feet above grade, over relatively open terrain.[2] The resulting wind velocity maps are generally based on a 50-year wind speed.[2] However, in hurricane-prone regions, wind velocity maps have been modified to include an adjusted value based on both hurricane simulation techniques and 500-year wind speed records. This "3 second gust" method is an improvement over the earlier method in that the fastest mile did not account as well for the effect of short duration gusts. Also, the older codes did not include the more severe winds anticipated in hurricane-prone regions.

The mapped wind velocity is not directly used to design buildings. Instead, the mapped wind values are modified depending on terrain conditions, elevation, and topographic effects such as hills or ridges that can cause local high-velocity conditions to occur. The design forces are calculated from these site-modified wind velocities, considering the building's shape, its flexibility, the quantity of openings that can allow fluctuating wind pressures to enter the building, and the total building area that may be subjected to locally varying wind gust pressures. Design load standards provide guidance to engineers on how to determine the appropriate pressures to design building components for relatively regular and normal looking buildings. Buildings that are very tall, flexible, or unusual in shape sometimes require special wind-tunnel testing using scale models in order to determine appropriate design wind pressures. In fact, more extensive use of, and reference to, wind tunnel testing techniques are the subject of one of the 30 recommendations of the NIST study of the World Trade Center disaster.[3]

Earthquake Forces. Earthquakes do not directly exert forces on buildings. Rather, they produce ground accelerations and deformations that vary with time. The response of the building to these ground movements results in stresses and deformations throughout the building. The severity of these effects depends on the event magnitude, its distance from the structure, local soil conditions, and the weight and stiffness characteristics of the building structure itself. Building codes provide procedures that allow engineers to determine the design forces. These are calculated as pseudo-inertial forces equal to the building mass times specified design accelerations. These design accelerations are determined from mapped values of design ground accelerations found in building codes, modified to account for the building's structural characteristics (Figure 1.2.5).

As with wind loads, the definition of the design ground acceleration used in building codes has evolved. Until 1991, building codes included maps that presented design ground motions

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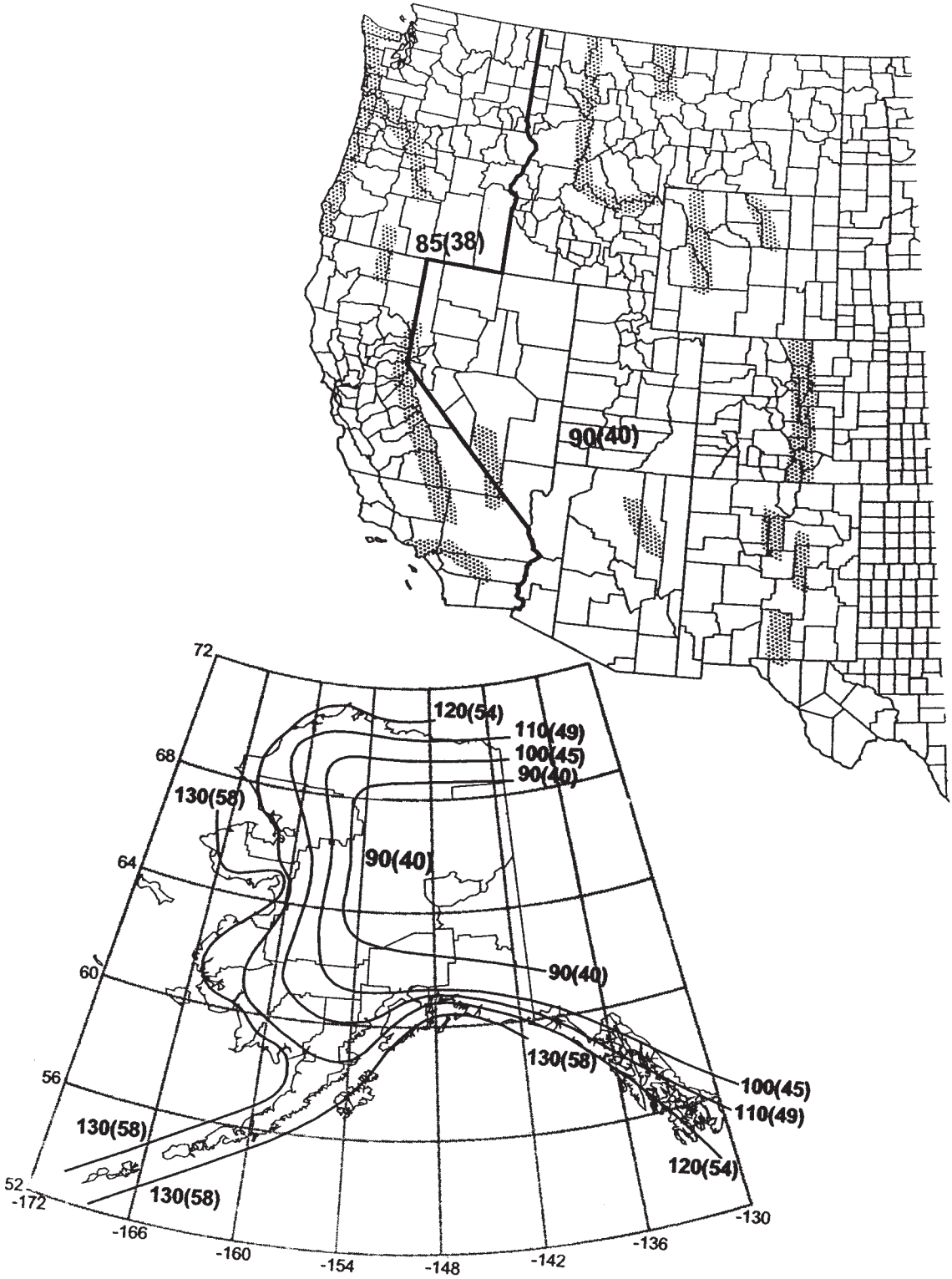

FIGURE 1.2.1 Basic Wind Speed (Source: Reprinted with permission from ASCE/SEI 7)

in the form of seismic zones. The seismic zones covered broad geographic regions, often encompassing several states. Within each seismic zone, the building codes specified earthquake acceleration values that approximately represented the most severe shaking likely to occur in any 500 year period—in statistical terms, having a 10 percent chance of being exceeded in 50 years. The use of broad geographic seismic "zones" resulted in these accelerations being very approximate.

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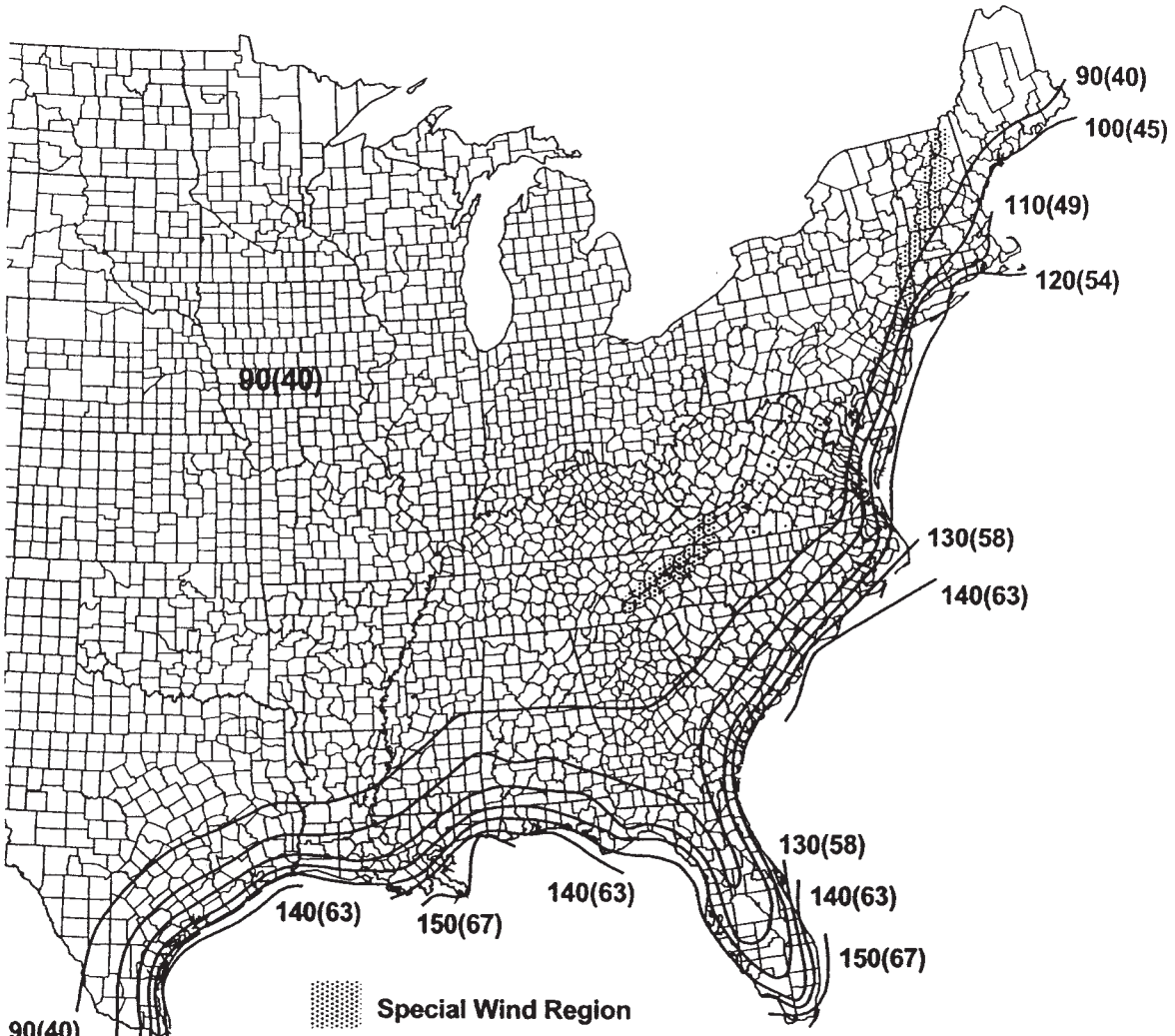

Location	V mph	(m/sec)
Hawaii	105	(47)
Puerto Rico	145	(65)
Guam	170	(76)
Virgin Islands	145	(65)
American Samoa	125	(56)

Notes:

1. Values are nominal design 3-second gust wind speeds in miles per hour (m/sec) at 33 ft (10 m) above ground for Exposure C category.
2. Linear interpolation between wind contours is permitted.
3. Islands and coastal areas outside the last contour shall use the last wind speed contour of the coastal area.
4. Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

FIGURE 1.2.1 Continued

Starting in 1991, codes began to abandon seismic zones and present design ground motions on maps in the form of ground motion "contours" that more precisely presented the likely levels of ground motion at any given site. Using these maps, each site location has a unique value of design ground acceleration depending on its location relative to known faults and seismic source zones. The newer mapped earthquake acceleration contours also represent a more unlikely event, corresponding to

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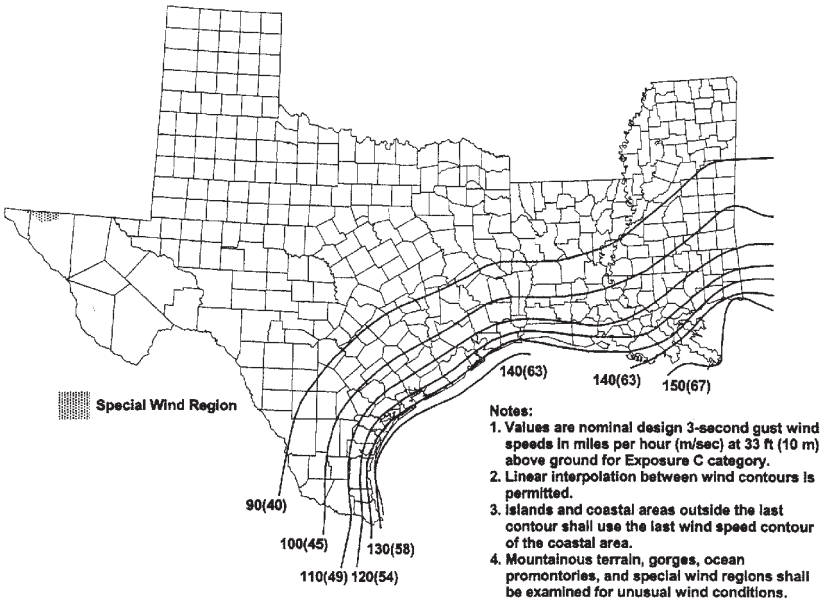

FIGURE 1.2.2 Basic Wind Speed: Western Gulf of Mexico Hurricane Coastline (Source: Reprinted with permission from ASCE/SEI 7)

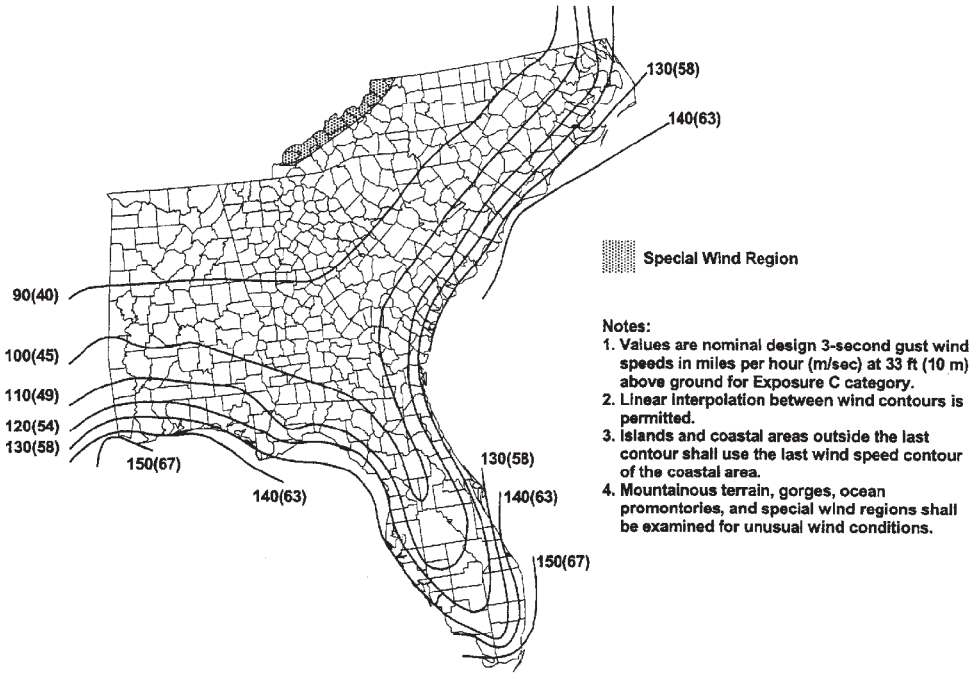

FIGURE 1.2.3 Basic Wind Speed: Eastern Gulf of Mexico Southeastern U.S. Hurricane Coastline (Source: Reprinted with permission from ASCE/SEI 7)

a 2500 year event, or one having a 2 percent chance of being exceeded in 50 years. This rather rare event is more appropriate for sites in the eastern United States, for example, where large earthquakes occur infrequently, and does not significantly increase the hazard in the western United States, where destructive ground shaking occurs more often. The intent of the newer building code regulations is to prevent structural collapse for these 2500 year events. However, actual design is based on providing a less severe level of damage for design ground accelerations taken as two-thirds of the mapped values.

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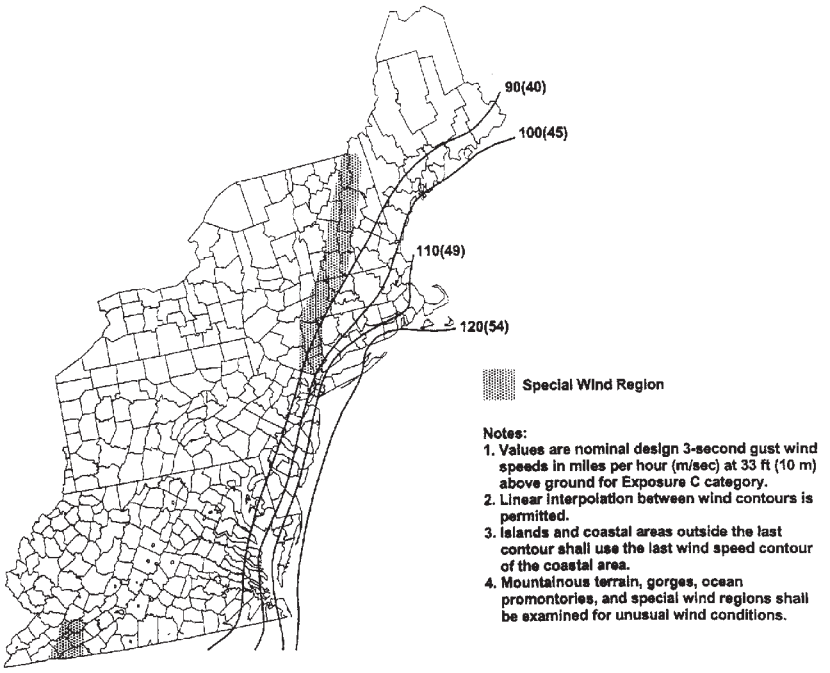

FIGURE 1.2.4 Basic Wind Speed: Mid- and Northern Atlantic Hurricane Coastline (Source: Reprinted with permission from ASCE/SEI 7)

In regions with moderate or strong earthquake potential, design ground acceleration values are so large that engineers cannot economically design ordinary buildings to resist the full acceleration values without also permitting some degree of damage. In fact, most buildings are designed to crack and yield when affected by design level shaking, ultimately holding together and not collapsing. The intent of the earthquake code provisions for ordinary buildings is to perform for and protect "life safety," but not protect property investments. In order to accomplish this, design forces are calculated using special reduction factors *R* that reduce the predicted ground accelerations into artificial design values. These *R* values are specified in the building codes, based on the type of structural system used and the historical performance of various systems.

In addition to specification of minimum design forces, building code provisions for earthquake resistance also include prescriptive detailing requirements intended to provide sufficient toughness to hold buildings together as they deform. The prescriptive provisions regulate the types of connections and reinforcements that are used in different types of construction and also the configuration (geometric shape) of the building and its elements. In addition, in locations where stronger accelerations may occur, some types of construction, such as unreinforced masonry, are not permitted.

Other Loads. Building codes and design load standards also include provisions for other common types of loading, including flood loads, soil loads, hydrostatic pressure, impact, and forces caused by thermal expansion and contraction or impact. However, building codes have either very limited provisions or no provisions at all for some very unusual types of loads such as those induced by tornadoes, blasts, or explosions. Industry-specific design standards, such as those developed by the military, the U.S. General Services Administration, the Department of State, or the Department of Energy, are typically used for the design methods of structures that must resist such load conditions.

Combining Design Loads. Once the individual design forces have been determined, they must be combined to consider the effects of simultaneous application; for example, the occurrence of high wind loads and occupancy-related loads such as furnishings and equipment. When combining loads of different types, the probability that loads occur concurrently is considered and loads that occur infrequently are typically not combined together. For instance, a full design snow load would not be combined with a full design wind or earthquake event, although some portion of the design snow might be considered. Building codes include equations for required combinations of loading that must be considered in building design. Some special types of structures also use load combinations defined in industry-specific standards. As an example, tanks are designed for earthquake inertial forces in conjunction with forces caused by earthquake-induced sloshing of tank contents.

Actual Versus Design Loads

Building codes deal with the uncertainties associated with predicting design loads through the use of probability and statistics. For example, building codes define a 50 year wind, or a 2500 year earthquake event. However, the resulting design maps correspond only to a statistical representation of the

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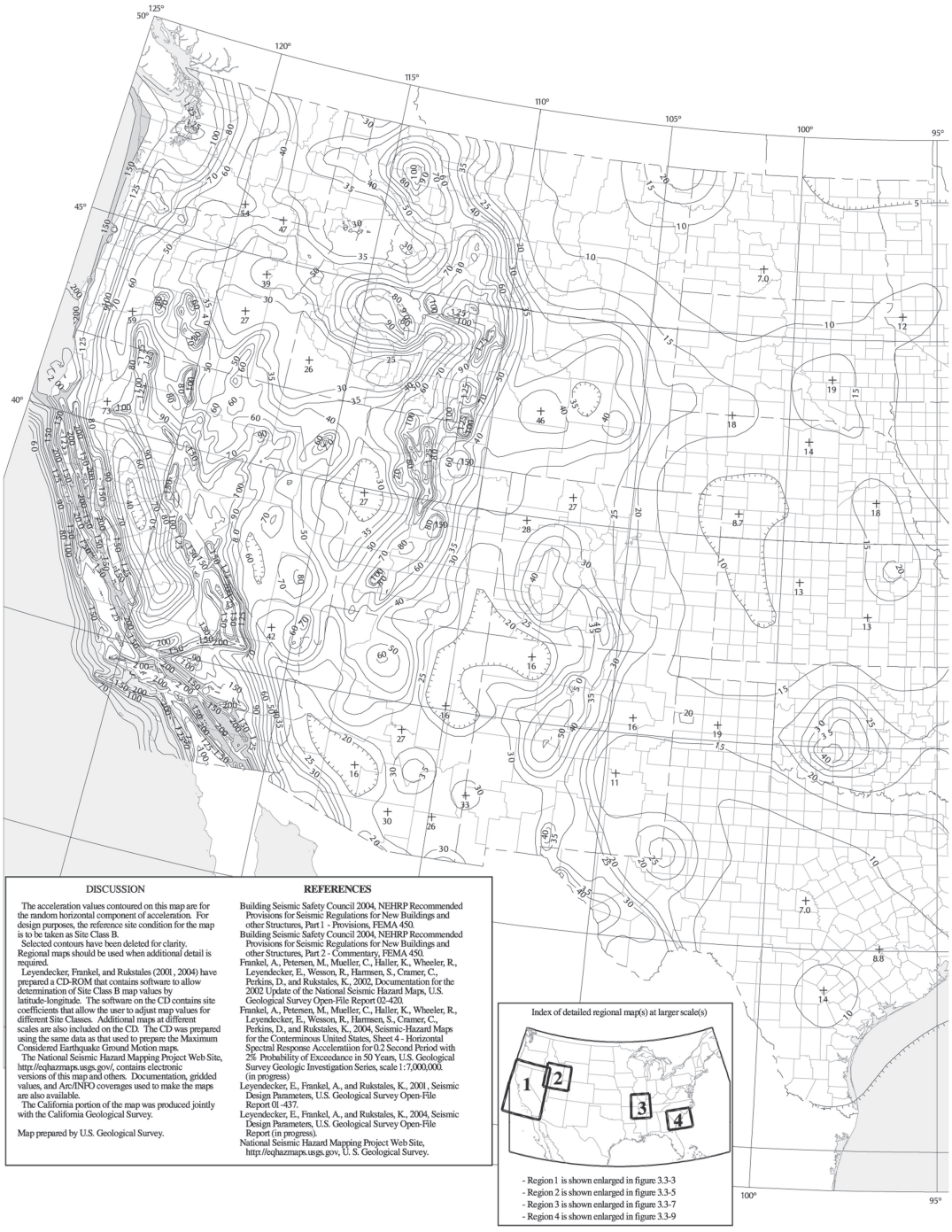

FIGURE 1.2.5 Maximum Considered Earthquake Ground Motion for the Conterminous United States of 0.2 Second Spectral Response Acceleration (5% of Critical Damping), Site Class B (Source: National Earthquake Hazards Reduction Program Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, FEMA 450, 2003, Figure 3.3-1)

probabilities, based in part on the historical record and also in part on the experience and judgment of the code developers. Because neither can completely predict the future, it is possible that code-specified design loads will be exceeded. For example, earthquakes sometimes occur on previously undiscovered fault lines, or changes in global climatic patterns can result in increased wind or snow hazards that are not accounted for by the building codes.

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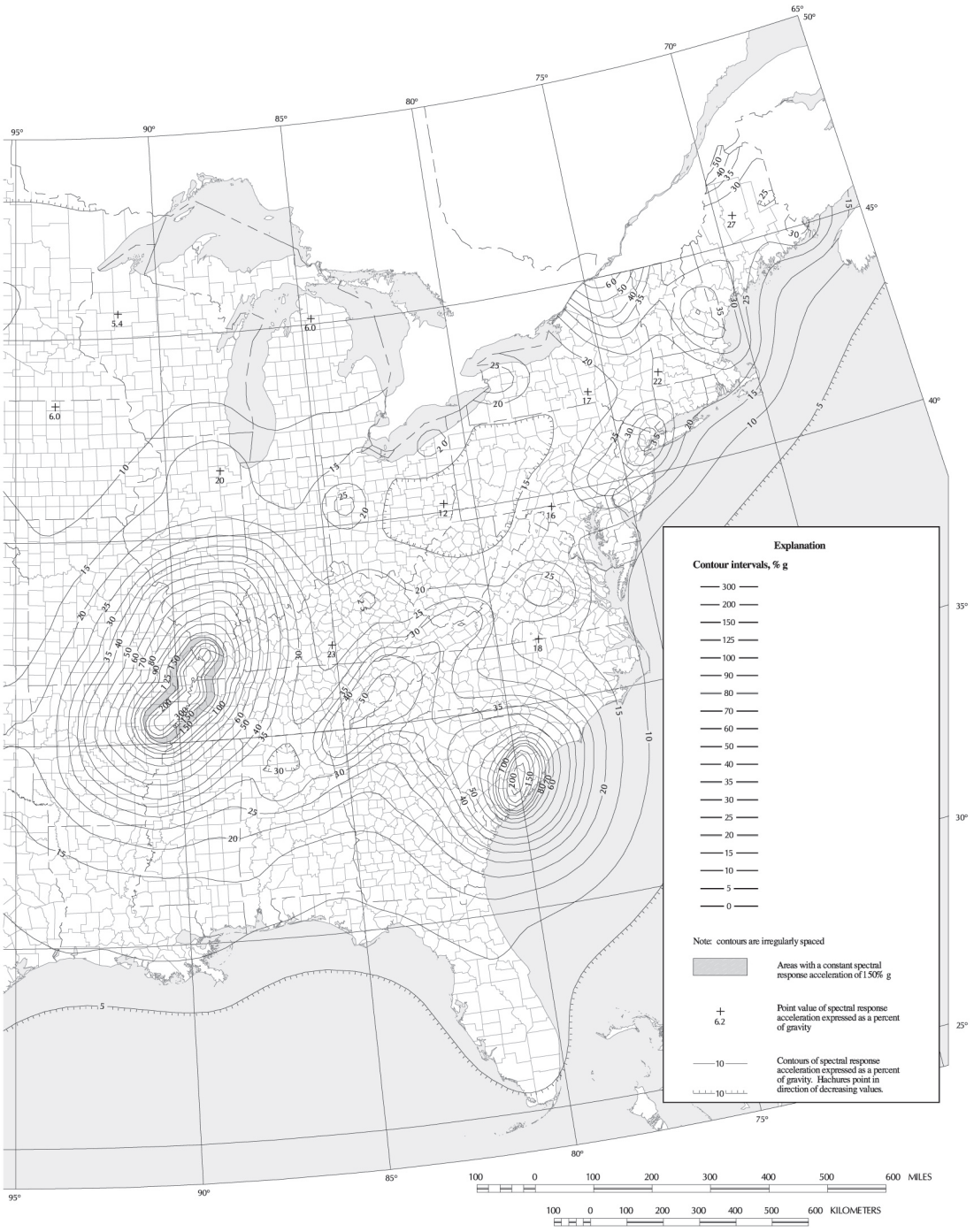

FIGURE 1.2.5 Continued

External Versus Internal Forces

Building codes define loads and forces such as dead, live, and snow loads, and wind or earthquake forces that are considered externally applied, in that they act upon the structure. When these forces and loads are applied on a structure, they result in movement (deflection) of the structure and also the development of internal forces or stresses within the individual structural elements. The building's structural elements, such as floors, beams, columns, or walls, are designed to control the magnitude of these deflections and stresses. Engineers must therefore use the external forces specified by the building code to calculate the distribution of internal forces and deflections in each building element. Although such calculations can be performed using manual methods, today elaborate computer programs are commonly used to assist the engineer in this task.

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Internal forces calculated in individual elements include tension, compression, shearing, and bending forces (or bending "moments"). After the engineer determines these forces, they are compared against maximum permitted material strengths that are defined in building codes to verify the adequacy of each proposed design.

BASIC BUILDING SYSTEMS AND COMPONENTS

Basic Building Systems

Basic building systems include the building envelope system, the structural system, the foundation system, the plumbing system, mechanical systems (such as heating, ventilating, and air-conditioning systems), and the electrical system. Other critical building systems include the fire protection system and the security system, for example.

This chapter focuses primarily on the building envelope system and the structural system and briefly addresses the foundation system. The building envelope and structural systems enable a building to withstand the loads and forces placed on it. Stated another way, the building envelope and structural systems keep the building intact and standing; the skin and skeleton fulfill similar functions in human anatomy.

Building Envelope System

The building envelope has been described as being composed of "several building components that work together to protect the building's structure and its contents from the elements."[4] The building envelope consists of building elements such as windows, precast or similar nonstructural wall panels, and like elements that enclose and protect the building and create the finished appearance.

Basic Structural Systems

To resist both vertical loads such as dead weight and snow, and lateral forces such as those produced by winds or seismic effects, any stable building or structure requires two distinct structural systems: a vertical support system and a lateral force-resisting system. Each system consists of a series of structural components (beams, columns, walls, etc.) that combine to provide resistance against either vertical or lateral loading. These structural components can consist of individual elements, such as columns, or they may consist of combinations of elements that connect to produce subsystems, such as shear walls, moment-frames, braced frames, and so on.

Vertical Support System. Basic structural components that combine to form the vertical support system include roof and floor framing systems, columns, bearing walls, and foundations. All structures must have complete and sound vertical load-supporting systems or they would collapse under their own weight and that of their contents. This is in contrast to structures with missing or inadequate lateral force-resisting systems that could conceivably stand indefinitely, because extreme lateral loading events (high winds and earthquakes, for example) are quite rare.

Lateral Force-Resisting System. Basic structural components that provide lateral force-resistance include shear walls, braced frames, and moment-resisting frames, as well as diaphragms (such as roof decks, floor slabs, or horizontal bracing systems) and foundations. Depending on the type, use, and geometry of the structure in each application, these components can be combined to form a structural system.

Comparison of Vertical Support and Lateral-Force Resisting Systems. Frequently, there is little visible difference between the frames, bearing walls, and so on, used to provide vertical support, and the similar frames, shear walls, and so on, used to resist lateral forces. The basic distinction that exists between vertical support and lateral-force-resisting systems arises from the following factors:

- All loads applied to a structure tend to be resisted first by the structural components that have the greatest rigidity (relative to other components) in the direction of load. Thus, vertical loads supported by an elevated floor slab tend to be borne by the closest adjacent columns. On the other hand, lateral forces applied against a floor diaphragm may span entirely past interior support columns (which provide little or no lateral rigidity) and be resisted by more distant (but very rigid) walls or braced frames.
- The connections used to fasten components must provide adequate strength to resist the imposed forces and deflections. In addition, the various components that form a structure must be designed considering the likely deflection and rigidity of adjacent elements. Where the design assumptions require a rigid or inflexible link between lateral load resisting components, the connection must impart rigidity; however, where independent motion is more appropriate, the connection must provide adequate flexibility to accommodate structure deformations without impact or binding.

Structures must be able to resist forces that are imposed from any direction. Most structures are therefore designed with two separate lateral-force-resisting systems, one for each of two orthogonal axes of the building. When forces are applied about either orthogonal axis of the structure, some of the resisting elements are aligned parallel to the forces. Wall and bracing elements have high relative rigidity in-plane and thus provide substantial lateral support. However, walls or bracing systems have low relative strength and rigidity when aligned perpendicular to the direction of load, and thus must be properly attached to and supported by structural components that are parallel to the forces.

Types of Basic Structural Systems. Building codes define certain standard structural systems, called basic structural systems. In essence, basic structural systems are those that resist vertical and lateral loads. These basic structural systems are the following:

- *Bearing wall system.* Any structure in which vertical walls and/or diagonally braced frames simultaneously support both the weight of the structure and resist lateral loads.

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- *Building frame system.* System in which the weight of the structure is completely supported by beams and columns. Resistance to lateral loads is independently provided either by walls, termed shear walls, and/or diagonally braced frames.
- *Moment-resisting frame system.* This structure is composed of beams and columns that are rigidly interconnected into moment-resisting frames to provide resistance to both vertical loads and lateral forces, without assistance from walls or diagonal braces.
- *Dual system.* System that provides two independent lateral-force-resisting systems, each capable of resisting all or part of the total lateral design forces. One system must always be a moment-frame system; the other can consist of either reinforced shear walls or braced frames that are added at selected locations.
- *Special systems.* Special systems include base-isolated systems or guyed systems, which do not fit the previous descriptions. A base-isolated system is a special type of seismic-resistant construction in which the structure is mounted on rubber bearing or sliding steel plates. A guyed system is a structure that is braced by guy wires, such as a radio-transmission tower.

Diaphragm Systems. Diaphragms are horizontal-spanning systems that tie vertical walls and columns together, provide stability to walls and other vertical elements, prevent excessive torsional (plane) deformations, and transfer forces to shear walls or frames below. Lateral forces resisted by diaphragms originate from wind forces applied against exterior walls, from seismic inertial forces, or from forces transmitted from shear walls or frames above.

The use of building floor and roof systems as diaphragm systems can be very efficient, because most of the structural elements required for diaphragm action are also required for these systems. Horizontal bracing systems provide diaphragm-like performance for applications where solid-surface construction cannot be used or is not required.

Building Foundation Systems

Foundation systems are used to transfer vertical and horizontal loads from the aboveground structure into the underlying soils. Common foundation types include piles, piers, caissons, spread footings, and mats. Piles, piers, and caissons are deep foundation systems designed to support heavy buildings on soft, compressible surface soils. Spread footings and mats are shallow foundation systems designed to support light buildings or heavier buildings on stiffer, stronger surface soils (Figure 1.2.6)

Basic Building Components

Basic structural components that collect loads from roof and floor levels and transfer them to foundations include moment-resisting frames, vertical walls, diagonally braced frames, and diaphragms and horizontal bracing. These underlying structures are surrounded and protected from the environment by the building envelope. Critical structural design considerations for the building envelope include resistance to lateral pressure or impact, accommodation of transient building movements, and accommodation of long-term building movement.

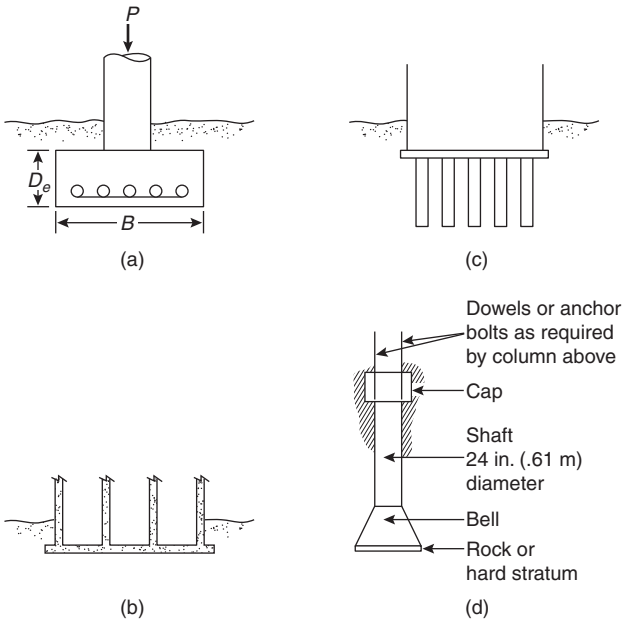

FIGURE 1.2.6 Common Types of Foundation Systems: (a) Spread Footing, (b) Mat, (c) Pile, and (d) Pier or Caisson

Resistance to Lateral Pressure or Impact. Exterior walls, windows, and doors provide the primary protection against wind pressures and small stones and missiles thrown up by wind. Windows must be designed to resist design wind pressures while still maintaining moisture protection at surrounding gaskets. In special hurricane-prone areas, impact protection may be required as well. Near grade and around entrances, missile or impact resistance may also be required for protection against small stones thrown up by lawnmowers or attempted forced entries. Walls must have adequate shear and bending strengths and strong enough connections to resist code-defined wind pressures and earthquake inertial forces.

Accommodation of Building Movements. The structure that supports the building sways and drifts during windstorms or earthquakes. The attached building components must be designed to accommodate these movements without damage. Frequently, by adding jointing and special connection details that allow structural movements without binding against cladding or window elements, these movements can be accommodated. In relatively flexible buildings, glass panels may need to be able to rock within their frames to accommodate building sway without binding. These sway or drift limits are part of the serviceability of performance and must remain within a certain tolerance level to prevent occupants from feeling motion sickness under "usual" conditions.

Accommodation of Long-Term Building Movements. After completion of construction, all buildings experience some

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degree of long-term movements as the building adjusts to its environment. Building components can experience some shrinkage or expansion. Foundations can slightly settle. Over the long term, some of this movement may continue in the form of thermal cycling or perhaps continuing foundation movements due to moisture-related expansive soil conditions. These movements often cause slight cracking and distress that can be observed in many buildings. Although not specifically a code-regulated issue, the details of building construction used should attempt to minimize both the amount of such movement that occurs and the damage sustained as a result of such movements.

Moment-Resisting Frames. Moment frames rely on bending forces developed at the connections of the beams to the columns to resist lateral forces. Because moment frames tend to be much more flexible than either shear walls or braced frames, lateral deflections of moment-frame structures tend to be much greater. The ratio between relative story deflection and story height is called the story drift ratio. Moment frames that permit too much story drift during windstorms or earthquakes may permit an excessive amount of damage to nonstructural components, such as siding, partitions, and contents.

Critical design elements of moment-resisting frames include beams and columns and the beam-column connection.

- *Beams and columns.* Frame elements must be designed to resist internal bending and shear forces. Optimum performance is gained when the members selected are stronger in shear than in bending and when the building's columns are stronger in bending than its beams. This provides a controlled damage mode under very large loads and forces and, in multistory frames, increases the total energy dissipation capability of the frame.
- *Beam-column connection.* The stability of the frame is dependent on the rigidity and strength of the beam-column connection. Adequate strength and toughness must be provided in the connection to permit repeated cycling of stresses without a loss of integrity. Connections can be made of bolted or welded components, or a combination of bolted and welded elements. Since the toughness of welded joints is highly dependent on the workmanship, special quality control measures are often required in the most critical welds.

Shear Walls. The shear wall is designed as a vertical beam element. As shown in Figure 1.2.7, critical design considerations for shear walls include in-plane shear, in-plane bending, and bending from forces perpendicular to the wall:

- *In-plane shear.* The wall acts as a web, or shear membrane, to resist in-plane shear forces. Adequate anchorage must be provided along the top and bottom edges of the web to transfer the shearing forces into and out of the web.
- *In-plane bending.* To resist bending stresses due to overturning moments, structural elements, called chords or boundary elements, are concentrated at the vertical edges of the wall. Chords are tension-only elements, which resist the tension component of bending forces. Boundary elements are tension-compression elements, which resist tension forces as well as extremely large compression strains (large enough to cause crushing of unconfined concrete) due to bending and vertical loads. Boundary elements are required by building codes only in high-seismic zones. Both chord and boundary elements must be anchored into a foundation that is capable of transferring the vertical components of overturning forces into the ground.
- *Bending from forces perpendicular to wall.* Adequate bending strength and anchorage must be provided to resist in-

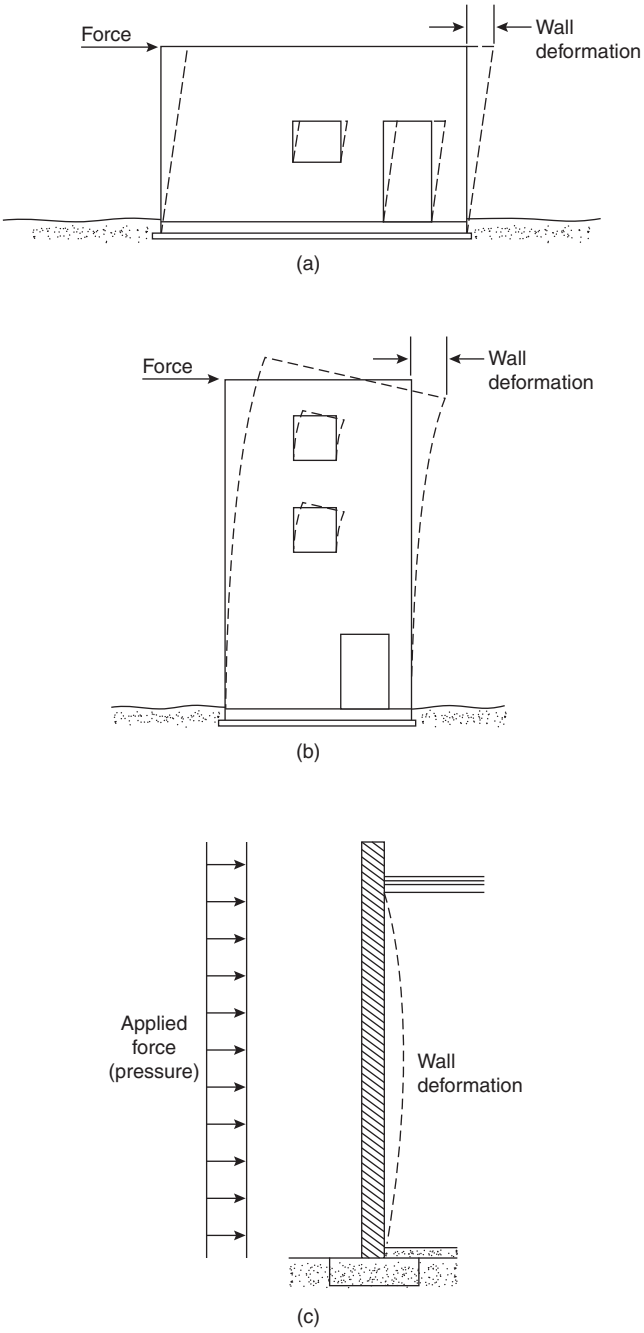

FIGURE 1.2.7 Types of Wall Deformation: (a) In-Plane Shear Deformation, (b) In-Plane Bending Deformation, (c) Bending from Forces Perpendicular to Wall

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ertia loads and wind pressures applied perpendicular to the plane of the wall.

Diagonally Braced Frames. Braced systems rely on the axial rigidity of vertical and diagonal elements to resist lateral forces. The configuration of diagonal elements within the bracing can vary, and some configurations have better seismic performance than others. Commonly encountered types of bracing systems, in order of relative performance (best to worst) when subjected to overload or damaging conditions, include the following:

1. *Eccentrically braced frame (EBF).* A special type of bracing system that is designed to provide a high degree of overload resistance by permitting controlled overstresses within a short, ductile beam segment, called a "link." Figure 1.2.8 shows examples of eccentrically braced frames.
2. *Concentrically braced frame (CBF).* A type of bracing system that provides overload resistance by permitting controlled overstresses in the bracing members. Buckling-restrained braced frames (BRBF) are considered a special class of concentrically braced frames, with a high degree of seismic resistance. Figure 1.2.9 shows examples of other concentrically braced frames:
   - *Tension-compression bracing.* Diagonal elements are provided either singly or paired in an "X" pattern to resist forces both in tension and compression.
   - *Chevron bracing.* Arranged in either a "V" or inverted "V" configuration, the diagonal elements resist lateral forces by sharing the load between tension and compression elements. Bracing in this configuration also resists vertical loads applied to the beam, although building codes require that the beam be designed to resist vertical loads as if the bracing did not exist. This configuration can experience problems when overstressed because buckling of the diagonal undergoing compression creates a force imbalance that increases bending forces on the beam.
   - *Tension-only bracing.* Similar to tension-compression bracing, except that the diagonal elements, by being very slender, are assumed to buckle at very low compression forces. This configuration can experience a loss of strength under repeated tension-compression cycles. In regions subject to significant ground shaking, tension-only bracing is limited to structures of less than two stories in height.
   - *K-bracing.* This system provides the poorest overload performance. Overstresses in the diagonal elements can lead to buckling of the diagonal undergoing compression. The resulting force imbalance creates a lateral force on the column, which could possibly lead to a general collapse of the system. Building codes include several restrictions on the use of this type of bracing.

As shown in Figure 1.2.10, critical design elements of bracing systems include diagonal elements, vertical elements, and horizontal elements:

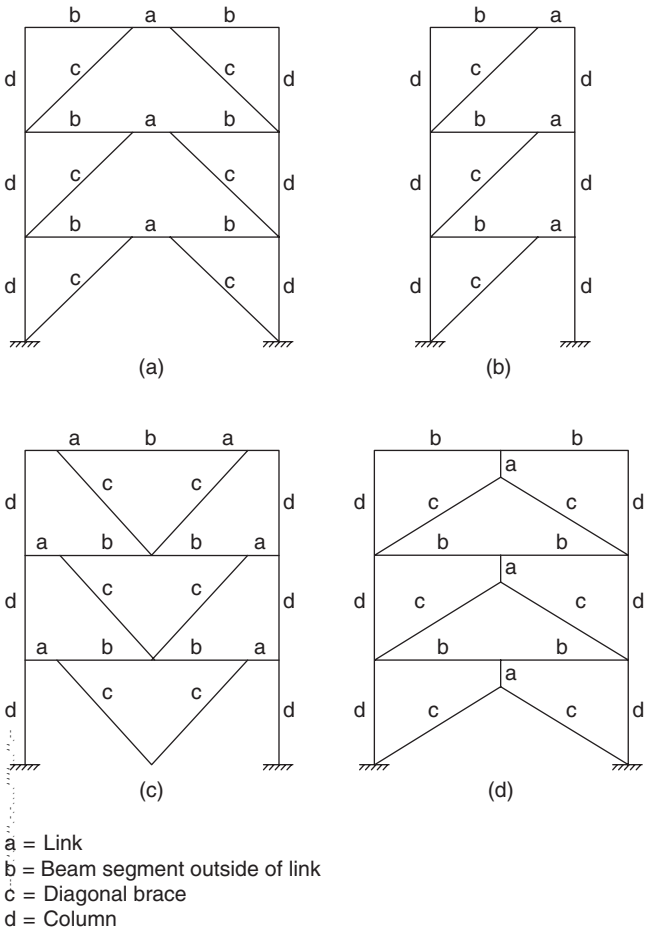

FIGURE 1.2.8 Examples of Eccentrically Braced Frames (Source: Copyright © American Institute of Steel Construction, Inc. Reprinted with permission. All rights reserved.)

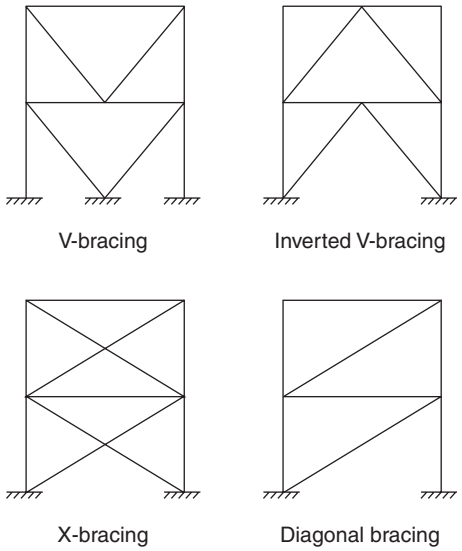

FIGURE 1.2.9 Examples of Concentric Bracing Configurations (Source: Copyright © American Institute of Steel Construction, Inc. Reprinted with permission. All rights reserved.)

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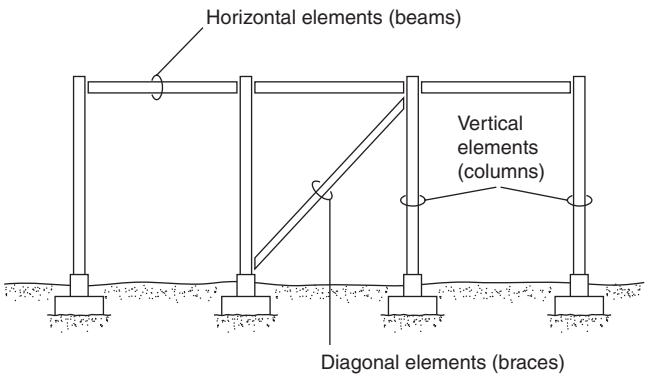

FIGURE 1.2.10 Diagonal Elements, Vertical Elements, and Horizontal Elements

- *Diagonal elements.* Designed to resist lateral (story shear) forces. Because bracing connections often tend to have brittle modes of failure, for some loading conditions the connections must be designed to be stronger than the braces themselves.
- *Vertical elements.* Designed to resist overturning forces.
- *Horizontal elements.* Designed as axial struts to collect and transfer tension and compression forces into the diagonal elements. The strut system can be sloped, such as when pitched roof elements are used as struts.

Diaphragms and Horizontal Bracing Components. Diaphragms are generally designed as beams that span between the vertical-resisting elements (frames, walls, braced frames, etc.). Critical design elements of diaphragm systems include the following:

- *Shear membrane.* The floor or roof acts as a web, or shear membrane, to resist shear forces. The web is assumed to resist shear forces only (no tension or compression).
- *Chords and boundary elements.* Located at the extreme edges of the diaphragm, the chords resist tension forces caused by bending in the diaphragm, in a manner similar to the flanges of an I-beam. When compressive stresses warrant, boundary elements may also be required to resist the compressive forces caused by bending.
- *Collectors.* Also called drag struts, collectors are used to resist axial tension and compression forces within the diaphragm by:
  - Collecting shear forces from the diaphragm and transferring them to the vertical resisting elements (walls, braces, or frames)
  - Redistributing chord forces at diaphragm offsets and gathering loads and distributing them to intersecting walls, braces, or frames
  - Redistributing diaphragm shear forces and local chord forces around openings within the diaphragm
  - Distributing points of concentrated force into the diaphragm, such as from heavy rooftop equipment

Foundation Components. Critical design issues for foundation systems include bearing strength, overturning resistance, sliding resistance, bending and shearing strength, and ground hazards:

- *Bearing strength.* The foundation system must have sufficient strength to transfer the weight of the structure to the surrounding soils without adverse settlements.
- *Overturning resistance.* Piles must have sufficient compressive and tensile capacity to resist overturning loads; spread footings must be massive enough and/or support adequate soil surcharge to counteract uplift.
- *Sliding resistance.* Either passive soil pressure, friction, or a factored combination of both may be used, depending on the soil type and foundation geometry.
- *Bending and shearing strength.* The foundation system must have adequate strength to transmit loads without failure or excessive deflections.
- *Ground hazards.* Some sites are susceptible to special hazards that can occur within the site itself, such as excessive settlement, potential slope failures, water-induced scour or shaking-induced-liquefaction. In some instances, the risk of these hazards can be reduced by conducting site improvements prior to construction, such as by soil densification or by removal of unsuitable materials. In other instances, the site itself may not be suitable for the structure.

FUNDAMENTAL DESIGN CONCEPTS

General Structural Integrity

Building codes and their referenced design load standards require structures to be designed so that, when damage is sustained locally, the damage does not spread to an area disproportionate to the original area of local damage. This is most often accomplished by providing designs that have a robust load path, stable geometry, and structural systems that are designed specifically for overstress.

Load-Path Concept

The load-path concept requires a continuous system of interconnected elements throughout the structure, adequately connected to transfer applied loads and forces from the points of origin or application to the final points of resistance. As an example, columns are used to transfer loads from roof beams to foundations. While providing a continuous load path is an obvious design requirement for vertical loads, a continuous load path is sometimes overlooked or not completely developed when designing for lateral force resistance. The failure to review all members and connections for each combination of load can lead to weak links in the load path.

Important aspects of developing, designing, and detailing the lateral load path include the following:

- Considering all likely conditions of load. In addition to the basic design loads such as gravity forces, forces caused by thermal expansion or contraction, and outside events such

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as wind or earthquakes, the possible directions of application of these forces must be considered.
- Providing means of collecting load or force from one element (such as roof sheathing) and transferring it to another (such as a wall).
- Ensuring stiffness compatibility of load-resisting elements acting in parallel (before and after yield). For example, welding cannot be used to "increase" the strength of a connection using bolts, because slight movement or slip within the bolted connection may cause the more rigid weld to bear all of the force and fail.
- Considering eccentric loading or attachment conditions. It is often not physically possible to attach parts together in a concentric manner and some eccentricity must be permitted in order to make the attachment. This eccentricity causes additional bending and deformation forces in the local area around the connection that the structure must be designed to resist. These local forces are often referred to as secondary. However, they can be very large and often cause failures if not adequately considered in the design.
- Considering transfer of design loads through the foundation system into the surrounding soil. Inadequate consideration may result in portions of a structure sliding in the soil or in local foundation settlements due to high bearing pressures.

Structural Geometry

Although it is typically the structural engineer's responsibility to determine the actual details of structural resistance, the architect and other design team members can also greatly affect the ultimate resistance of the structure by controlling the configuration of the structure and the distribution of weight. The configuration of a structure can have significant impact on the way it behaves when subjected to extreme loads.

Although architectural design impacts the overall structural configuration, local geographic, cultural, and climatologic conditions can also dictate many aspects of building geometry. In coastal flood zones, for example, structures may need to be elevated on columns or piers above potential storm surge or flood heights. In inner-city areas, local planners often promote street-level plazas or parking into the design of tall buildings, which redefines the building geometry in lower levels.

A simple, symmetrical, and regular structural geometry tends to result in better performance of structures subjected to extreme loads such as earthquakes or blasts. Buildings with significant irregularities in geometry, mass, or stiffness tend to twist or deform unevenly as the building is overloaded, resulting in local areas of high stress concentration. Although irregular features often create pleasing aesthetic effects, such areas can also become early damage initiation points that can rapidly degrade structural integrity and result in poor performance unless additional attention is given to them during design and construction.

It is the mutual responsibility of the architect and structural engineer to identify and resolve geometry problems early in the design process. The challenge to the design team is to create a building with a structural system that is reasonably regular and yet still retains the intended form and function. Poor geometry can result in poor performance unless special attention is given during the design process (often at increased design and construction cost).

Designing Structures to Resist Overstress

Traditionally, the possibility of overload or overstress has not often been considered in structural design, except in areas of active seismicity or buildings subject to possible blast pressures. Structures designed without such consideration of inadvertent overload could collapse when subjected to moderate overloads or an inadvertent failure of a single member. Structures specifically designed to resist strong earthquakes or large blast pressures, however, are typically detailed with toughness and redundancy. Tough and redundant structures may have the same strength and general appearance as other structures, but contain a reliable method of resisting possible overloads without collapse.

Although buildings are designed to resist most load conditions without damage, unpredicted overload conditions can occur, and for some design load conditions, overstress and damage can result. When these unpredicted conditions happen, structures may experience undesirable failure modes. Undesirable failure modes include those resulting in total collapse of the structure, such as caused by progressive column failures, and those involving sudden failure, such as a buckling or brittle (e.g., shear) failure.

During overload conditions, structural materials that are overstressed may crack, buckle, or yield. Once such behavior, often termed *nonlinear behavior,* occurs, the load-deformation characteristics of the element—that is, its ability to resist loading without adverse deflection—changes substantially. When nonlinearity occurs, the structural elements either behave in a brittle manner, in which rapid loss of load carrying capacity occurs, or in a ductile manner, in which the element can continue to carry load, but may have substantially increased deformation and deflection. The difference between brittle and ductile behavior can be demonstrated by the following example. If a piece of chalk is bent, the chalk quickly breaks, as the bending stress exceeds the tensile strength of the chalk. On the other hand, if a metal paper clip is bent, the metal deforms and refuses to break unless bent back and forth many times. The chalk is brittle; the metal paper clip is ductile.

Ductility is a material property that exists only for nonbrittle materials such as steel. It is a measure of the material's ability to undergo nonlinear deformation without fracture (breaking). Nonlinear behavior can be safely accommodated in structures that use ductile materials (such as steel) either as the primary structural element or as reinforcing for more brittle materials. For example, plain concrete and masonry are brittle materials, but properly reinforced concrete and masonry can behave in a ductile manner and produce structures that exhibit satisfactory seismic performance. Conversely, although steel is an inherently ductile material, proper proportioning of members and design and detailing of connections is necessary to assure ductile behavior of the overall structural system. A structure can be designed to resist overstresses in a ductile

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manner. Important features of ductile design include (1) selecting ductile materials and member configurations, (2) assuring that connections are stronger than the elements they connect, (3) providing redundancy or backup systems, and (4) controlling damage modes.

Redundancy in a structural system allows for redistribution of internal loads around local areas of overstress or failure. Redundancy effectively provides a backup system for protection against collapse when localized failures occur. As an example, a cantilever is a nonredundant structural system and collapses when yielding occurs at the base of the cantilever.

Some elements behave in a ductile manner if subjected to one type of loading and in a brittle manner if subjected to other types of loading. For example, reinforced concrete or masonry beams generally behave in a ductile manner when overloaded in bending, but behave in a brittle manner when overloaded in shear. Careful design practice can control the actual failure mechanism by proportioning the beam to be stronger in shear than it is in bending, so that the more ductile mode then controls the behavior.

BASIC DESIGN METHODOLOGY

In building design, there are three basic approaches: allowable stress design, load and resistance factor design (LRFD), and performance-based design.

Allowable Stress Design

Allowable stress design is the simplest and most common method used for building design. Fundamentally, it requires that the applied forces or stresses on any element not exceed the strength of that element divided by a factor of safety. The factor of safety used generally varies from 1.5 to 3.0, depending on the reliability or variability of the data on which the value of strength is determined and also the consequences of failure. Forces in individual elements are calculated using the various design loads and forces prescribed by the building code. Element strengths are calculated in accordance with procedures specified by material design standards published by different organizations supported by the materials industries.

EXAMPLE: A steel beam is made from material with a specified minimum yield strength of 36,000 lb/in.^{2} (248,000 kPA). Building codes require a minimum factor of safety of 1.5 for simple gravity (dead plus live) loads. Thus, the beam must be designed for this condition using a maximum "allowable stress" of 36,000/1.5 = 24,000 lb/in.^{2} (248,000/1.5 ≈ 165,000 kPa).

One drawback associated with the allowable stress design method is that the factors of safety used are generally independent of the certainty inherent in the definition of the applied loading. Structures that support basically nothing other than self-weight are designed using the same factor of safety as structures that support highly variable and unpredictable types of loading, such as vehicular traffic, although it would be more appropriate to provide a greater margin of safety when the loading is uncertain.

Load and Resistance Factor Design (LRFD)

The load and resistance factor design method is an alternative procedure that provides several improvements over the allowable stress design method. These include the following:

- Load and resistance factor design separates the factor of safety into components that are separately applied to the types of loading experienced and the types of elements used. Hence, the factor of safety in any structure or element varies, based on the uncertainty in both the expected loading and the predictability of the element strength.
- The procedures for calculating the strength of structural sections more realistically estimate the likely value than those used in allowable stress design procedures. This provides the opportunity to compare the strengths of any element relative to another, so that the path of failure due to overload becomes more transparent. By calculating the expected strength of each component, the engineer gains the opportunity to proportion the structure in a manner so that overload conditions are less likely to result in catastrophic failures.

Although the load and resistance factor design method offers many improvements over the allowable stress design method, many engineers regard the method as more complex and confusing. Hence, both methods are still commonly used. Although load and resistance factor design is common for concrete elements, allowable stress design has been common for the design of steel, timber, and masonry elements. The design profession is slowly moving toward universal adoption of LRFD procedures.

A Third Approach

Although both the allowable stress and load and resistance factor design methods incorporate a finite probability of structural failure, this may be misunderstood by the public, who may believe that there is no possibility of failure of a code-conforming structure. For example, owners of relatively new buildings may be upset to learn, following relatively moderate earthquakes, that their damaged building had performed within the intent of the building code. The expected response after a hurricane may be similar.

Ordinary occupancy buildings designed in accordance with building codes are intended to provide good and serviceable performance for load conditions commonly encountered, resist relatively rare load conditions with moderate but repairable damage, and provide protection against collapse for very rare extreme events (see Section 1, Chapter 7, "Protecting Against Extreme Events"). For some hazards such as tornadoes, very little protection is provided. Essential facilities such as hospitals and fire stations are designed with expectations of somewhat better performance. Specifically, the minimum permissible design loads for such structures are increased relative to those for ordinary occupancy structures. However, the extent that the actual performance of these essential facilities is improved is not quantifiable. Although very special structures such as nuclear power plants can be and have been designed to resist all kinds of extreme events without damage, the added cost of design and

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construction and the required limitations on architectural freedom have limited building codes to providing lower levels of protection.

Sophisticated owners of very valuable or important facilities have sought better quantification of the risks associated with extreme events, to permit them to make better business decisions and tradeoffs between paying added initial costs for better building construction and avoiding the future costs of insurance protection, damage repair, and potential business interruption. This has led to the development of a third design methodology—*performance-based design.*

Performance-Based Design

Rather than following prescriptive requirements contained in the building codes, the design professional using performance-based design procedures directly develops a design capable of achieving specific performance goals and objectives. Performance-based procedures intended to ensure adequate fire/life safety protective features in buildings have been under development for a number of years. Recently, structural engineers have also begun to develop performance-based design procedures, primarily for application to earthquake-resistant design.

The structural engineer using performance-based design applies a procedure to predict and estimate damage or behavior anticipated of a structure's design to design events, compared against preselected objectives. The design is revised until the predictive methodology indicates that acceptable performance can be obtained. Predictive methods can include calculation procedures as well as construction and laboratory testing of prototype designs. Performance-based design benefits owners who want to understand how their buildings may be expected to perform if they are subjected to various design events. It also helps them determine levels of acceptable performance based on the costs of different levels of performance.

Building owners have the three following basic interests in relation to building performance:

- Preservation of safety
- Preservation of capital
- Preservation of function

Some building owners may not be particularly interested in either preservation of the capital invested in a building or in maintaining its function, feeling that the probability of a damaging event is low and that insurance is available and sufficiently inexpensive to provide protection against these rare unexpected events. For other building owners, performance-based structural design is an attractive alternative approach that provides financial justification for providing the same or better performance than that defined in the building code.

Building Importance Defined in Building Codes. The basic reason that municipalities adopt building codes is to protect the public safety; the primary goal of building codes is, therefore, to protect life safety for the most severe events (fire, wind, earthquake, etc.) likely to affect the structure during its life. In effect, codes deem some buildings more important than others. For some types of buildings, structural failure could result in greater loss of life than other types or could result in the loss of vital disaster recovery services. Greater protection is warranted for such buildings. To assist with the assignment of appropriate levels of safety to buildings with different intended occupancies and uses, the American Society of Civil Engineers' *Minimum Design Loads for Buildings and Other Structures*[5] defines several standard occupancy categories. An abbreviated summary of these occupancy categories follows:

- *Occupancy type I.* This category includes structures such as sheds or agricultural buildings that are normally unoccupied. The failure of such buildings is unlikely to result in significant probability of life loss. Therefore, relatively little protection is required for such structures, and it is considered acceptable if they collapse during a rare event.
- *Occupancy type II.* This category includes most types of buildings, including most commercial, residential, and institutional structures. It is literally defined in the building codes as all buildings except those specifically included in other categories. Under extreme loading these structures are expected to be heavily damaged but not collapse.
- *Occupancy type III.* This category includes important buildings that accommodate a large number of people, that provide important public services (such as utilities), or that house occupants with limited mobility such as schools or detention facilities. It also includes facilities that house moderately hazardous substances, such as certain chemicals or petroleum products, and facilities with potential to cause a substantial economic impact or mass disruption of life in the event of failure. Greater protection against collapse is warranted for these structures for rare events, and less damage is acceptable for more moderate events.
- *Occupancy type IV.* This category includes buildings that are deemed to be essential to the public welfare such as hospitals; fire, rescue, and police stations; and essential communication, transportation, and water storage facilities. It is highly desirable that these facilities be capable of functioning following even a rare event.

Benchmark Damage Levels. In recent years, a series of standard definitions of tolerable damage levels, termed *performance levels,* have been developed. Standard definitions are found in *NFPA 5000®*, *Building Construction and Safety Code®*:

- *Serviceability performance.* The serviceability level of performance is a state in which structural elements and nonstructural components have not sustained detrimental cracking or yielding, or degradation in strength, stiffness, or fire resistance requiring repair that is troubling to occupants or disruptive of building function. Nonstructural components and permanent fixtures and features have also not become displaced or dislodged.
- *Immediate occupancy performance.* The immediate occupancy level of performance is a state in which minor, repairable cracking, yielding, and permanent deformation of the structure and nonstructural elements may have occurred. Although repair may be required, the structure would not be considered unsafe for continued occupancy.

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- *Collapse prevention performance.* Under this level of performance, the building may experience substantial damage to structural and nonstructural elements, with some failures occurring. However, collapse is avoided and emergency responders can effect occupant rescue and building evacuation.

Quantification of Risk. The fundamental improvement that the performance-based design method offers is a quantification of the degree of risk of damage associated with load events that are likely to occur, might possibly occur, and could conceivably occur during the existence of a structure. Benefits of this approach are a structure unlikely to experience unwanted damage, and quantification of risk that can be directly used in financial analysis by evaluating the cost/benefit of increased performance versus future insurance payments and risk of loss (Figure 1.2.11). For the basic occupancy types defined in building codes, risk levels for various types of transient loading are defined to be consistent with the performance objectives outlined in Figure 1.2.11.

Criteria to Confirm Compliance. To assess the damage level associated with any risk level of loading, design procedures must present criteria for determining the strength or deformation resistance of each building element at each damage level. ASCE/FEMA 356 "Prestandard for the Seismic Rehabilitation of Buildings"[6] and Appendix G of the SEAOC "Recommended Lateral Force Criteria and Commentary"[7] provide criteria that may be used to determine these values.

SUMMARY

The combination of building codes, design load standards, material design standards, and the engineering process provides a reasonably uniform factor of safety to building design. Design load standards provide a statistically derived method to define the vertical loads and lateral forces to which buildings may be subjected, as well as uniform margins of safety in design. Material design standards define the means to determine the usable strengths of building components. The engineering process provides a rational method to determine the minimum levels of strength and toughness in individual building components and also a measure of warning to permit occupants to evacuate if overload conditions occur. Various methodologies used to design building components in the engineering process include the allowable stress, load-and-resistance factor, and performance-based design methods.

There are many challenges to safe building design. Each building is unique in location, geometry, use, construction, and condition. Because building codes, materials, and methods of construction change with time, and uncorrected deterioration may reduce the strength or safety of buildings with time, many buildings exist that would be considered substandard relative to current building codes. Even in new construction, mistakes or misunderstandings during either the design or construction process can result in building defects. In addition, design load standards referenced in building codes cannot define with certainty the actual ranges of loading or exposure to snow, wind, or other extreme events to which any building may be subjected throughout its existence.

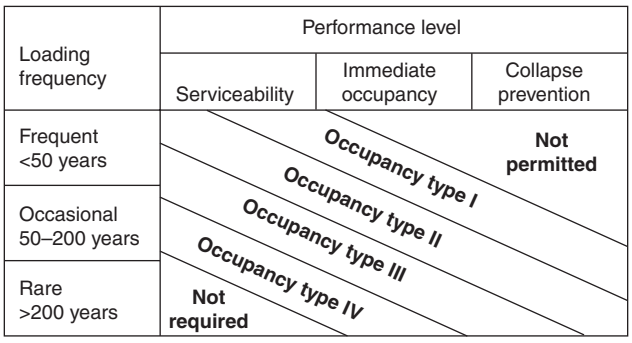

FIGURE 1.2.11 Performance Objectives for Building Occupancy Types

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NFPA Codes, Standards, and Recommended Practices

Reference to the following NFPA codes, standards, and recommended practices will provide further information on fundamentals of safe building design discussed in this chapter. (See the latest version of The NFPA Catalog *for availability of current editions of the following documents.)*

NFPA *101®*, *Life Safety Code®*
NFPA 5000®, *Building Construction and Safety Code®*

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