Performance-Based Design

Course No: A01-001
Credit: 1 PDH

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2 Performance-Based Design

2.1 Background

The model building codes define the minimum design requirements to ensure the safety of occupants during specific design events. Recent natural disasters have prompted recognition that significant damage can occur even when buildings are compliant with the building code. Many critical facilities, including school buildings, are closed after natural disasters, even if damage is relatively minor, suggesting that satisfying the minimum code criteria may not be sufficient to ensure continued functionality. Communities also depend on school buildings to provide reliable shelter and critical services. In order to meet that need, school buildings should be designed and constructed according to criteria that result in continued and uninterrupted functionality.

The term “**performance**,” as it relates to exposure to natural hazards, usually refers to a building’s condition after a disaster, i.e., it signifies a level of damage expected or a load that can be resisted.

Building performance is an indicator of how well a structure supports the defined needs of its users. Acceptable performance indicates acceptable (or tolerable) levels of damage or condition that allow uninterrupted facility operation. Consequently, performance-based design is the process or methodology used by design professionals to create buildings that protect functionality and the continued availability of services.

The performance-based design approach is not proposed as an immediate substitute for design to traditional codes. Rather, it can be viewed as an opportunity to enhance and tailor the design to match the objectives of the community's stakeholders. For a school project, the stakeholders include everyone who has an interest in the successful completion of a school project (i.e., the school board members, responsible officials, members of the design team, the builders, the community at large, parents, and code enforcement officials). The design team is made up of the architects, engineers, and other design professionals and consultants.

Performance-based codes define acceptable or tolerable levels of risk for a variety of health, safety, and public welfare issues. Currently, codes include the *International Code Council Performance Code for Buildings and Facilities* (ICC PC) produced by the International Code Council (ICC, 2009), and the *NFPA 5000. Building Construction and Safety Code* (NFPA, 2009) and *NFPA 101: Life Safety Code* (NFPA, 2008) produced by the National Fire Protection Association (NFPA). The ICC PC addresses all types of building issues, while the provisions of NFPA 101, "Performance-Based Option," address only issues related to "life safety systems." NFPA 5000 sets forth both performance and prescriptive options for design and construction.

The various prescriptive building, fire, and life safety codes all contain provisions for what is known as "alternative methods and materials" or "equivalency." These provisions allow for the use of methods, equipment, or materials not specified or prescribed in the code, provided the alternative is approved by the code official. A performance-based design approach can be employed under these provisions. While the "alternative methods and materials" clause of the prescriptive codes allows the use of performance-based design procedures, the 2010 edition of the American Society of Civil Engineers (ASCE) Standard 7, *Minimum Design Loads for Buildings and Other Structures*, addresses performance-based design when the standard is used directly, without reference from a building code.

Within ASCE 7-10, "Performance-based Procedures" represent one of three approaches for design. Under the performance-based approach, both structural and nonstructural components and their connections must be shown to provide a reliability not less than that expected under the approach referred to as the "strength procedures." A combination of testing and analysis can be used to demonstrate the achievement of target reliability that is described in the Commentary that accompanies ASCE 7. Factors that affect target reliability include Risk Category (or Occupancy Category), extent of structural failure, and whether loading conditions include or exclude earthquake.

In 2006, FEMA published FEMA 445, *Next-Generation Performance-Based Seismic Design Guidelines. Program Plan for New and Existing Buildings.* This document includes guidance for developing detailed modeling, simulation of building response to extreme loading, and estimates of potential casualties, loss of occupancy, and economic losses. The outlined process allows the design of a building to be adjusted to balance the level of acceptable risks and the cost of achieving the required level of building performance. Although the process outlined in FEMA 445 is applied to seismic hazards, it can be generalized for application to other hazards.

2.2 Prescriptive vs. Performance-Based Design

Design and construction in the United States is generally regulated by building codes and standards. Building codes are intended to ensure the health, safety, and well-being of people in buildings by establishing minimum requirements to address structural strength, adequate means of egress, sanitary equipment, light and ventilation, and fire safety. Building codes may also promote other objectives, such as energy efficiency, serviceability, quality or value, and accessibility for persons with disabilities. These prescriptive standards are easy for architects and engineers to understand, and easy for community inspectors to monitor. This ease of use is their great strength.

Historically, building codes have been based on a prescriptive approach that limits the available solutions for compliance. Prescriptive or specification-based design emphasizes the “input,” or the materials and methods required. In contrast, the focus of performance-based design is the “output,” or the expectations and requirements of the building’s primary users and stakeholders.

This approach provides a systematic method for assessing the performance capabilities of a building, system, or component, which can then be used to verify the equivalent performance of alternatives, deliver standard performance at a reduced cost, or confirm the higher performance needed for critical facilities such as schools.

The ICC PC defines **performance-based design** as “An engineering approach to design elements of a building based on agreed upon performance goals and objectives, engineering analysis and quantitative assessment of alternatives against the design goals and objectives using accepted engineering tools, methodologies and performance criteria.”

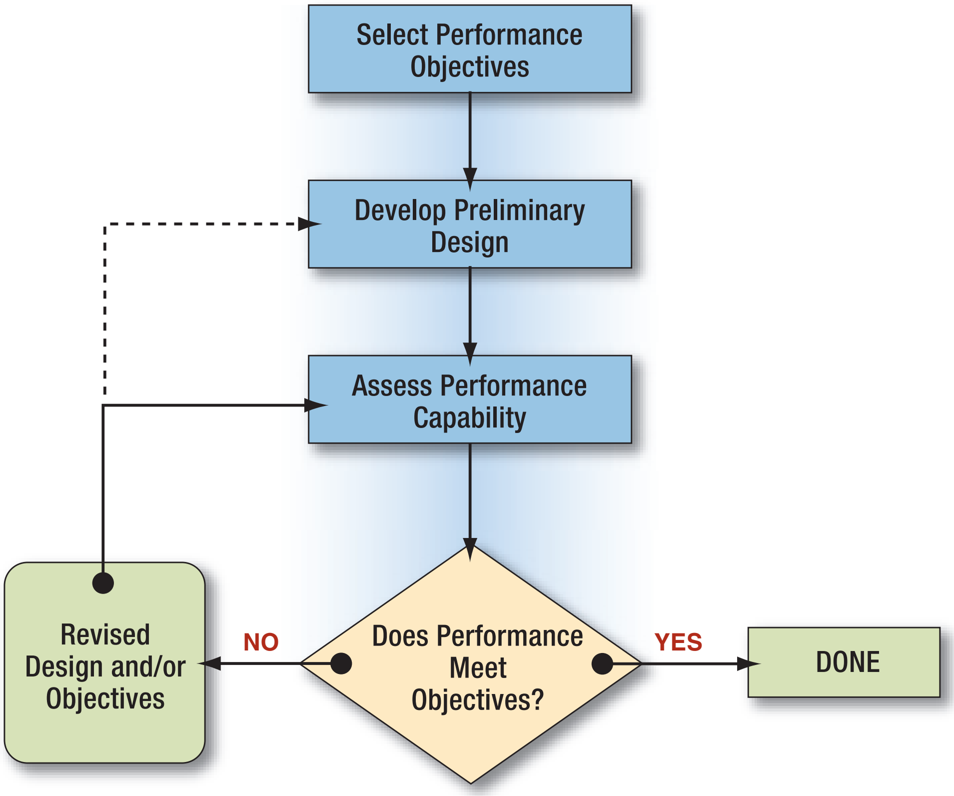
2.3 The Performance-Based Design Process

The performance-based design process explicitly evaluates how building systems are likely to perform under a variety of conditions associated with potential hazard events. The process takes into consideration the uncertainties inherent in quantifying the frequency and magnitude of potential events and assessing the actual responses of building systems and the potential effects of the performance of these systems on the functionality of buildings. Identifying the performance capability of a facility is an integral part of the design process and guides the many design decisions that must be made. Figure 2-1 presents the key steps in this iterative process.

Performance-based design starts with selecting design criteria articulated through one or more performance objectives. Each performance objective is a statement of the acceptable risk of incurring different levels of damage and the consequential losses that occur as a result of this damage. Losses can be associated with structural or nonstructural damage, and can be expressed in the form of casualties, direct economic costs, and loss of service costs. Loss of service costs may be the most important loss component to consider, especially for critical facilities such as schools.

Figure 2-1:
Performance-based design flow diagram

SOURCE: HAMBURGER, 2003



Acceptable risks are typically expressed as acceptable losses for specific levels of hazard intensity and frequency. They take into consideration all the potential hazards that could affect the building and the probability of their occurrence during a specified time period. The overall analysis must consider not only the intensity and frequency of occurrence of hazard events, but also the effectiveness and reliability of the building systems to survive the event without significant interruption in the operation.

Hazard. A source of potential danger or adverse conditions. Natural hazards include events such as floods, earthquakes, tornadoes, tsunamis, coastal storms, landslides, and wildfires.

Risk. The estimated impact that a hazard event would have on people, services, facilities, and structures in a community, or the likelihood of a hazard event resulting in an adverse condition that causes injury or damage.

2.4 Acceptable Risk and Performance Levels

The performance-based design process begins with establishing the acceptable risk and appropriate performance levels for the building and its systems. Acceptable risk is the maximum level of damage to the building that can be tolerated from a realistic risk event scenario or probability. The ICC PC formalizes four performance levels in terms of tolerable levels of damage to the building, its contents, and its occupants that apply to all types of hazards. Types of damage vary according to the hazard. The four performance levels are as follows:

- **Mild Impact.** At the mild impact level, there is no structural damage and the building is safe to occupy. Injuries are minimal in number and minor in nature. Nonstructural systems needed for normal use and emergency operations are fully functional. Damage to contents is minimal in extent and minor in cost. Minimal hazardous materials are released to the environment.
- **Moderate Impact.** At the moderate level, moderate, repairable structural damage, and some delay in re-occupancy is expected. Nonstructural systems needed for building use are fully operational, although some cleanup and repair may be required. Emergency systems remain fully operational. Injuries may be locally significant, but are generally moderate in number and in nature; the likelihood of a single life loss is low and the likelihood of multiple life loss is very low. Some hazardous materials are released to the environment, but the risk to the community is minimal.
- **High Impact.** At the high impact level, significant damage to structural elements, but no large falling debris, is expected. Repair of structural damage is possible, but significant delays in re-occupancy can be expected. Nonstructural systems needed for normal building use are significantly damaged and inoperable. Emergency systems

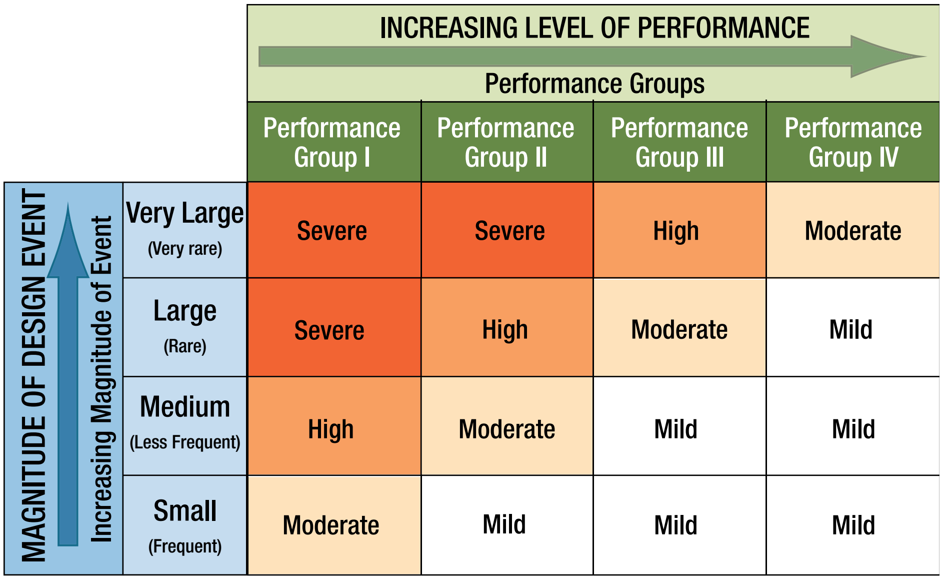
may be significantly damaged, but remain operational. Injuries to occupants may be locally significant with a high risk to life, but are generally moderate in number and nature. The likelihood of a single life loss is moderate, and the likelihood of multiple life loss is low. Hazardous materials are released to the environment and localized relocation is required.

- **Severe Impact.** At the severe impact level, substantial structural damage is expected and repair may not be technically feasible, though all significant structural components continue to carry gravity load demands. The building is not safe for re-occupancy, because re-occupancy could cause collapse. Nonstructural systems for normal use may be inoperable, and emergency systems may be substantially damaged and inoperable. Injuries to occupants may be high in number and significant in nature. Significant hazards to life may exist. The likelihood of single life loss is high and the likelihood of multiple life loss is moderate. Significant amounts of hazardous materials may be released to the environment and relocation beyond the immediate vicinity is required.

The 2012 edition of the ICC PC will use the same system to classify performance groups that is used in ASCE 7-05 to classify structures. The groups are based on use or occupancy and each has different requirements. Prior to the 2010 edition, the ASCE 7 classification of structures included schools in Occupancy Category III and Occupancy Category IV, based on capacity. ASCE 7-10 categorizes buildings and structures into “risk categories” and no longer includes occupancy type. The risk categories are equivalent to the “performance groups” that are used in the ICC PC. The performance groups that apply to schools include:

- **Performance Group IV** (Risk Category IV) includes buildings and structures designated as essential facilities, and those for which failure could pose a substantial hazard to the community. Essential facilities are defined as those “intended to remain operational in the event of extreme environmental loading from wind, snow, or earthquakes.”
- **Performance Group III** (Risk Category III) includes buildings and structures for which failure could pose a substantial risk to human life and those not included in Risk Category IV with “potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure.”

The ICC PC relates performance group and the maximum level of damage to be tolerated for different magnitudes of design events, as shown in Figure 2-2. Figure 2-3 relates the magnitude of design event to the mean return period (recurrence interval) for seismic, flood, and wind hazards. For example, consider a Performance Group III building that the stakeholders determine should be designed such that it will have a “moderate” level of performance (or moderate damage is the maximum level of damage to be tolerated). As indicated by Figure 2-2, to provide that level of performance, the building must be designed for large (or rare) events. And, based on Figure 2-3, if it is located in an area exposed to seismic risk, it should be designed for a seismic event that has a 475-year return period. To address flooding, the designers would have to determine the site-specific exposure (i.e., whether the location is exposed to flood hazards in addition to the 1-percent-annual-chance [100-year] flood, such as levee failure or dam failure). And to address high winds, the building should be designed for winds with a 100-year return period.



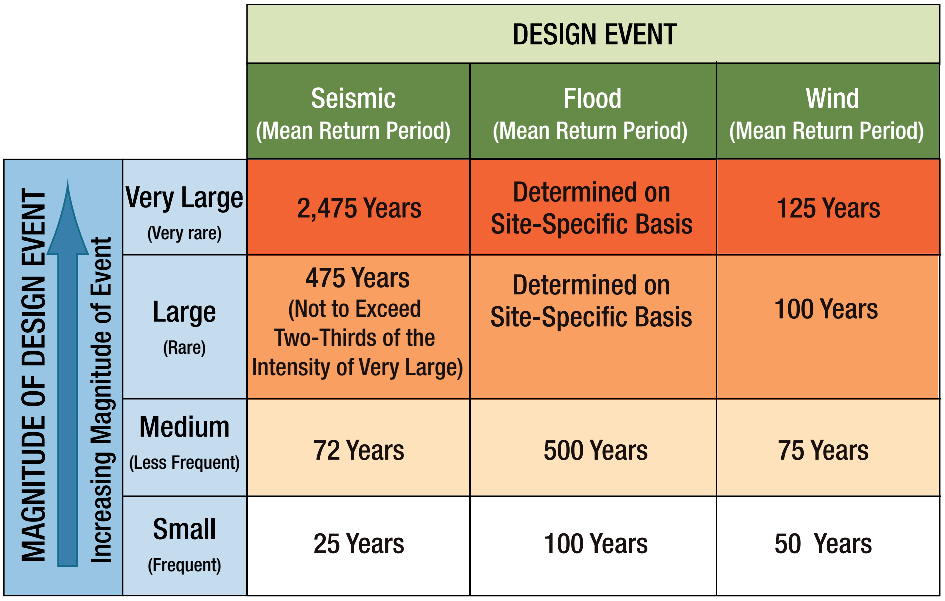
	Performance Group I	Performance Group II	Performance Group III	Performance Group IV
Very Large (Very rare)	Severe	Severe	High	Moderate
Large (Rare)	Severe	High	Moderate	Mild
Medium (Less Frequent)	High	Moderate	Mild	Mild
Small (Frequent)	Moderate	Mild	Mild	Mild

Figure 2-2: Maximum level of damage to be tolerated based on performance groups and magnitude of design event

SOURCE: ICC, 2009

Figure 2-3:
Relative magnitude and return period for seismic, flood, and wind events

SOURCE: ICC, 2009



MAGNITUDE OF DESIGN EVENT Increasing Magnitude of Event	DESIGN EVENT		
	Seismic (Mean Return Period)	Flood (Mean Return Period)	Wind (Mean Return Period)
Very Large (Very rare)	2,475 Years	Determined on Site-Specific Basis	125 Years
Large (Rare)	475 Years (Not to Exceed Two-Thirds of the Intensity of Very Large)	Determined on Site-Specific Basis	100 Years
Medium (Less Frequent)	72 Years	500 Years	75 Years
Small (Frequent)	25 Years	100 Years	50 Years

2.5 Considerations For Achieving Continuous Operation Performance Level

After the preliminary design has been developed based on the selected performance level, the next step in the performance-based design process is to perform a series of simulations (analyses of building response to loading) to estimate the probable performance of the building under various design scenario events. Using fragility relationships (vulnerability functions defining the relationship between load and damage) developed through testing or calculation, building responses are equated to damage states expressed as levels of performance. If the simulated performance meets or exceeds the performance objectives, the design may be considered complete. If not, the design must be revised in an iterative process until the performance objectives are met. In some cases, meeting the stated objective at a reasonable cost will not be possible, in which case the team of designers, decisionmakers, and stakeholders may elect to modify some of the original performance objectives.

Continued and uninterrupted operation is an important performance requirement for schools, regardless of the level of structural and nonstructural building damage, especially schools that are designated as community shelters. In other words, the acceptable performance is achieved as long as the structural and nonstructural damage to the building does not disrupt or impair the continued operation and functionality. In recent hurricanes, structures that did not sustain any structural damage were rendered inoperable as a result of nonstructural damage resulting in unacceptable performance (FEMA, 2006).

In terms of affecting the functionality and performance of a facility, the failure of nonstructural systems (roofing; exterior envelope; heating, ventilation, and air-conditioning [HVAC]; emergency systems) can be as significant as the failure of structural components. Performance-based design provides a framework for considering the potential hazards that can affect a facility or site, and for explicitly evaluating the performance capability of the facility and its components—including nonstructural systems and components.

Designers must also consider the likelihood that at least a portion of the distribution systems of critical infrastructure services (e.g., electrical power, communications, potable water, and sanitary sewer) could be interrupted. The impact of interruptions in service should be assessed, and the time until service could be restored or supplemented should be estimated. To protect the continued operation of schools, especially those designated as community shelters, the most reliable approach is to provide alternative onsite systems in the form of: (1) emergency power generation capabilities; (2) local wireless communications; (3) potable water supplies; and (4) temporary onsite storage for sanitary waste.

While the practice of performance-based design is more advanced in the field of seismic design than the fields of flood and high-wind design, the theory of performance-based design is transferable to all hazards. The practice of performance-based design will prompt designers and owners of buildings in flood- or high-wind-prone regions to begin thinking in terms of a few basic objectives:

- Can the real probabilities and frequencies of flood and high-wind events during the useful life of the building be defined with an acceptable degree of accuracy?
- Can the extent and kinds of damage that can be tolerated be defined?
- Are there ways in which an acceptable level of performance can be achieved?
- Are there alternative levels of performance that can be achieved, and how much do they cost over the lifetime/ownership of the building compared to the benefits of reduced damage and improved performance?
- How do these levels compare to the performance levels of designs using the minimum requirements of the applicable building code?

2.6 Performance-Based Flood Design

The performance levels and objectives for schools and other critical facilities exposed to flood hazards are:

- **Mild Impact.** The facility sustains no structural or nonstructural damage, emergency operations are fully functional, and the building is immediately operational. The site is not affected by erosion, but may have minor debris and sediment deposits.
- **Moderate Impact.** The facility is affected by flooding above the lowest floor, but damage is minimal due to low depths and the short duration of flooding. Cleanup, drying, and minor repairs are required, especially of surface materials and affected equipment, but the building can be back in service in a short period of time.
- **High Impact.** The facility may sustain structural or nonstructural damage that requires repair or partial reconstruction, but the threat to life is minimal and occupant injuries are few and minor. Water damage to the interior of the facility requires cleanup, drying, and repairs, and may preclude occupancy of all or a portion of the facility for several weeks to several months.
- **Severe Impact.** The facility is severely damaged and likely requires demolition or extensive structural repair. Threats to occupants are substantial, and warning plans should prompt evacuation prior to the onset of this level of flooding. This performance level is applicable to facilities affected by all types of flooding, including those that result from failure of dams, levees, or floodwalls.

Planning and design to achieve an appropriate level of flood protection should include avoidance of flood hazard areas and the addition of a factor of safety (freeboard) to the anticipated flood elevation. Performance evaluation of a facility affected by flooding should consider the building response to the following load conditions (fragility functions must be developed to relate calculated response to actual damage states):

- Lateral hydrostatic forces
- Vertical (buoyant) hydrostatic forces
- Hydrodynamic forces
- Surge forces
- Impact forces of floodborne debris
- Breaking wave forces
- Localized scour

2.7 Performance-Based High-Wind Design

The performance levels and objectives for schools and other critical facilities exposed to high-wind hazards are:

- **Mild Impact.** The facility is essentially undamaged and is immediately operational.
- **Moderate Impact.** The facility is damaged and needs some repairs but can be functional and occupied after minor repairs to nonstructural components are complete.
- **High Impact.** The facility may be structurally damaged but the threat to life is minimal and occupant injuries are few and minor. However, damage to nonstructural components (e.g., roofing, building envelope, exterior-mounted equipment) is great, and the cost to repair the damage is significant. If rain accompanies the windstorm, or if rain occurs prior to execution of emergency repairs, water damage to the interior of the facility may preclude occupancy of all or a portion of the facility for several weeks to several months.
- **Severe Impact.** The facility is severely damaged and will probably need to be demolished. Significant collapse may have occurred, and there is a great likelihood of occupant casualties unless the facility has a specially designed occupant shelter. This performance level is applicable to facilities struck by strong or violent hurricanes or tornadoes. For other types of windstorms, this performance level should not be reached.

The challenge with respect to performance-based high-wind design is assessing the wind resistance of the building envelope and exterior-mounted equipment, and the corresponding damage susceptibility. Several factors make this assessment challenging:

- Analytical tools (i.e., calculations) are currently not available for many envelope systems and components, and realistic long-term wind resistance data is lacking.
- Because of the complexity of their wind load responses, many envelope systems and components require laboratory testing, rather than analytical evaluation, in order to determine their load-carrying capacities.
- Eventually, finite element analysis will likely augment or replace laboratory testing, but substantial research is needed before finite element analysis can be used for the broad range of existing building envelope systems.
- Significant research is needed before design professionals can accurately assess the response of buildings and components to the effects of high winds.

2.8 Performance-Based Seismic Design

For performance-based seismic design, the performance levels described in ASCE 41, *Seismic Rehabilitation of Existing Buildings* (2007), for both structural and nonstructural systems are the most widely-recognized characterizations. These performance levels are summarized in a matrix (see Table 2-1) and allow specification of an overall performance level by combining the desired structural performance with a desired nonstructural performance.

Table 2-1: Combinations of structural and nonstructural seismic performance

Nonstructural Performance Levels	Structural Performance Levels and Ranges					
	S-1 Immediate Occupancy	S-2 Damage Control Range	S-3 Life Safety	S-4 Limited Safety Range	S-5 Collapse Prevention	S-6 Not Considered
N-A Operational	Operational 1-A	2-A	Not Recommended	Not Recommended	Not Recommended	Not Recommended
N-B Immediate Occupancy	Immediate Occupancy 1-B	2-B	3-B	Not Recommended	Not Recommended	Not Recommended
N-C Life Safety	1-C	2-C	Life Safety 3-C	4-C	5-C	6-C
N-D Hazards Reduced	Not Recommended	2-D	3-D	4-D	5-D	6-D
N-E Not Considered	Not Recommended	Not Recommended	Not Recommended	4-E	Collapse Prevention 5-E	No Rehabilitation

Four of the ASCE 41 performance levels identified in Table 2-1 are analogous to the ICC PC performance levels. “Mild” is similar to Operational (1-A); “Moderate” Is similar to Intermediate Occupancy (1-B); “High Impact” is similar to Life Safety (3-C); and “Severe” is similar to Collapse Prevention (5-C). These four performance levels are described below.

Operational Building Performance Level (1-A)

Buildings that meet this building performance level are expected to sustain minimal or no damage to their structural and nonstructural components. The building is able to continue its normal operations with only slight adjustments for power, water, or other utilities that may need to be provided from emergency sources.

Under low levels of earthquake ground motion, most schools should be able to meet or exceed this target building performance level. However, designing buildings to achieve this performance level under very rare, intense ground shaking, may not be cost effective except for buildings that offer unique services or that contain exceptionally hazardous material.

Full functionality is normally considered difficult to achieve in the immediate aftermath of strong earthquake shaking. Offsite issues, such as staff availability and potential loss of utilities that are not under the control of the facility, may more seriously impair operations. In addition, relatively minor onsite damage to key components can significantly affect overall functionality. For example, failure of a single anchor point for a primary emergency generator could disrupt functionality at least for a short period of time.

Immediate Occupancy Building Performance Level (1-B)

Buildings that meet this building performance level are expected to sustain minimal damage to their structural elements and only minor damage to their nonstructural components. While it is safe to reoccupy a building designed for this performance level immediately following a major earthquake, nonstructural systems may not function due to power outage or damage to fragile equipment. Consequently, although immediate occupancy is possible, some cleanup and repair and restoration of utility services may be necessary before the building can function in a normal mode. The risk of casualties at this target performance level is very low.

Many building owners may wish to achieve this level of performance when the building is subjected to moderate earthquake ground motion. In addition, some owners may desire such performance for very important buildings even if exposed to severe earthquake ground shaking. This level provides most of the protection obtained under the Operational Building Performance Level without the costs of standby utilities and rigorous seismic equipment performance.

Designing to the Immediate Occupancy Building Performance Level is more realistic than the Operational Building Performance Level for most buildings, and at a minimum, should be the design goal for all new school buildings. However, because even the smallest disruption of nonstructural systems may be too detrimental for continued operation of a school that is designated as a shelter, owners and designers should consider an even higher level of protection for critical functions associated with this use. For instance, stakeholders should consider providing for the independent operation of critical utilities for a minimum of 4 days. Critical utilities usually include electric power, water, sanitary sewer, and, depending on the local weather conditions, fuel for heating and cooling.

Life Safety Building Performance Level (3-C)

Buildings that meet this building performance level may experience extensive damage to structural and nonstructural components. Repairs may be required before re-occupancy, though in some cases extensive restoration or reconstruction may not be cost effective. The risk of casualties at this target performance level is low.

This building performance level allows somewhat more extensive damage than would be anticipated for new buildings designed and constructed for seismic resistance. The Life Safety Building Performance Level should prevent significant casualties among able-bodied school occupants.

Collapse Prevention Building Performance Level (5-E)

Although buildings that meet this building performance level may pose a significant hazard to life safety resulting from failure of nonstructural components, significant loss of life may be avoided by preventing collapse of the entire building. However, many buildings designed to meet this performance level may be complete economic losses.

Sometimes this performance level is selected as the basis for mandatory seismic rehabilitation ordinances enacted by regulatory authorities because it mitigates the most severe life-safety hazards at the lowest cost. The Collapse Prevention Building Performance Level is intended to prevent only the most egregious structural failures, and does not allow for continued occupancy and functionality or cost-effective damage repair of structural and nonstructural components.

2.9 References

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