NIST Grant/Contractor Report
NIST GCR 23-037

Resilience for Critical Facilities

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Resilience for Critical Facilities

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Executive Summary

Critical facilities are those facilities within our communities that society depends on to function through, or soon after, a major disruptive event. The ability of critical facilities to quickly return to providing pre-event services will significantly influence the community's ability to respond and recover.

Most individuals believe that complying with the building codes and standards adopted by their local jurisdictions will result in buildings that are "earthquake proof, flood proof, or windstorm proof." However, codes and standards in the United States are minimum design standards with the performance objective of providing life safety. This means that the buildings are designed to allow the occupants to safely evacuate the building during or following a major event, however the building might be significantly damaged and not immediately, or ever, occupiable.

Further complicating the restoration of societal services, lifeline infrastructure systems (e.g., water, electric power, transportation, etc.) are designed using practices, regulations, codes, and standards, which are independently developed and do not always match the performance objectives of the building codes. This disconnect can lead to varying performance levels among these different systems for the same hazard event.

The three categories of critical facilities addressed in this document are hospitals, K-12 educational facilities, and data centers. This review focuses on both requirements for new building design as well as for existing building renovations or additions for the flood, wind, and seismic hazards. An overall review of current design practices for these three categories of critical facilities within our communities is discussed, along with some of the best practices currently being utilized to provide more resilience

within these facilities. The target audience of this report includes industry associations, design professionals, building code officials, city planners, and researchers.

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Glossary of Terms

Addition (*IEBC (ICC 2021a))* An extension or increase in floor area, number of stories, or height of a building or structure.

Alteration (*IEBC (ICC 2021a))* Any construction or renovation to an existing structure other than a repair or addition.

Base Flood *(ASCE/SEI 24 (ASCE 2014))* Flood having a 1% chance of being equaled or exceeded in any given year.

Base Flood Elevation (BFE) *(ASCE/SEI 24 (ASCE 2014))* Elevation of flooding, including wave height, having a 1% chance of being equaled or exceeded in any given year.

Building Cluster *- (NIST 2016)* A set of buildings and supporting infrastructure that serve a common function such as housing, healthcare, retail, etc. Clusters are not necessarily geographically co-located and may be distributed throughout the community.

Collapse Prevention *(ASCE/SEI 41 (ASCE 2017))* Collapse Prevention is defined as the post-earthquake damage state in which a structure has damaged components and continues to support gravity loads but retains no margin against collapse.

Design Flood *(ASCE/SEI 24 (ASCE 2014))* The flood associated with the greater of the following two areas: (1) area within a floodplain subject to a 1% or greater chance of flooding in any year, or (2) area designated as a flood hazard area on a community's flood hazard map or otherwise legally designated.

Design Flood Elevation (DFE) *(ASCE/SEI 24 (ASCE 2014))* Elevation of the design flood, including wave height, relative to the datum specified on the community's flood hazard map.

Dry Floodproofing *(ASCE/SEI 24 (ASCE 2014))* A combination of measures that results in a structure, including the attendant utilities and equipment, being watertight with all elements substantially impermeable and with structural components having the capacity to resist flood loads.

Heavy Damage (*ATC-20-1 Bhutan Field Manual – UNSAFE (Red))* Unsafe but stable. Repairs may be possible; Unsafe but stable. May not be repairable; At risk from adjacent premises or ground failure.

Immediate Occupancy *(ASCE/SEI 41 (ASCE 2017))* Immediate Occupancy is defined as the post-earthquake damage state in which a structure remains safe to occupy and essentially retains its preearthquake strength and stiffness.

Lifeline Infrastructure Systems Lifeline infrastructure systems include water, wastewater, drainage, communication, electric power, gas and liquid fuels, transportation, and solid waste systems (Duke and Moran, 1975). These systems are critical to the functioning of a modern society. Communities are unable to recover after an earthquake, or any other major natural hazard strike, until these systems can operate at a level to provide their basic services.

Life Safety *(ASCE/SEI 41 (ASCE 2017))* Life Safety is defined as the post-earthquake damage state in which a structure has damaged components but retains a margin of safety against the onset of partial or total collapse.

Light Damage (*ATC-20-1 Bhutan Field Manual – INSPECTED (Green))* Occupiable, no immediate further investigation required; occupiable, repairs may be necessary.

Limited Safety *(ASCE/SEI 41 (ASCE 2017))* Limited Safety is defined as a post-earthquake damage state between the Life Safety Structural Performance Level and the Collapse Prevention Structural Performance Level.

Moderate Damage (*ATC-20-1 Bhutan Field Manual – RESTRICTED USE (Yellow))* Short-term entry; occupiable, repairs required for safe entry to damaged parts.

Retrofit - The act of altering portions of a building's structure or nonstructural components with the intent of enhancing the building's ability to resist collapse or loss of function.

Substantially Impermeable *(ASCE/SEI 24 (ASCE 2014))* Use of flood damage-resistant materials and techniques for dry floodproofing portions of a structure, which result in a space free of through cracks, openings, or other channels that permit unobstructed passage of water and seepage during flooding, and which result in a maximum accumulation of 4 in. of water depth in such space during a period of 24 h.

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1.0 Introduction and Purpose

Events like Hurricane Katrina in 2005, the Christchurch, New Zealand earthquake in 2011, Hurricane Sandy in 2012, and Hurricane Maria in 2017 have underscored the devastating impacts that natural disasters can inflict at a local, regional, state, and multi-state level. The Federal government has defined the National Preparedness Goal as: "A secure and resilient Nation with the capabilities required across the whole community to prevent, protect against, mitigate, respond to, and recover from the threats and hazards that pose the greatest risk" (FEMA 2015).

One strategy to achieve this National Preparedness Goal is to plan for and implement programs and strategies to improve disaster resilience at the local, regional, state, and national level. The National Institute of Standards and Technology (NIST) *Community Resilience Planning Guide for Buildings and Infrastructure Systems* (*Guide*) provides a framework for development of an integrated community-level resilience plan that seamlessly incorporates disaster preparedness and recovery actions to help communities be more resilient (NIST 2016). The *Guide* also highlights that buildings and infrastructure systems in a community are designed and built to meet social and economic needs of the community and that recovery goals of the built environment should be driven by social and economic needs during the response and recovery phases following a hazard event. Past community resilience planning efforts [such as those in San Francisco (SPUR 2009a-d) and Oregon (OSSPAC 2013)] as well as national response and recovery frameworks developed by FEMA can provide useful information on societal needs and expectations for critical buildings, such as hospitals, schools, data centers, and associated supporting infrastructure systems (e.g., electric power, water, wastewater, etc.), during the response and recovery phases.

The National Response Framework (FEMA 2019) provides a foundational emergency management doctrine that focuses on emergency response operations and short-term recovery activities. It identifies seven interdependent community lifelines: Safety and Security; Food, Water, Shelter; Health and Medical; Energy (Power & Fuel); Communications; Transportation; and Hazardous Material (see Figure 1-1). These seven community lifelines are the most basic services a community relies on and, if stable, can enable all other activities within a community. Stabilizing these community lifelines is critical during response to reduce threats and hazards to public health and safety, the economy, and security. These seven community lifelines identified by the National Response Framework include both social services (e.g., food, shelter, health) and infrastructure services (e.g., energy, communications, transportation). The NIST Guide treats infrastructure services (including buildings) as the foundation to supporting community's social service lifelines.

Figure 1-1. Seven Community Lifelines (Source: FEMA 2019).

The National Disaster Recovery Framework (FEMA 2016) uses the recovery continuum (see Figure 1-2) to define three recovery phases: short-term, intermediate, and long-term. The short-term phase usually covers a period of days, and it focuses on search and rescue, stabilization of the community, and preparation for recovery. Note that the National Response Framework addresses the short-term recovery period. As incidents become stabilized, the recovery of the community is moved on to the intermediate phase, which focuses on restoring neighborhoods and meeting social needs. This phase typically lasts weeks to months and includes the implementation of temporary repairs or workarounds to restore services as quickly as possible to as much of the community as possible. In the long-term phase, the recovery activities focus on restoring the community's economy and social institutions and repairing or reconstructing buildings and physical infrastructure systems (with permanent solutions). The long-term recovery phase may take years to complete (NIST 2016). The duration of these three response and recovery phases is highly dependent on the level of damage that results from the hazard event. This level of damage, in turn, is both a function of the severity of the hazard and the preparedness of the community. For instance, a flood-prepared community (i.e., one with most of its buildings and lifeline infrastructure located outside the floodplain) may respond to and recover from a severe flood much more rapidly than a community that is less flood prepared.

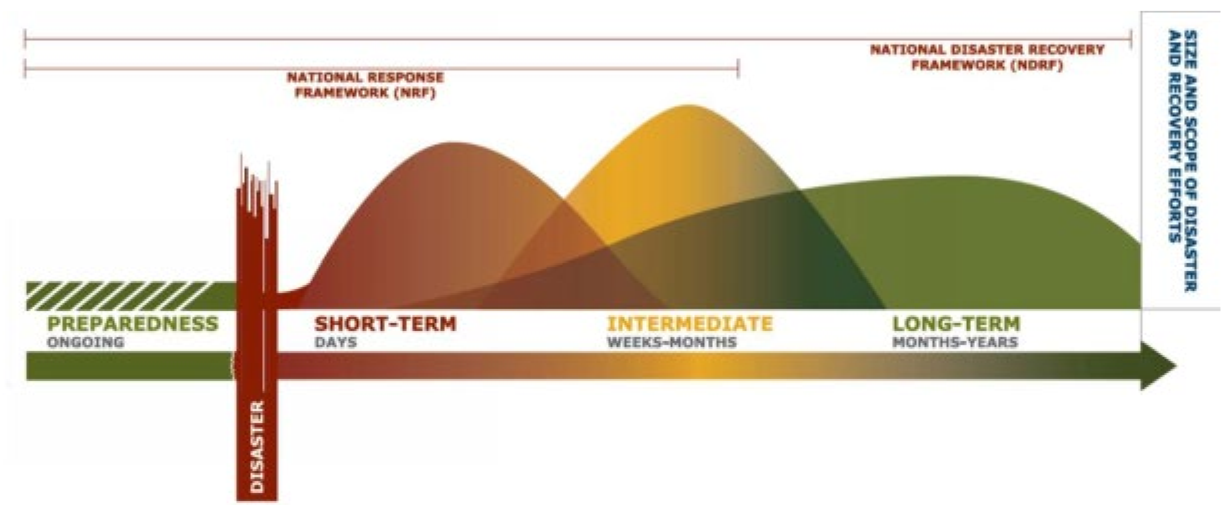


Figure 1-2. Recovery Continuum (FEMA 2016).

The United States has one of the most complex building code development and enforcement processes in the world in that there is no "national building code" and most of the states and local jurisdictions can amend the provisions of the model International Building Code (IBC) developed by the International Code Council (ICC 2021). The IBC structural loads and loading conditions are based upon the provisions of the ASCE/SEI Standard No. 7, "*Minimum Design Loads and Associated Criteria for Buildings and other*

Structures" (ASCE 2021). These references are used throughout this document and establish a minimum performance baseline for building designs in the United States.

> "The IBC is a model code that provides minimum requirements to safeguard the public health, safety and general welfare of the occupants of new and existing buildings and structures."
>
> "This standard provides minimum loads, hazard levels, associated criteria, and intended performance goals for buildings, other structures, and their nonstructural components that are subject to building code requirements." (ICC 2021)

The only type of building for which higher performance goals are specified in our standards is for,

> "Structural systems and members and connections thereof assigned to Risk Category IV shall be designed with reasonable probability to have adequate structural strength and stiffness to limit deflections, lateral drift, or other deformations such that their behavior would not prevent function of the facility immediately following any of the design level environmental hazard events specified in this standard. Designated nonstructural systems and their attachment to the structure shall be designed with sufficient strength and stiffness such that their behavior would not prevent function immediately following any of the design level environmental hazard events specified in this standard. Components of designated nonstructural systems shall be designed, qualified, or otherwise protected such that they shall be demonstrated capable of performing their critical function after the facility is subjected to any of the design level environmental hazards specified in this standard." (ASCE 2021)

Other than for Risk Category IV structures noted in ASCE/SEI 7 (ASCE 2021), the building codes and standards in the United States are based on a *life safety performance objective*, which provides an extremely low probability of failure of structural members and collapse of the structure during a design level event, but the building may be significantly damaged and not immediately, or ever, occupiable. Chapter 1 of ASCE/SEI 7 (ASCE 2021) states that Risk Category IV facilities should have a high probability of resuming their function following design level hazard events. Being able to resume function right after a major event is referred to in NIST SP-1224 as the Immediate Occupancy Performance Objective (Sattar et al, 2018). In many instances, short periods of downtime, hours or up to a few days, following a major event are acceptable, depending on the functions of the facility. In such cases, the driving consideration is the time between the event and when the facility needs to restore its basic functions. FEMA P-2090 / NIST SP-1254 (FEMA/NIST 2021) defines this as a functional recovery objective.

FEMA P-2090 / NIST SP-1254 (FEMA/NIST 2021) differentiates collapse, safety, reoccupancy, functional recovery (i.e., recovery of basic intended function), and full functionality. A building that may be occupiable may not be functional. In that condition, the building likely has minimal structural damage, but enough nonstructural damage that architectural or mechanical, electrical, and plumbing (MEP) systems are damaged in a manner that impedes recovery of building function. An example of this would be the loss of cooling in a data center. If the cooling system does not work, the servers will overheat and render the facility non-functional. In this case, there is a timeframe between the event and when the critical systems can be repaired or replaced to bring critical functions online. Basic intended functions are those which the facility is intended to provide, setting aside other tangential functions. For example, an office building that houses a data center may not require portions of the office building to be functional in the same timeframe as the data center portion of the building. So, the mechanical, electrical, and plumbing systems that serve the office may be designed to receive more damage or designed to be rerouted to serve the data center. The time to each of these milestones is known as recovery time.

Determining functional recovery timeframes involves estimating the time it takes to begin and complete the repairs. Estimating repair time is somewhat straight forward because engineering procedures can identify which structural members and nonstructural components are likely to sustain damage and the extent of that damage in each event, whether the event be a flood, windstorm, or earthquake. The FEMA P-58 series of reports (FEMA 2018) presents a statistically based methodology for estimating damage and repair time due to earthquakes.

Estimating the time between the event and the onset of repairs is more difficult. There are a number of impeding factors which can delay the beginning of repair. Some of these impeding factors (ARUP 2013 and ATC 2022) are:

- Time for an engineer to inspect the facility and identify damage that requires repair.
- Time for an engineer to design the repairs.
- Time to obtain a building permit to permit a general contractor to construct the repairs.
- Time to obtain materials and long lead-time nonstructural components (such as elevators or electrical equipment).
- Time to abate environmental hazards, like mold from a flood event, before repair can commence.
- Time for the contractor to engage subcontractors and mobilize to begin the repair.

Any one of these impeding factors can extend the recovery time by months. A recently released report, ATC 58-7 (ATC 2022), indicates that many of the factors listed above are more than three months individually, meaning that a facility will not be able to even start repairs until at least three months from the date of the event. For many critical facilities this may not be acceptable. Therefore, providing additional resilience considerations for these facilities likely requires designing to limit damage so these impeding factors are not triggered.

It is important to remember that post-event functionality of a critical facility does not mean full building functionality; it means the ability to perform the critical functions to support community recovery. Determination of these specific functions is a challenging task and the absolute minimum building functionality needed to support their continuity may vary for the same type of facility. For example, a building in a moderate western US climate that is unlikely to see major rain events may not need a façade that maintains weather tightness against wind driven rain following an earthquake like one that in a region where major rain events are common.

Another challenge to contend with in determining overall resilience is that current code requirements are not consistent across hazard and structural systems. Some provisions are based solely on life safety, others on limiting damage, and still others on providing Immediate Occupancy and resumption of function. ASCE/SEI 7-22 (ASCE 2022) presents tables on the target performance objectives for different environmental hazards. Earthquake, wind, and flood all have different target reliabilities, with earthquake being based on system collapse while wind and flood are based on individual member failure. FEMA 58-5 (2018) discusses how the performance of different structural systems can vary significantly when subject to the same hazard. In that study (FEMA 2018) repair cost and likelihood of an unsafe placard varies considerably with structural system, Figure 1-3.

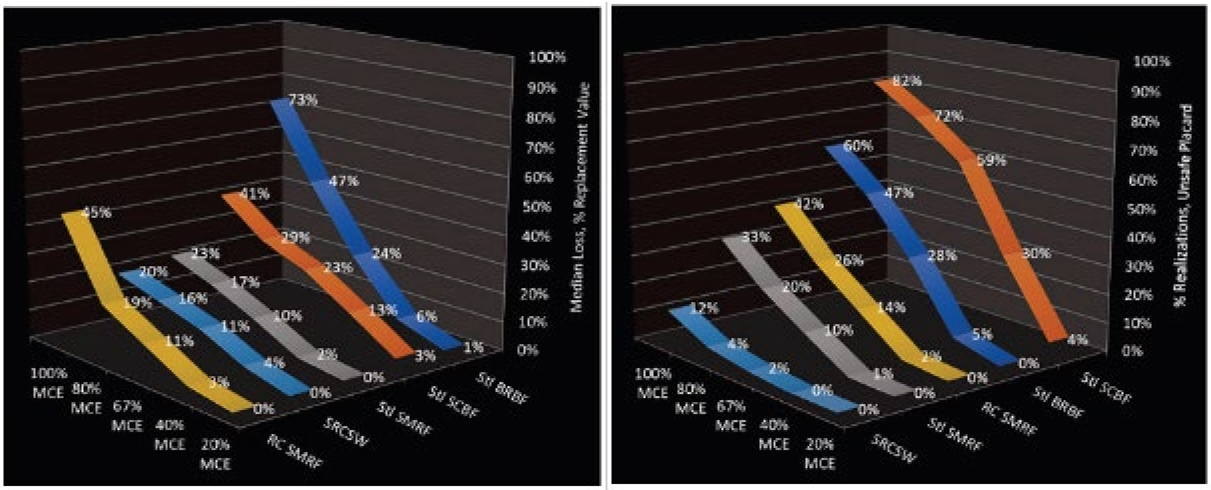


Figure 1-3: Comparison of Repair Cost as percentage of replacement cost (left) and probability of an unsafe placard (right) for four different structural systems under increasing earthquake shaking intensity. (FEMA 2018)

While many researchers and practitioners are trying to improve and synthesize codes and standards, the approval process can be challenging because of varying opinions among stakeholders regarding the role of the building codes. Building codes and standards are consensus-based documents, which means they are a snapshot in time of a majority national opinion that then may be locally modified and subjected to adoption delays; many local building codes lag the latest versions of the design standards (ICC 2021).

While building codes and design standards are regularly updated to provide better design criteria for the performance of new construction, significant issues remain for existing buildings. As shown by the damage following hazard events, buildings designed and constructed to older codes and standards have significant vulnerabilities that may render them at risk of collapse. Unfortunately, the costs to retrofit existing buildings can be significant, and the disruption of doing so in an occupied building (e.g., moving tenants out temporarily) can make improvements more difficult for private building owners to justify.

Many owners of new buildings are considering performance upgrades that go beyond code in hopes of providing better resilience to hazards. The exception comes with developer buildings that are immediately sold to one or many third-party buyers. There are ongoing conversations regarding the imposed risk on a third-party buyer who is likely not conversant on the performance provided by a code-level design. If a developer mandates a design to only meet the code minimums, the buyer has no say and likely no understanding of the performance level of the purchased building. While a special inspector or a home inspector *may* be able to help a buyer understand the likely performance and vulnerabilities, there is currently no protection or disclosure required for buildings that may incur damage or loss of function to natural hazards even if designed to code.

1.1 Resilience Objectives

Resilience is “the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions” (PPD-21 2013). Typically, resilience performance goals are defined at a community level, however the performance of each individual building or structure supports the resilience of the community. “The built environment can suffer severe damage during a hazard event. Depending on the event’s severity, many people could be ill-prepared to manage on their own, especially for an extended period. To support vital social needs, such as emergency response and acute/emergency healthcare, communities need to determine in advance which buildings and infrastructure systems are most essential and must be functional during and immediately after a hazard event. They also need to determine if and how the rest of the built environment can return to functionality in the subsequent days, weeks, and months of recovery “(NIST 2016). Buildings support many social needs and functions for the community, such as places to live, learn, provide healthcare services, and house the technology needed for everyday life. Implementing resilience design considerations for each individual building (functional recovery), new or renovated, will incrementally improve the overall resilience of the community, and improve the ability of the community to recover more rapidly from a future hazard event.

1.1.1 Reliability

It is important to reiterate that codes and standards are designed to deliver a life safety-level building based on performance reliability of the primary structural systems. In ASCE/SEI 7 (ASCE 2021) the hazard loads and load combinations are evaluated against reliability (annual probability of failure) targets for a 50-year lifespan per the assigned Risk Category. The reliability of the structure is based on the failure of a key structural member, or system of members, for the given hazard level. However, while reliability supports resilience, ASCE/SEI 7 (ASCE 2021) reliability is not a measure of resilience.

When considering ASCE/SEI 7 (ASCE 2021) reliability targets, some potential shortfalls for resilience revolve around the corollary damage to non-structural systems. The current reliability targets and design requirements for the life safety of structural systems may need to be modified to also reduce damage to nonstructural systems. For example:

- A 50-year target lifespan might be considered too short for building when considering resilience goals.
- While the failure of a primary structural element could render a building non-functional after an event, other non-structural failures, such as damaged cladding or mold in a building after a flood, can equally render a building non-functional.

- Increased reliability can be provided with additional robustness (load resistance and/or ductility) of the primary structural members. However, as hazard levels increase, the ability for a building to recover may be determined by other elements not considered in ASCE/SEI 7 (ASCE 2021). For instance, magnifying the loads produced by the 100-year flood will only increase the reliability of the structural elements that see the load. If a 500-year flood happens, where the depth exceeds that of the 100-year flood, then non-structural elements that were shielded by the 100-year flood resisting system will now see flood loads that previously saw none. The participation of these non-structural elements is not considered in structural reliability.

In addition, because of the increasing pressure of climate change, many hazard levels established in ASCE/SEI 7 (ASCE 2021) may occur more frequently than the established mean recurrence intervals and target reliability. Design for resilience may require adjustments to the ASCE/SEI 7 (ASCE 2021) loads, including allowance for climate changes, and analyses that target critical structural and non-structural system failures that will affect reoccupancy.

1.1.2 Goals

Community leaders and stakeholders need to establish resilience-based goals for the community. Typically, a community is looked at in terms of “building clusters” when setting community goals. “Building clusters” are a set of buildings that support a social function (i.e., education, healthcare, shelter, etc.). Building cluster goals should be based on the understanding that not all buildings within the cluster will suffer the same level of damage during the event and therefore the timeframe to return to a level of functionality may be less than that for an individual building. It should be noted that the number of facilities in each building cluster, and redundancy of building types, is dependent on the size of the community. For instance, a small community may have only one hospital (or none), while a larger community may have several hospitals. Community resilience goals will help the owners of critical facilities establish resilience goals for their individual facilities and inform the designers of these facilities as to what performance objectives need to be considered.

1.1.3 Objectives

Resilience objectives for the community, and its buildings, are independent of the hazard type being considered. Some buildings need to function immediately following a disruptive event, typically these are the critical facilities being examined in this report. Often these objectives are expressed in terms of facility requirements for performance and a timeframe for being returned to function. However, design solutions to meet resilience performance objectives are often hazard specific. Overall performance of an individual building is dependent on many factors, such as the type of occupancy and the designated Risk Category that the building codes require to be utilized during its design.

1.1.4 Redundancy

Where it can be difficult to qualify and quantify the external threats for an individual building in a specific location and provide a cost-effective design for a range of hazard possibilities, some building owners are using site redundancy as a resilience strategy by having a second building in a different area of the community, county, state, or country. While this strategy helps support the idea of community resilience, it may be the most resilient option for a given business as it is independent of their building *and* the community surviving the hazard; both components are needed for a business to resume operation after an event.

During the intermediate phase of recovery, as shown in Figure 1-2, getting schools reopened is a critical step in successful community recovery efforts, often marking the shift from response efforts to recovery efforts. Reopening schools within a few weeks fulfills two basic functions, it allows parents to know that their children's education is continuing, and it helps enable the parents to return to work. These two challenges are primary reasons why families, and therefore workers, leave communities following a disaster. Based on community resilience plans developed in San Francisco (SPUR 2009a-d) and Oregon (OSSPAC 2013), a common goal is to re-open schools within 30 days. This means that classrooms, if used as shelter spaces, need to be transitioned back to hold classes while gymnasiums could continue to be used for shelter purposes as needed based on a community's recovery situation.

Resilience objectives are based on the time to recover functionality, or stages of functional recovery. Full functionality may not be attainable for an extended period; however, a building may be able to provide an adequate level of service for its original purpose in a shorter period. For the critical facilities discussed in this document, the level of recovery can be defined by percentages of operational capacity. This approach is based on the community resilience goals for a "building cluster" (NIST 2015) for all facilities supporting a service, such as healthcare facilities. For an individual building or infrastructure system, additional specific performance objectives are also needed [See Table 1-2 from the NIST Technical Document 2209 (McAllister et al 2022)]. For individual facilities, similar qualitative resilience goals can be expressed as:

- Thirty percent operational capacity of a facility is considered the lowest level at which a facility may start to operate after the initial recovery efforts for the facility.
- Sixty percent operational capacity of a facility is considered the level at which daily operation of the facility can resume at a reduced capacity.

- Ninety percent operational capacity of a facility is considered the level at which normal operations can occur.

Table 1-1. Relationship between Community and Project Resilience Goals (NIST 2022).

Community Resilience Goal	Project Resilience Objective
• Improve/expand existing infrastructure to support projected population growth	• New and existing infrastructure (water system) meet code/regulations, including the ability to recover function for a 500-yr seismic event within X days, with temporary measures (generators and pumps as needed.
• Minimize infrastructure loss of function/services from a specific hazard event	• New infrastructure (hospital) meets code and can provide critical functions after a 500-yr flood event with no loss of services.
• Improve reliability and redundancy for specific community functions before and after a hazard event	• New infrastructure (electric power distribution) meets code/regulations for a 700-yr wind event and can deliver power to specified facilities with no loss of service.

The time needed to return to these levels of operational capacity is measured in terms of days, weeks, and months and the return-to-capacity timeframe goals depend on the “redundancy” of the services that a building relative to the building cluster provides to the community. For example, if there are multiple hospitals serving a community, then the return to full operational capacity for an individual hospital might be less urgent for the societal needs of the community than if it is the only hospital serving that community.

In combination with the operational time frames, the resilience objectives for the facility should be determined for varying degrees of the hazard being considered (NIST 2016):

- *Routine* – Those events that are below the design level, and occur frequently (e.g., approximately a 50% chance of exceedance over a 50-year period),
- *Design Level* – Those events that are the basis of the code-level design (e.g., approximately a 10% chance of exceedance over a 50-year period),

- *Extreme* – Those events that exceed the design level, and are possible but occur infrequently (e.g., approximately a 2% chance of exceedance over a 50-year period).

Understanding resilience goals and objectives in terms of the timeframe to operational capacity, as well as the level of event being considered, will provide the designer with guidance for considerations that should be incorporated into their design to meet the needs of the facility and community. These objectives may vary depending on whether the facility is a new facility, or the design is for a retrofitted facility. Typically, specified resilience objectives can be addressed during the design process of a new facility, while upgrading an existing facility might be infeasible in terms of performance or cost. One of the main points in the SPUR report (SPUR 2009) was the concept of designing new buildings for higher performance levels to compensate for the existing facilities (which still need to be upgraded) in the community.

1.2 Scope and Purpose

The critical facilities being examined in this document are hospitals, K-12 schools, and data centers. Each of these facilities meets different societal needs within the community response framework, however all these facilities are critical to the response and the recovery of a community following an event. Currently, as seen in Table 1-2 which summarizes new building Risk Categories, only new hospitals are required to be designed as an Essential Facility, benefitting from the enhanced Immediate Occupancy performance criteria associated with Risk Category IV. To accelerate the recovery efforts within a community, all three of the facility types that are highlighted in this document, both new and existing, should consider resilience concepts during the design and retrofit of the individual facilities, beyond the code minimum requirements.

Table 1-2. IBC Risk Categories of Examined Facilities (ICC 2021).

Facility Type	Risk Category
Data Center	II*
Hospital	IV
K-12 School	III*

* Assumes building is not designated as an Essential Facility

Each community faces potential disruption from a unique set of hazards based upon its geographical region and exposure and thus there are many combinations of hazards to be considered during the design process. To help focus the discussion and to provide examples of resilient design opportunities for these critical facilities, the natural hazards being considered in this document are limited to seismic, wind (excluding tornadoes) and flood (coastal, pluvial, and riverine) events. These hazards are the most prevalent hazards that have occurred over the twenty-year period between 1995 through 2015 according to the United Nations and have resulted in the most deaths from natural hazards.

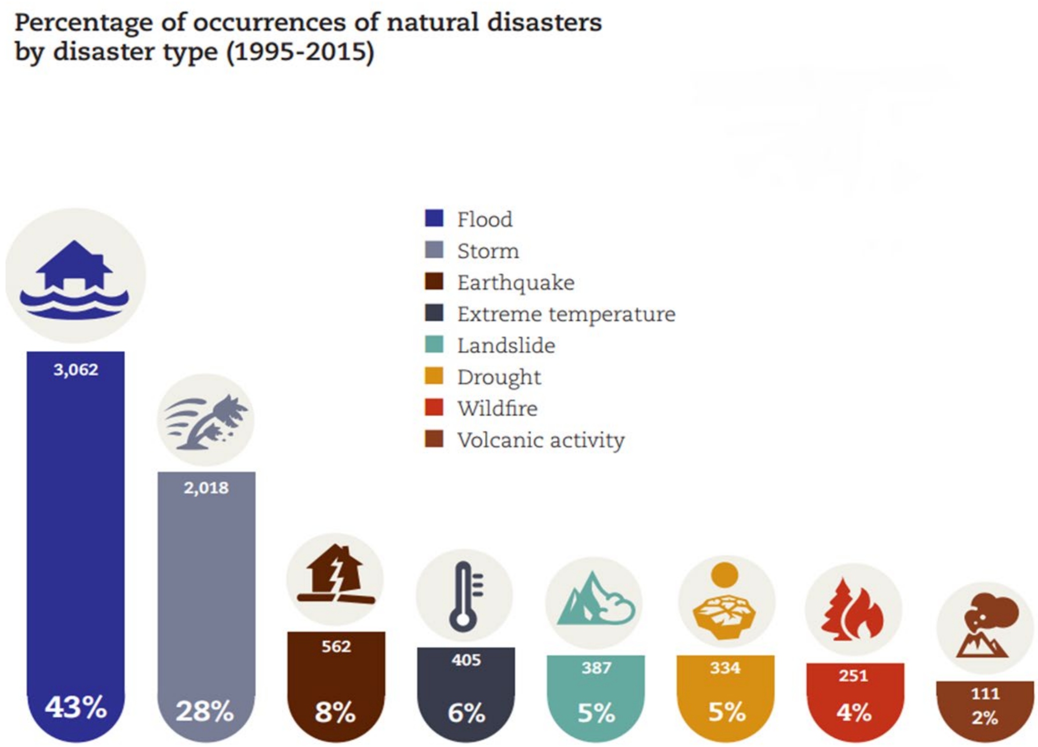


Figure 1-4. Occurrence of Hazard Types 1995 – 2015 (UN/CRED)

This document is intended to serve as a best practices resource for designers for addressing resilient performance in critical facilities beyond what is achieved by a code-level design. This includes understanding and considering the role of the facility in the community, identifying performance objectives and design practices that incorporate types of structural and nonstructural damage, and associated recovery actions and timelines. The document is limited to facilities for healthcare, K-12 education, and data/IT services, but certainly many of the best practices could be applied to any designated critical facility.

1.2.1 Hospitals

Hospitals as a building cluster are essential to delivering community medical care services as part of stabilization of the *Health and Medical* community lifelines (see Figure 1-1). The community expects hospitals to function and operate, during and after a hazard event, to continue to serve existing patients and treat new patients who are injured during the event. To fulfill this expectation of providing services, all the community's infrastructure lifeline systems need to function at some level to allow hospitals to function.

1.2.2 Schools as Emergency Shelters

Emergency shelters are an important part of the *Food, Water, Shelter* community lifeline. Schools are often used as emergency shelters after a hazard event as communities almost never design and build single purpose emergency shelters. As an elementary school is likely within walking distance for the community it is serving, they are well positioned to be community distribution centers or points for water and emergency relief supplies, and could be a hub for day-to-day community needs, such as information transfer, assistance with obtaining needed resources, or charging cell phones. Middle schools and high schools typically have larger facilities with gymnasiums, locker rooms, kitchen, cafeteria, athletic fields, etc. that make them ideally suited for use as emergency shelters. In addition, the school grounds also provide open spaces to allow for the distribution of supplies and services for others in the community. If an elementary school has a larger gymnasium and cafeteria space, they may also be considered for use as an emergency shelter. Communities expect emergency shelters to be established within 24 to 72 hours after a major disaster.

1.2.3 Data Centers

For the past thirty years, public agencies and private businesses have been moving their operations to internet-based systems, such as cloud storge and web-based services. These business practices have created a new dependency on data centers in addition to electric power and telecommunications. It is anticipated that government agencies and infrastructure owners will continue to migrate their critical business elements to the cloud. In addition, more infrastructure devices and equipment require internet connections to work, including major medical equipment. After a major disaster, communities expect data centers that support community lifelines, communications, and equipment to be operational immediately after a hazard event.

1.3 Technical Approach

The project began with a review of the current national codes, standards, and best practices relating to the current considerations of resilient design and construction of hospitals, K-12 educational facilities and data centers built in the United States. This review included the following:

- Current design practices, codes, standards, local regulations, and best practices for these critical facilities regarding the flood, seismic and wind environmental hazards.
- The role of dependencies and recovery of function objectives addressed in the current literature for these facility types.
- The differences between modern designs and the upgrading of these existing critical facilities.

1.4 Organization of Report

This document is organized as follows. Chapter 2 contains an overview of hospitals, K-12 educational facilities, and data centers and associated risk categories, a summary on the evolution of codes and standards related to flood, seismic, and wind hazards, and discussion of the current codes and standards for design of these facilities (including both structural and nonstructural systems). Chapter 3 provides an assessment of current codes and standards, including design criteria, design review and coordination, and construction inspection, as well as best practices for achieving resilience of these critical facilities. In Chapter 4, several case studies are included to demonstrate how some of the best practices have been implemented to improve resilience of the critical facilities. Chapter 5 summarizes key findings from Chapters 2 through 4.

2.0 Design of Critical Facilities

The critical facilities considered in this document are hospital facilities, educational facilities, specifically K-12 buildings serving the community, and data center facilities which serve many businesses, infrastructure systems, and government agencies within a community. These facilities provide societal services to the community but without operational functionality the recovery of the community is delayed.

A review of the current design requirements for critical facilities is conducted. This review includes discussion of the types of structural systems utilized for these facilities, the design objectives for the facility and identification of the gaps these requirements yield when considering recovery efforts or providing the services that communities need from these facilities. A discussion of non-structural component design requirements is included, as following many hazard events, it is these elements that lead to the closing of the facility until they can be repaired. Also discussed are the specific flood, wind, and seismic requirements and their basis in current codes and standards.

2.1 Overview

Building code design requirements differ for each of these types of critical facilities, beginning with the Risk Category designation. Data centers can be classified as a Risk Category II facility by the code, while K-12 educational facilities are classified as Risk Category III facilities because of the number of individuals in the building, and hospitals are classified as Risk Category IV structures because of emergency surgery or treatment facilities. These Risk Category designations lead to differing environmental design load requirements in each facility's design. The intent of this difference in the loading is to help reduce the damage for higher Risk Category structures during a design level event. Risk Category IV is the only category where the structural design standards indicate that protecting function is a design consideration.

History has shown that, while the building structural system might perform as intended by the building code, the overall facility may not because of a breach of the building envelope or damage to non-structural elements – the architectural components, mechanical, electrical, and plumbing (MEP) components, and furniture, fixtures, and equipment (FF&E) and contents. It is the nonstructural damage that tends to lengthen the operational recovery time for these facilities. Water intrusion due to the building's envelope losing its water tightness or wind-borne debris damage can lead to environmental hazards like mold, which require the facility to be shut down until health, safety, and operational requirements are restored. Unintended discharge of the fire suppression system because a sprinkler head hit a ceiling tile in an earthquake can have a similar effect.

Sometimes, the observed performance of the building's structure is not what the code intended. This is most prevalent with earthquakes, where major damage to buildings identified gaps in the code. For example, the 1971 San Fernando earthquake caused disproportionate damage to concrete buildings, leading to significant changes in the requirements for proportioning reinforcement. The 1994 Northridge earthquake identified issues with weld fractures at beam-to-column connections in steel moment frame buildings that were unexpected and led to major changes in design and detailing. While codes and standards are changed to address these issues, requirements to go back and mitigate conditions in existing buildings rendered non-compliant are rare, as will be discussed in more detail in the existing building sections of this document. The following sections will discuss each of the selected critical facilities, each of which has some unique characteristics to be considered in their designs that can affect their response to and recovery from hazard events.

2.1.1 Hospital Facilities

Communities assume that hospital facilities are available 24-hours a day every day, including during, and following a major hazard event. The ASCE/SEI 7 (ASCE 2021) standard recognizes this need and requires that hospitals be designed for a Risk Category IV classification, the highest classification currently contained in the building code.

ASCE/SEI 7 (ASCE 2021) requires *functionality* in a Risk Category IV structure. In Section 1.3.3 of the standard it notes, “Structural systems and members and connections thereof assigned to Risk Category IV shall be designed with reasonable probability to have adequate structural strength and stiffness to limit deflections, lateral drift, or other deformations such that their behavior would not prevent function of the facility immediately following any of the design-level environmental hazard events specified in this standard.” However, Chapter 1 of ASCE/SEI 7 (ASCE 2021) is not referenced in the International Building Code (IBC) (ICC 2021) and thus this requirement is not mandated in the IBC.

There are a few healthcare services that are necessary on a regular basis that cannot be entirely fulfilled by hospitals in a community, for example dialysis services. These types of services are often provided in facilities that have been assigned to a lower Risk Category and thus can suffer significant damage in a design level event that would prevent occupancy of the facility. The needs of the community should be considered in the design and construction of non-acute care facilities providing these types of services and their design levels increased to facilitate operation following a design level event.

Typically, the cost of the structural system in a hospital facility is minor in comparison to the overall cost of the facility, including medical equipment and other associated costs. Thus, the incremental cost needed to provide advanced structural analysis and design beyond the code minimum, to achieve increased building performance, can be reviewed with the owner to provide the enhanced resilience characteristics assumed by the public.

2.1.1.1 New Hospital Facilities

New hospital facilities are designed for the highest code-specified load levels in the current building code (Risk Category IV) in hopes of providing operational functionality following design level or lesser hazard events. For most communities, emergency treatment facilities are essential for responding to the needs of community recovery. Thus, in addition to the higher design levels, many states require such things as emergency power generation for up to a 96-hour period without outside support and onsite wells or water storage to provide the volume of water necessary for essential functions to operate the hospital.

Many designers are currently using best practices for the placement of the electrical transformers and distribution systems within the hospital based on the potential for flooding during a wind or seismic event by broken water piping within the building. Essential services in a flood-prone region are being elevated above the ground floor, not just above the Design Flood Elevation, to prevent loss of functionality during an event. Flooding also requires consideration of alternative entrances to the hospital during an event. For the structural system, lateral displacement, or drift, is typically limited to prevent damage to the exterior building envelope and non-structural elements. However, wind uplift, wind-borne debris impact and other hazards need to also be considered in the design process to reduce the damage to the building envelope and downtime for the facility.

For a hospital, the goal for recovery typically ranges from hours to a maximum of a few days to reach the 90% operational functionality goal for essential services. These recovery goals can be met by considering items such as building movement, equipment elevation, and windborne debris impacts, and their effects on the non-structural elements and the exterior envelope of the facility.

2.1.1.2 Existing Hospital Facilities

Existing hospital structures have the same issues as described above for new facilities; however, the level of design loads may be less than what would be required by the current code. Until the 1976 Uniform Building Code (ICBO 1976) introduced the concept of Occupancy Importance Factors, in large part due to the collapse of the months-old Olive View Hospital (USGS, 1971), there were no enhanced design requirements for hospitals compared to other buildings. With the introduction of the ANSI A58.1 *Minimum Design Loads for Building and Other Structures,* (ANSI 1982) standard in 1982, the level of wind loads were revised from previous editions of the building codes. ANSI A58.1 (ANSI 1982) was adopted into the regional building codes in the United States by 1988 and the wind loads on the non-structural elements of the building significantly increased from the pressures specified in the previous building codes. Seismic loads have continued to increase between editions of the building codes, especially after major earthquakes, depending on the facility location within the US.

Thus, many existing facilities were not designed for the same level of loads and other criteria required by current codes. This can lead to increased lateral drifts during a design level wind or seismic event, resulting in possible structural damage and increased structural and non-structural damage within the facility. Existing structures are typically upgraded using the International Existing Building Code. However, this code is based upon the principle of limiting upgrades to the existing structural system, based on the following criteria:

- Structural upgrades are required if more than 30% of the existing building structural elements are going to be modified.
- If upgrades are required, they are often limited to 75% of the current code design load requirements.

For hospitals located in seismically active areas, the use of ASCE/SEI 41 *Seismic Evaluation and Retrofit of Existing Buildings (*ASCE 2017) is typically utilized for the upgrade of the building structure. It is more difficult to reach the 90% operational functionality goal for an existing hospital because funding is not available for resilience considerations such as renovations or upgrades to the existing structure and configuration of the facility.

2.1.2 K-12 Educational Facilities

The re-opening of K-12 schools is an important milestone after a major disaster, and symbolically marks the transition from the response to recovery phase. In accordance with the Oregon Resilience Plan (OSSPAC 2013), schools need to be safe and should be re-opened, within 30 days, to ensure that the workforce can go back to work, and children can return to a normal routine. Re-opening within 30 days implies that only minor structural damage is acceptable. If schools are undamaged after a wind or flood hazard event or meet the Operational Building performance level as defined in ASCE/SEI 41 (ASCE 2017) after a seismic event, then they potentially can be used as emergency shelters for residents of the local community and could potentially be opened within approximately 72 hours or less after an event. To achieve this functional level of school performance, the school buildings need to be “safe and usable” immediately after the event and served by the infrastructure system they depend on (including transportation, energy, water, wastewater, communication, and information systems).

Schools can be improved to serve as post-disaster centers during the design process for new facilities or when scheduled for rehabilitation. As demonstrated with the Oregon Resilience Plan (OSSPAC 2013), with deliberate planning in the short-term and long-term, solutions can be found to build or retrofit schools to higher seismic design standards, and establish utility service backbones (consisting of key supply, treatment, transmission, distribution, and collection elements that, over the 50-year timeframe, have been upgraded, retrofitted or replaced to withstand a Cascadia Subduction Zone earthquake) to supply the school functioning as a resource center and/or emergency shelter with necessary utility services.

2.1.2.1 New K-12 Educational Facilities

Schools are currently designed to meet Risk Category III wind and seismic design requirements specified in IBC (ICC 2021) and ASCE/SEI 7 (ASCE 2021), and Flood Design Class 3 requirements specified in ASCE/SEI 24 (ASCE 2014) (which typically involves ensuring that school buildings are located outside the 100-year flood plain). Some school districts have elected to design portions of their facilities as emergency shelters or tsunami evacuation buildings and have designed them to meet Risk Category IV requirements.

The Florida Building Code (FBC 2020) requires new educational facilities for school boards and community college boards to have appropriate areas designed as enhanced hurricane protection areas (with certain exceptions). These spaces are intended to provide emergency shelter and protection for people for up to 24 hours during a hurricane. The building code provisions include criteria for basic occupant life safety and health requirements, including means of egress lighting, sanitation, ventilation, fire safety, standby emergency power system, and minimum required floor area per occupant.

During a design level earthquake event, typical school buildings are intended to achieve the life safety performance objective (i.e., ensuring building occupants will not suffer life-threatening injuries), but the building may be significantly damaged and may not be usable without lengthy and costly repair. If inundated by a flood, school buildings will likely be unusable for several months as water and potentially mold damage are addressed.

2.1.2.2 Existing K-12 Educational Facilities

As certain areas of school buildings may be used as emergency shelters, different performance targets are defined based upon the function of area of the school. Existing schools, when undergoing voluntary seismic rehabilitation and infrastructure modernization, are often evaluated, and retrofitted using ASCE/SEI 41 (ASCE 2017). School buildings which are not used as emergency shelters are sometimes evaluated and retrofitted to achieve the Basic Performance Objective for Existing Buildings (BPOE) for Risk Category III (Business Oregon 2018). When school buildings are intended to be used as emergency shelters, their performance objectives are typically set to be equivalent to the Basic Performance Objective for Existing Buildings (BPOE) for Risk Category IV (Business Oregon 2018). Such a policy is intended to balance performance, societal needs, and construction cost. However, the implication on community resilience needs to be further studied.

Retrofit of existing school buildings for wind loads is not commonly implemented as there is no design standard for wind related evaluations and upgrading for existing buildings. For existing school buildings located within the floodplain, school districts sometimes opt to build new facilities on sites outside the floodplain to mitigate their flood hazard exposure (see a case study in Section 4.2.2).

2.1.3 Data Centers

A data center is a building, or a space within a building, containing many computer servers and the equipment that supports them. The primary difference between a data center and a server room is the number of computers and their function. Many server rooms support an individual office, while a data center provides support for a sizable portion of an organization, the entire organization, telecommunication entities, or online services. While dedicated computer rooms in buildings have existed as far back as the 1940s, the prevalence of full-building data centers expanded exponentially in the 1990s in concert with the original internet boom. During the 1990s, a transition from server rooms or server floors led to expansion into dedicated buildings containing thousands of servers.

Many buildings housing data centers did not start out as data centers. This is especially common in older buildings where the building was originally an administrative office building for a company and the server room grew as the company’s reliance on computer systems grew. Over time the server room expanded, and the roles of the servers evolved from supporting that specific building to supporting sizable portions of an organization. This presents a unique resilience challenge because the original building was unlikely to ever be retrofitted as it evolved into a critical data center.

When data centers are dedicated buildings, they are typically single-story facilities. Multiple story data centers exist, especially in urban areas where land is constrained, but are not as prevalent as single-story buildings. Unless the data center is part of a large office building, the number of people in the facility is small relative to the building's size, with occupancies like a warehouse.

Data centers have extensive mechanical, electrical and plumbing systems (MEP) and temperature control is critical for its functionality. Server units produce a significant amount of heat as they operate, but will cease to function if overheated, placing significant demands on the building's cooling system. Dedicated units called Computer Room Air Conditioning (CRAC) units are installed throughout the server room in addition to base building cooling units. Servers have power demands more than typical buildings, requiring more electrical equipment and conduits. In addition, the critical nature of data centers demands uninterrupted power, which exceeds what utilities can provide. Large battery units, known as uninterrupted power supplies (UPS), are installed in the server rooms to improve reliability of service.

Because data centers can serve many functions, the Uptime Institute has a four-tier classification for data centers (Turner et al. 2005). The four tiers distinguish the facility's reliability level with respect to the computers available to serve their intended function. A Tier I facility is the baseline where the data center has an uninterrupted power supply (UPS) for variations in local utility power, dedicated cooling systems, and a backup generator for power outages. Tier II facilities have redundancies in the mechanical and electrical systems. Tier III data centers have more redundancies, to the point where components within the facility can be serviced or replaced without a shutdown affecting its operation. Tier III data centers have (N+1) redundancy, meaning if the facility needs 'N' number of components, there is one more than needed. Tier IV data centers have independent and physically isolated systems that provide an even greater level of redundancy. Tier IV data centers typically have 2N+1 redundancy, meaning they have two times the number of components required plus an additional component. Conversely, the Uptime Institute Tier classifications do not provide requirements or guidance on the resilience of the building and MEP systems to support the data center during hazard events.

Like hospitals, the cost of the data center building's structural system is a small portion of the cost of the entire facility, with the MEP systems being a much greater percentage of the total building cost than a typical structural system. The substantial number of cables required to interconnect the servers and connect the servers to the outside often necessitates placing the servers on a raised floor (typically called an access floor), allowing the cables to be run between this and the primary floor slab. Computer servers, CRAC units, and UPS units are very heavy, weighing significantly more than the typical live load for a building. This leads to data centers being located on grade rather than on upper floors in multi-story buildings, when possible. In multi-story buildings, data centers in the basement are susceptible to flooding.

A new trend is modular data centers, which are self-contained units consisting of the computer servers, mechanical systems, and UPS systems in structures that resemble a semitruck trailer. They can be deployed independently, within existing data center buildings or on expansive outdoor slabs that have supporting MEP systems that can connect to the modular units.

Because of the critical nature of data centers, large organizations often have fully redundant data center facilities located in various parts of the country to hedge against natural disasters and other events that can cause a data center to temporarily cease operations. Often, it is other issues, such as loss of power, which drive data center operators to build redundant facilities. Redundancy adds a different dimension to providing resilience. Instead of investing more (and in the case of retrofit significantly more) in a single existing facility, it is often preferable to have a redundant facility in another region.

2.1.3.1 New Data Centers

The International Building Code (ICC 2021) does not have a specific classification for data centers, unless the data center is integral with public utilities or supports emergency communications and operations centers, aviation control towers, acute care hospitals, or other critical national defense functions. Therefore, most data centers are assigned to Risk Category II. Data centers supporting critical functions or essential facilities, like hospitals or emergency operations centers, are assigned to Risk Category IV. Data centers can also be assigned to Risk Category III if located in or serving a building that is assigned to Risk Category III. Regardless of the Risk Category assigned, many data center owners and operators direct design professionals to design for greater resilience. The most common approach used to achieve greater resilience is by following the Risk Category IV design requirements in ASCE/SEI 7 (ASCE 2021).

Tilt-up concrete construction with steel frame gravity systems is a common structural system for single story data center buildings. The roof is typically constructed utilizing an untopped metal deck over open-web steel joists structural system. The tilt-up concrete panels are desirable because of the superior thermal insulation compared to other curtain wall systems that would be used on similar buildings. Some data centers are steel construction with braced or moment frame lateral force resisting systems, but still employ concrete panels for the enclosure. Modular data centers are typically constructed of steel framing with insulated panels that sit on pre-poured concrete slabs or mats.

2.1.3.2 Existing Data Centers

Many existing data centers evolved from a single server room in an office building through a series of renovation projects. Consider the following example: In the 1980's a portion of a company's office building was dedicated to a computer system that served the building. The room was outfitted as a computer room with an access floor and local MEP system upgrades to manage added power and cooling demands. As the organization became more dependent on computers and the internet allowed interconnection of offices, the server room expanded to encompass more of the floor area. New MEP systems were added to serve the larger computer room. Eventually, this computer room became a full-fledged data center, critical to the organization. However, the organic nature of evolution never presented an opportunity to plan for resilience through facility upgrades. Installing a data center in an existing building or expanding an existing data center does not require any structural assessment or upgrade for wind, earthquake or flood or review of existing nonstructural components utilized in the facility.

Dedicated data center buildings constructed of reinforced masonry or concrete tilt-up wall panels with steel framing and untopped metal deck roofs may be expanded with structurally dependent or independent additions. Depending on the type of addition, the original structure may never be upgraded to meet current code requirements.

As will be discussed, the level of alteration required to trigger structural retrofit is high and nonstructural retrofit requirements are not addressed in the International Existing Building Code (ICC 2021a). Fitting out a new building to be a data center may not trigger a structural retrofit. Therefore, many data centers are in buildings that do not meet current code requirements for safety, let alone requirements for higher resilience that would limit damage so that the facility can function following a design-level wind, flood, or earthquake event.

2.2 Structural Systems

2.2.1 New Facilities

Structural systems are designed to current codes and standards to meet the minimum life-safety performance level. Critical facilities sometimes have performance needs that exceed the code requirements and then alternate design procedures, as allowed by the building codes, are utilized to meet these performance requirements. Typically, these alternate building design procedures are “performance-based seismic design” (ASCE 2017) and recently “performance-based wind design” (ASCE 2019).

The most common materials used for new facilities are reinforced concrete, structural steel, reinforced masonry, and wood framing. For new hospitals, reinforced concrete or structural steel is the most common material utilized. However, for rural single-story hospitals, wood framing is still utilized. For K-12 educational facilities, all the common structural materials are used. For data centers, reinforced concrete tilt-up walls or reinforced masonry materials are typically used.

Structural bracing systems for the lateral force resisting system of these facilities consist of shear walls or steel braced frames to limit lateral drift. Reinforced concrete or structural steel moment frames are utilized for buildings that need flexibility in their space planning, however the inherent flexibility of these systems makes it more difficult to limit lateral drift that can lead to damage of the non-structural elements. Moment frames typically experience greater amounts of lateral drift during a design level event than shear wall or braced frame systems, so the additional movement needs to be considered in the design of the nonstructural elements and the building enclosure.

The structural codes and standards in the United States are developed using a reliability basis to provide consistent performance (i.e., the same probability of failure) by risk category for structures across the country. If a building is designed to the provisions contained within ASCE/SEI 7 (ASCE 2021), it is assumed to comply with the reliability requirements listed in Chapter 1 of the standard. The use of performance-based design procedures for the design of facilities should also meet these reliability targets.

For most of the environmental hazards, the basis of the reliability values specified have been developed on the yielding of a structural member within the building structure. However, for seismic hazard the reliability values are based on the overall structural system instead of an individual structural member.

This type of system approach was recently used in developing the ASCE/SEI Prestandard for Performance-Based Wind Design (ASCE 2019). The Prestandard provides a reliability that is generally consistent with the target reliabilities found in ASCE/SEI 7 (ASCE 2021).

2.2.2 Existing Facilities

Most existing buildings were designed to older codes and standards that may be less stringent when compared to current requirements for new buildings. Building codes and the structural engineering standards referenced therein are always evolving. As was discussed previously, wind loads have increased as the ASCE/SEI 7 (ASCE 2021) standard has evolved. Earthquakes have identified gaps, deficiencies, and flaws in building codes and standards since earthquake design provisions have been incorporated in building codes (SEAOC 2009), as illustrated in Table 2-1.

Existing facilities, in general, will not provide comparable performance to new buildings, let alone provide enhanced performance to meet resilience objectives discussed in this document. Building codes have evolved primarily in response to unacceptable performance observations in major natural disasters as illustrated in Table 2-1.

Table 2-1. North American Earthquakes and Subsequent Uniform Building Code (UBC) Changes. (SEAOC 2009)

Earthquake	UBC Edition	Enhancement
1971 San Fernando	1973	Direct positive anchorage of masonry and concrete walls to diaphragms
	1976	Seismic Zone 4, with increased base shear requirements
		Occupancy Importance Factor *I* for certain buildings
		Interconnection of individual column foundations
		Special Inspection requirements
1979 Imperial Valley	1985	Diaphragm continuity ties
1985 Mexico City	1988	Requirements for column supporting discontinuous walls
		Separation of buildings to avoid pounding
		Design of steel columns for maximum axial forces
		Restrictions for irregular structures
		Ductile detailing of perimeter frames
1987 Whittier Narrows	1991	Revisions to site coefficients
		Revisions to spectral shape
		Increased wall anchorage forces for flexible diaphragm buildings
1989 Loma Prieta	1991	Increased restrictions on chevron-braced frames
		Limitations on b/t ratios for braced frames
	1994	Ductile detailing of piles
1994 Northridge	1997	Restrictions on use of battered piles
		Requirements to consider liquefaction
		Near-fault zones and corresponding base shear requirements
		Revised base shear equations using 1/T spectral shape
		Redundancy requirements
		Design of collectors for overstrength
		Increase in wall anchorage requirements
		More realistic evaluation of design drift
		Steel moment connection verification by test

2.2.2.1 Wind Design

Prior to the introduction of the ANSI A58.1 – 1982 (ANSI 1982) standard, wind loads were specified for design of the building lateral force resisting system (LRFS) in the building codes by applying a uniform pressure over the projected area of the building. These pressures were specified to increase with height and were based on geographic location. The wind pressures for the building cladding and roofing design were specified by a single modification factor to the uniform LFRS pressure specified and did not vary with height on the building. With the introduction of the ANSI A58.1 (ANSI 1982) standard the wind pressures were specified on all surfaces of the building, varying with height on the windward surface and uniform on the other building faces. The wind pressures for the design of components and cladding varied on many surfaces of the building instead of the same pressures for all components and cladding surfaces in earlier editions of the codes. This standard introduced the concept of higher pressures in the "areas of discontinuity." The areas of discontinuity are the areas on the building where the wind flow separates from the building surface yielding higher suction pressures on the components in these zones.

Since the development of ANSI A58.1 (ANSI 1982) subsequent editions of the standard (now ASCE/SEI 7 (ASCE 2021)) largely kept the LFRS wind design pressures consistent until the ASCE/SEI 7 (ASCE 2021)-16 edition, where the LFRS wind design pressures for many areas of the country were lowered. This lowering of the design pressures was a result of a new basic wind speed study performed for the continental United States that accounted for many additional years of recorded wind speed data that was available from previous studies and new statistical method used to analyze the data. However, the wind pressures used for the design of the components and cladding elements on the building have varied significantly in the latest editions of ASCE/SEI 7 (ASCE 2021) as compared to those found in the ANSI A58.1 (ANSI 1982) document. These increases and decreases were the result of the latest information from wind tunnel studies available at the time of publication of the new standard.

2.2.2.2 Flood Design

The National Flood Insurance Program (NFIP) was created in 1968 and provided federal disaster assistance after flood losses. NFIP Regulations, 44 CFR Parts 59, 60 describe requirements to be part of NFIP coverage and these have been adopted in many jurisdictions. In most jurisdictions, these floodplain management regulations pre-date flood provisions in building codes, so designers have two sets of flood requirements to consider in design. There is an excellent FEMA/ICC document that provides comprehensive details on navigating floodplain regulations: 'Reducing Flood Losses Through the International Codes – Coordinating Building Codes and Floodplain Management Regulations,' 5th Ed. 2019 (FEMA 2019a).

For designers, guidance comes from three avenues:

- Floodplain Management Regulations – which vary by area
- Building Codes
- Consensus Standards – ASCE/SEI 7 (ASCE 2021) and ASCE/SEI 24 (ASCE 2014)

NFIP, I-Codes, and ASCE Consensus Standards share a common performance requirement:

> *Structural systems of buildings or other structures shall be designed, constructed, connected, and anchored to resist flotation, collapse, and permanent lateral displacement due to the action of flood loads associated with the base/design flood.* (ASCE 2021)

Before the 2000 International Building Code, mandatory flood-resistant design and construction requirements existed mainly in community flood regulations. Flood provisions in legacy codes were optional:

- Southern Building Code (SBC) (1980): Appendix M, evolved into separate Standard for Floodplain Management SSTD-4
- Uniform Building Code (UBC) (1997): Sec. 1611.9, sent users to optional Appendix Chapter 31
- CABO 1- and 2-Family (1997): no mention of flood
- National Building Code (NBC) (1997): no mention of flood

Flood requirements have been in the ASCE Standards since approximately 1995:

ASCE/SEI 24 **–** Flood Resistant Design and Construction

- 1995 – ASCE produced a Flood Pre-Standard
- 1998 – 1st edition, ASCE/SEI 24-98
- 2005 – 2nd edition, ASCE/SEI 24-05
- 2014 – 3rd edition, ASCE/SEI 24-14

ASCE/SEI 7 (ASCE 2021) – Minimum Design Loads and Associated Criteria for Buildings and Other Structures

- 1995 – Flood loads added (sec. 5.3)
- 1998 – introduced Flood Hazard Area, Design Flood Elevation, Coastal A-Zone, load factors for flood, combined wind/flood
- 2002 – added flood borne debris impact loads to *commentary*
- 2005 – defined CAZ based on 1.5 ft wave height
- 2010 – no changes
- 2016 – update references for Chapter 5, and inclusion of new Chapter 6 (Tsunami Loads and Effects)
- 2022 – no changes. 2022 Supplement, currently out for public comment at the time of writing of this document, ed will provide a comprehensive rewrite that will be the starting point for 2028.

It is challenging to apply flood standards to existing buildings. Like the other hazards, the model codes mandate compliance with new building standards for additions or substantial alterations. The flood loads and load combinations within ASCE/SEI 7 (ASCE 2021) and ASCE/SEI 24 (ASCE 2014) are calibrated together to provide reliable life safety performance. ASCE/SEI 7 (ASCE 2021) has varying load factors for structures in and out of the Coastal High Hazard Zones and ASCE/SEI 24 (ASCE 2014) assigns structures to a Flood Design Class based on the risk to human life, health, and welfare associated with damage or failure due to flooding and by nature of their occupancy. In addition, ASCE/SEI 24 (ASCE 2014) defines what building uses are permitted to be dry floodproofed, meaning what spaces are allowed to exist below the Design Flood Elevation. These spaces are parking for vehicles, building access, storage, and vestibules for egress from elevated floors; in general, representing only spaces that represent a low risk to human life and damage. When owners embark on elective flood hardening of an existing building, unless they intend to elevate the building, it implies that spaces not permitted by ASCE/SEI 24 (ASCE 2014) will exist below the Design Flood Elevation. To dry floodproof an existing hospital patient area, a school classroom, or a data center office requires the façade, comprised of many non-structural components, to be substantially impermeable to water infiltration during the design flood. Designing non-structural components to the substantially impermeable criteria, defined as less than 4-inches (10 cm) of accumulated water within a 24-hour period, moves the performance target from life safety to that of immediate occupancy (light damage). This represents a three-fold increase in performance that was not envisioned in the new ASCE building flood standards:

1. Applying modern hazard loads to an aged building.
2. Changing the performance from life safety to immediate occupancy via the substantially impermeable criteria.
3. Making the non-structural building envelope be the primary load resisting system with dry floodproof habitable spaces below the Design Flood Elevation. [Note: It is possible to consider alternate solutions where barriers shield the envelop from the load in lieu reinforcing the envelope, but this comes with all the construction and challenges of a full perimeter barrier system.]

While the obvious conclusion is that the ASCE/SEI 7 (ASCE 2021) and ASCE/SEI 24 (ASCE 2014) flood provisions are not calibrated or intended for existing buildings, many owners, designers, and building officials are trying to achieve all the ASCE/SEI 7 (ASCE 2021) loads and load combinations in an elective retrofit. While a noble goal for the future resilience of the existing building, it is a challenging task to have non-structural components (designed only for wind) and deployed barriers resist debris impact and wave loads in addition to hydrostatic and hydrodynamic flood loads. Designers of these types of elective upgrades must have educated, realistic discussions with the building owners and officials to determine how best to meet the resilience performance objectives, instead of mandating that any design meets the intent of new codes and standards. In many cases, a rigid stance by governing bodies or reviewers of resilience requirements have served to stop owners from taking any measures at all since many options can be cost prohibitive; incrementally improved resilience is better than none.

2.2.2.3 Seismic Design

The first seismic design requirements were included as an appendix in the 1927 Uniform Building Code. Following the 1933 Long Beach Earthquake, the State of California required seismic design be considered for most commercial buildings. Additionally, an unacceptable number of schools collapsed or had safety-threatening damage in the Long Beach Earthquake which led the State of California to mandate higher seismic performance for public schools. This became the precursor to the Risk Category III categorization, but the concept of Risk Categories would not enter the building codes until 1976. Following the unacceptable performance of two large hospitals in the 1971 San Fernando earthquake, the 1976 Uniform Building Code (ICBO 1976) introduced the concept of occupancy importance factors which increased design loads by 1.25 for assembly use buildings (including schools) and 1.5 for essential facilities (including hospitals). The 1976 Uniform Building Code (ICBO 1976) also introduced requirements for concrete detailing that exceeded what would be required in non-seismic regions.

There are some classes of existing buildings with significant safety hazards, but to date there are very few requirements for existing buildings to be retrofitted to meet the basic safety objectives of the current building codes. Even when there are requirements for buildings to be retrofitted, whether through explicit mandate or because of other retrofits, a performance objective that is less than the current code is often considered.

Improving the resilience of existing facilities often starts with improving their safety. In an analogy to Maslow's hierarchy of needs (Maslow 1943 and 1954), before discussing a return to function, the issues that could lead the building to collapse, kill or seriously injure its occupants should be addressed first. Since the 1930's it has been well documented that unreinforced masonry buildings can collapse in earthquakes. While unreinforced masonry buildings were banned in new construction in the State of California by the 1940's, unreinforced masonry building retrofit ordinances were not enacted into the International Existing Building Code until the 1990's. When enacted, the retrofit ordinances required consideration of forces significantly less than those for new buildings. Outside of the State of California, unreinforced masonry buildings were not banned until much later and there are no mandates to retrofit unreinforced masonry buildings currently (but some jurisdictions have been considering such, like Seattle, Portland, and Salt Lake City). Unfortunately, many school buildings are unreinforced masonry construction, which is why Salt Lake City has a voluntary, incentivized retrofit program specific to school buildings.

Similarly, the structural engineering profession has known since the 1970's that concrete buildings designed without explicit consideration for ductile member response can experience catastrophic failures. A report commissioned by the California Seismic Safety Commission (ATC 40, 1996) indicated that the collapse of a multi-story reinforced concrete building "has the potential for more loss of life than any other catastrophe in California." In the 2011 Christchurch earthquake, over half the fatalities came from the collapse of two multi-story reinforced concrete buildings. Many hospitals and school buildings were constructed of reinforced concrete before the 1980's, when the 1976 Uniform Building Code took effect and mandated better concrete detailing. Nonductile concrete building evaluation and retrofit ordinances do not exist in national codes and standards, except for some triggered conditions in the *International Existing Building Code* discussed later in this document. There are very few state or local nonductile concrete ordinances, hospitals in California as discussed in a case study later and all building built before 1977 in the City of Los Angeles and three surrounding communities.

2.2.2.4 Building Codes and ASCE Standards

The International Existing Building Code (IEBC) (IEBC 2021a) serves as the basis for most jurisdictions' regulations for existing buildings. The IEBC is based on damage or planned work triggering evaluation and retrofit of the building. The IEBC uses the International Building Code (IBC) (IBC 2021) as a baseline but contains few provisions that require consideration of full seismic or wind loads when assessing an existing building. In the IEBC, most renovation of existing buildings, especially if the renovation does not affect the structure, can be done without any need to evaluate or structurally retrofit the building. There are even options to repair damaged structural elements by only restoring them to their original condition, regardless of how out of conformance with current code requirements that the element may be. With respect to the flood hazard, the IEBC only requires consideration of flood loads and criteria when an addition or alteration creates a substantial improvement, defined as costing more than 50% of the building's fair market value. If this threshold is crossed, full code flood design requirements are invoked.

The main reason for the aversion to retrofitting existing buildings is because doing so can be costly and disruptive. Most existing facilities are in operation, and many cannot accommodate the level of work needed to bring them up to current code standards while maintaining its operation. Designing a new building's structure allows for increased performance with minimal increases in total costs (NIST 2013). However, enhancing resilience in existing buildings can be done by augmenting the existing structural system or shifting to a new one. Augmenting the structural system in an existing building often requires significant demolition of architectural finishes and relocation of base building systems. Nonstructural components can be specified to meet the performance requirements. Getting material into the existing building can be a challenge and increase costs.

The IEBC references the International Building Code (IBC), which in turn points to ASCE/SEI 7 (ASCE 2021) for the determination of baseline design loads to be used when evaluating an existing structure. For wind, it is always 100% of the baseline loads – "full code" – that would be used for modern design. For seismic it is either "full code" loads or "reduced code" loads, depending on the specific trigger. Additions and changes of occupancy require full code loads, while alterations and repairs only require reduced code loads. The concept of using reduced code loads for seismic, specified as 75% of full IBC loads in the IEBC, began in the 1970s with a recognition that the retrofit of the primary structural system of an existing building can be very costly, so, there should be a willingness to accept lesser performance.

One major challenge with using the IBC and ASCE/SEI 7 (ASCE 2021) seismic provisions with existing buildings is the need to determine a system response coefficient (R-factor). The IEBC allows use of an "ordinary" system R-factor unless "it can be demonstrated that the structural system will provide performance equivalent to that of a "Detailed," Intermediate," or "Special" system." Even deferring to an "ordinary" system R-factor is fraught with issues (Hohener et al., 2018). The R-factor assumes the system behaves in a uniform manner. That is not always the case with existing structures, where elements could have structural detailing that would not be permitted, even in "ordinary" systems, such as concrete elements with deficient reinforcing steel lap splices.

The IEBC permits the use of ASCE/SEI 41 (ASCE 2017) for seismic evaluation and retrofit in lieu of the provisions of the IBC and ASCE/SEI 7 (ASCE 2021). ASCE/SEI 41 (ASCE 2017) is fundamentally different from ASCE/SEI 7 (ASCE 2021) in its reliance on individual element acceptance criteria. ASCE/SEI 41 (ASCE 2017) is a performance-based standard that lets the user select the structural (and nonstructural) performance level desired at a given seismic hazard level. The IEBC provides tables aligning the seismic hazard levels with the structural performance levels of ASCE/SEI 41 (ASCE 2017). ASCE/SEI 41 (ASCE 2017) recognizes that existing building components can have a range of ductility, often with more options than "ordinary," "intermediate," or "special." This performance-based approach, contingent on individual element behavior, is often more suited to existing buildings, especially in the context of providing higher performance than "Life Safety."

It is challenging to apply the ASCE/SEI 7 (ASCE 2021) and ASCE/SEI 24 (ASCE 2014) flood provisions to existing structures. ASCE/SEI 24 (ASCE 2014) establishes minimum elevations for the ground floor, which likely are not met by the building in its current condition, hence the need to retrofit. Therefore, these provisions can never be met unless the building is elevated. While elevating is quite common for single-family homes, this is almost impossible for larger structures. For the larger structures, owners attempt to reinforce the building to resist the ASCE/SEI 7 (ASCE 2021) flood loads and meet the ASCE/SEI 24

(ASCE 2014) dry floodproofing requirements. However, this is a challenging task because the magnitudes of the loads are, in many cases, much higher than those required in the original design and dry floodproofing means that non-structural elements are the primary load resisting components. Section 5 expands further on this discussion and presents additional details on the challenges.

2.3 Nonstructural Systems

The structural system of a building makes up roughly 20% of the total cost. The remaining 80% consists of the nonstructural components, meaning the architectural, mechanical, electrical, plumbing, fire suppression systems, and the furnishings, fixtures, and equipment. The ratio of structural to nonstructural component cost is even more skewed toward the nonstructural components for hospitals and data centers. Damage to nonstructural components is also the most expected damage and causes loss of function in major wind, flood, and earthquake events. The reason for this varies. For wind and flood events, structural damage is often minimal, but damage to the building envelope which allows for water intrusion is significant. Most earthquakes in the United States have been less than the code design earthquake intensity, meaning that only the most vulnerable buildings experienced major structural damage. However, most buildings had some level of nonstructural damage. This is not surprising given the percentage of the nonstructural components and systems relative to the structural system. Figure 2-1 illustrates the relative cost of the structural system and the nonstructural components and systems in a typical building and a hospital.

ASCE/SEI 7 (ASCE 2021) contains detailed provisions for the design of nonstructural components for seismic loads. ASCE/SEI 7 (ASCE 2021) has some provisions for nonstructural component design for wind. However, ASCE/SEI 7 (ASCE 2021) does not currently contain any direct provisions for loads on nonstructural components for flood.

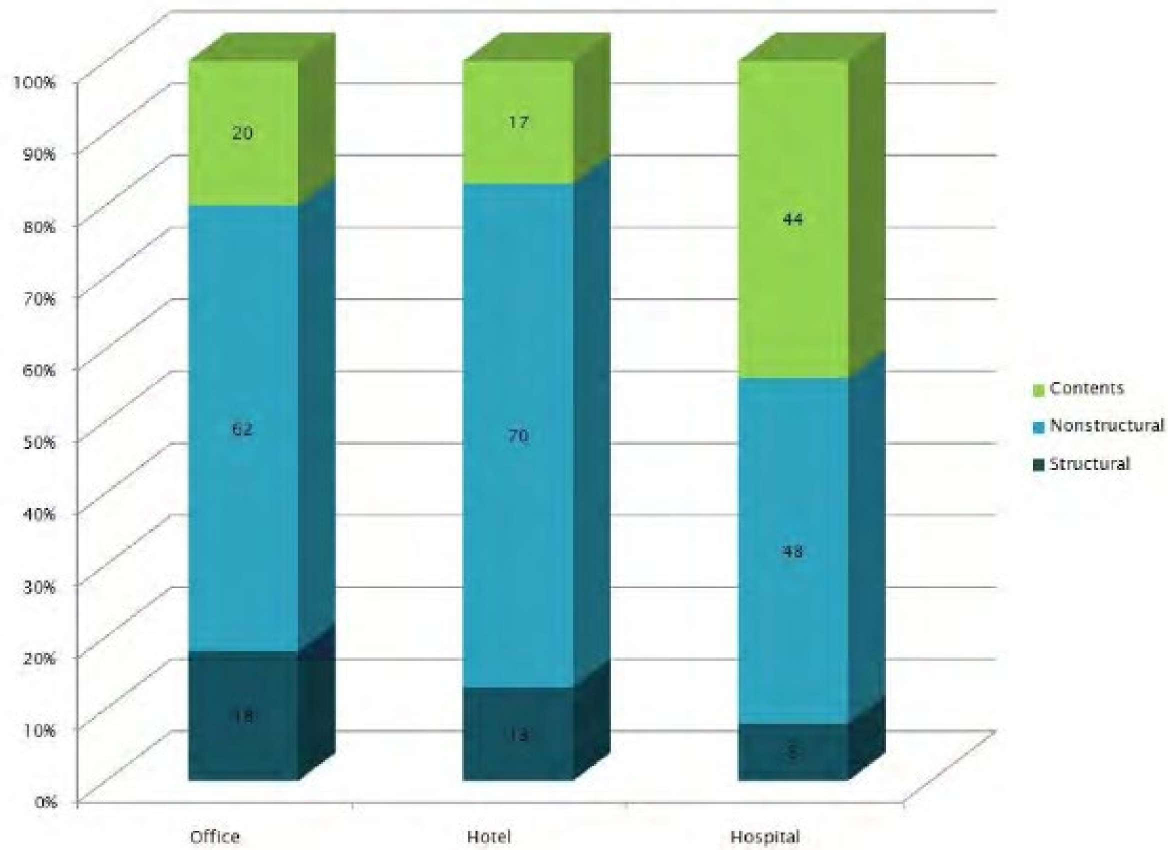


Figure 2-1. Structural and Nonstructural Costs of a Building (FEMA 2011a).

2.3.1 Wind Criteria

Nonstructural components and their attachment to the structure need design criteria for wind loads, debris impact, and wind-driven rain. There are wind design pressures for components and cladding in ASCE/SEI 7 (ASCE 2021) for the required attachment of the envelope element. Rooftop and exterior equipment can sustain damage from debris impacts in a windstorm. However, except for windows and doors, there are no requirements for nonstructural components to be designed for debris impacts in high wind events, like hurricanes and tornadoes. Windows has a testing method that considers wind-driven rain, however the wind pressure requirements for these tests are significantly less than the current required design wind pressures on the exterior components of a building. There are no design provisions for the impact of wind-driven rain for other nonstructural components.

Nonstructural components do not need to be assessed, or otherwise certified, to resume operation following a design windstorm, like essential nonstructural components after seismic events. However, failure of specifically, the envelope on essential facilities can keep these facilities closed for many months following an event because of the wind driven rain that enters the building, and its associated damage.

2.3.2 Flood Criteria

Damage to nonstructural building elements comprises most of a flood event's loss. When a building is elevated above a flood or protected by an exterior barrier, damage to nonstructural elements is greatly reduced. If neither of these are true, the building envelope is the first line of defense. If the envelope is breached, and water infiltrates the building, major damage to nonstructural components will occur, as discussed later in Section 5.

2.3.3 Seismic Criteria

The seismic design of nonstructural components is predicated on the seismic design category of the facility and whether the component is assigned a nonstructural component importance factor, I_p, of 1.0 or 1.5, as summarized in Table 2-2. Components that would be assigned an I_p = 1.5 are fire suppression and life safety systems, those containing toxic, highly toxic, or explosive substances, and those components required for continued operation of a Risk Category IV facility. All other components are designated with an I_p = 1.0. All nonstructural components are exempt from seismic bracing for a facility designated in Seismic Design Category A. Architectural components are exempt from seismic design for facilities in Seismic Design Category B, unless I_p = 1.5. All mechanical, electrical, and plumbing equipment are exempt from seismic design requirements for a facility designated in Seismic Design Categories B and C, except when I_p = 1.5.

Table 2-2. Nonstructural Seismic Considerations.

	Description of components	Lowest Seismic Design Category Considered	Design Load	Equipment Certification
I_p = 1.5	Life Safety Systems Hazardous Materials storage or distribution Needed for operation of a Risk Category IV facility	Architectural– SDC B MEP – C	1.5x Ea. (13.3-1)	Demonstrated to function following DE by testing or analysis
I_p = 1.0	All other components and systems	Architectural– SDC C MEP – D	Ea. (13.3-1)	None

ASCE/SEI 41 (ASCE 2017) refers to the nonstructural component importance factor when I_p = 1.5 as the *Operational* nonstructural performance level. ASCE/SEI 41 (ASCE 2017) designates nonstructural components with an I_p = 1.0 as the *Position Retention* nonstructural performance level. These components are anchored to the structure according to ASCE/SEI 7 (ASCE 2021) requirements and should be designed to remain in place during the design earthquake. Components with an I_p = 1.5 require design of their anchorage for higher loads and their performance should be certified through analysis or physical testing that the components can resume their pre-event function following the design earthquake. Assessment to confirm distribution systems with an I_p = 1.5 do not impact adjacent nonstructural components or portions of the structure is also required.

ASCE/SEI 7 (ASCE 2021) provides requirements that nonstructural components, specifically conduit, cable trays, and raceways with I_p=1.5, be able to accommodate displacements between structures or portions of structures at seismic joints. However, it does not specify the level of performance that the components must meet in terms of accommodating drift. For example, piping crossing a seismic joint or thermal joint should accommodate the relative movement. But the standard does not clearly state if that means the pipe cannot experience structural failure or that the pipe must be 100% leak-tight at the relative displacement. This ambiguity can lead to critical distribution systems being designed for something less than fully leak-tight.

ASCE/SEI 41 (ASCE 2017) has two additional nonstructural performance levels – *Life Safety* and *Hazards Reduced*. The quantitative requirements for these performance levels are the same, but the components that need to be considered for *Hazards Reduced* are a subset. Nonstructural systems with a likelihood of causing loss of life if they or their anchorage fail are considered in the *Life Safety* nonstructural performance level. *Hazards Reduced* nonstructural performance level only considers a subset of the *Life Safety* components whose failure could endanger a considerable number of people, like cladding falling from a high-rise onto a busy downtown sidewalk.

2.3.4 Nonstructural Design and Coordination

Even with explicit provisions for the design of nonstructural components and systems, proper design and coordination between the various nonstructural systems does not always occur. Often the anchorage and bracing design of nonstructural components is conducted by design professionals engaged by the subcontractor installing the system, not the engineer-of-record for the base building structural design. There are provisions in ASCE/SEI 7 (ASCE 2021) that require design professionals to consider the "consequential damage" caused by the interrelationship of components, their supports, and their effects on each other. Unfortunately, this is rarely done in practice because different parties often design the nonstructural components and other nonstructural systems. Frequently, there are several different engineers responsible for the anchorage and bracing design of different nonstructural components and systems. Additionally, code enforcement of nonstructural anchorage and bracing is not as stringent in many jurisdictions as for structural design and base-building construction. In many cases, alterations to the building over its lifetime occur where nonstructural components and systems are modified, but their anchorage and bracing are not reviewed or inspected. These oversights can compromise the overall resilience of a facility.

Table 2-3 lists common architectural, mechanical, electrical, and plumbing system components found in hospitals, schools, and data centers. While the specifics of this equipment may vary between facilities, the general functions provided and the components' effects on loss of function of the facility are similar. The table summarizes how damage to each component type can affect the functionality of a facility. Much of this information is taken from two reports on the seismic performance and design of nonstructural components – FEMA E74 (FEMA 2011a) and NIST GCR 18-917-43 (NIST 2018). While these documents only address seismic criteria, the concepts related to how various components affect building function are universal and can be extrapolated to how wind and flood events cause damage and affect nonstructural components.

Water can become a significant driver of damage and loss of function in critical facilities. There are no explicit requirements to design pipes with a high reliability against leaking. One water damage source not discussed in Table 2-3 is due to unintended discharge of the fire suppression system or failure of non-life safety water pipes. In the 1994 Northridge earthquake, ten hospitals had to be closed and evacuated due to water damage from internal pipe failures (FEMA 2011a). ASCE/SEI 7 (ASCE 2021) requires that fire suppression sprinkler heads have at least 3 inches (7.6 cm) of clearance from the ceiling in each direction, to avoid the sprinkler head impacting with the ceiling and discharging. Where the 3 inches (7.6 cm) of clearance cannot be achieved, flexible hoses instead of rigid pipes can be used to connect the sprinkler heads to the ceilings.

Expansion joints in buildings can present several issues for nonstructural component performance during wind, flood, and earthquake events. These joints create unique waterproofing issues, which are highly susceptible to failure in wind, flood, or seismic events, leading to water intrusion. Another issue with expansion joints is pipes and ducts crossing them may not have flexible or adequately sized joints. While this is required now per ASCE/SEI 7 (ASCE 2021), it was not always and is often overlooked. In an earthquake event, the two portions of the building may move opposite each other at expansion joints, racking the pipe or duct. Such racking can lead to failure of the pipe or duct.

Table 2-3. Function and Potential Damage of Nonstructural Components.

Note: For the flood hazard the table will assume the element is located above a reasonably established Design Flood Elevation (DFE), because the component damage is significant and significantly different if not.

	Effect on Building Function	Wind Hazard	Seismic Hazard	Flood Hazard
Architectural Components				
Cladding	Prevents water intrusion Key component to the building's indoor temperature control	Loss of water tightness due to lateral drift, which can lead to environmental hazards such as mold. Window damage due to wind or wind-born debris can lead to loss of doors. Loss of doors can change buildings from enclosed to partially enclosed conditions, leading to higher wind pressures.	Loss of water tightness due to lateral drift, which can lead to environmental hazards. Falling hazards created by heavy cladding such as concrete or masonry cladding units.	Water damage and intrusion via wave cresting or runup above the DFE leading to damage of other components.
Roofing	Prevents water intrusion Key component to the building's indoor temperature control	Loss of water tightness, which can lead to environmental hazards.	Heavy roofing and rooftop appendages can create falling hazards.	N/A – this is via the associated wind hazard.
Interior walls and partitions	Separates critical from non-critical functions. Separates special climate-controlled environments. Provides disease control in hospitals. Can have distribution system components passing through them.	Water infiltration from damaged cladding or roof systems can lead to loss of climate or disease control and create environmental hazards such as mold.	Walls can crack and lose the ability to isolate climate or provide disease control. Walls can create a hard point that can cause damage to the distribution system component as they pass through the wall and attempt to deform in an earthquake.	Water damage and intrusion via wave cresting or runup above the DFE leading to damage of other components. Also, possible roof collapse if interior wall is bearing.

	Effect on Building Function	Wind Hazard	Seismic Hazard	Flood Hazard
Ceilings	Separates special climate-controlled environments. Provides disease control in hospitals.	Water infiltration from damaged cladding or roof systems can lead to loss of climate or disease control and create environmental hazards such as mold.	Can present falling hazards. Cleanup of fallen ceilings can impede reoccupancy.	Infiltrating water damage can lead to environmental hazards.
Access floors	Mounts computer equipment above the floor to allow cables to run underneath.	Water infiltration from damaged cladding or roof systems can lead to loss of climate or disease control and create environmental hazards such as mold.	Collapse of access floors could disrupt computer room operations.	Infiltrating water damage can lead to damage to computer equipment and environmental hazards.
Stairs	Required for occupant egress.	N/A	Seismic deformations can cause damage or dislodging of stairs, preventing egress.	Stairs extend from the lowest floor elevation down to grade and are generally less robust than the primary structural systems. These a generally dislodged in a flood and can drag portions of the superstructure creating greater overall damage.
Egress doors	Required for occupant egress.	Damage due to wind or wind-born debris can lead to loss of doors. Loss of doors can change buildings from enclosed to partially increased leading to higher wind pressures.	Seismic deformations can cause damage or jamming of doors, preventing egress.	These are required to be above the DFE or protected, but inadequacies will prevent required egress or rescue.
Mechanical and Plumbing Components				

	Effect on Building Function	Wind Hazard	Seismic Hazard	Flood Hazard
Air handling units, chillers, and cooling towers	Climate Control and air quality.	Component damage due to wind shifting the component off its mounting or wind-born debris impact can lead to equipment failure.	Internal damage due to seismic shaking or toppling due to lack of anchorage can lead to equipment failure.	Water inundation can lead to equipment failure.
Pumps	Cooling systems, potable water, fire suppression system.	N/A since typically not roof mounted.	Internal damage due to seismic shaking or toppling due to lack of anchorage can lead to equipment failure.	Water inundation can lead to equipment failure.
Boilers	Heating system, domestic hot water.	N/A since typically not roof mounted.	Internal damage due to seismic shaking or toppling due to lack of anchorage can lead to equipment failure.	Water inundation can lead to equipment failure.
Pipes	Heating and cooling system, potable water, fire suppression system.	Rooftop pipe damage due to wind-born debris impact can lead to pipe rupture.	Damage due to seismic shaking causing support or joint failure or impact with adjacent ducts, pipes, ceilings, or other items can lead to pipe failure.	N/A
Ductwork / variable air volume (VAV) boxes	Climate control, air quality, disease control, stair pressurization.	Duct damage due to wind shifting the component off its mounting or wind-born debris impact can lead to pipe rupture.	Damage due to seismic shaking causing support or joint failure or impact with adjacent ducts, pipes, ceilings, or other items can lead to pipe failure. VAV boxes can dislodge and become falling hazards.	Water inundation can lead to environmental hazards.
Fans	Climate control, air quality, disease control, stair pressurization.	Component damage due to wind shifting the component off its mounting or wind-born debris impact can lead to equipment failure.	Internal damage due to seismic shaking or toppling due to lack of anchorage can lead to equipment failure.	Water inundation can lead to equipment failure.
Elevators	Occupant transportation.	N/A	Seismic shaking damages elevators or their components, leading to loss of function	Equipment and pits can be inundated, causing loss of function.
Electrical Systems				

	Effect on Building Function	Wind Hazard	Seismic Hazard	Flood Hazard
Transformers and switch gear	Electric power supply.	Component damage due to wind shifting the component off its mounting or wind-born debris impact can lead to equipment failure.	Internal damage due to seismic shaking or toppling due to lack of anchorage can lead to equipment failure.	Water inundation can lead to equipment failure.
Bus ducts and conduit	Electric power system distribution.	Water infiltration from damaged cladding or roof systems can lead to equipment failure.	Damage due to seismic shaking causing support or joint failure or impact with adjacent ducts, pipes, ceilings, or other items can lead to bus duct and conduit failure.	Water inundation can lead to equipment failure.
Light fixtures	Emergency lighting, facility use.	Water infiltration from damaged cladding or roof systems can lead to equipment failure.	Seismic shaking causes falling of light fixtures.	Water inundation can lead to equipment failure.
Furniture, Fixtures, and Equipment				
Computer Servers	IT infrastructure, Internet connection.	Water infiltration from damaged cladding or roof systems can lead to equipment failure.	Internal damage due to seismic shaking or toppling due to lack of anchorage can lead to equipment failure.	Water inundation can lead to equipment failure.
Cable Trays	IT infrastructure, Internet connection.	Water infiltration from damaged cladding or roof systems can lead to equipment failure.	Damage due to seismic shaking causing support failure or impact with adjacent ducts, pipes, ceilings, or other items can lead to support failure. Heavily loaded cable trays can be a falling hazard.	Water inundation can lead to equipment failure.
Medical Equipment	Essential to hospitals.	Water infiltration from damaged cladding or roof systems can lead to equipment failure.	Internal damage due to seismic shaking or toppling due to lack of anchorage can lead to equipment failure.	Water inundation can lead to equipment failure.
Cabinets	Storage of critical supplies.	N/A	Toppling over can be a safety hazard or lead to loss of critical supplies.	Water inundation can lead to loss of critical supplies.

	Effect on Building Function	Wind Hazard	Seismic Hazard	Flood Hazard
Storage racks	Storage of critical supplies.	N/A	Toppling over or failure of rack members can be a safety hazard or lead to loss of critical supplies.	Water inundation can lead to loss of critical supplies.

2.3.5 Dependencies

Being able to use a building following a hazard event depends both on the building being structurally adequate and on the nonstructural systems remaining functional. While these requirements are necessary, they are the only considerations as to whether a building is functional. For a fully functional facility, services provided to the building by lifeline infrastructure systems (including transportation and utilities) are also required. As indicated in Figure 2-2, functionality of critical facilities depends on transportation system for access to the site and on various utilities that serve the building, including electric power, natural gas, telecommunication, and water and wastewater systems. The impacts of damage to roads, bridges, and utility infrastructure systems also need to be considered. This requires (1) coordination with the infrastructure system owners to understand anticipated performance and restoration timeframe of their systems and their resilience plan and (2) assistance to critical facility owners to develop an interim solution and a long-term strategy to meet their functional recovery needs.

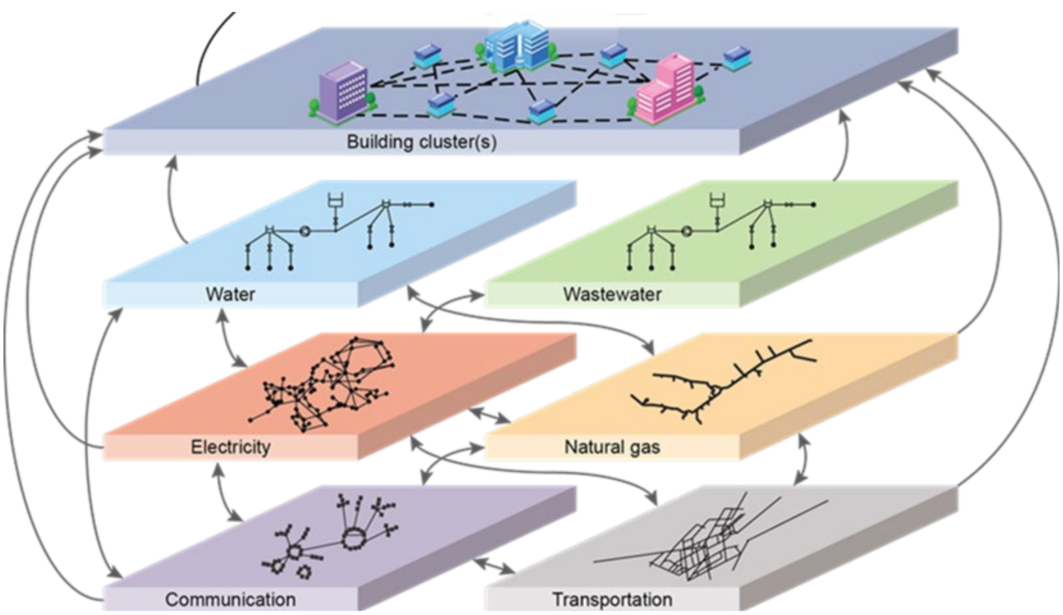


Figure 2-2. Dependencies of Building Clusters on Lifeline Infrastructure Systems (Mieler and Mitrani-Reiser 2018).

As part of the building design, buried pipelines and conduits connecting the critical facility to utility system mains need to be designed with proper materials and joint types to withstand hazard induced temporary and permanent ground deformations. Also, connection at the interface between each buried utility system and the building needs to be detailed with adequate flexibility to accommodate relative displacement at the interface.

2.4 Existing Building Considerations

Most existing buildings do not meet current code safety objectives, let alone higher performance goals like Immediate Occupancy. When codes and standards change, they do so for new buildings; new code provisions do not retroactively apply to existing buildings. A sizable portion of the building stock, including critical facilities, in most major United States cities consist of buildings designed to codes that fall short of today's standards. Enhancing the resilience of existing critical facilities requires voluntary retrofit projects initiated by the building owner, code triggers based on other work occurring in the building, or mandatory mitigation ordinances. Ordinances are the most effective, as can be seen with the California SB-1953 program for hospitals in the case study in Section 4.1, but they also place a significant burden on the owners of the facilities.

Performance retrofits should be considered for all existing critical buildings, especially if they do not meet code safety objectives. Resilience and safety are not exclusive. While existing buildings often require retrofits to bring them up to the same (or to a lesser but accepted) level of safety as a new building, such retrofits can have an appreciable improvement on the building's performance, leading to improved overall resilience. Often retrofits that target life safety for design hazard levels, such as the ASCE/SEI 7 (ASCE 2021) Design Earthquake or Maximum Considered Earthquake, can significantly enhance the performance of the structure at earthquakes with a lower shaking intensity, such as a 100 or 225-year return period. Existing buildings often have less ductility than new buildings, so retrofitting them to achieve safety-based objectives, whether for wind or seismic, requires adding considerable strength and stiffness. One can provide resilience for hazard events less than design levels by focusing on life safety retrofits in the design or larger event. Design events have become larger and rarer than they were 15 years ago. This is an important concept for existing buildings. Codes, such as the IEBC, and organization policies, have specific performance objectives that buildings must meet. Sometimes getting from 90% to 100% of the target performance objective can double the cost of a retrofit. If the project is not subject to a mandatory requirement, completing a retrofit to the just shy of the target is still a prudent use of resources.

Sometimes significantly increasing the stiffness or performance of a structural system as part of a retrofit can create more severe demands on nonstructural components and other ancillary systems. In seismic design, the added strength and stiffness can result in essentially elastic performance at lower hazard intensities, leading to undamaged structural systems. However, the increased stiffness can affect resilience of the facility if the nonstructural systems are not retrofit at the same time for the resulting higher accelerations. In flood design, dry floodproofing a facility or space imposes many residual loads on other nonstructural elements as the envelope is engaged in the resisting system.

When retrofit is considered, even if its primary goal is to enhance the safety of the building, consideration should be given to how the retrofit can improve the building performance to meet the owner’s resilience goals. Not all retrofit approaches are equal. Some retrofit options can provide significantly increased performance for hazard intensities less than the design event. For example, the choice to use fluid viscous dampers as opposed to conventional braces in the retrofit of an older steel-framed building will often lead to better building performance for wind and earthquake events because of the greater reduction of deformations and floor accelerations. Supplemental conventional braces can have the opposite effect of stiffening the structure, thereby increasing accelerations.

Some strategies for reducing the cost of a significant structural retrofit lie in bundling the retrofit with other major alterations, additions, or phasing the retrofit over several years. A sizable portion of a structural retrofit cost is the removal of the existing finishes to expose the structure and then replacement of the finishes after the retrofit occurs. Older buildings can have finishes containing hazardous materials, which increases the cost of retrofit due to the abatement required to access the structure. If the retrofit can be coupled with already planned renovation projects, the retrofit cost can be lessened. Major renovations also present an opportunity to retrofit base-building nonstructural components and to make sure that all new nonstructural components are installed correctly.

Some entities, like the United States General Service Administration (ICSSC 2011) and the California Division of State Architect (the body that oversees all public-school design and construction in the state) (CEBC 2019) have retrofit triggers based on the amount of work that is proposed to be done to an existing building. If the cost of a renovation project exceeds a percentage of the building’s replacement cost or fair market value, a hazard-resisting system retrofit is required to be included as part of the renovation.

It is possible to phase retrofits over many years. If such an approach is undertaken, care should be given to ensure that the building’s performance is not adversely affected because only part of the retrofit is completed. For example, in seismic design, a partial structural retrofit could create a discontinuous system because retrofit elements were added on upper floors before they could be added to lower floors. In flood design, if egress doors are retrofitted with deployed flood barriers but the adjacent exterior walls not reinforced to withstand the flood loads, more damage will occur because now the envelope will collapse instead of simply letting in water that will balance the load. Phasing the retrofit can also reduce another major cost driver, which is shutting down the facility or moving people around to accommodate the retrofit construction. Retrofit phases can be aligned with tenant move-out / move-in or planned shutdowns for maintenance.

3.0 Review of Current Codes and Standards

This section reviews existing design criteria for wind, flood, and seismic hazards, and how they have developed over the years with respect to current performance objectives. It also addresses how resilience concepts for each hazard can be incorporated into design criteria, design reviews, and construction observations. Finally, this section introduces the concept of a project resilience coordinator position that can benefit the design and construction process.

3.1 Hazard Design Criteria

3.1.1 Wind Criteria

The overall intent of the code and standard wind design procedures is to limit the building deflections (drifts) and to keep the structural system from yielding. A secondary goal of these provisions is to maintain the integrity of the exterior envelope to prevent the wind and wind driven rain from entering the building. Design procedures for wind pressures on a building are defined by ASCE/SEI 7 (ASCE 2021) and are widely adopted by the national codes and other standards. The wind pressures used to design the main wind force resisting system (MWFRS) have been consistent for roughly the past two decades and there has not been any building collapses because of high winds in the United States. over that period. This can be attributed to the philosophy of designing the building structure to remain elastic (no permanent deformations) during a wind event. High wind failures over this period have been failures of the building envelope resulting in pressurization of the building from the resulting increased internal wind pressure. When this situation occurs, the building tends to “blow up like a balloon” and if the internal pressure is not quickly relieved it can lead to an overall failure of the building MWFRS. Also, many of the failures associated with hurricane events along the coastline are a result of the storm surge and not from the high winds. However, there are some common types of structural failures in wind events. In buildings with untopped metal deck roofs, roof component and cladding wind uplift loads can cause the metal deck to pull away from the roof structural members, leaving the roof members unbraced, which can lead to collapse of the exterior wall and other elements.

Unfortunately, the wind pressures used to design the building envelope (also referred to as components and cladding (C&C)) have been more difficult to quantify, as these pressures are constantly varying and are difficult to measure and apply during the design of a building. For these reasons, the peak values of these pressures are utilized for design. Many C&C failures have occurred on structures throughout the years. These envelope failures can lead to considerable damage to the building’s interior, loss of functionality, and require extended periods of time to clean up and repair.

Current codes have some provisions to prevent envelope failures, however they are limited in many aspects, particularly in the areas of wind-borne debris damage and wind driven rain. There are currently no provisions to design for wind driven rain, only a procedure in ASTM E1105 (ASTM 2015) which describes the testing of doors, windows, and cladding system for water infiltration. The required pressures in the ASTM test are low as compared to what a building can experience in a high-wind event, at its specific site and envelope component location. Any envelope failure can shut down a critical facility for weeks or months to repair the damage.

The key factor to be considered for the wind design of a facility is the design wind speed, this is because the wind speed is a squared term when determining the wind pressure on a building. The selection of the design wind speed is based on the wind speed maps contained within the ASCE/SEI 7 (ASCE 2021) document that have been developed from historical data from recording stations distributed across the United States.

One of the factors that has the greatest impact on the wind speed at the site is the surrounding roughness of the earth's surface. The roughness of the area surrounding the facility is affected by the number of other buildings, trees, etc., or the lack of these elements. In the case of the facility being located adjacent to a large body of water the roughness is the least and results in the highest wind speeds at the site of the facility. However, if the site is surrounded by trees, which can significantly lower the wind speed at the site, there is a greater potential for wind-borne debris impacting and damaging the building envelope. As noted above this damage to the building envelope is the greatest cause of downtime for a facility because it can lead to water damage, mold and other issues that can take significant time to clean up.

Along with damage from surrounding trees, one of the significant potential hazards that can damage the facility envelope in high winds is the use of roof gravel as ballast on the building adjacent to the facility. In many of the reconnaissance surveys completed after high wind events it has been this gravel blowing off adjacent buildings that has damaged and required the closure of many critical facilities. There have been attempts in the code development process to limit the use of gravel ballasted roofing systems adjacent to critical facilities because of this issue, however the restriction of this type of roofing system has always failed in the code process. There is a design procedure contained in the IBC (ICC 2021) that can be used to help limit the gravel from blowing off of the lower roof surfaces, but this has only recently been provided and there were many existing facilities constructed with these types of roofing systems prior to the inclusion of these provisions into the IBC (ICC 2021).

3.1.2 Flood Criteria

Flood is a challenging hazard to define or standardize because of the wide variations in which the hazard manifests itself. Flood loads encompass hydrostatic and hydrodynamic components, debris impact, and waves – each of which varies when in a coastal, inland, urban, or suburban location. Currently, there are three publications considered to be standards on the subject: ASCE/SEI 7 (ASCE 2021), ASCE/SEI 24 (ASCE 2014) and the USACE (United States Army Corps of Engineers) Coastal Engineering Manual [EM 1110-2-1100]. However, these resources are not always able to fully explain the basis and evolution of the provisions even within an expanded commentary. The FEMA P-55 — Coastal Construction Manual (multi-hazard) — and Chapters 5 and 6 of ASCE Manual of Practice 140: Climate-Resilient Infrastructure are two comprehensive references that go into detail on the following important topics:

- FEMA map usage, meaning, and interpretation
- Riverine vs pluvial vs coastal flooding
- Types of flood loads and associated parameters
- Climate changes relative to the mapped Base Flood Elevation (“100-year flood”)
- Use of freeboard in design and misconceptions

Flood is a vastly different hazard from wind and seismic in that depth (water elevation), not load, primarily defines the hazard level. Certainly, with higher flood depths all associated loads are higher, but flood load resisting systems can have a sudden ‘failure’ of the entire system if the height of the resisting barrier is exceeded. In wind and seismic, if the predictive load level is exceeded by 10%, the lateral load resisting system of the primary structure continues to function with a minor overage in stress for individual system members. When a design flood depth is exceeded by 10%, a levee, shield, or dry floodproofed barrier may be overtopped (not over stressed) such that, in a matter of minutes, the water level on the dry and wet side of the barrier can be equalized – rendering the system a total failure. In addition, as the water level exceeds the predicted or design level, other elements may now receive flood loading that were never envisioned to do so, making their flood load go from zero to a significant amount (via debris impact) very quickly. This concept is the biggest concern within ASCE/SEI 7 (ASCE 2021) in terms of meeting target performance reliability for a building.

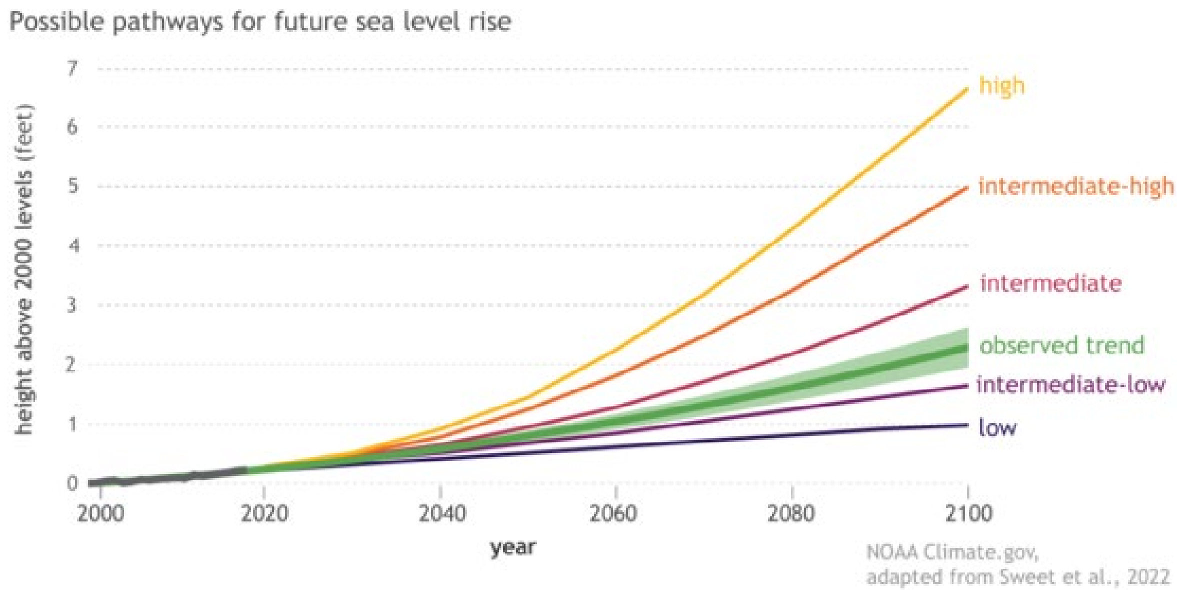
There is nuance in flooding regarding the term ‘overtopping.’ When a site-wide flood resisting system, such as a flood wall, berm, or levee, is overtopped by a flood depth greater than the system/barrier elevation, the area being protected will be inundated and the water levels will balance over a short amount of time. When a site-wide flood resisting system is overtopped by waves, only a finite volume of water is delivered over the barrier which may or may not be considered a system failure. Wave overtopping results in water behind the barrier that can be dealt with via an internal drainage system and pumping. In many cases the wave overtopping volume is significantly less than a ‘100-year’ rainfall volume, which the internal drainage system is designed to manage. For an individual building that is protected by a flood shield or similar height-limited barrier, overtopping wave water can enter the building. This water volume may or may not exceed 4-inches (10 cm) of standing water within the protected space, which is the ASCE/SEI 24 (ASCE 2014) definition of dry floodproofed.

In general, structural factors of safety for a given hazard can be applied to the loads to achieve a target level of performance, but with flood, since there are variations on the load *and* the depth, many additional situations need to be considered for both the primary structural system and nonstructural components (as part of the dry floodproofing definition). ASCE/SEI 7 (ASCE 2021) clearly defines all components of flood loading and both ASCE/SEI 7 (ASCE 2021) and ASCE/SEI 24 (ASCE 2014) define the hazard depth – which is strictly tied to the FEMA FRIM 1% chance of annual exceedance probability (AEP) maps. ASCE/SEI 7 (ASCE 2021) has load factors to account for the uncertainties in different flooding zones, but nothing directly for the depth. ASCE/SEI 24 (ASCE 2014) establishes the minimum elevation for the lowest level floor based on a Design Flood Elevation which could have fixed, additive flood depth to the Base Flood (1% AEP). ASCE/SEI 7 (ASCE 2021) flood performance and load definition follow the established wind and seismic model where magnifying the load provides more robust load resisting structural elements, leading to the ASCE/SEI 24 (ASCE 2017) objectives. However, since factors of safety on flood depth are not considered in the standards, other than the freeboard established in Table 2-1 of ASCE/SEI 24 (ASCE 2014), then there are two critical concepts for designers to consider when establishing target performance for a structure:

- If designing an elevated structure, ASCE/SEI 7 (ASCE 2021) will appropriately magnify the flood loads for the supporting columns so that these elements meet the ASCE/SEI 24 (ASCE 20147) target performance objectives. So, a debris impact load applied at or below the Design Flood Elevation will have a 2.0 load factor if in a coastal zone to design these important structural elements. But if the flood depth exceeds the 1% AEP-based Design Flood Elevation, and climbs above the lowest floor level, the façade, perimeter building walls, and interior shear walls will have a significant debris impact load (in addition to hydrodynamic and hydrostatic load) where they previously had none. And, while the supporting columns will perform as intended, the superstructure above the elevated platform will have significant, unplanned damage, becoming fully unseated and dislocated from the base.

- ASCE/SEI 24 (ASCE 2014) has dry floodproofing requirements for selected spaces that include the structural performance for nonstructural components to meet the substantially impermeable definition. Therefore, all elements of the dry floodproofed enclosure, which could include nonstructural walls, glazing, louvers, and aluminum shields, must remain undamaged and substantially impermeable for ASCE/SEI 7 (ASCE 2021) flood loads that are calibrated for ASCE/SEI 24 (ASCE 2014) primary structure performance targets. Also, if the Design Flood Elevation, which was established via the 1% AEP FEMA FIRM maps plus freeboard (which is not calibrated to local uncertainty or sea level rise projections), is exceeded, overtopping of barriers will occur and the structure will be flooded. And, while damage may not occur to the primary structure due to the balancing of water levels, there will likely be heavy damage in terms of building finishes and systems, leaving the building unfit to be occupied.

Designers, in concert with building owners, need to realistically evaluate the performance targets for the building and apply appropriate flood depth values. The load and design standards are based on the Base Flood (1% AEP) as defined in the most recent FEMA FIRMs. Some maps have been recently updated, based on new modeling, and others are in process or lagging. But in either instance, the return period for the maps has stayed the same. For this reason, many owners are considering a higher AEP for their project because there is a 40% chance of seeing a Base Flood in a 50-year lifespan. In addition, load, and design standards are backwards looking documents, where most significant changes in the hazard definition occur by rationalizing events that happened in the past to inform proposed changes. Scientific data predicts a continued worsening of relative global sea level change, which would significantly affect the flood hazard. Figure 3-1 below from NOAA (National Oceanic and Atmospheric Administration's website (climate.gov)) shows projections that vary between 1 and 7 feet (0.3 and 2.1 m) for the year 2100 depending on the location and the ability to curb greenhouse gas emissions. ASCE24 (ASCE 2014) (and by association ASCE/SEI 7 (ASCE 2021)) considers 1 or 2 feet (0.3 to 0.6 m) of 'freeboard' depending on the Flood Design Class.



Observed sea level from 2000-2018, with future sea level through 2100 for six future pathways (colored lines) The pathways differ based on future rates of greenhouse gas emissions and global warming and differences in the plausible rates of glacier and ice sheet loss. NOAA Climate.gov graph, adapted from Sweet et al., 2022.

Figure 3-1. Future Sea Level Rise Projection Ranges.

The minimum freeboard, as specified in ASCE/SEI 24 (ASCE 2014), is a factor of safety to compensate for the many unknowns that contribute to flood heights greater than the height calculated for a selected size flood and floodway conditions, such as wave action, bridge openings, and the hydrological effect of urbanization of the watershed. However, there is a misconception that freeboard is intended to cover all uncertainties for the future of a building, inclusive of sea-level rise. For a building, designed for a 50-year service life, and which will realistically serve beyond that lifespan, ASCE/SEI 24 (ASCE 2014) minimum freeboard criteria will barely cover the low-end sea-level rise projections, not even accounting for other factors (erosion, subsidence, and other general ground lowering) that could increase flood depth. In addition, an added 1-foot (0.3 m) of freeboard does not generate a linear increase in flood hazard across all areas since coastal zones have the compounding effects of waves. Volume 2 of the FEMA P-55 has a figure on page 7-10 that outlines best practices and why designers and owners should consider designing beyond the Base Flood.

Codes and standards are currently calibrated to the Base Flood because of ties to guidance in Title 44 of the Code of Federal Regulations which links to the National Flood Insurance Program (NFIP). These guidelines are not recommendations for performance or resilience to flooding, they are simply the absolute minimum requirements to qualify for the program. While the NFIP and insurance carriers continue to make updates based on damage events, Table 5-2 in Volume 1 of FEMA P-55 provides an excellent summary of the minimum requirements and the associated cross-references to NFIP, International Residential Code, International Building Code, ASCE/SEI 7 (ASCE 2021), ASCE/SEI 24 (ASCE 2014), FEMA P-55 (FEMA 2011), and FEMA P-499 (FEMA 2010).

While many interpretations and best practices have been noted, it is important to note the following: *Including NFIP requirements in a design may not meet an owner's desired resilience target and providing enhanced resilience elements in a design may not meet the requirements of NFIP* (FEMA 2010).

Even though greatly enhancing protection, some wet and dry floodproofing barriers and strategies do not meet NFIP requirements. Two examples are:

A campus perimeter flood wall or levee does not comply with NFIP unless certified and mapped. The FEMA FIRMs specifically note: *This area is shown as being protected from the 1-percent-annual chance or greater flood hazard by a levee system. Overtopping or failure of any levee system is possible. For additional information see the "accredited level note" in notes to users."* The standards mentioned above are excellent resources but, like the future effects of climate change, there are other limitations to the guidance documents. Expanding further on the depth reliability of the 1% AEP flood listed on the FEMA FIRMs is a correlated discussion of hazard extent. The FIRMs show areas designated as 'shaded X-zones' that represent the 0.2% AEP (or 500 year) flood plain. Currently there are no requirements to design projects located in these areas for any flood loads. But if owners and designers are considering events beyond the '100-year' criteria, or if the facility is considered critical, then the 0.2% AEP areas should be considered as a minimum.

In terms of the flood loads, there are many gaps as flooding traverses a developed urban environment. The size, location, layout and spacing of buildings and streets can have a significant effect on how flood flows and waves vary throughout the developed area, and therefore, on how flood loads vary on buildings therein. Better estimates of flood hazards and flood loads are needed for building design in developed regions subject to coastal inundation events. Using the simplified approach presented in the standards, designers (1) obtain flood depth from or based on FEMA's FIRM, Flood Insurance Study or an AHJ flood elevation requirement; (2) estimate flow velocity at the project site based on the flood depth (by using conservative equations in standards or other guidance, and assuming the flow could come from any direction); (3) assume depth-limited breaking waves at the site approaching from any direction; and (4) assume debris objects present in the vicinity of the shoreline could reach the project site and strike any building face at the flow velocity estimated above. While all but one of these simplified assumptions are extremely conservative, standards must evolve to provide designers with better guidance on the effects of shielding in urban centers. The one exception is the flow velocity. While calculating a flow velocity based on depth is conservative for bare earth conditions, neglecting the appropriate increases due to street channeling effects will underestimate debris impact loads at building corner zones – where critical vertical elements are located.

3.1.3 Seismic Criteria

Since the inception of seismic design, it was recognized that buildings could not be designed to sustain no damage under rare, large earthquakes; however, Developments in performance-based earthquake engineering and low-damage technologies have challenged this belief. The focus of earthquake design provisions in the United States have been on protecting the safety of building occupants. Damage to the structure and nonstructural components is tolerated, and in some situations encouraged, provided the damage does not lead to a building collapse or create falling hazards that could endanger a person's life. This performance is managed through provisions in ASCE/SEI 7 (ASCE 2021), and the various construction material standards put forth by the American Institute of Steel Construction (AISC 2022), the American Concrete Institute (ACI 2019), the American Wood Council (AWC 2021), the Masonry Society (TMS 2022), and the American Iron and Steel Institute (AISI).

The seismic hazard varies throughout the country, necessitating distinctive design requirements based on the level of hazard. Since the first seismic provisions were outlined in the 1927 Uniform Building Code, building codes have recognized that some regions are susceptible to earthquakes and others are not. For those parts of the country that are, buildings should be designed for enhanced lateral load requirements. The 1935 edition of the Uniform Building Code recognized that seismic hazard was not binary, but different parts of the country could be subject to varying earthquake shaking intensities, leading to the creation of three earthquake zones. Regions with the highest earthquake risk due to their proximity to active faults, such as coastal California, were placed in the highest seismic zone while regions with little seismic hazard, such as the mid-west, were placed in the lowest seismic zone. As the profession's understanding of earthquake hazard increased, the zones changed, giving way to designs based on shaking intensity due to a specific earthquake hazard (ATC 3-06, 1978).

The 1959 Structural Engineers Association of California Blue Book (SEOAC 1959), which formed the basis of the earthquake design requirements in the 1961 and future editions of the Uniform Building Code, stated the intent of the earthquake design provisions was to prevent loss of life in major earthquakes, limit loss of function in moderate earthquakes, and sustain little to no damage in frequent earthquakes. The design provisions specified a lateral load, which varied based on seismic zone, building use, structural system, building height, and eventually subsurface soil conditions, and design requirements that specified structural system requirements, such as limiting irregularities or poor member detailing that had demonstrated unfavorable post-earthquake performance. These provisions also came to stipulate anchorage and bracing loads for common nonstructural components. It was postulated that buildings designed using these provisions would meet the design intent.

The concept of using lateral loads dependent on seismic zones for earthquake design evolved to use loads based on a specific seismic hazard. ATC 3-06 *Tentative Provisions for the Development of Seismic Regulations for Buildings* (ATC 1978) proposed using a representation of the acceleration that a building would be subject to be based on a seismic hazard with a 10% probability of exceedance in 50 years, an event with roughly a 475-year return period. Selecting a uniform hazard for design explicitly captured the regional difference in seismic hazard and the magnitude of the acceleration parameters defines the seismic zone or seismic design category of a site.

In the late 1990's a joint FEMA and United States Geological Survey project, referred to as Project 97 (FEMA 303, 1997), comprehensively examined the appropriate design hazard level. There was concern that using design parameters from a 475-year seismic hazard would not capture the rare, but possible events in the Cascadia Subduction Zone, the Wasatch Fault region, and the New Madrid Fault region. While large magnitude earthquakes in these regions are thought to be extremely rare, their occurrence could not be ruled out, so a larger seismic hazard was needed. Project 97 team members settled on acceleration parameters with a 2% probability of exceedance in 50 years, a seismic hazard with approximately a 2,475-year return period. Recognizing that in regions with several large active faults, acceleration parameters from such a rare event could result in an upper-bound estimate of shaking that could be produced by any individual fault, a cap on acceleration parameters was introduced based on the 84th percentile (mean plus one standard deviation) estimate of acceleration parameters from the maximum event that any fault in the region could produce (FEMA 302/303, 1997).

The goal for design under this new, Maximum Considered Earthquake (MCE), was to prevent the collapse of buildings. The MCE acceleration values were larger than the previous design earthquake parameters. The design earthquake's intent was to protect life through mitigation of falling hazards and a margin against collapse. The decision was made by another project team, Project 17 (BSSC 2020), to retain the concept of a design earthquake and define it as 2/3 of the MCE. The 2/3 factor was arrived at through judgement of the project team members, who believe that a building designed to the provisions of the 1994 National Earthquake Hazard Reduction Program (NEHRP) provisions, or the 1994 Uniform Building Code would have a margin of safety against collapse of 1.5. The concepts of an MCE and design earthquake as a ratio of the MCE were adopted in the 1998 edition of ASCE/SEI 7, the 2000 International Building Code (IBC), and subsequent editions of each.

The definition of the MCE was further modified in the 2009 NEHRP provisions, which were adopted in the 2010 edition of ASCE/SEI 7 and the 2012 IBC. The main change was to move away from a uniform hazard of 2% in 50-year probability of exceedance and transition to a uniform risk definition for the MCE. This new “risk targeted” MCE (MCE_R) selects acceleration parameters which would proportion a structure to have a 1% probability of collapse in 50-years when every possible earthquake hazard scenario at the site was considered. Shifting to an absolute risk targeted approach necessitated defining the reliability of the current design provisions. To understand the risk of collapse given all possible seismic hazard intensities, a curve representing probability of structure collapse with respect to seismic hazard intensity is needed. Based on a review of studies of common structural systems (FEMA P695, 2010 and NIST GCR 10-917-8, 2010), Risk Category II buildings and other structures designed to ASCE 7-05 appeared to have a 10% probability of collapse given MCE shaking. Therefore, the probability of collapse fragility curve used to integrate with a curve representing all possible seismic hazard intensities at the site was derived by assuming a lognormal distribution, a coefficient of variation of 0.6, and anchored at 10% probability of collapse given the MCE_R shaking intensity. Like previous editions, the MCE_R is capped in regions where there is a deterministic event of appreciable size, primarily along the San Andreas fault in California. In addition to shifting from a risk targeted approach, the seismic hazard parameters were changed from a geomean to the maximum direction acceleration at a given site. Also, the underlying hazard model the United States Geological Survey uses to develop the acceleration parameters was changed in 2008 to incorporate the new ground motion models proposed by the Pacific Earthquake Engineering Research Center (PEER) as part of their next generation attenuation relationship project (Abrahamson and Silva 2008, Boore and Atkinson 2008, Campbell and Bozorgnia 2008, and Chiou and Youngs 2008).

The current edition of ASCE/SEI 7 (ASCE 2021) retains the MCE_R definition and the 10% probability of collapse reliability for Risk Category II buildings and other structures. The probability of collapse given MCE_R acceleration parameters is reduced for Risk Category III and IV buildings to 5% and 2.5% respectively. The ground motion models have been updated based on further work by Pacific Earthquake Engineering Research Center (PEER) (Abrahamson et al 2014, Boore et al 2014, Bozorgnia and Campbell 2014, and Chiou and Youngs 2014), incorporating their updated models for the western and eastern United States. Additionally, the general response spectrum used for design based on the United States Geological Survey hazard model is now based on acceleration parameters at 30 periods as opposed to a curve constructed from acceleration parameters at three periods.

The above discussion on the evolution of seismic hazard parameters used in design was provided to illustrate the dynamic nature of one of the most fundamental components to seismic design – the hazard parameters used to determine the lateral loads. These changes have led to significant variations in design loads. Figure 3-2 illustrates the variation in the seismic load (base shear) coefficient for a concrete structural wall building since 1976. These values have been normalized between early codes based on allowable stress design (prior to 1997) and strength design (1997 and later). The changes in values are due primarily to reclassification of the hazard parameters, they do not capture further changes to structural element detailing requirements, configurational limitations, and changes in site amplification, all things that have also changed as understanding of seismic hazard and structure response have evolved. For the concrete wall building shown in the example, there have also been major changes in detailing requirements for wall buildings in high seismicity. First were the provisions for confined boundary regions at the wall ends that came following the 1971 San Fernando earthquake. Second were requirements for added detailing of the gravity frame members following the 1994 Northridge Earthquake. Last were the recent changes to require cross wall ties and specific aspect ratios in the latest edition of ACI 318 (ACI 2019). As was discussed in Section 1, there are no mandates to retrofit structures when the building code and reference standards change.

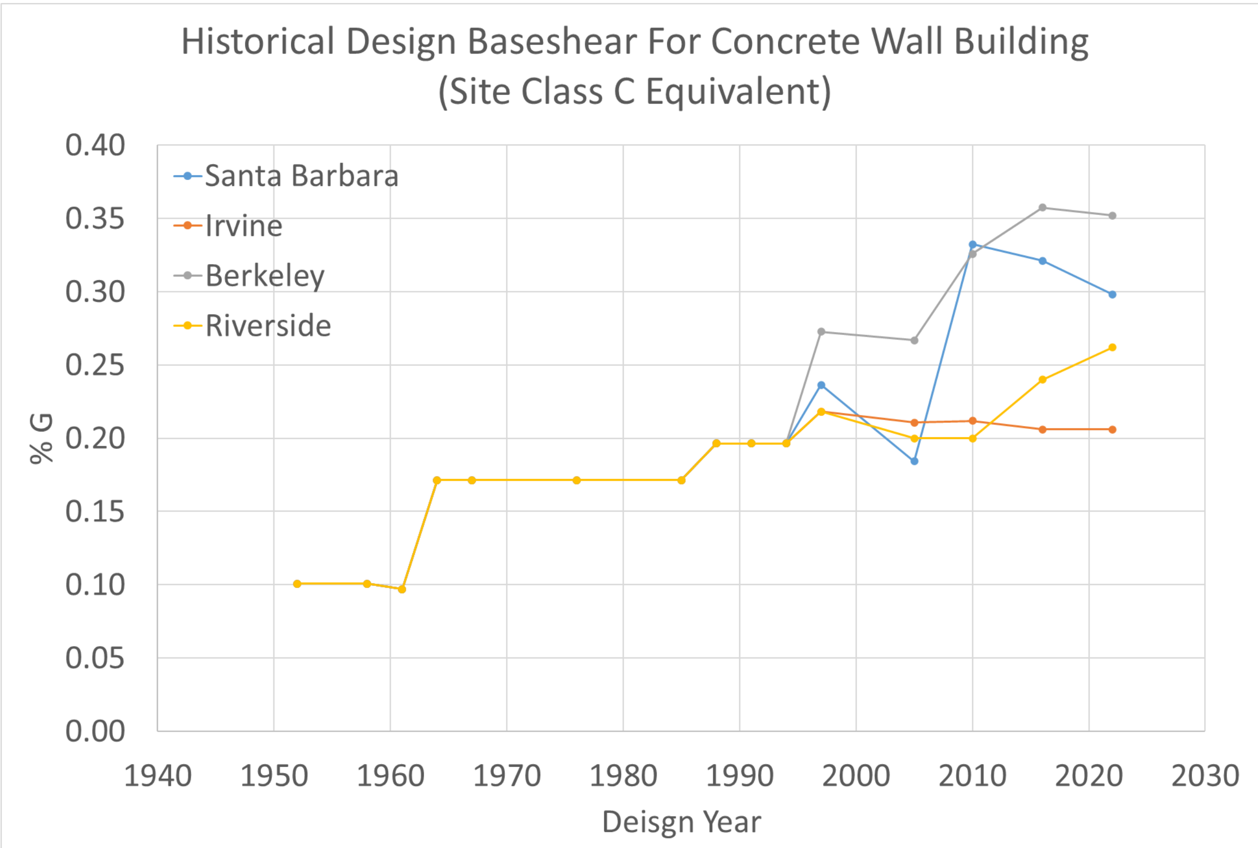


Figure 3-2: Seismic Design Force Coefficient for a Concrete Structural Wall Building Over Time (from Degenkolb Engineers)

The ASCE/SEI 7 (ASCE 2021) seismic provisions recognize the effect that different subsurface media have on amplifying seismic waves. The weaker and more flexible the underlying subsurface media is, the more seismic waves will be amplified, leading to higher acceleration demands on structures founded in this media. ASCE/SEI 7 - 16 (ASCE 2016) and previous editions defined six different site classes, ranging from very hard rock (Site Class A) to soft clay soils (Site Class E) and soils with high potential for liquefaction (Site Class F). ASCE/SEI 7 (ASCE 2021) added three additional site classes, bringing the total to nine. The difference in acceleration parameters between site classes can vary by a factor of six between Site Classes A and E.

ASCE/SEI 7 (ASCE 2021) has six Seismic Design Categories (SDC), A through F. Structures are assigned to these categories based on the acceleration parameters at the site. Because SDC is determined by the acceleration parameters, the site effects of different site classes are included in its determination. Therefore, different regions can have several different SDC within the same city, if the subsurface varies significantly. Figure3-3 illustrates the variation of SDC across the contiguous United States assuming Site Class D soil throughout.

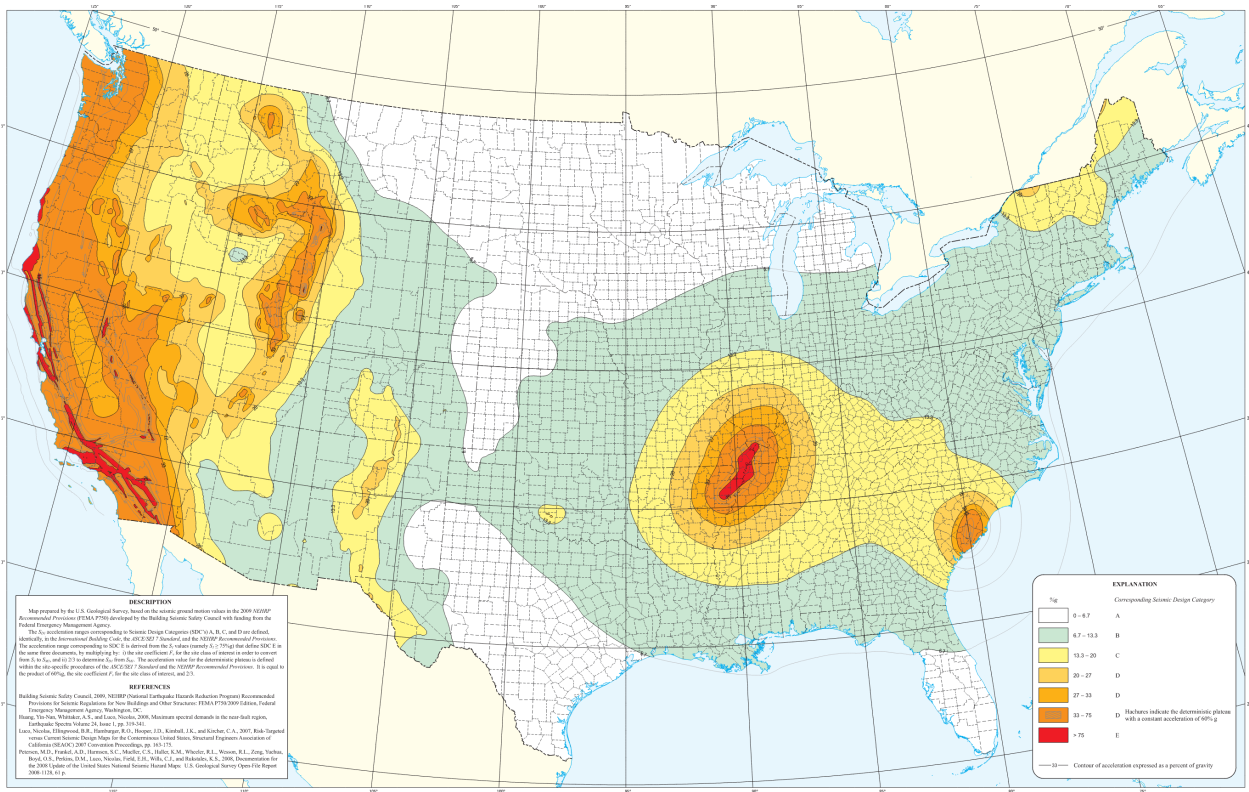


Figure 3-3: Seismic Design Categories based on Site Class D (from USGS)

The SDC for a structure is assigned to determine the extent of seismic design provisions that apply. If a structure is assigned to SDC A, there are very few seismic design requirements. Structures must be designed for a nominal lateral load of 1% of the weight of each floor. This load is often less than the lateral load due to wind loads, which in turn then governs the lateral load resisting system design. SDC A requires several structural integrity requirements, such as mandating that all members have continuous lateral load paths and members are connected to their support for a lateral load of 5% of the dead and live load reaction. Additionally, structural walls must be anchored to the floors and roof for a minimum lateral load of 20% of the wall's weight or 5 psf (24 kg/m^2) pressure over the tributary area to the connection.

Structures assigned to SDC B and higher must have full seismic design. In SDC B almost all structural systems are permitted without limitation on height, while SDC C and higher begin to exclude certain structural systems or require special detailing of members when certain structural systems are used. For example, reinforced concrete moment frames in SDC C must have intermediate or special detailing and in SDC D and higher must have special detailing, regardless of height. Reinforced concrete walls have no height limits in SDC B and C but are limited to 160 ft (49 m) in SDC D and E and 100 ft (30 m) in SDC F despite also being required to have special detailing.

SDC D and higher are traditionally the regions of high seismicity. These are the regions where enhanced seismic design is required with most systems requiring special detailing and other specific requirements. SDC E and F are specific areas close to active faults with even more structural systems and irregularity restrictions. SDC F is reserved for Risk Category IV buildings in areas classified as SDC E even if the building or other structure is a lesser Risk Category.

ASCE/SEI 7 (ASCE 2021) and the ACI (2019), AISC (2022), TMS (2022) standards referenced therein use the terminology ordinary, intermediate, and special to describe structural systems with increasing detailing requirements. Because the seismic design provisions intend structural system components to be stressed beyond their elastic limit and sustain damage, while maintaining overall stability, different structural systems are sometimes subjected to special detailing requirements. ASCE/SEI 7 (ASCE 2021) limits the use of ordinary and intermediate systems to areas of low or moderate seismicity. Following the failure of concrete buildings in the 1971 San Fernando Earthquake, building codes and standards began requiring special detailing for structural systems, with concrete moment frames being the first. These special structural systems require additional considerations to preclude brittle or less desirable failure modes in structural elements, thus enhancing its ability to sustain inelastic deformations while maintaining overall stability of the structural system. Ordinary systems are generally the structural system one would arrive at following the material design standards without any specific consideration for precluding brittle failures. Intermediate systems adopt some of the special systems requirements, those meant to preclude the most egregious brittle actions. Table 3-1 presents a high-level summary of special detailing requirements for common structural systems. Some structural systems, like steel buckling restrained braced frames and eccentrically braced frames, only have special detailing requirements with no analogous ordinary detailing provisions. In many cases the requirements for special systems lead to structural systems with significant overstrength and limit damage in the structural elements, especially in hazard intensities less than the MCE_R (FEMA P-58-5, 2018)

Table 3-1. Summary of Special Detailing Requirements for Common Structural Systems

Structural System	Intermediate Requirements	Special Requirements
Reinforced Concrete Moment Frames	• Preclude shear failures before flexural yielding in the beams and columns.	• Preclude shear failures before flexural yielding in the beams and columns. • Specific requirements for transverse reinforcement to confine the concrete and prevent longitudinal bar buckling.

		• Design columns to be stronger than the beams in flexure. • Design column so joint region area is stronger than the beams framing in.
Reinforced Concrete Structural Walls	N/A	• Preclude shear failures before flexural yielding in the beams and columns. • Specific requirements for transverse reinforcement in the boundary region to confine the concrete and prevent longitudinal bar buckling. • Wall height to thickness limits to preclude wall buckling. • Specific requirements for transverse reinforcement in the boundary region to confine the concrete and prevent longitudinal bar buckling. • Specific requirements for transverse reinforcement outside of the boundary region prevent longitudinal bar buckling.
Steel Moment Frame	• Requirements that beam-column connections be evaluated to accommodate approximately 2% story drift and maintain at least 80% of the beam capacity at that drift. • Specific requirements for welding procedures and weld filler metal used in the member connections. • Enhanced member thickness requirements to prevent local buckling under inelastic strains. •	• Requirements that beam-column connections be evaluated to accommodate approximately 4% story drift and maintain at least 80% of the beam capacity at that drift. • Specific requirements for welding procedures and weld filler metal used in the member connections. • Enhanced member thickness requirements to prevent local buckling under inelastic strains. • Enhanced bottom flange out-of-plane bracing to preclude lateral torsional buckling. • Design columns to be stronger than the beams in flexure. • Enhanced column splice requirements to prevent premature failure of the column splice. • Design the panel zone region to yield in concert with the beam-column connection. • Prohibition of welding or making alterations to members in areas where inelastic deformations are expected to occur.
Special Concentric Steel Braced Frames	While there is not an "intermediate" braced frame, the "ordinary" braced frame provisions in AISC 341 are considered different than a braced frame not specifically detailed for seismic, so those provisions are included here. • Requirement that braced connections are designed for amplified seismic loads. • Requirement that the beam in a chevron or "V" frame be designed for unbalanced loads. • Prohibition on using "K" braces.	• Requirement that braced connections are stronger than the members. • Requirement that the beam in a chevron or "V" frame be designed for unbalanced loads. • Specific requirements for welding procedures and weld filler metal used in the member connections. • Prohibition on using "K" braces. • Prohibition of tension-only frames. • Brace slenderness limits. • Brace member thickness requirements to preclude local buckling. • Beam-to-column connections requirements when gusset plates are present. • Requirement that frame columns be stronger than braces framing into them.

In addition to requiring special detailing for certain structural systems, ASCE/SEI 7 (ASCE 2021) also limits configurational irregularities or provides penalties that enhance the design because of those irregularities. In most cases, configurational irregularities, such as weak or soft stories, discontinuous lateral force resisting elements, torsional irregularities, diaphragm stiffness discontinuities, and lack of redundancy in the seismic force resisting system require amplification of design seismic loads around the irregularities. Elements supporting discontinuous lateral force resisting elements, such as columns under a wall that stops at the first floor and do not continue into the below grade levels, must be designed for amplified seismic loads. Irregularities are not prohibited in SDC A through C. The only irregularity prohibited in SDC D is the extreme weak story irregularity. In addition to the extreme weak story irregularity, any weak story irregularity is prohibited in SDC E and F, along with extreme soft story.

The design loads for the structural system depend on which type is selected. Each structural system has a structural response, R-factor, which reduces the loads generated by the design earthquake shaking intensity (which itself is 2/3 of the MCE_R shaking intensity) to a load that can be used to proportion the structural system, subject to any additional detailing requirements in the material design standards. Structural systems that can sustain significant inelastic deformations and maintain stability are assigned high R-factors, whereas structures that cannot are assigned low R-factors or prohibited. A steel or reinforced concrete special moment resisting frame is assigned an R-factor of 8 and allowed for any height, while an intermediate precast concrete tilt-up wall is assigned an R-factor of 4 limited to 40 ft (12 m) in SDC D. The intermediate precast concrete tilt-up wall does not have a height limit in SDC B and C.

The specific rules for structural system detailing are found in the referenced material design standards, ACI 318 (ACI 2019), AISC 360 (AISC 2022a) and 341 (AISC 2022b), TMS 402 (TMS 2022), and AWC NDP (AWC 2021a) and SDPWS (Special Design Provisions for Wind and Seismic) (AWC 2021b). These documents are updated on the same cycle as ASCE/SEI 7 (ASCE 2021) and are coordinated with each other. However, the provisions evolve separately because there are different committees responsible for the provisions. In recent years, there have been several changes made to the detailing requirements for special reinforced concrete walls to make them more ductile and to control, or limit, damage. The changes were made in response to damage observed in the 2010 Chile and 2011 Christchurch earthquakes coupled with new research efforts on structural walls. These changes have occurred without there being any change in the R-factor or height limits for the system.

For certain structural systems, the most concerning issues are not in the design of the horizontal or vertical seismic force resisting system, but with the interconnection of the gravity supporting members. Most significant is the connection of rigid walls to the floor or roof diaphragm for out-of-plane loads. Failure of the roof-to-wall connections have been observed in almost every earthquake, as it is often the governing failure mode in unreinforced masonry buildings. In the 1971 San Fernando earthquake, a new structural system using concrete wall panels that were cast on the ground and tilted up into place exhibited significant failures when these panels pulled away from the roof attached to them, leading to roof collapse where the panel pulled away. The 1976 Uniform Building Code attempted to address this issue, but the 1994 Northridge Earthquake demonstrated that those provisions were still inadequate and even larger design loads were needed. ASCE/SEI 7 (ASCE 2021) contains provisions for anchoring heavy concrete and masonry walls to the floor and roof, including requirements for special regions of the diaphragm adjacent to the walls, called sub diaphragms, and continuous crossties running from one end of the building to the other.

ASCE/SEI 7 (ASCE 2021) requires all structures be designed to control their story drift. In recognition that the design loads are reduced from the actual loads and therefore the displacements from those loads will be less than the actual deformations, each structural system has a deformation amplification factor, C_d. The deformations from the R-factor reduced design loads are multiplied by C_d to produce an estimate of the maximum deformations the building will see in the design earthquake shaking. Most structural systems, except masonry shear walls, four stories and less are limited to 2.5% story drift under the design earthquake and taller structures, except masonry, are limited to 2%. The commentary to ASCE/SEI 7 (ASCE 2021) discusses controlling damage as a primary reason for controlling drift.

In addition to design of the structural system, ASCE/SEI 7 (ASCE 2021) requires geologic hazards caused by earthquakes be considered and mitigated. A geotechnical investigation should assess the site's potential for slope instability, liquefaction, lateral spreading, surface displacement due to fault rupture and seismic induced settlements. These phenomena must be assessed at the MCE_G shaking intensity and provisions made to mitigate them if required. As with structural damage, the magnitude and effect of geologic phenomena are often nonlinear with respect to seismic hazard intensity. Thus, mitigating the MCE_G shaking intensity will provide significant performance benefits to the effects of these geologic conditions at lower shaking intensities. Furthermore, structures assigned to SDC E or F should not be located where an active fault could cause ground rupture.

The two primary ways ASCE/SEI 7 (ASCE 2021) differentiates the design requirements between buildings and other structures assigned to Risk Category I and II and those assigned to Risk Category III and IV are through an Importance Factor, $I_{e.,}$ that reduces the R-factor, thereby increasing the design loads, and by reducing the drift limits. The Risk Category III $I_{e.,}$ is 1.25 and the drift limits are reduced to 2% for four stories and less and 1.5% for greater than four story structures. The Risk Category IV $I_{e.,}$ is 1.5 and the drift limits are reduced to 1.5% for four stories and less and 1% for greater than four story structures. These increases in design loads and reduction in allowable drift serve to reduce the probability of collapse and limit damage. Specifically, the reduction in drift, which is proportionally larger than the increase in design loads, is in place to control damage.

Both ASCE/SEI 7 (ASCE 2021) and the 2020 NEHRP provisions acknowledge a design objective to preserving the function of Risk Category IV facilities following a design earthquake intensity event in addition to providing an extremely low probability of collapse in the MCE_R intensity event. As discussed in the preceding paragraph, Risk Category IV structures are designed for drift limits that are half those required for typical structures. Reducing drifts that significantly, while still requiring special seismic detailing, often produces structural systems that sustain little damage under design earthquake and lesser shaking intensities (FEMA P58-5 2018). In addition, there are significant requirements for the nonstructural components and systems, discussed in the following paragraphs, which are intended to ensure the systems resume functioning following a design earthquake intensity event.

ASCE/SEI 7 (ASCE 2021) contains provisions for the seismic design of nonstructural components and their anchorage to the structure based on the SDC the building or other structure is in and whether the specific nonstructural component or system should be assigned an I_p of 1.0 or 1.5. Buildings and other structures assigned to SDC A have no seismic design requirements for nonstructural components. The only seismic nonstructural requirements in SDC B are for architectural components that have an I_p of 1.5 designation. All architectural components must have seismic design considerations in SDC C, but only mechanical, electrical, and plumbing (MEP) systems where they are assigned an I_p of 1.5. All nonstructural components require seismic design considerations in SDC D through F.

Nonstructural component seismic provisions are not directly tied to the building Risk Category. Instead, the consequence of failure or the importance of the nonstructural component or system dictates its design requirements. ASCE/SEI 7 (ASCE 2021) has two classes of nonstructural components and are assigned an I_p of 1.0 or 1.5. Components assigned an I_p of 1.5 are either required to function for life safety purposes following an earthquake, such as the fire protection system and egress stairways, components with toxic or explosive substances, and components in a RC (Risk Category) IV building or other structure whose failure would impair continued operation of the facility. All other components are designated an I_p of 1.0.

When required, nonstructural components must be evaluated for seismic loads and attached to the structure to resist those loads. In SDC D, E, and F, nonstructural components cannot be attached to the structure with mechanisms that rely on friction, there must be a positive mechanical attachment. In recognition of the complexity of nonstructural components response in an earthquake and the varying demands placed upon them (NIST GCR 18-917-43).

In addition, nonstructural components must be capable of accommodating the building story drift at the design earthquake intensity. Many nonstructural components have specific requirements intended to limit their damage, often based on industry standards published by the American Society of Mechanical Engineers and the National Fire Sprinkler Association. For example, elevators have requirements for seismic switches which stop the elevators from functioning if a threshold acceleration is measured.

Nonstructural components with an I_p of 1.5 have additional requirements. The component, system and anchorage must be designed for 50% higher loads than components with an I_p of 1.0.

The International Building Code (ICC 2021) requires special inspection and structural observation of the construction of the seismic force resisting system. Furthermore, many of the material design standards have additional special inspection requirements for special seismic force resisting system components. Structural observation, special inspection and other quality assurance provisions are needed to ensure the building is constructed according to the design documents. Special inspection provisions often require an independent, third-party inspector to observe specific elements of the design and witness the construction of some of these elements, like performing demand critical welds. Material sampling and testing and nondestructive testing are often included in the special inspection. Most concrete used in seismic force resisting system elements must have samples taken during the concrete pour and tested to confirm that the material installed meets the specified strength requirements noted on the construction documents. Demand critical welds in special steel systems must be witnessed and inspected with nondestructive testing methods to confirm that they were made without flaws that could compromise their strength.

3.2 Resilience Concepts and Performance Objectives

3.2.1 Flood Criteria

As with each of the hazards discussed in this document, incorporating flood resilience into new structures is significantly easier than retrofitting existing ones. For new buildings providing resilience to the flood hazard is primarily achieved through the building elevation. Elevating the significant non-structural or light frame building elements like the perimeter walls, doors, windows, etc. above the elevation of standing water, wave, and debris strikes provides the best possible resilience to flood hazards. In addition to providing resilience to the flood hazard other key benefits to elevating a structure are:

- Better view of surroundings
- Improved ventilation as air flow below helps to regulate indoor temperature which reduces mold and mildew growth
- Better resistance to differential settlement of when local deep foundation elements are used in lieu of typical spread and continuous foundation systems
- Better for improvements and replacements related to water, sewer, electricity when the services are accessible below the building
- Added safety since first floor windows are elevated, reducing visibility to the inside

While elevating a building is the most effective flood resilience measure, there are challenges to consider. There is an added expense to provide longer runs for utilities and there is now an additional area of the building's envelope to consider for finishing, moisture, and temperature control. However, the largest concern is with building access. Higher elevations obviously require more stairs, intermediate landings, and significant ramps where ADA access is needed. But once there is a decision, or requirement to elevate a structure by 3 or 4-ft, there is only a minor premium to go to 8-feet (2.4 m), where parking could be introduced below.

Currently ASCE/SEI 24 (ASCE 2014) requires the lowest occupied floor to be elevated either 1 or 2-ft above the FEMA FIRM BFE depending on the flood design class. Once again this represents the minimum Design Flood Elevation and, while this elevation does include correlated 1% AEP waves, structures meeting only the minimum elevation can suffer damage to the structure of the first floor from wave breaking and the façade above the first floor from wave runup. When possible, and permitted by zoning, it is best to add additional elevation beyond the minimums dictated by the current building code. This is especially important for shore zones where a 1-ft minimum freeboard is much less impactful than for inland structures.

What remains are significant vertical structural columns that must resist the design flood loads. The hydrostatic loads will balance for columns but will need to be considered where load imbalances occur at cores or rooms not designed as breakaway elements. The columns will be significant structural elements to resist appropriate debris and wave impact loads and their foundations appropriately designed for erosion and scour.

Existing structures have three primary ways to achieve flood resilience: *elevate, harden, or enclose*. Like wind and seismic, existing structures are not required to be upgraded to meet the current building code (loading and dry floodproofing requirements) unless there is repair of significant damage, a new addition, or a significant alteration. For many single-family homes, elevation is a possible and common option. FEMA (FEMA 2019a) lists key advantages and disadvantages for elevating an existing building in the following Table 3-2:

Table 3-2. FEMA Building Elevation Advantages and Disadvantages (FEMA 2019a).

Elevation Advantages and Disadvantages

Advantages	Disadvantages
Brings a substantially damaged or improved building into compliance with the NFIP if the lowest floor is elevated to the BFE	May be cost-prohibitive
Reduces flood risk to the structure and its contents	May adversely affect the structure's appearance
Eliminates the need to relocate vulnerable items above the flood level during flooding	Does not eliminate the need to evacuate during floods
Often reduces flood insurance premiums	May adversely affect access to the structure
Uses established techniques	Cannot be used in areas with high-velocity water flow, fast-moving ice or debris flow, or erosion unless special measures are taken
Can be initiated quickly because qualified contractors are often readily available	May require additional costs to bring the structure up to current building codes for plumbing, electrical, and energy systems
Reduces the physical, financial, and emotional strains that accompany flood events	Requires consideration of forces from wind and seismic hazards and possible changes to building design
Does not require the additional land that maybe needed for floodwalls or levees	

When buildings are elevated a series of needle beams and jacks are installed in trenches below the slab-on-grade, and it is slowly raised and re-supported on new girders, piers, and foundations. FEMA’s Homeowner’s Guide to Retrofitting (FEMA 2014) provides a comprehensive look at the considerations for decision making and methods of construction. While additional elevation comes with the same considerations discussed above for new structures, it is best to elevate above the minimums required for NFIP for the best overall hazard protection.

While elevating an existing building is a great option, it is simply not possible for larger buildings like the data centers, schools, and hospitals that are the focus of this document. Additional flood resilience for these structures comes by way of hardening or a perimeter enclosure. The decision to harden or enclose is decided by the number of structures requiring protection or if there are critical elements within the campus site that require protection. For instance, it is more economical and less intrusive for a high school campus of one to three structures to harden the individual buildings, allowing the surrounding grounds to flood. But a sewage treatment plant with dozens of buildings and site containment tanks benefits more from a perimeter flood wall.

As previously discussed, elevating a structure takes the building enclosure elements out of the flood resisting system where a dry floodproofed enclosure must be designed to be substantially impermeable. For larger buildings, which cannot be elevated, the enclosure is generally comprised of non-structural components designed only for wind loads. To resist flood loads, and be substantially impermeable, all perimeter elements and penetrations need to be evaluated, and likely reinforced.

As the design flood depth increases, or there are significant wave loads, this becomes a significantly more difficult endeavor. Since there is no mandated Design Flood Elevation for an elective upgrade, many owners consider 42” +/- above the finished floor, corresponding to the bottom of the windows. This then leaves the walls, doors, service penetrations, and the lowest horizontal floor construction to consider.

Design considerations and techniques for the non-structural components will be discussed in a later section, but it is important to review the participation of the lowest horizontal floor in the flood resisting perimeter. Figure 3-4 is a flood load diagram published by FEMA that shows loads around the resisting perimeter. In many cases, especially when a basement is involved, it is the buoyancy force that is the hardest to resist. Since this is a critical force, it is imperative that designers evaluate this carefully for the site-specific conditions. While it is acceptable to simply assume the buoyant force is the specific weight of water times the distance from the bottom of the floor to the Design Flood Elevation, this can be very conservative. Both coastal and pluvial flood events travel primarily above grade since there is no material resistance. Whether or not the hydrostatic and buoyant forces reach the full depth of a below grade structure is a function of both the surface and subsurface porosity and time.

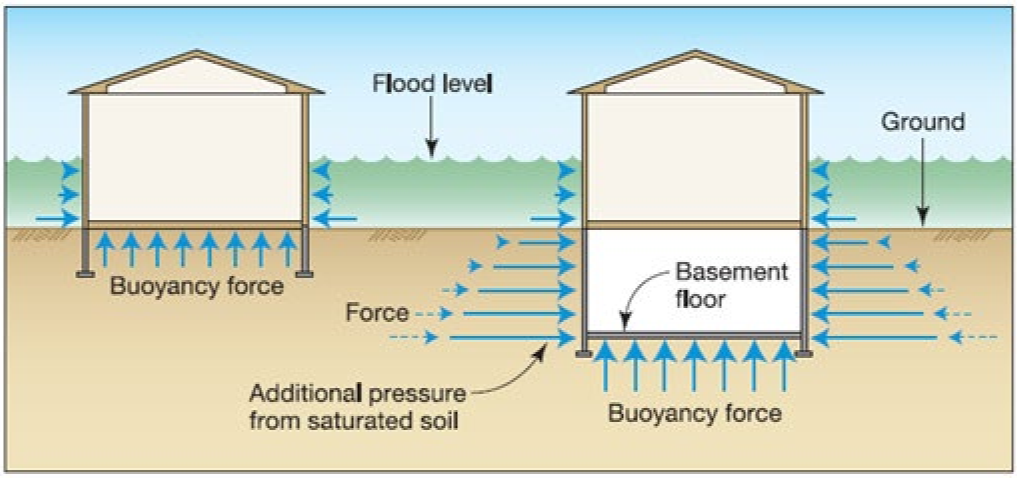


Figure 3-4. FEMA Flood Load Diagram.

A coastal storm surge event is linked to a tide cycle and lasts 8-hours or less. Pluvial events that are linked to multi-day rainstorms, like after Hurricane Harvey in Houston, can have standing water in low areas for many days. So, for an urban hospital surrounded fully by paved surfaces, above-grade flood water will not exert significant pressure on a basement wall or floor within the duration of a coastal storm surge event. But this loading should be considered carefully via geotechnical data and a subsurface seepage analysis to ensure it is not overly reduced.

Where the surface and subsurface are porous, and if the event duration is significant, the basement side wall and buoyant forces can be significant. For reference, a 4-foot (1.2 m) design flood depth with a ten foot (3 m) below grade depth to the bottom of the basement floor equates to almost nine hundred pounds per square foot (43 kPa) of uplift. There is no way to resist a load of this magnitude with a slab-on-grade, via spanning and self-weight. In addition, there is typically a joint around the wall perimeter not watertight. Possible ways to resolve buoyancy forces are:

- Consider a time-dependent subsurface seepage analysis to reduce the load on all or part of the basement floor slab
- Add weight to the floor slab construction – the bearing capacity of the soil will need to be checked as well
- Consider the spanning capacity of the floor slab between walls and columns – make sure there is an adequate hold down mechanism at the walls and columns and that the slab is not floating
- Consider the weight of permanently installed equipment – adds weight and provides vertical point loads that could be considered vertical supports for slab spanning
- Add tie-down anchors – slab will still need to span between these and might be difficult to get equipment in the basement to install
- Consider a reduced factor of safety against uplift – the uplift load for a given Design Flood Elevation is known, so consider a 1.1 strength design load factor in lieu of 1.6
- Provide foundation wall vents and let the basement flood – but remember this then makes the ground floor the flood resisting perimeter with similar challenges, just a smaller load
- Install a perimeter subgrade cutoff barrier to shield water from the foundations walls or seeping below the slab – remember this needs to be capped at the surface so water does not seep between the cutoff barrier and the foundation wall.

If it ends up being possible to resolve the buoyancy force, a confirmation of the foundation wall strength and watertightness of all below grade surfaces and penetrations is needed.

When protection is needed for a campus of buildings, especially when there are critical site elements, like a rail yard or a treatment plant, a perimeter barrier is the best option. A perimeter barrier can be comprised of one, some, or all the following:

Table 3-3. List of Perimeter Barrier Elements and Key Considerations.

Perimeter Barrier Element	Items to consider
Permanent flood wall	• Permanent visual element that may create security challenges • Requires maintenance and possible visual treatment • Requires a structural foundation • Most expensive constructed option
Berm or levee	• Permanent visual element that may create security challenges • Relatively inexpensive to construct but much wider element to fit onto site • Opportunity for exterior seating, benching, and park elements
Natural change in grade	• Most effective option if available • Still must consider below-grade seepage path
Deployed flood barriers and gates	• Still requires a structural foundation • May require significant human intervention to deploy • Must have a manually deployed option in case power is not available
Building wall(s) that can resist flood loads	• Same building hardening challenges mentioned above • Need to check the building globally for hydrostatic load imbalance since not fully surrounded
Below-grade seepage cutoff	• Need to ensure controlled water transmission path below any above grade barrier option • Difficult to construct as there are typically many utility crossings and obstructions to navigate

A cantilevered structural sheet pile is a very cost-effective way to achieve both an above grade permanent flood wall and a below-grade seepage cutoff with a single element. This dual usage makes sheet piles the most cost-effective perimeter barrier system but, as with any system of economy, there are challenges:

- Driving (or vibrating) can be difficult in areas where there are many obstructions 8 to 20 feet (2.4 to 6.1 m) below grade and operation requires large equipment
- Not possible where below grade utilities are present
- Need a coating system and sacrificial thickness (above and below grade) where high ground water and/or corrosive soils/chlorides are present
- Not an attractive system visually but can be covered with an architectural panel where public facing
- Not possible adjacent to deployed flood barriers and gates that span horizontally and concentrate load at the jambs
- Requires watertight knuckles and lifting hook holes to be sealed
- At grade deflection under design load can fill with sediment and leave permanent displacement of the system
- Less ability to spread debris impact point loads horizontally

As designers evaluate which perimeter barrier system is most appropriate for their project site, there are three important concepts to remember. First, a perimeter barrier creates a bathtub for rainwater or wave overtopping when the gates are closed. This interior water must be either detained, absorbed, or drained and pumped to avoid areas of significant ponding. Second, while effective regardless, a perimeter barrier does not count for dry floodproofing or NFIP consideration unless it is a certified FEMA levee. Third, the performance, operation, and maintenance of gates and their associated components are critical to the system's success. Owners must institute an inspection, training, and exercising program for these elements to ensure success.

As have been discussed, there are two distinct objectives for building performance relative to the flood hazard. The first relates to traditional structural performance objectives that are similar for all other hazards. These are 'life safety' objectives where damage is limited or delayed for occupants to safely exit during or soon after the hazard event. As a result of the event, there may be moderate or heavy damage to the building such that demolition and rebuilding is the only feasible option. So, primary building structural elements must be designed to, at a minimum, resist collapse or have controlled damage due to code-level hydrostatic, hydrodynamic, debris impact, and wave loads. While evacuation prior to a flood hazard is common, theoretically an occupant would be able to safely ride out the event while the building resists loads at or below the design level. Whether the occupant is truly safe in this scenario is a subject of debate. It is certainly possible that the building may be flooded with standing water in contact with live electricity, creating an extremely dangerous environment even if the building's primary structure is stable.

However, it is more common for the public, and a building owner, to think that a building designed to current code will remain dry, and undamaged, during a flood event. For a building to remain dry, it is the performance of the non-structural components that typically controls. Building walls, windows, penetrations, and deployed barriers are the key to successful performance. Previously it was discussed that the definition of substantially impermeable (dry) means 4-inches (10 cm) or less standing water in a 24-hour period. This understanding provides clarity on two key points: completely dry is not a realistic or intended performance objective, the standing water allowance recognizes that all dry floodproofing barriers leak.

Dry flood proofing barriers are comprised of both permanent and deployed components. Permanent components make up most of the system and are ready to always resist the load. With the large number of participating components and the importance of being sealed, maintenance is important. Continuous thermal movement and prolonged exterior exposure damages sealant materials that are critical components of a dry floodproofed system. These should all be identified in an operations and maintenance plan for the system and checked annually. In addition, components resisting flood loads must consider stringent deflection criteria to ensure the associated joints and seams do not separate and remain within acceptable leakage rates.

Deployed barriers bring in a component of resilience like shutters for wind. Human intervention and proper deployment are critical to successful performance. But unlike shutters, deployed flood barriers need to be properly sealed in addition to resisting a structural load. Appendix D of ASCE Manual of Practice 140 (ASCE 2018) outlines many of the systems available and their pros and cons. There are many different systems commercially available, and no two operate in an identical manner, so it is important to research which is the best for both the application and the intended deployment strategy.

Unlike other hazards, comprehensive flood resisting systems are harder to hide within the fabric of the site or architecture. Building elevation and physical barriers, especially for significant flood depths, can be difficult to blend away. For this reason, having many deployed elements seems like an attractive solution; there is no reason to hinder daily operation and look for the occasional hazard. But deployed elements add a significant amount of overall system risk. A building is unprotected without these elements securely in place; a perimeter that is 80% permanent and 20% deployed is 0% effective until the deployment happens.

Deployed barriers installed and evaluated in a controlled facility generally have particularly reliable results (minimal leakage) for hydrostatic water loads of significant depths. Hydrodynamic loads are considered via added static depth, as permitted in ASCE/SEI 7 (ASCE 2021) for lower flow velocities. 'Off-the-shelf,' lightweight barriers have limited impact load testing, but it is really meant to protect against smaller debris objects. There is no ability to resist larger debris objects or waves until considering custom structural steel gates.

Lightweight aluminum planks are quite a common system, with the ability to be handled easily and constructed quickly for variable heights and long lengths – under good conditions. Unfortunately, most systems will be deployed in the closing hours before a possible event, where the installer is under duress and potentially combating medium to high winds. In addition, the versatility of the system comes with a kit of parts required to close and seal. The more parts a human to find, maintain, and deploy, the more chance of system failure. Table 3-4 from the July 2021 STRUCTURE Magazine article 'Playing Tetris in a Hurricane' describes how the number of pieces in a deployed system equates to probability of failure in a cumulative binomial distribution.

Table 3-4. Probability of System Failure Given Different Number of Deployable Parts. (Gribble et all, 2021)

Table 2. Probability of system failure given different numbers of deployable parts.

Total number of components (N)	Scenario	P = 0.5%	P = 1.0%	P = 2.0%
30	2 assemblies	13.96%	26.03%	45.45%
15	1 system, all parts	7.24%	13.99%	26.14%
10	1 system, less 5 parts	4.89%	9.56%	18.29%
5	1 system, less 10 parts	2.48%	4.90%	9.61%
1	One part	0.5%	1.0%	2.0%

A single deployed aluminum plank door barrier with a 4-ft design flood depth has fifteen discreet system parts (the jambs are permanently installed, and planks are 6-in tall). So even with a miniscule one half of one percent probability of failure of a single part (which means part failure or improper installation), there is a 7.24% chance that the barrier fails. And even if a single barrier fails, a building is 0% protected since the water will infiltrate and self-balance very quickly. Using the table above, a solid 4.5-ft aluminum plank could be considered, dropping the system by eight parts and the chance of failure would be roughly 3%. This strategy is always preferred assuming the deployment team can store and handle the larger panel.

3.2.2 Wind

Enhancing resilience in the wind design process of a facility is typically considered easier than for both the flood and seismic hazards because the effects of the wind hazard on the MWFRS of the structure are better understood by most designers than for the flood and seismic hazards. However, there is a higher annual cost of damage from wind hazards than any of the other hazards being considered in this document (NOAA 2022). Most of the damage caused by wind events is in the breaching of the building envelope which allows the wind to enter the building or allowing the wind-driven rain to penetrate the building.

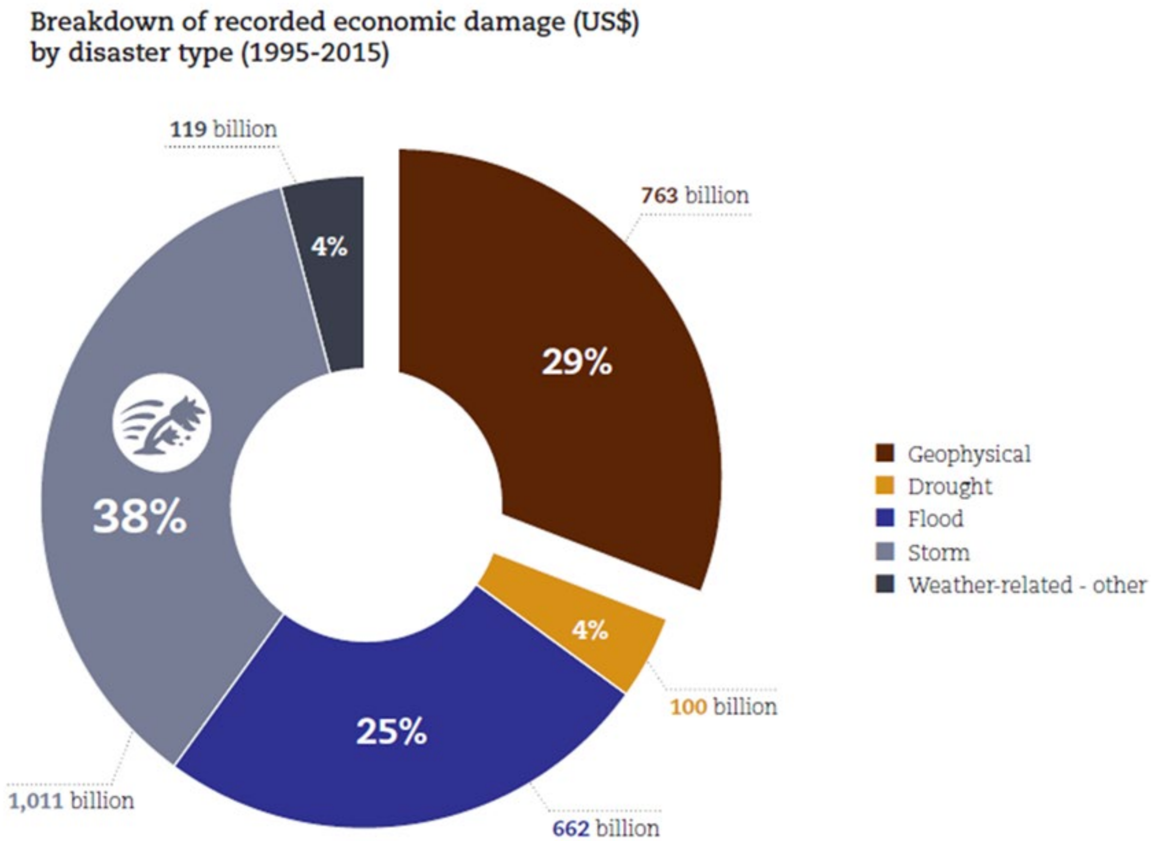


Figure 3-5. Cumulative Economic Cost of Natural Hazards 1995 – 2015 (UN/CRED)

Enhancing resilience to wind events for these critical facilities primarily involves controlling the drift of the building and the design of the components and cladding systems of the building to prevent breaching of the exterior envelope. This includes the cladding system, the roofing system and the installation of roof top mechanical equipment and any other penetration through the envelope.

The design of the components and cladding and their connections to the building is controlled by the high wind pressures experienced at the areas of discontinuity of the building. The areas of discontinuity are areas on the surface of the building where the wind flowing around the building separates from the building surface which leads to high suction pressures. These areas of discontinuity occur at roof edges, building corners and any abrupt change in the plane of the building surface.

The detailing, and installation of the building envelope, particularly at these areas of discontinuity, are critical to support the desired performance level of these critical facilities during a wind event. One major obstacle to obtaining the desired performance level is that there typically is not a single entity responsible for all the design and detailing of the individual pieces of the building envelope and thus coordination between these individual elements contained in the building envelope does not occur often. The consideration of impact resistance glazing in the windows to resist wind-borne debris, anchorage of the roof top units to prevent openings that allow wind and water to enter the building, and the careful detailing of roofing and flashing attachments are essential to ensure the tightness of the building. The discussion of many of these elements and recommendations for their design and detailing are contained in the *Prestandard for Performance Based Wind Design* (ASCE 2019).

From a more overall structural perspective the connections of roof structural members to bearing walls have been a particular point of failure of facilities. The loss of these connections is caused by the uplift pressure found at the roof's perimeter, applied simultaneously with the exterior wall pressures. This connection issue is particularly critical in buildings that utilize lightweight roof structural systems, without appreciable roof dead load. Careful detailing at this interface can limit the loss of this connection and the accompanying loss of support of the exterior wall.

3.2.3 Seismic

Resilience to earthquakes primarily involves controlling damage to the structural system and nonstructural components. Controlling damage in the structural system is done through careful system selection and controlling the drift of those systems. Therefore, Risk Category IV structures must meet drift limits half of what typical buildings structural systems are held to. Most special structural systems perform well and limit damage in design earthquake and lesser shaking intensities. Table 3-5 presents the median data from FEMA P58-5 (2018) on probability of an unsafe placard, damage as a percentage of the building replacement cost, and repair time for several common structural systems for a Risk Category II building with significant contents like a laboratory or medical office building (a data center would be more like this than a traditional office building) and a Risk Category IV hospital located in SDC D.

Table 3-5: Performance Metrics for Common Structural Systems

System	Risk Category II High Value Contents			Risk Category IV Hospital		
System	Probability of Unsafe Placard	Repair Cost Percentage	Repair Time (days)	Probability of Unsafe Placard	Repair Cost Percentage	Repair Time (days)
Steel Special Moment Frame	8%	13%	34	1%	5%	24
Reinforced Concrete Special Moment Frame	10%	14%	41	1%	5%	25
Reinforced Concrete Special Wall	2%	17%	41	0%	8%	31
Steel Special Concentrically Braced Frame	59%	28%	70	20%	16%	59

An unsafe placard indicates that the structural system or nonstructural components have sustained damage that may endanger a person’s life and the building should not be reoccupied until the damage is repaired. Minimizing or eliminating the possibility of an unsafe placard is an essential performance level for critical facilities, since they must be occupiable after a major event. The table shows that most special structural systems will provide good protection against damage that would lead to the building being deemed unsafe. Further certainty can be obtained by designing for Risk Category IV criteria.

For most options, the repair time and repair cost are low, indicating only isolated damage. In addition, most of the options show a low probability of an unsafe placard; it is reasonable to infer that the buildings would not have sustained major structural damage that requires repair before reoccupancy. Therefore, most of the cost is due to nonstructural damage. However, not all nonstructural damage is equal when considering a facility's ability to reopen. Cleanup of items such as cracked partitions and fallen ceilings can be done quickly by building maintenance professionals and often does not impede the facility's return to function. While damage to base building mechanical systems, loss of the building's weather resistant envelope, or damage to the electrical system requires special tradespeople to repair and replace equipment that can have long lead times. This highlights the importance of nonstructural element design considerations.

One of the most straight forward ways to achieve quickly recover from earthquake hazards is to design new buildings using Risk Category IV requirements. Not only does this entail design for 50% higher loads and more stringent drift limits, but in regions of SDC B or C, the Risk Category IV designation raises the SDC one level. Raising the SDC has two significant implications. The first is in structural system selection. Some systems will no longer be permitted, typically those with the highest propensity for damage, and will require additional special detailing that will enhance performance. Second is the increased requirements for nonstructural components. As noted in the previous section, very few nonstructural components have seismic design requirements in SDC B, and most MEP system components do not in SDC C. So, increasing the seismic design category from C to D means that most nonstructural components will require bracing. In addition, the Risk Category IV designation requires equipment critical to the facilities operation be designed with an I_p of 1.5, meaning higher design loads and requirements for the equipment to be certified.

Even with Risk Category IV requirements, there are still provisions in ASCE/SEI 7 (ASCE 2021) that can be improved upon if enhanced recovery speed is desired. For example, where elements support discontinuous systems, such as columns under a discontinuous wall, the columns must be designed for loads amplified by the overstrength factor. In some instances, the overstrength factor may not be large enough to amplify the loads to equate to the loads imparted on the columns if the wall yields. In such instances, capacity-based design provisions should be employed to determine the upper-bound estimate of the loads on the discontinuous elements. A similar approach should be considered at all locations where loads are amplified by the overstrength factor.

The bulk of the provisions in ASCE/SEI 7 (ASCE 2021) are based on the use of linear analyses. The standard also has provisions for nonlinear response history analyses. Nonlinear response history analyses involve developing a computer model of the building with nonlinear force-displacement or moment-rotation relationships for each structural element that may deform beyond their elastic limit. Representative ground motion acceleration records are then input into the model and the building's response to each ground motion record is analyzed. Using different ground motion records allows the analysis to pick up variability in the structure's response to different earthquake shaking patterns. Allowing the structural elements to deform nonlinearly and redistribute forces provides a more accurate representation of the demands the structural elements experience in an earthquake. This comprehensive analysis can provide a better understanding of the building structure's performance, allowing the designer to modify the system to provide better overall performance, decreasing the time to reopen.

ASCE/SEI 7 (ASCE 2021) requires ground motion records to be selected and scaled to the MCE_R hazard level. Often performance is assessed at the design earthquake intensity level. When seeking a full picture of the building's performance, it may also be prudent to conduct a nonlinear analysis with records scaled to the design earthquake intensity. Assessing member deformations and loads from a design earthquake suite of records can provide insight into the damageability of the structural elements, the nonlinear deformations an element undergoes are directly correlated with the amount of visible damage. A nonlinear response history analysis will also provide a range of drift and member deformation profiles, one for each record, which can be used to understand the variability of the structure's response and the consequences of providing median versus 90% reliability for a given performance state. The wealth of data on a structure's response generated by a nonlinear response history analysis can be used in conjunction with performance-based provisions, such as those of ASCE/SEI 41 (ASCE 2017) or the methodology set forth in FEMA P58-1 (2018).

ASCE/SEI 41 (ASCE 2017) *Seismic Evaluation and Retrofit of Existing Buildings* contains a performance-based method for evaluating and, if desired, designing a seismic retrofit for an existing building. While not explicitly stated, the provisions can and have been used for the design of new buildings. ASCE/SEI 41 (ASCE 2017) marries structural and nonstructural performance levels, defined in terms of the post-earthquake state of the building, with seismic hazard levels to create a performance objective. The structural performance levels range from Collapse Prevention to Immediate Occupancy and are described in Table 3-6 below. The nonstructural performance levels range from Hazards Reduced to Operational and are described in Table 3-7 below. The standard stipulates acceptance criteria in the form of explicit member deformations and allowable loads, or ductility demands that correspond to each performance level. The user assesses the structural and nonstructural component's demands under a seismic hazard level or multiple seismic hazard levels against those performance levels to determine if the building meets the performance objective. An example performance objective, used for Risk Category IV new buildings, is Immediate Occupancy Structural performance and Operational nonstructural performance under the ASCE/SEI 7 (ASCE 2021) design earthquake.

Table 3-6 ASCE/SEI 41 (ASCE 2017) Structural Performance Levels

Structural Performance Level	ASCE/SEI 41 (ASCE 2017) Definition	Notes:
Immediate Occupancy	The structure remains safe to occupy and essentially retains its pre-earthquake strength and stiffness.	The goal of this performance level is to minimize structural damage to a level that a reasonable person would consider the building safe to reoccupy. There should be very little, if any, loss of strength or stiffness. Risk Category IV new buildings target this performance level in the Design Earthquake.
Damage Control	A damage state between Performance Levels S-3 and S-1. Acceptance criteria for evaluation or retrofit based on the Damage Control Structural Performance Level shall be taken halfway between those for Immediate Occupancy and Life Safety.	This performance level allows for more damage than would occur in the immediate occupancy performance level. The performance level accepts more inelastic deformations in structural components, which indicates more damage is likely. It is felt that damage in this performance level would not warrant an unsafe placard but may require limited repairs.
Life Safety	The structure has damaged components but retains a margin of safety against the onset of partial or total collapse.	This performance level will protect the people in the building but may lead to an unsafe placard following the event. The level of damage acceptable in this performance level might require repairs before the building can be reoccupied.
Limited Safety	A damage state between Performance Levels S-3 and S-5. Acceptance criteria for evaluation or retrofit based on the Limited Safety Structural Performance Level shall be taken halfway between those for Life Safety and Collapse Prevention.	Similar to Life Safety, this performance level will require repairs of the structure before the building can be reoccupied.
Collapse Prevention	The structure has damaged components and continues to support gravity loads but retains no margin against collapse.	This performance level connotates extensive damage, to a level that may not be safe or economically feasible to repair.

Table 3-7 ASCE/SEI 41 (ASCE 2017) Nonstructural Performance Levels

Nonstructural Performance Level	Post-Earthquake Damage State Description	Notes:
Operational	Nonstructural components can provide the functions they provided in the building before the earthquake. Nonstructural	This performance level requires equipment that has been certified through shake table testing or analysis to

	components in compliance with the acceptance criteria of this standard for Operational Nonstructural Performance (N-A) and the requirements of ASCE/SEI 7 (ASCE 2021), Chapter 13, where I_p = 1.5, are expected to achieve this post earthquake state.	function following the design level earthquake. Additionally, the seismic loads used for the component, component frame, anchorage and impact on structure are 1.5 times higher than those for other performance levels.
Position Retention	Nonstructural components might be damaged to the extent that they cannot immediately function but are secured in place so that damage caused by falling, toppling, or breaking of utility connections is avoided. Building access and Life Safety systems, including doors, stairways, elevators, emergency lighting, fire alarms, and fire suppression systems, generally remain available and operable, if power and utility services are available. Nonstructural components in compliance with the acceptance criteria of this standard for Position Retention Nonstructural Performance (N-B) and the requirements of ASCE/SEI 7 (ASCE 2021), Chapter 13, are expected to achieve this post earthquake state.	All components are anchored and braced, but components may sustain internal damage due to an earthquake that causes them to lose function.
Life Safety	Nonstructural components may be damaged, but the consequential damage does not pose a life-safety threat. Nonstructural components in compliance with the acceptance criteria of this standard for Life Safety Nonstructural Performance (N-C) and the requirements of ASCE/SEI 7 (ASCE 2021), Chapter 13, are expected to achieve this post earthquake state.	Many MEP systems critical to building function are exempt from consideration in this performance level. Those systems may sustain damage that makes a building unoccupiable until the system is repaired or replaced, making it unadvisable for critical facilities.
Hazards Reduced	Nonstructural components are damaged and could potentially create falling hazards, but high-hazard nonstructural components identified in ASCE/SEI 7 (ASCE	Even more MEP systems and a substantial number of architectural items are exempt from consideration and will likely sustain

	2021) Chapter 13, Table 13-1, are secured to prevent falling into areas of public assembly or those falling hazards from those components could pose a risk to life safety for many people. Preservation of egress, protection of fire suppression systems, and similar life-safety issues are not addressed in this Nonstructural Performance Level.	significant damage. In addition to similar consequences of MEP system damage preventing building function restoration, the amount of damage to the architectural components may require significant clean up and repair before a building can be occupiable.

Damage Control and Immediate Occupancy are the two most appropriate performance levels to target to provide faster recovery of function for a critical facility under an earthquake. Significant structural damage can lead to a red tag (ATC 20, 1989), so selecting performance objectives that minimize the likelihood of structural damage is important. Ideally, one would target Immediate Occupancy structural performance, but doing so, for an existing building can be cost prohibitive. The more structural damage, the longer it will take to inspect the building, even if the damage is only superficial. Since return to occupancy and resumption of function are tied to getting the building inspected and, if needed, repaired, any structural damage will extend this time. Recent research appears to indicate that if structural damage or damage to critical nonstructural components is sustained and requires repair, the facility's return to function can be impeded by up to six months (ATC 138, 2022).

Position Retention and Operational are the two most appropriate nonstructural performance levels. The Operational nonstructural performance level is desirable, but it requires obtaining equipment seismically certified to function following the design earthquake. This is especially important for components which are critical to building function. As was discussed above, if critical components sustain damage, getting replacement components or the specialty contractors needed to repair such damage can take months. Like the Immediate Occupancy structural performance level, achieving the Operational nonstructural performance level may not be practical. In an existing facility, meeting the operational performance level may require replacement of existing base building MEP systems, such as elevators, cooling towers, chillers, electrical switchgear, and cladding. ASCE/SEI 41 (ASCE 2017) recognizes this and only requires Position Retention nonstructural performance for Risk Category IV structures designed to the Basic Performance Objective for Existing Buildings. Position Retention requires that all components and supporting frames be designed for seismic loads and anchored to the structure. There is a recognition that components meeting the Position Retention level may sustain internal damage that inhibits function. Cladding systems meeting the Position Retention nonstructural performance level may sustain damage to their seals that compromise their ability to maintain watertightness.

The methodology presented in FEMA P58-1 (FEMA 2018) allows a user to explicitly assess performance states in a probabilistic manner. The method focuses on assessing the probability of an unsafe placard (red tag), repair cost, repair time, injuries, and casualties. While the FEMA P58-1 (FEMA 2018) methodology can be used with any analysis procedure, it is best paired with a nonlinear response history analysis where the building's response to different ground motions records representing a single hazard is provided as the input parameters. The method uses story drift and floor accelerations to assess each structural and nonstructural component in the building. Each component has multiple damage states, each with a different repair cost, repair time, effect on occupancy, and potential to injure correlated to either story drift or floor acceleration. The method takes all the drift and acceleration input parameters from the building's response and requires Monte Carlo simulation runs with the component damage parameters. Using this method, a user could obtain parameters shown in Table 3-5 at the median and 90th percentile (or any other percentile).

The FEMA P58-1 (FEMA 2018) method is especially helpful at identifying what specific structural and nonstructural components in a building impede resumption of function or trigger an unsafe placard. It is also beneficial to assess different retrofit options for an existing facility.

The FEMA P58-1 (FEMA 2018) methodology provides an estimate of repair time. That is different than total facility downtime because it does not account for the time between the event and when the repairs begin. Several factors can affect the time it takes to begin the repair. Even if a building appears undamaged, a formal inspection is typically required after a major earthquake before the building can be reoccupied. Unless the owner has contracted with an engineer prior to the event and the local jurisdiction has deputized that engineer, the building owner must wait for a jurisdiction employee or deputized volunteer to assess the building. If damage is found, it must be evaluated, and repairs designed. If the damage is substantial, the International Existing Building Code (ICC 2021a) does not permit the building to simply be repaired to the pre-event level; it must be retrofit to meet the current code level. Those repairs must be permitted and then constructed. General contractors, subcontractors, building materials and building components are often scarce in a post-disaster environment. Some MEP system components have long lead times, even in normal times. All these impeding factors can lengthen the amount of time a facility is down. A FEMA funded project through the Applied Technology Council (ATC 138, 2022) is currently developing a method to assess the consequences of these impeding factors, so they can be married with the FEMA P58-1 (FEMA 2018) repair time to provide a complete picture of a facility's post-earthquake downtime until function can be restored.

ASCE/SEI 7 (ASCE 2021) and ASCE/SEI 41 (ASCE 2017) contain provisions for seismic isolation and supplemental energy dissipation systems. These technologies reduce the acceleration an earthquake imparts to the building either through directly isolating the structure from the ground shaking or by dissipating energy with damping systems throughout the structure. Both technologies were developed as low-damage technologies intended for critical facilities. They can have a significant effect limiting damage for both new buildings and existing buildings. Seismic isolation can be highly effective for existing buildings because it reduces the acceleration of the structure and, more importantly, the nonstructural systems. For many critical facilities, this may be significantly more cost effective than attempting to retrofit all the critical MEP systems. Seismic isolation technology has even been used on specific nonstructural components and systems. The critical piece of equipment is placed on an isolation platform, which reduces the acceleration the equipment feels compared to the acceleration of the supporting floor.

3.3 Design Review and Quality Assurance

Design review practices in the United States vary by jurisdiction. Many jurisdictions employ licensed structural engineers that provide sophisticated, in-depth reviews of the design and detailing of the building structural system, while other jurisdictions have no structural engineers and do not have the technical ability to provide any structural review. These jurisdictions rely upon the building designer's ability to meet the basic code requirements in their designs. This situation can lead to inconsistent levels of design and detailing on similar structures located in adjacent jurisdictions.

For many of the most complex building designs, or for structural systems that do not meet the prescriptive provisions of the building code, a structural peer review is sometimes mandated. This provides a review of the structural system, mainly the lateral-force resisting system, to ensure compliance with, or compliance with the intent of, the provisions of the building code. This review is typically performed by structural experts that have experience with the system design being considered for the building and will be discussed in-depth in the next section.

For construction inspections offered by the authority having jurisdiction many of the same issues noted above for the building reviews are present. Many jurisdictions have specific structural building inspectors that provide an excellent review of the building structural system, ensuring compliance with the provisions of the building code and the building structural drawings. However, many jurisdictions have only one or a limited number of inspectors to cover all inspections or might only have experience in mechanical or electrical system inspections. Again, this situation can lead to inconsistent levels of construction for similar projects.

As noted above, the design review and construction inspections for the building structural system can vary across the United States; however, the level of review and inspection for the nonstructural systems, including the building envelope, are typically poor. This lack of design review and construction inspection is caused by the number of elements to be reviewed and inspected during the construction process, there are simply too many to consider. Nonstructural component design reviews are typically performed by the building designer through the shop drawing review process and the construction inspections are typically assigned to special inspectors hired by the owner who are reviewing only for conformance with the individual element shop drawings or building drawings, but not reviewing the system in its entirety.

3.4 Current Peer Review Practice and its Issues

Guidelines for Performing Project Specific Reviews for Structural Projects, published by the American Council of Engineering Companies (ACEC 2014), helps define the standard of care for a design peer review. A design peer review's purpose is to achieve higher quality assurance and confidence in the building's design. As a result of the peer review process, where two different structural engineering teams have participated, the design deliverables should have better assurance that they conform with the building code and design criteria, have fewer errors or omissions, and have clearer construction documents with improved detailing. Peer reviews tend to focus on the primary structural support system and help achieve higher confidence in the expected performance and safety of the design. It typically excludes review of building components critical for functional recovery, including nonstructural components (such as architectural components, mechanical and electrical equipment, and associated distribution systems), and utility systems from a service provider's main to the building. The current peer review is structural system focused, not recovery-centered unless specifically scoped for a given project.

Building designs going beyond the current code prescribed limits for their structural systems or designs that do not meet the code prescribed detailing requirements are required to utilize the peer review process. Many times, these designs can provide the best performing buildings during large hazard events.

3.5 Integrated Review to Improve Reliability of Nonstructural Seismic Bracing

In terms of nonstructural seismic bracing considerations, there are several potential issues related to conventional design and construction. Seismic bracing design is typically performed in a siloed and fragmented manner. Other than limited bracing details shown in architectural drawings, mechanical and electrical design engineers specify seismic design requirements for the contractor's engineer to complete the final engineering. Each trade subcontractor's design engineer then designs seismic bracing and specifies bracing locations without communication or coordination with the others. Each discipline follows the standards and guidelines of their practice and pays little attention to how the design can affect other discipline's work. When reviewing design submittals, the structural engineer-of-record verifies if design approaches follow design requirements and provides review comments related to the submitted design calculations. It is common to leave all field coordination to the general contractor for addressing any potential field conflicts. Without deliberate coordination among all the trades led by the general contractor, trade contractors sometimes find that there is a lack of physical space for their seismic bracing due to presence of another large equipment/distribution systems installed before them.

Based on seismic evaluations of existing facilities, this type of field conflict creates several types of defective installations of seismic bracing, ranging from omission of seismic bracing, incomplete bracing, inadequate bracing, or significant deviation from the submitted and approved design details. Unless the owner retains a knowledgeable and strict special inspector, this type of defective installation is generally left unaddressed and becomes a possible weak point in the ability to control and limit recovery time.

Some nonstructural components, depending on their cross-section dimension or weight, are not required to have seismic bracing per current design standards. Unless there is adequate clearance with adjacent components, these components may impact other components during a seismic event, leading to potentially avoidable damage. In general, the subcontractor’s design engineers do not specify required clearance to avoid this impact. Even if the clearance is specified, without deliberate coordination among all trades, clearance for components may not be properly enforced.

To improve the reliability of the seismic performance of nonstructural components, it is highly desirable for a member of the design team to coordinate bracing details and their locations, and clearance for nonstructural components that are not required to be seismically braced, among all disciplines. For example, the owner for one recent mega-project in the Pacific Northwest required design teams to include an engineer in the role of Seismic Resilience Lead, who was responsible for interdisciplinary integration of the project's resilience design requirements. It is recommended that each seismic bracing location is accurately reflected in the project Building Information Model (BIM). If deferred design elements cannot be minimized or avoided, a member of the design team and/or the general contractor should proactively collaborate with these design engineers to address any conflicts via project BIM model during the construction phase. For the nonstructural components that are not required to be seismically braced, if adequate clearance cannot be feasibly provided, seismic bracing or restraint shall be provided to minimize any potential impact with adjacent components (i.e., potential consequential damage). Before construction, it is recommended that a design team member meet with construction special inspectors and clearly communicate project expectations and special inspection requirements. Building owners may elect to have the Structural Engineer-of-Record or a third-party perform a confirmation nonstructural seismic evaluation during and after the completion of construction using the ASCE/SEI 41 (ASCE 2017) procedure to confirm that nonstructural components will be able to achieve Operational seismic performance, and state as such in their final report.

3.6 Enhancement of Construction Inspection with Resilience Perspective

Incorporating resilience objectives into design and construction is a new concept that may not be familiar to contractors and construction inspectors. It is unlikely that more than the minimum special inspection and testing requirements specified by the building code would be implemented unless the design professional requires resilience-focused construction inspection and appropriate training for contractors and construction inspectors is provided. Like the peer review during the design phase of a project, construction inspection plays a critical role in ensuring that the final constructed project will achieve its performance objectives consistent with the owner's resilience target. It is recommended that building owners foster the development of a training program to assist construction inspectors working on their projects to raise awareness of why resilience is vitally important to the community and how

Individual projects are raising the bar above historical design and construction practices. The construction inspector should be familiar with the structural and nonstructural performance objectives established for the project and recognize that the design will involve more stringent construction and inspection requirements than minimum standards.

In most cases, enhanced provisions and training for resilience inspections will involve more attention to system-wide details for elements than these inspections currently emphasize. For example, seismic resilience of primary structural members can be seen via enhanced connections, material properties, and potentially proprietary components. Certainly, additional training and competencies will be needed, but these are enhancements of the already required wood, steel, or concrete Special Inspections.

Flood resilience, however, needs to incorporate a new series of critical system inspections and training relative to deployed barriers. The term ‘deployed barriers’ covers both stored-in-place and remotely stored components. In general, remotely stored barriers are part of a pre-engineered system and have been evaluated in the factory according to ANSI/FM 2510. This testing requires sequential loading and unloading for hydrostatic loads and a debris impact test for which barrier strength and leakage is measured. While this testing is only loosely realistic because there is no hydrodynamic loading, wave loading, and the debris impact is generally less than that in ASCE/SEI 7 (ASCE 2021) (because in the Commentary), there is at least a minimum standard that has been provided. Conversely, many stored-in-place barriers are custom made for the application, without standard product testing protocols. For this reason, the design specifications need to explicitly cover the gaps in testing and inspection requirements. Some best practices for flood barrier design specifications include:

- Minimum fabricator and installer qualifications of 5 years with comparable products and installations.

- Submission of comprehensive shop drawings showing criteria, component materials and finishes, deployment procedures (operating instructions), and maintenance (component exercise and replacement) requirements.
- Submission of structural calculations demonstrating the ability to resist the design loads and meet the associated criteria (deflection criteria and leakage rate).
- A reasonable warranty on all components of the system.
- Shop testing per ANSI/FM 2510 with the design hydrostatic depth and a debris load in accordance with the design value. A single debris impact should be simultaneous with the hydrostatic load, at the point of maximum influence, and should be applied in such a way that water drag does not influence the load.
- One full-size, in-place hydrostatic water test at a representative barrier.
- An air or hose test for all remaining in-place barriers.

3.7 Additions and Alterations

Additions and alterations to existing buildings present an opportunity for structural retrofit and to mitigate nonstructural deficiencies. There are typically two main classes of additions – structurally dependent and structural independent additions. Alterations can range from simple nonstructural renovation to complicated structural modifications.

The International Existing Building Code (IEBC) (ICC 2021a) sets provisions for additions and alterations. In general, the provisions require structural elements to be evaluated for current code wind loads. Additions require compliance with full code seismic loads and alterations require compliance with reduced code seismic loads (wind loads are always checked at full code level in the IEBC). When determining full or reduced code seismic loads, the IEBC permits the use of ASCE/SEI 7 (ASCE 2021) but allows the user to use seismic response modification factors (R-factors) for systems that would not be permitted in new construction. Issues regarding this approach are discussed in Section 2.4. ASCE/SEI 41 (ASCE 2017) can be used in lieu of ASCE/SEI 7 (ASCE 2021) when assessing the consequences of an addition or alteration on the seismic force resisting system of the building and performing a seismic retrofit of the building.

The IEBC stipulates those additions and alterations of buildings in a “flood hazard area” established in the International Building Code (IBC) (ICC 2021) that result in a “substantial improvement,” defined as having a cost more than 50% of the fair market value of the building, require the building to be assessed for the flood provisions in the IBC, all other work is exempt from mandatory compliance.

Structurally independent additions are typically new additions to an existing facility that extend horizontally from the original footprint, with the new portion having a structural system designed to meet new code requirements. Structurally independent vertical additions are less common but can occur. Openings are created in the roof and floor(s) of the original building for columns to be erected on new or existing foundations. The same code provisions apply for both types of additions, where the new structure and nonstructural components must be designed for full code loads and requirements, but existing structural and nonstructural components can remain without retrofit.

Allowing the original building to remain without retrofit often ensures the structurally independent addition will be more resilient to wind, flood and seismic than the original building. The main issue is the code does not require that the original building be retrofit because the addition is designed as a separate structure. So, there can be a mismatch in performance. One example where the mismatch in performance can compromise the performance of both the existing and addition is when base building systems are in the original, unmodified buildings or distribution elements such fire suppression piping crosses the joint between the two buildings. Differential movement between the original and addition can cause damage to the piping, leading to rupture. Such differential movement may be greater than the pipe joint capacity that maintains water tightness of the entire system.

Structurally dependent additions attach to the original structure for some portion of the addition. In this case, the original structure must be shown to meet full code requirements or retrofit. There is an exception which permits the original structure to remain without retrofit if the addition causes changes in the demand-to-capacity ratio of the original structure’s members by less than 5% for gravity load and 10% for wind and seismic. When ASCE/SEI 7 (ASCE 2021) is used for seismic, the IEBC (ICC 2021a) permits the use of ordinary system R-factors. These R-factors may be unconservative for safety (Hohener et al 2018). This approach may produce a new, combined structure that meets the code requirements, but may undergo severe damage in a code-level seismic event, compromising the facilities’ ability to recover.

Alterations to structural components require compliance with full code loads for gravity and wind and reduced code loads for seismic. The reduced code approach is permitted for alterations based on the belief that requiring full code retrofit would be prohibitively expensive. Consideration should be given to using full code loads if one desires to enhance the overall performance of the facility as part of the alteration. Like a structurally dependent addition, the code permits the original structure to remain without retrofit if the addition causes changes in the demand-to-capacity ratio of the original structure’s members by less than 5% for gravity load and 10% for wind and seismic.

Nonstructural alterations, such as tenant improvements, installation of new medical equipment, changing out or upgrading existing mechanical, electrical, or plumbing (MEP) system components, do not require structural evaluation or retrofit, unless the new components are heavier than the components they are replacing. New nonstructural components need to meet current code requirements, but existing components they interface with do not. If a rooftop air handling unit (AHU) is replaced, the existing distribution system components attaching to the unit can remain unbraced and any roof screens around the equipment can remain, even if they do not meet code wind loads. Further, there is no requirement that new MEP equipment should be placed above the inundation depth.

With all the addition and alteration provisions, there are no provisions to evaluate and retrofit existing nonstructural components or systems. Any new nonstructural elements added due to the addition or alteration must be compliant with new code nonstructural provisions, but existing elements that remain do not need to be evaluated or retrofit. Often the components and systems most critical to the facility's ability to recover are untouched. Building cladding is rarely replaced as part of an alteration and only modified where the addition interfaces with it. The primary MEP components, such as chillers, pumps, switchgear, AHUs (Air Handling Unit), and cooling towers, are not replaced. Nothing in the IEBC (ICC 2021a) compels the owner or operator to relocate base building components to locations above the flood inundation depth and older components are unlikely to be seismically certified to function following an event.

Additions and alterations present an opportunity to retrofit the structural and nonstructural components, even though it is not explicitly required by code. These retrofits should be investigated as part of the addition or alteration project. Often, the cost of the retrofit can be reduced because the costs associated with removing finishes to access the structural system are already accounted for in the addition or alteration budget.

4.0 Case Studies

In this section, case studies for the critical facilities examined in this document are used to illustrate how best practices can be implemented to improve the performance and recovery of critical facilities faced with earthquakes, floods, and wind hazards. Section 4.1 describes how the State of California improves seismic performance of its hospitals through a thoughtful balance between performance, cost, and compliance timelines. Section 4.2 presents how two school districts in Oregon developed their resilience visions to improve school design for earthquake and flood hazards to better support their community's response and recovery needs. Section 4.3 provides design consideration for improving resilience objectives of two datacenters, one as a stand-alone new construction and the other as part of an existing office building, against earthquake, flood, and wind hazards. Since the existing office building is seismically deficient, a balanced strategy is developed to improve performance of the datacenter while minimizing construction costs for the building owner.

4.1 Healthcare Facilities

4.1.1 California SB-1953 (1994) Program for Hospitals – Be Flexible

Following the unacceptable performance of some hospital buildings in the 1994 Northridge Earthquake, the California legislature passed SB-1953 (1994), which required all hospitals in the state be retrofit or taken out of service by specified dates. SB-1953 set a tiered approach to the retrofit program by prioritizing completion of retrofits to hospitals that did not meet the Life Safety performance level by 2007. Following that, all hospitals had to meet the Immediate Occupancy level by the year 2030. The program initially spurred a significant amount of new hospital construction and retrofit projects. However, the cost of compliance started to become more apparent and significant.

California's Office of Statewide Hospital Planning and Development (OSHPD), the state agency charged with overseeing hospital design and construction, showed a willingness to be flexible and make reasoned adjustments to the program. The first was an extension of the 2007 deadline. The second was creating an alternate compliance method for the Life Safety performance level which passed some buildings that originally had not passed and led to reduced requirements for retrofit in others. As the 2030 deadline approaches, California's Department of Healthcare Access, and Information (HCAI, the rebranded OSHPD agency) has shown a continued willingness to adapt the program to the realities of its cost burden. This flexibility by the authority having jurisdiction has resulted in a significant improvement in the effectiveness of the hospital system upgrade program in the State of California, more than if the state had held firm to its initial deadlines and performance levels (Tokas 2020). The number of hospitals not meeting the basic Life Safety performance level in a design earthquake has been reduced from over 1,000 to less than 25.

The flexibility OHSPD/HCAI has and is showing should be a model for other jurisdictions looking to enact mandatory retrofit for existing buildings. Existing buildings pose the greatest risk but setting up performance criteria or compliance timelines that are not economically feasible can lead to reduced compliance and potentially loss of critical facilities.

4.2 K-12 Education Facilities

4.2.1 Seismically Resilient School Designs to Support Community Recovery

Schools are unique public facilities. Not only do they shelter thousands of our children every day, but they are also distributed throughout most neighborhoods and walkable from homes nearby. With some forethought, they could be significant resources in helping communities recover in the aftermath of an earthquake or other major disaster. The Oregon Resilience Plan (OSSPAC 2013), published in February 2013, indicated that after a major Cascadia Subduction Zone earthquake, existing schools, and emergency shelters in the Willamette Valley region of Oregon may take 18 months to repair before they are able to reopen (OSSPAC, 2013). In response to this finding from the Oregon Resilience Plan, a few school districts in Oregon have elected to build their new schools to exceed building code requirements in certain critical aspects to better support the community after a Cascadia Subduction Zone earthquake. These new schools are intended to be safe, be available as a community emergency shelter within 72 hours after a major earthquake and be ready to reopen for education within 30 days following the earthquake. To achieve these recovery goals, several key features have been incorporated into the design and construction of these schools. From a case study of Beaverton School District's two new schools, one key conclusion is that these enhanced design features require only a nominal increase to the overall construction cost (SEFT, 2015; Yu, et al., 2018).

The Beaverton School District (BSD) vision has been to explore how to prepare the district and the surrounding communities for an eventual Cascadia Subduction Zone earthquake. The district recognizes the importance of school buildings for post-earthquake response and recovery, with schools typically functioning as emergency shelters after a disaster. Using the Oregon Resilience Plan (OSSPAC 2013) as a guide, the BSD constructed two new schools as a demonstration project to explore how schools can be designed for use as shelters in the immediate aftermath of a Cascadia earthquake and be reopened in a timely manner to aid recovery efforts − all within their budget constraints (Yu, et al., 2018).

BSD also recognizes that enhanced performance efforts need to be both realistic and flexible. It would not be realistic to expect the school to be a completely self-sufficient emergency shelter were the Cascadia earthquake to happen tomorrow. Many of the requirements for an emergency shelter are dependent upon continued lifeline (i.e., utility and transportation systems) support and services to the shelter. Not every desired infrastructure system can be available at each BSD facility operating as an emergency shelter. Flexibility in the school design is important to have an adaptable building layout that can accommodate future performance improvements as resources become available. BSD also wanted to partner these resilience goals with their existing sustainability goals of reduced energy consumption, natural ventilation, and natural daylighting.

Mountainside High School

The design of Mountainside High School includes approximately 30,660 square meters (330,000 square feet) of educational and support space in a three-story structure with a partial basement. With an enrollment capacity of 2,200, the high school has a main gym, auxiliary gym, aerobics/dance room, commons, kitchen, fifty classrooms, and many offices. The overall building construction was completed in 2017 at an approximate construction cost of $98 million. The resilience planning for the high school occurred alongside the design effort. The objective of the resilience planning was to identify enhanced performance measures that could be seamlessly integrated into the building's design without notably impacting the cost, schedule, or design of the structure. Through a collaborative resilience planning process among all stakeholders, many enhancements were identified.

The site layout and access lend itself to recovery functionality in a post-earthquake environment without major impacts to the site plan. The site can provide services for on-site distribution of supplies and services for the initial 30 days and beyond with minimal impact to school operation. Two surface parking and circulation routes allow for flexibility in allowing one-way traffic for vehicles to enter the campus and obtain supplies and services. The site also has an area for portable classrooms. Routing electrical, water, and wastewater services to these portables would come at little cost and provide additional flexibility for relief operations. The site has parking areas and fields available for portable shelters and distribution of supplies as needed during the first 30 days (and for any extended shelter needs once the school has reopened). Finally, the site has adequate play areas for children.

The district decided to fully utilize all the open spaces (such as main gym, auxiliary gym, and commons) and large classrooms for shelter use (see Figure 4-1 for floor plan and associated shelter capacities). The approximate shelter sleeping capacity is estimated to be 860. In addition, a covered area has been pre-designated for pets. To meet American Red Cross requirement of having a safe and usable building, the project team chose to:

1. Design the building as an essential facility (i.e., Risk Category IV) promoting a high probability that the building will be safe to occupy after a large M9.0 Cascadia Subduction Zone earthquake.
2. Design nonstructural components required for operation as an emergency shelter to Risk Category IV and special certification requirements.

The shelter requirements set minimum standards for heating, ventilation, and cooling of the shelter. To accommodate sheltering in the high school, the following features were recommended:

1. Utilize current Oregon Energy Standards for insulation and windows so that heat generated by people, lights and equipment will keep the temperature at acceptable levels, assuming

occupants will be dressed in jackets or wrapped in blankets.

2. Use natural ventilation from doors and windows to provide ventilation and cooling during hot weather to keep indoor temperature at or below the outside temperature. This was already part of BSD's sustainability design standards.

3. Add exhaust fans to supplement natural ventilation to shared areas during hot weather and ensure they are on the emergency power circuit.

Emergency power is a basic code requirement, but code only establishes a minimal level of service that provides power for egress lighting and for the operation of elevators for egress purposes. This power only needs to be provided for a brief period. While emergency power is not a requirement for using the building as a shelter, there are many potential features that would increase the school's usefulness as a shelter, such as:

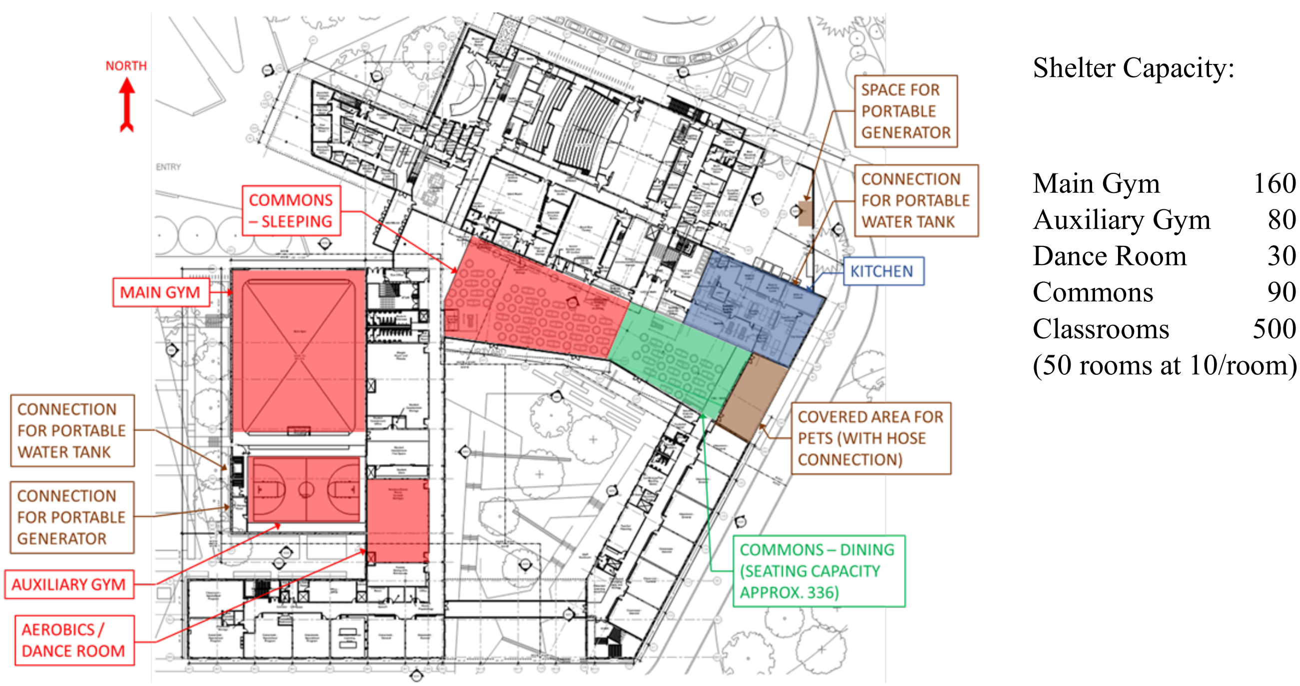


Figure 4-1. Mountainside High School First Floor Plan.

1. Provide the largest sized generator that the budget will allow.
2. Provide accommodations for hooking up additional emergency power generators.
3. Add exhaust fans, common-lighting, and hot plates in the kitchen to an emergency power circuit.
4. Provide on-site use of a photovoltaic power array with inverter.
5. Provide seismic bracing of electrical system components intended for emergency shelter use to satisfy Risk Category IV seismic bracing requirements and utilize special certification requirements for equipment expected to be operational after an earthquake.

The school's functionality as a shelter depends on the availability of utility services to the site. Enhanced performance features include both short-term and long-term objectives for both BSD and the utility providers to consider. Those features are as follows:

1. Ensure water service is on the backbone system to receive water within 24 hours once the municipal system is upgraded to its resilience goals.
2. Design water piping installed between the utility main and school building to consider seismic resilience.
3. Provide pre-established temporary connection points at the building exterior for water supply via a portable water tank and pump. This can be used to supply water until the backbone system is established.
4. Route water from external water tanks to supply key building areas, including the kitchen, locker rooms and showers, drinking fountains in common spaces, and restrooms serving the common spaces.
5. Provide seismic bracing of plumbing system components intended for emergency shelter

use to satisfy Risk Category IV bracing requirements.

6. Ensure wastewater service is on the backbone system to provide services within 1-2 weeks once the municipal system is upgraded to its resilience goals.
7. Design wastewater piping installed between the utility main and school building to consider seismic performance.
8. Provide a seismic shutoff valve at the meter to reduce the potential fire hazard associated with natural gas leaks after an earthquake.

Table 4-1. Mountainside High School - adopted resilience design features.

Resilience Feature	Cost Estimate
1) Design building structure's lateral-force resisting system for seismic Risk Category IV.	$500,000
2) Provide 500 kW emergency generator with 96-hour run time fuel storage. Emergency generator, switch gear, ventilation fans, and other equipment expected to be operational after an earthquake should satisfy the special certification requirements of ASCE/SEI 7-10, referenced by the OSSC.	$330,000
3) Provide electrical service to power lighting and ventilation fans in communal areas and gymnasium on emergency power; does not provide heated or conditioned air.	$8,000
4) Provide stub-outs at building exterior to allow use of portable water tank and associated pump to supply water to key building areas: kitchen, locker rooms and showers, drinking fountains in common spaces and restrooms serving the dining commons.	$15,000
5) Provide two electrical outlets in the kitchen on emergency power to allow hot plates for water boiling, etc.	$5,000
6) Provide natural gas seismic shutoff valve at meter.	Negligible
7) Provide hardened water service line from the City of Beaverton Water Division (BWD) water line to the building.	TBD
8) Provide hardened sanitary sewer service line from Clean Water Services (CWS) sewer line to building.	TBD
9) Provide seismic bracing/anchorage design of nonstructural components based on Risk Category III requirements except those components required for use of the school as emergency shelter satisfy Risk Category IV requirements.	Negligible
Approximate Total	**$900,000**

Due to budget and design schedule limitations, not all the enhanced performance features that were discussed as part of this project could be incorporated into the design, construction, and operation of Mountainside High School. The features adopted are summarized in Table 4-1. The overall cost premium associated with these selected features was less than 1% of the building construction cost. The intent behind these selected options was to build in as much flexibility as possible to pre-position for future performance upgrades. As additional funding becomes available or the cost of certain technologies (photovoltaic inverters, battery storage, etc.) decreases, it may be possible to provide additional resilience features that will make using the school as an emergency shelter easier or enable additional services to be provided by the shelter.

Tumwater Middle School

The design of Tumwater Middle School includes approximately 15,330 square meters (165,000 square feet) of educational and support space in a two-story structure. With an enrollment capacity of 1,100, the middle school has a main gym, auxiliary gym, multi-purpose room, choir room, band room, commons, kitchen, forty classrooms, and many offices. The approximate shelter sleeping capacity is estimated to be 725. The overall building construction cost was approximately $43 million. The findings for the middle school proved to be remarkably like those of the high school. The overall cost premium associated with the selected enhanced performance features was slightly more than 1.5% of the building construction cost.

4.2.2 Rebuild Vernonia Schools with improved performance to save a town

The City of Vernonia, Oregon is a small rural town with a population of around 2,200, located in Columbia County, about forty-five miles northwest of Portland. Situated in the Upper Nehalem Valley on the eastern side of the Oregon Coast Range, Vernonia was established along the Nehalem River in the heart of one of the most important timber-producing areas in Oregon. In addition to its exceptional natural beauty, the city has many amenities, including a well-known state trail, a state park, and several city parks. Once a thriving timber town until the late 1960s when its supply of tall trees was exhausted, it has been struggling to regain its economic footing. Like many other small towns across the Pacific Northwest, Vernonia is faced with higher employment, aging infrastructure, and the exodus of its youth. Located adjacent to the Nehalem River, Vernonia had the misfortune of being hit with two '500-year' floods in just over a ten-year period, the first on February 8, 1996, and the second on December 3, 2007. During the 2007 winter flood, nearly half of the homes and one-third of the downtown buildings were affected. All its schools (elementary, middle, and high schools) were severely impacted with several feet (about 1 to 2 m) of inundation.

Figure 4-2. City of Vernonia Under Water on December 3, 2007 (source: Dailyastorian.com).

As the schools tie together the community and the school district provides more than eighty jobs, it was existentially critical for Vernonia to rebuild its schools. Instead of implementing another round of repairs after the 2007 flood, the school district and elected officials at the county and state levels decided that new schools should be rebuilt better by moving them to a site on higher ground located outside the

'500-year' flood plain. Implementing this vision requires navigating land use and zone regulations, raising funds for construction, and building roads and infrastructure. In April 2008, the Governor designated rebuilding Vernonia's schools an Oregon Solutions project so that this problem could be tackled efficiently and effectively through collaboration among the government at all levels, the school district, industry representatives, and civic and philanthropic organizations. To save long-term operational and maintenance costs, all three schools were integrated to create a unique K-12 campus. Leveraging the City's cultural and historic connections to its forest, the school was envisioned to support a new green economy through several ideas, including (a) foster stewardship of the Upper Nehalem Watershed through K-12 curriculum, (b) incubate new natural resource businesses and entrepreneurs and provide workforce training for students and the community, and (c) foster rural-urban relationship through scholarship, teaching, and community engagement. In 2009, this collaborative team identified a site to build a safe and sustainable school outside the '500-year' floodplain. The school district passed a $13 million bond program to partially pay for the $38 million new school. In 2011, FEMA acquired the existing Vernonia school buildings through its Flood Mitigation Assistance program and contributed $11.2 million to construction of the new school. The rest of the construction funding was from over 125 individuals and organizations. The new school was designed as the first LEED platinum-certified public K-12 building in the country. In August 2012, the new school campus was opened. The campus includes a Vernonia Rural Sustainability Center with labs and classrooms for workforce education and job skills training. The City of Vernonia demonstrated how school investment could catalyze rural economic development and preserve a community.

Figure 4-3. Vernonia New Schools Under Construction (source: Oregon Solutions).

4.3 Datacenter Facilities

Redundancy

If a data center is a single point of failure, consider exceptional facility performance against all hazards. When considering designing or retrofitting a data center for enhanced performance, the first consideration should be whether the data center is or should be redundant. There are many things that can impact the hour-by-hour operation of a data center, from power failures to human caused water intrusion. Elimination of these issues may not be possible, making it prudent to have a fully redundant facility at another geographic location. Computer technology has advanced to the point where data can be written almost simultaneously on geographically dispersed servers. As will be discussed, the costs for providing improved building performance against wind events, floods or earthquakes can be very large, especially for existing buildings. So, building a redundant facility should be considered as part of any planning effort.

If the data center cannot be made redundant, the new facility design or existing facility retrofit should consider enhanced performance requirements in the structural and nonstructural design beyond what would be needed for a typical Risk Category II building.

4.3.1 New Datacenter

The first thing to consider when designing a new data center is where it should be sited. The easiest way to provide enhanced performance to natural disasters is to locate in areas where there is little exposure. So, if possible, a new data center should be located where the seismic hazard is low, outside of a flood zone (ideally for a 500-year instead of a 100-year flood) and has a low likelihood of being affected by a major wind event. This hypothetical case study assumes that the building cannot be located outside of any hazard area and is subject to all the hazards discussed in this document to provide the reader with a full picture of how they could go about designing for enhanced facility performance to all hazards. Very few sites in the United State would be subject to extremes of all three hazards.

The new datacenter is one-story and consists of concrete tilt-up wall panels along the exterior, steel columns and girders with open web joists between them supporting an untopped steel deck roof. The requirements of ASCE/SEI 7 (ASCE 2021) Supplement 3 and ASCE/SEI 24 (ASCE 2014) require the first floor be elevated above the Design Flood Elevation. The 500-year still water elevation is used as the baseline flood level because of the critical nature of the data center. The first floor is an elevated concrete slab spanning between concrete beams that sit atop concrete pedestals over the footings. The superstructure steel columns are founded on top of the elevated slab. The datacenter uses hot/cold aisle construction to limit the volume of space that must be cooled by the mechanical systems. All the mechanical, electrical, and plumbing systems are within the building. The data center does not have any significant office space, it is solely for the servers, the MEP systems, and the people supporting the facility.

Because the datacenter is a single point of failure for the organization and therefore critical, the design uses all provisions for Risk Category IV in ASCE/SEI 7 (ASCE 2021) with Supplements 1, 2, and 3 as the starting point and augments beyond that. This means that the roof will be designed for wind pressures from 3,000-year MRI (Mean Recurrence Interval) wind event. The roof construction is an untopped steel deck over open web joists that frame into ledger angles in the tilt-up panels and joist girders between the steel columns. The attachment of the untopped metal deck to the open web steel joists and the deck itself will be designed to resist uplift loads. Failure of the deck attachment to joint girders is a critical failure of buildings with untopped steel decks in major wind events. Another potential point of failure in major wind events is the connection of open web steel joists to the girder or wall ledger framing. Per the Steel Joist Institute Code (SJI) of Standard Practice (SJI 2015), the engineer-of-record is responsible for the design of the attachment of the joists to the structure and the joist manufacturer is responsible for the design of the seat based on the uplift loads provided by the engineer-of-record. The engineer-of-record cannot design a connection between the joist seat and the structure without an understanding of the seat configuration. Therefore, the engineer-of-record should reach out to joist manufacturers during design to discuss the likely seat configurations based on the uplift loads on the joist seats. The manufacturer may be able to provide recommendations on bolted versus welded connections to restrain the joists against uplift. Designers are referred to SJI Technical Digest 6 (2012) for more information on designing joists under uplift loads.

The seismic design is based on Risk Category IV criteria. A geotechnical evaluation was performed to get the site class and a site-specific response spectrum was developed in accordance with Chapiter 21 of ASCE/SEI 7 (ASCE 2021) for the site to provide the most accurate seismic hazard information.

For a rigid wall / flexible diaphragm building, Risk Category IV requires enhanced anchorage loads between the tilt-up wall panels and the diaphragm. Because of the critical nature of this connection, the engineer-of-record specified more special inspection on the connections and intends to perform structural observation to enhance the reliability that the wall out-of-plan anchorage connections are constructed in general conformance with the design intent.

The structures that enclose portions of the servers in a hot / cold aisle configuration are cold-formed steel bolted moment frames. Like the main structural system, these structures are designed using Risk Category IV provisions. Risk Category IV limits the drift of moment frames. This has the added benefit of controlling the deformations on the panels that seal the region that must be cooled to keep the servers from overheating. If the seal in these areas is damaged during a seismic event, the cooling system may not be able to control the temperature of the servers, causing them to overheat and cease to function. These cold formed bolted moment frame systems also support much of the cabling, ducts, and pipes in the MEP system. Because these are independent structures, their relative displacement with respect to both the roof (which may itself be deforming significantly in a seismic event) and floor must be considered when laying out the distribution systems that will be supported by them or cross them. Flexible joints are recommended in large ducts, pipes, and conduit when they are attached to both the roof and the cold form bolted moment frame structures.

All the nonstructural components of the MEP systems are required to be seismically certified. The component anchorage has special inspection requirements. The bracing of the distribution system components is designed using I_p =1.5 requirements. The engineer-of-record performs structural observation of the MEP system bracing to ensure that common construction mistakes, like bracing to the bottom chord of an open web steel joist, instead of the top chord, which is attached to the diaphragm, is not done. Since there are so many different pipes, ducts, and cable trays hung from the ceiling, a unified building information model, is developed by the general contractor to confirm that all system components have enough separation so they will not impact against other system during an earthquake.

All MEP system components should be seismically certified. The engineer-of-record or the project resilience lead should review the seismic certifications to confirm that they have been conducted with the equipment operating. Some seismic certifications are performed with the equipment off during shaking and then they turn it on after shaking to demonstrate it works. This can be an issue because internal equipment damage can be more severe if there are moving components in motion during the seismic shaking. For the servers, the most rugged racks that can be purchased should be. Many vendors make special racks for high seismic regions. Also, the servers should use solid state hard drives instead of magnetic spinning drives to eliminate moving components that can be damaged during seismic shaking.

Rooftop equipment and distribution components, such as ducts, should be hardened to protect them from high winds and windborne missiles. Unfortunately, there are no standards for these systems' design for windborne missile impact. The engineer will have to review and adopt standards for windborne missile resistant glazing and doors to develop criteria for the screen material.

4.3.2 Existing Datacenter

The hypothetical exiting data center case study building is a four-story building in a suburban office park. Like the new data center case study, it is assumed that this building is sited in a location subject to all hazards covered in this document. The building was designed in 1981. The building was originally an administrative building for a major corporation. In the 1980’s a server room was installed. Over the years, that server room grew and expanded to encompass most of the second floor of the building.

The building's structural system is steel framed beams and columns. Floors consist of concrete filled steel decks over wide-flange beams. The roof consists of an untopped steel deck. There is a one-story deep basement with concrete walls along the perimeter. The steel columns continue down to the basement level and are founded on spread footings. Along the perimeter, the steel columns are encased in the basement walls. The building is clad with a glass and aluminum curtain wall system. Insulated glazing panels are installed between aluminum mullions. There is 8-feet (2.4 m) of landscaping between the curtain wall and the parking lot.

The lateral force resisting system of the building consists of steel moment frames along its perimeter. The moment frame beams are attached to the columns by welding the beam flanges directly to the column flanges with complete penetration welds and by bolting the web of the beam to a shear tab welded to the face of the column flange. This type of connection is commonly called the pre-Northridge Welded Unreinforced Flange with Bolted web (WUF-B). The designation pre-Northridge is used because this connection was the most common beam-to-column connection detail used from the mid-1960s up to the 1994 Northridge earthquake. Many steel framed buildings employing the WUF-B connection had fractures in the weld between the beam flange and the column flange. The discovery of this unexpected failure mode prompted a major research effort to study steel beam-column connections and assess the resilience of existing ones (FEMA 350 2000a and FEMA 351 2000b). The columns in the building are spliced together just above the third floor using partial penetration welds between the web and flanges of the upper and lower column. Failure of partial penetration welded column splices were observed in the 1995 Kobe Earthquake and were also noted in laboratory testing in the early 1990's (Brunea and Mahin 1990). Because the building employs both the partial penetration welded column splice and pre-Northridge connection detail, it is unlikely to meet performance objective intended for new Risk Category II buildings, let alone a higher performance level for enhanced resilience.

Since the building was originally intended to be an office building and the data center evolved over time into a critical piece of the organization's infrastructure, a comprehensive assessment of the building's hazard performance was never conducted. Data centers are assigned to Risk Category II just like office buildings, so the presence of a critical data center never triggered a change of occupancy retrofit per the IEBC (ICC 2021a). There were never any substantial alterations or damage to the building that required assessment and retrofit per the IEBC (ICC 2021a) either. Therefore, the first step in understanding the hazard performance of the facility is to assess it using modern codes and standards for environmental loads to understand where the facility stands with respect to current code performance levels and potentially higher levels for an enhanced design. For wind and flood, there is no existing building specific standard, so the latest editions of ASCE/SEI 7 (ASCE 2021) and ASCE/SEI 24 (ASCE 2014) should be used. For seismic, there is an existing building specific standard, ASCE/SEI 41 (ASCE 2017), which is better suited for evaluating existing buildings than using ASCE/SEI 7 (ASCE 2021), which is intended for new construction. ASCE/SEI 41 (ASCE 2017) provides direction for assessing structural systems that do not conform to today's standards. If one wishes to use ASCE/SEI 7 (ASCE 2021) for a seismic evaluation, the user must discern what the appropriate structural system is and assign an R-factor, which is often not straightforward when the existing structural component details do not conform to the base requirements of the material design standards.

The building was assessed for wind loads using ASCE/SEI 7 (ASCE 2021). The moment frames were found to have sufficient capacity as main wind force resisting system elements for wind loads up to the Risk Category IV level. Even though the original building was designed as an office building, the high seismic hazard required significantly more substantial moment frame members than Risk Category II wind loads would have required. The only structural components that are overstressed under wind loads are the untopped steel deck roof and the connection of the roof to the framing. The connection of the deck to the framing members is overstressed for Risk Category II wind loads, while the deck itself is overstressed for Risk Category III wind loads.

The cladding mullions are overstressed and have excessive deformations for Risk Category II wind loads at the corners of the building and Risk Category III wind loads everywhere else. Additionally, it cannot be confirmed that the cladding joint details can maintain their watertightness under deformations imposed by Risk Category I or higher wind loads. This may pose an issue because the building may become exposed to water intrusion due to wind-driven rain.

The building was evaluated using ASCE/SEI 41 (ASCE 2017) using the existing building seismic hazard intensity levels, BSE-1E (20% in 50-year probability of exceedance) and BSE-2E (5% in 50-year probability of exceedance). The building first underwent a Tier 1 screening. Based on the number of potential deficiencies identified in the Tier 1 screening, a full-building Tier 3 evaluation would be the same level of work as a deficiency-only Tier 2 evaluation. The initial, linear Tier 3 evaluation indicated that the building would not meet the Collapse Prevention performance level at the BSE-1E hazard level. The two fundamental issues were the potential fracture of the partial penetration welded column splices and excessive demands on the pre-Northridge WUF-B beam-column connections.

Since the building is critical to the organization, the engineer chose to perform a nonlinear response history analysis using the same hazards with the belief that the nonlinear analysis would provide better indication of the actual deficiencies. While the nonlinear analysis indicated the building did meet the Life Safety performance level at the BSE-1E hazard level, it would not meet the Collapse Prevention performance level at the BSE-2E. Additionally, the nonlinear analysis indicated that there would be significant weld fractures in the beam-to-column connections in the BSE-1E hazard level, preventing the building from receiving a green tag and preventing re-occupancy. The nonstructural components and systems were screened using ASCE/SEI 41's (ASCE 2017) Tier 1 checklists. The screening focused on the Position Retention performance level instead of the Life Safety or Hazards Reduced performance levels because the goal is to assess the hazard performance ability of the building, not just identifying potential falling hazards. If the Life Safety performance level had been used, most of the nonstructural components would have passed. The only two nonstructural components that did not meet the Life Safety screening were the stairs and elevators. The stairs could not accommodate building drift. The elevators because they were original to the building and did not have modern seismic safety features like emergency stops and guardrails that met current ASME A17.1 (ASME 2019) requirements for strength and stiffness.

While not presenting life safety hazards, all the mechanical, electrical, and plumbing (MEP) system components are unbraced or do not have proper seismic anchorage, which will lead to extensive damage. Since most of the base-building MEP system components are original, they are not seismically certified. The fire suppression piping was braced, but the sprinkler heads were at risk of striking the ceiling in an earthquake and discharging from the impact. Seismic drifts in the BSE-1E hazard level are large enough to deform the exterior cladding to a point that it will lose its watertightness.

There are several issues with the nonstructural components on the data center floor. The access floor the sever racks sit on is not anchored to the floor, nor does it meet the special access floor requirements in ASCE/SEI 7 (ASCE 2021). The server racks are not anchored or braced. The racks are also not the rugged models intended for high seismic regions. The computer room air conditioning (CRAC) units are not anchored to the structural slab. The data center portion uses the same fire suppression system as the base building and is also at risk of accidental discharge over the servers due to head impact against the ceiling or other suspended MEP distribution system components. The partition walls that enclose the datacenter are rigidly connected to the floor and underside of the floor above. This rigid connection will lead to damage to the partitions during an earthquake, which could create an issue for keeping the room insulated and cooled.

The original building was designed without any consideration for flooding, as was common at the time of construction. The building is in a non-coastal A-Zone, was constructed prior to regulations that required elevating the bottom of structure of the lowest floor to a 100-year flood-based Design Flood Elevation, and there is a desired resistance to a flood that extends 3-feet (0.9 m) above exterior grade. Flood loads are large and affect many building elements, so retrofitting an existing building to be dry floodproofed is particularly challenging.

Because of the importance of the building to the organization and the results of the hazard evaluations identify several issues at moderate hazard intensities that could compromise function of the data center, the owner chose to retrofit against all hazards. Because significant work will be required, some of the retrofit will occur initially, while other portions will occur in phases with other major renovations, as will be discussed. Given the cost of retrofit the owner has deemed retrofitting to the equivalent of Rick Category IV performance for a new building to be too significant. The appropriate performance objective for each hazard is considered separately, based on the cost and disruption of the retrofit compared to the enhancement in the building’s performance.

Overall, wind hazards posed the lowest threat to the facility. The data center is on the second floor, so losing the roof due to a major wind event would only compromise the data center if the rooftop equipment were damaged or there was a high likelihood of rain as part of or following the wind event. Nevertheless, the attachment of the roof to the framing is augmented to the point where it is stronger than the bending of the steel deck roof. While the roof may be overstressed Risk Category III and IV wind loads, it will deform excessively, but not be dislodged. Replacing the deck is deemed too costly but augmenting its connection to the structural framing can be done concurrent with a re-roofing project, to bundle some of the costs. The issues with the cladding deforming and lowering its watertightness can only be fixed by recladding the building, which is cost prohibitive. Therefore, a means to mitigate that issue would be to provide interior wall construction around the datacenter that can prevent water intrusion into the data center region in the event the building envelope loses its ability to keep wind driven rain out of the building. This wall construction will also have to accommodate seismic deformations, which will also be discussed. The last wind hazard item undertaken is to provide roof screens around the rooftop mechanical units and their distribution systems components that can absorb the impact of windborne missiles, preventing them from damaging the ducts or the units.

A structural seismic retrofit is needed to enhance the performance of the building, but the level of desired enhancement will impact the retrofit. One option that the engineer presented to the owner was to simply retrofit all the beam-column connections and column splices to prevent brittle weld fractures and permit ductile response of the members. The nonlinear response history analysis indicated that this retrofit would meet Immediate Occupancy performance level in the ASCE/SEI 41 (ASCE 2017) BSE-1E but would not meet Immediate Occupancy or Damage Control performance in the ASCE/SEI 7 (ASCE 2021) Design Earthquake. To meet the Immediate Occupancy performance level in the ASCE/SEI 7 (ASCE 2021) Design Earthquake, supplemental dampers or buckling restrained braced frames would need to be added to select structural bays in addition to the beam-column connection and column splice strengthening. Because this is a voluntary retrofit, without any specific performance requirements, the owner elected to retrofit the beam-column connections and column splices, which provides a facility that meets the Risk Category IV structural requirements of ASCE/SEI 41 (ASCE 2017)'s Basic Performance Objective for Existing Buildings. All nonstructural components that are not braced will have seismic bracing installed. Because of the critical nature of the building, anything that supports the data center will be anchored or braced using I_p = 1.5 requirements of ASCE/SEI 7 (ASCE 2021). This bracing will not occur at once but will be phased with major renovations to portions of the office and data center, with the first phase addressing base building equipment that will be moved as part of the flood retrofit. As equipment is replaced, it will be replaced with seismically certified equipment. The fire suppression system in the data center will be changed from the traditional water-based to an inert gas system to eliminate the potential for water leaking onto the servers. On the floors above the data center, the fire suppression heads will be attached to flexible piping to reduce the chance of the head impacting the ceiling and discharging. As servers and UPS systems are changed out, the access floor will be upgraded, and the server racks replaced with more rugged ones intended for high seismic regions.

It is not practical to strengthen the existing exterior envelope or the basement slab-on-grade for flood loads based on the flood assessment conducted using ASCE/SEI 7 (ASCE 2021) and ASCE/SEI 24 (ASCE 2014). Therefore, the only approach that can protect the data center in the event of a major flood is to move all equipment that supports the data center to the second or higher floor. This is significant because the electrical switchgear, chillers, pumps, and boilers are all in the basement. To control costs, a project is planned to create a separate MEP system that will support the data center if the basement floods. An electrical room with an independent feed from the utility is installed on the second floor, along with a machine room to support the datacenter.

5.0 Best Practices for Resilient Design Features

This section discusses best practices and presents some recommended changes to codes and standards to improve the performance of critical facilities during hazard events. The assessment of codes and standards for each hazard in Section 3 identified gaps that need to be addressed when designing a critical facility for enhanced performance. The case studies in Section 4 illustrated many best practices that can be employed and are summarized in this section.

This section also addresses the importance of considering climate impacts and their effects on design hazard intensities. The need to align the resilience objectives of the facility to the realities of the infrastructure feeding it, or provide for those services on-site, are discussed in a section about critical dependencies. One of the main challenges to realizing enhanced building performance objectives identified in codes and standards and the case studies is the lack of a single party to oversee all the various design aspects of a critical facility to ensure that all design items, traditional, delegated, and design-build, are up to the same performance standards as the coordinated base building design. This section discusses the need for a resilience integration consultant or for one of the project team members to serve in that capacity. Lastly, the section presents a discussion of facility specific topics for enhancing overall building performance. Development of enhanced provisions and improved procedures would help facilitate the return to operation of the building allowing for the building to be utilized quickly following an event.

5.1 Hazard Design Criteria and Facility Performance Objectives

The current design and construction provisions for new buildings are similar for each of the critical facility types that are being considered in this document. In addition, there are a few unique requirements in codes and standards that would affect the overall performance of the building, with a few differences that are hazard dependent. In the simplest comparison, building codes and standards use the Risk Category designation to distinguish any provisions that help improve the hazard performance of the building. These provisions are discussed in the following sections.

5.1.1 Wind

5.1.1.1 Best Practices

It is the intent of the current codes and standards that the building structure remain undamaged for a design level wind event. It is also the intent that the building envelope remain intact and that the building can quickly be reoccupied. However, there are many known design, construction, and failure mode issues for nonstructural components that are not currently addressed in the codes and standards that need to be further developed to allow for buildings to be reoccupied quickly. Some of these issues are as follows:

- Design procedures for design of Components and Cladding (C&C) for wind-driven rain that match the current design level wind pressures specified in the codes and standards. Much of the infiltration from wind-driven rain is through gaps in the building envelope at the intersection of walls, windows, and doors or attachment failures for roof equipment.
- Development of design requirements for wind-borne debris for elements of the building envelope other than the current test methods for glazed windows and doors.
- Consistent design provisions for the elements of the building envelope to provide a uniform level of resistance to the design wind pressures.
- Improved design review and construction observation of the elements of the building envelope.
- Development of a standard for the wind-related upgrade of existing buildings.

The provisions of the current building codes and standards related to the main wind force resisting system for a new building provide adequate strength design requirements for most of the new buildings constructed, however the lack of wind drift requirements for buildings often lead to water infiltration into the building as joints become separated in a wind event. Specifically for the critical facilities being evaluated the codes and standards provide the following design requirements/criteria.

- Hospital Buildings (Risk Category IV)
  - Increased design wind pressures for both the MWFRS and components and cladding elements based upon the requirements for hospitals to be classified as Risk Category IV structures.
  - Requirement for glazed opening protection and doors from wind-borne debris impact for facilities located in high wind areas.
  - Limitations on the installation of gravel ballasted roof systems on and around the acute care portions of the hospital to limit wind-borne debris sources.
  - Requirements for local jurisdictions for the facility to provide 96 hours' worth of electricity and water to run the facility until connections to the normal electrical and water systems can be restored.
- K-12 Educational Buildings (Risk Category III)
  - Increased design wind pressures for both the MWFRS and components and cladding elements based upon the requirements for K-12 facilities to be classified as Risk Category III structures.

  - o Requirement for glazed opening and door protection from wind-borne debris impact for facilities located in high wind areas.

- Data Centers (Risk Category II)

  - o Requirement for glazed opening and door protection from wind-borne debris impact for facilities located in high wind areas.

5.1.1.2 Potential Code Changes and Research Needs

Even with the provisions stated above, code and standards need to be improved to increase the hazard performance for these critical facilities. The SEI *Prestandard for Performance-Based Wind Design* (SEI 2019) has design provisions to improve the performance of buildings in both the MWFRS and building envelope areas. The MWFRS provisions provide the opportunity for performance-based analysis of the building structural system to determine its actual performance in dynamic wind events using non-linear analysis methods coupled with site-specific wind time histories developed for the design of the building. The requirements for the building envelope go beyond what is required in the current codes and standards by requiring more stringent inspections and higher design loading for the components of the envelope and lists the current best practice documents for the design and installation of the elements.

Provisions that need to be improved to provide better performing buildings for wind design include:

- Established minimum drift limitations based upon the Risk Category of the building,
- Improved design and test criteria for wind driven rain to prevent water infiltration into the building,

- Improved design provisions, and coordination for the many elements contained within the building envelope.
- Special Inspection requirements that include all the critical facility building envelope construction and how the many elements function together as one system.
- Development of a standard to upgrade existing facilities subject to high winds.

5.1.2 Flood

5.1.2.1 Best Practices

Earlier chapters describe the flood hazard and the nuances and shortcomings of existing codes and standards. Codes and standards for flood design are less developed than for the other hazards; therefore, designers must rely more on alternate technical sources, engineering judgement, and best practices. This section highlights several best practices that can be used in conjunction with codes and standards, and it is divided into recommendations that pertain to both new and existing buildings, then only new buildings, then only existing.

New and Existing Buildings:

- Perform a site-specific flood analysis for all critical facilities.
    - Study should include flood depths for multiple storm levels, debris objects, waves, flow velocity and direction.
- Consider the hazard performance of all non-structural elements at or below the Design Flood Elevation to evaluate the building's ability to regain function after the event.
- Ensure proper erosion, scour, and buoyancy protection for all elements at or below the Design Flood Elevation.
- Reinforce all elements of the building's envelope on the shore-facing side to prevent breaches caused by wave run-up.

- Consider all wind-related best practices because the flooding storm event is coupled with a high wind event.
- Ensure proper construction quality control is performed for all elements part of the flood resisting system.

New Buildings:

- Elevate as much as practical; elevation is by far the best defense.
    - Design Flood Elevation (and therefore the lowest occupied floor per ASCE/SEI 24 (ASCE 2014)) should consider Codes and Standards-based minimums, local regulations, NFIP qualifications, fact-based future sea level conditions that accounts for the realistic lifespan of the building, and additional depth factors-of-safety.
- Design to loads and associated criteria in ASCE/SEI 7 (ASCE 2021) Supplement 3 which represents the best available information.

Existing Buildings:

- Perform a flood Hazard Vulnerability Assessment (HVA) of the building and discuss with the owner practical levels of reinforcing and protection that can be achieved for the specific site, building type, and resilience targets all within the framework of a detailed a benefit-cost-analysis. The HVA should include the following considerations:
- Evaluate various Design Flood Elevations considering Codes and Standards-based minimums, local regulations, NFIP qualifications, fact-based future sea level conditions that accounts for the realistic lifespan of the building, and additional depth factors-of-safety. [Many times, a cost-effective Design Flood Elevation is at the sill height of the windows. At this level, the loads are not excessive and only ground-level openings need deployed barriers, but the windows do not.]

- Consider loads and associated criteria in ASCE/SEI 7 (ASCE 2021) Supplement 3 but evaluate realistic reduction factors based achievable levels of performance and protection.
- Address how all penetrations below the Design Flood Elevation will be addressed.
- Address how all pedestrian and/or vehicular openings will be protected during the flood event, considering storage, deployment time, and available staff.
- Consider options to protect/harden only critical spaces within the building, while retrofitting others with wet floodproofing provisions. [This is not a violation of ASCE/SEI 24 (ASCE 2014) since an elective upgrade, unless regulated by local laws.]

5.1.2.2 Potential Code Changes and Research Needs

Much of what is needed is improved characteristics of a flood hazard due to, or while it passes through, developed areas. Both coastal and pluvial flooding have good overall definition in a 'bare earth' or unimpeded condition, but the loads and criteria that are defined in Codes and Standards can become both overly conservative and unconservative due to urban factors.

The upcoming ATC-149 publication: Coastal Inundation in Developed Regions: Experimental Results and Implications for Engineering Practice (ATC 2023) serves as a starting point for some of these discussions. ATC-149 starts the discussion in the following area:

> *Better estimations of flood hazards and flood loads are needed for building design in developed regions subject to coastal inundation events. Specifically, better estimates of flow, wave and flood borne debris effects are required in many designs that do not have the benefit of site-specific hydrodynamic modeling. Improved flood hazards and flood load calculation procedures are required so that design flood loads on a building can be calculated more accurately.*

While Codes and Standards permit more advanced flood hazard calculations, these are not used often by designers. Current flood-resistant design practice is limited by our ability to accurately specify flood hazards and our ability to accurately calculate flood loads once the flood hazards are specified and there can be considerable variation in the specification of flood hazards and the calculation of associated flood loads, even though most are based on the same basic information (a community's flood hazard study and map).

Some of the challenges in properly defining flood loads in current Codes and Standards are listed below:

5.1.2.3 Hydrostatic and Hydrodynamic Loads

Flow velocity and flow depth are required to determine a structure's hydrostatic and hydrodynamic loading. While ASCE/SEI 7 (ASCE 2021) Chapter 5, the dominant reference for model codes, permits site-specific modeling approaches, the direct equations and guidance listed give designers a simple approach that estimates flow velocity based on the depth attained from published FEMA sources. Flow velocity at the point of interest is conservatively represented as:

$$V = 0.5\sqrt{g\, d_f}$$

United States Army Corps of Engineers research has shown this equation to produce very conservative results for larger depths, but a better approximation has yet to be approved for use. Therefore, designers use the above equation for various points within an urban building array based on the depth obtained relative to local grade.

While it is true that the presence of buildings within the array serve as volumetric voids, this loss of local volume is insignificant relative to the overall volume of water, making the depth increase within the channels insignificant. But the calculated 'bare earth' velocity that exists outside of the building array must change when within the array; fluid mechanics necessitates a higher velocity to account for the restricted flow area. Research presented in ATC-149 showed that within a rectangular building array, the velocity was highest within the channels perpendicular to the shoreline, roughly increased by the blockage ratio. For a theoretical 40% building area blockage, the channel velocity was approximately 40% higher than the pre-array value. The flow velocity on the cross streets, parallel to the shoreline, was much less than the pre-array value, coming close to zero. Within the rectangular array, when the block ratio is constant, the velocities in all directions remain relatively constant.

The above findings can inform aspects of the current practice and can guide future research in the areas of hydrostatic and hydrodynamic loading. Since there was no change in depth, the hydrostatic portion of the flood load does not change when the flow encounters a building array.

The hydrodynamic, or drag, load on an object is a function of the square of the flow velocity as it flows around the partially submerged object. However, the fact that the channel velocity within an array increases by the same percentage as the blockage ratio does not readily translate to an increase in the hydrodynamic load. There are three conditions: the regular array, blockage at a 'dead end' street, or a random or offset array.

In the regular array, the higher channel velocity does not encounter an object in its path, so no object has an increased hydrodynamic load. In addition, the objects beyond row one serves to shield the hydrodynamic flow since the flow in the cross street is minimal. If one row is offset, creating a 'dead end' condition for the channel, the velocity creating the hydrodynamic load on the blocking building is significantly increased with respect to the bare earth value.

Designers using more analytical approaches may already have these conditions accounted for, but when using the simple standard-based approach, recommendations for hydrodynamic loads within arrays are as follows:

- Hydrodynamic loads on row one objects are correct since the velocity of the flow moving around them is the bare earth or pre-array velocity.
- In a regular array, hydrodynamic loads on rows beyond row one is significantly over estimated since the velocity flowing around shielded objects is minimal. Where designers are certain of this shielding effect, and that the shielding object will remain intact, a velocity reduction factor could be considered for the determination of hydrodynamic loads.
- Where an object 'dead ends' the channel of a regular array, the velocity used in the calculation of the hydrodynamic load should be increased by the blocking ratio.

There is not enough data in the ATC-149 study for an irregular array; therefore, it is best practice to continue to use the pre-array flow velocity as the hydrodynamic velocity for all objects. Data collection from these array variations should continue as part of a future study to provide informed hydrodynamic velocity values.

5.1.2.4 Debris Impact Loads

Velocity of the debris object is a key factor in the determination of its impact load, which is the controlling load for many structures. ASCE/SEI 7-16 equation C5.4-3 assumes the debris object velocity is equal to the velocity of water, which is the bare earth or pre-array velocity. The impact load is then modified by factors for importance, depth, orientation, and blockage or screening. Current practice, which is documented in the Commentary only, serves as a very good starting point, but the linked characteristics of velocity, depth, and screening are different from the Standard's suburban lens in an urban array of structures. The proposed changes to ASCE/SEI 7 (ASCE 2021) Chapter 5, soon to be published as ASCE/SEI 7 (ASCE 2021) Supplement 3, attempt to make debris impact more universal and similar to the approach in the tsunami chapter (ASCE/SEI 7 (ASCE 2021) Chapter 6).

However, because of the lack of data, the proposed changes still fall short for urban arrays and the loads remain over-conservative. The Blockage Coefficient, C_B, was removed because, if the screening were destroyed or uprooted, the loads would become significantly unconservative. In its place, though not entirely related, a Debris Velocity Stagnation Coefficient, C_S, was added to describe a more realistic view of fluid flow near a structure and eliminate a further layer of conservatism.

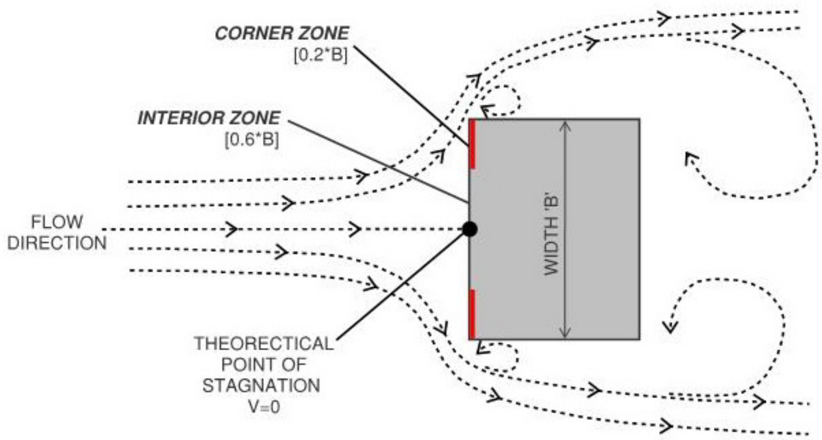


Figure 5-1 Debris Velocity Stagnation Coefficient Diagram as per ASCE/SEI 7 (ASCE 2021) Supplement 3

This approach, which uses a 0.5 factor for the velocity of the object in the interior zone and a 1.0 factor for the corner zones, still leaves much room for improvement. On the interior zones, laboratory studies have visually confirmed 'water piling' on a structure's face that serves to dampen an object impact. There is also a theoretical point of stagnation where the velocity perpendicular to the face is zero, but this significant exclusion is difficult to justify in a design standard without much more supporting data. As the flow splits and moves around the object the velocity increases and makes the corners zone a much more likely target and at a potentially higher velocity than currently mandated.

However, while ASCE/SEI 7 (ASCE 2021) assumes the velocity of an object to be the velocity of water, the center-of-channel velocity is not the velocity at the face of a submerged object, and therefore not the debris object velocity. Additional experiments are needed for determining exact object velocities and flow stagnation at an object before future code changes can be suggested.

Also, without the benefit of a site-specific flow analysis, conservative practice would dictate that a debris impact load is applied on a structure on all sides and at any point at or below the Design Flood

Elevation. Given the discussion regarding the channel and cross-street velocity above, conservative practice could significantly overestimate debris impact loads on some parts of the structure.

Flow directions in urban arrays due to storm surge will generally have an approach and a receding direction, and islands have a shoreline on many edges. Even a single shoreline can also have a flow direction not perpendicular to the coastline. For these reasons, and the possibility of seaward objects being destroyed, it may not be possible to consider a universal debris load reduction factor based on shielding. However, based on the data from the upcoming ATC-149 study, further targeted experiments could yield significant reductions. Future areas to consider:

- Does a storm truly approach and recede, such that debris object strikes must be inverted from the single flow direction?
- What are the flow and debris object velocities within a standard and offset array on all building faces?
- What are the flow and debris object velocities at the interior and corner zones of a submerged building?

5.1.2.5 Wave Loads

Like debris impact loads, without the benefit of a site-specific flow analysis, ASCE/SEI 7 (ASCE 2021) requires that wave loads shall account for 'waves breaking on any portion of the building or structure'. Chapter 5 Commentary goes on to clarify that the wave load equations are for depth-limited waves and that 'wave heights at a particular site can be less than depth-limited values in some cases. If conditions during the design flood yield wave heights at a site less than depth-limited heights, Equation (5.4-2) may overestimate the wave height and Equation (5.4-3) may underestimate the still-water depth. Also, Equations (5.4-4) through (5.4-7) may overstate wave pressures and loads when wave heights are less than depth-limited heights.

An urban building array, where waves are shielded from other structures and only approach from the shore-facing direction, should see substantial reductions in simplified code-based wave loads for most perimeter conditions. Future research, data from ATC-149, and findings in the 1977 National Academy of Sciences "Methodology for Calculating Wave Action Effects Associated with Storm Surges" can all be used in the correlation of proper wave height and directional load reduction factors for future editions of ASCE/SEI 7 (ASCE 2021).

Finally, further study and guidance is needed for the phenomena of wave run-up. When waves strike an object, they can explode vertically and damage elements well above the peak of the wave height and the Design Flood Elevation. While these loads do not generally fail primary structural elements, they do fail many elements of a building's envelope. An envelope failure will allow water intrusion into an elevated space, from other wave run-ups as well as from rain, which will affect the building's ability to recover from associated non-structural damage.

5.1.3 Seismic

Seismic is likely the natural hazard with the most advanced performance-based design guidelines and standards. Development of performance-based design guidelines was in part motivated by the 1994 Northridge Earthquake, which had a relatively small fatality count (57) given the immense population subjected to the earthquake, but an extraordinary property damage estimate of more than $20 billion (about $62 per person in the US). Following the earthquake, FEMA funded several projects to develop performance-based design guidelines that could be used by engineers to design structures to be more damage-resistant and to evaluate and retrofit existing structures to achieve specific building performance objectives (e.g., Immediate Occupancy, Collapse Prevention, etc.).

5.1.3.1 Best Practices

The simplest way to provide enhanced seismic performance for critical facilities is to design them using all the Risk Category IV requirements. This means designing for reduced drift limits in addition to higher loads and providing seismically certified nonstructural components and systems. The following is a list of other ways to provide a greater ability to recover from earthquakes.

- Since the performance of the structural system and nonstructural components is very dependent on the seismic hazard parameters, a detailed geotechnical investigation to classify the site and develop a site-specific response spectrum for each seismic hazard level being considered as part of the design will provide more accurate information than using a default site class and the general spectra derived from the United States Geological Survey hazard model.
- Consider configuring the structure to avoid vertical and/or horizontal irregularities (as defined by ASCE/SEI 7).
- Consider configuring the building's lateral-force-resisting-system such that the Redundancy Factor (ρ) is permitted to equal 1.0 per the requirements of ASCE/SEI 7.
- Consider using nonlinear response history analysis per ASCE/SEI 41 (ASCE 2017) to benchmark the performance of the structure. Nonlinear analysis can identify potential failure mechanisms or areas of disproportionate response that linear analyses may miss.
- For a higher degree of confidence in the ability of a critical facility to resume function following a major earthquake, the FEMA P58-1 (FEMA 2018) methodology should be employed to explicitly assess the design to confirm that the desired performance objective, either Immediate

Occupancy or a short downtime before necessary functions are restored, can be reasonably achieved. While it is possible to use the FEMA P58-1 (FEMA 2018) methodology with linear analyses, the method is significantly more accurate with nonlinear analysis results.

- Consider using low damage technologies like seismic isolation or supplemental damping. Both technologies can reduce floor accelerations, in addition to story drift, which significantly reduces demands on nonstructural components and systems.
- Follow all the requirements for I_p = 1.5 for nonstructural component and system design, including the amplified loads and need for seismic certification.
- Require General Contractor to coordinate deferred submittal nonstructural bracing/anchorage designs among the various trade subcontractors to address potential spatial conflicts among the work of the various trades and to ensure the ASCE/SEI 7 requirements associated with avoiding consequential damage are properly addressed.
- Review the design of and explicitly observe the installation of seismic anchorage and bracing of nonstructural components.
- Specify seismically certified equipment wherever possible. More frequent specifying of seismically certified equipment may drive producers to certify more of their product line.
- Consider designing and testing the cladding system for watertightness at the deformations predicted at the hazard immediate occupancy or functional recovery is desired if there is a likelihood of rain events within 6 months of an earthquake.
- Consider leveraging the potential cooperation between sustainability and resilience programs by incorporating sustainability features that also provide a benefit from a building recovery perspective (e.g., photovoltaic systems, energy efficient mechanical systems to reduce demand on backup power systems, high-performance building envelope, etc.).

- Consider designing and detailing the connection of buried utilities to structures to accommodate the anticipated earthquake-induced relative displacement at the interface between the structure and buried utilities.
- Consider designing and detailing buried on-site utilities to accommodate the anticipated earthquake-induced permanent ground deformation. For instance, this may include the use of restrained joint systems to enhance buried pipeline performance versus typical push-on type joints.
- Consider providing a backup for utility systems that are required to maintain functionality of a facility (e.g., emergency generator, water storage tank, wastewater holding tank, etc.) in case normal utility services are disrupted following an earthquake.

5.1.3.2 Potential Code Changes

In developing the recommendations in this report, two items rose to prominence that a potential code change should be considered.

- Require observation and special inspection of nonstructural components and systems. As discussed previously, nonstructural components make up the bulk of the damage in earthquakes. However, their anchorage and bracing design is frequently done by professionals other than the engineer-of-record, often as design-build items during the base-building construction. When heightened performance is desired, such as Risk Category IV facilities, installation observation of all components designed with an I_p = 1.5 should be considered.
- Require K-12 schools, or selected portions of K-12 schools that may be used as emergency shelters following a major disaster, to be designed per the requirements of ASCE/SEI 7 as Risk Category IV structures.

5.1.3.3 Research Needs

The design of buildings to perform better during earthquakes is an ever-advancing field and there are many research needs. Some of the ones identified in developing this report are below.

- The FEMA P58-1 (FEMA 2018) methodology is a great framework for conducting a performance-based assessment of a building. But the methodology is only as good as the data input into it. The fragility functions for nonstructural components could be improved. Many of the fragilities do not reflect modern, seismically certified components, which can lead to an overprediction of damage.
- Assessments conducted in support of the development of the FEMA P-58-1 (FEMA 2018) Methodology have indicated that the expected performance of code-conforming Risk Category IV structures designed with different lateral-force-resisting-systems may not all achieve the intended Operational building performance (FEMA, 2018). Additional research should be conducted to develop recommendations related to design guidance and/or preferred lateral-force-resisting-systems from a rapid functional recovery perspective.
- NIST GCR 18-917-43 (NIST 2018) discussed how complicated the response of nonstructural components to seismic excitation is to accurately define. Determining the accelerations that components experience is extraordinarily complex, being a function of the floor, the component is on, the period of the component relative to the building's modes of vibration, the earthquake shaking, the component attachment to the floor and the flexibility of the floor.

5.2 Existing Building Retrofit

Given that most critical facilities exist and were not designed and constructed to modern codes, there are many things that can be improved to enhance their hazard performance capabilities. However, retrofit is costly and building codes have few provisions that trigger full structural retrofit of a building and no provisions that require retrofit of the nonstructural components and systems.

5.2 1 Best Practices

The following is a list of ways to provide greater performance during hazard events:

All Hazards

- Consider structural and nonstructural component retrofit when major renovations occur. A significant portion of the cost of a major performance enhancement retrofit is removing and replacing existing nonstructural finishes and components to facilitate access to install elements. By doing a performance enhancement retrofit concurrent with a major renovation, that additional work can be lessened, if not eliminated.
- Consider phasing major performance enhancements over many years to spread out costs and disruption to occupants.

Seismic Hazards

- Consider designing structural retrofits for both safety and functional recovery. Elwood (2022) discusses how designers can consider both functional recovery and safety-based objectives concurrently in a design. For seismic hazards, ASCE/SEI 41 (ASCE 2017)'s performance-based approach is well suited for this. It provides a means to consider both safety at an extreme event, such as the ASCE/SEI 7 (ASCE 2021) MCE_R or the ASCE/SEI 41 (ASCE 2017) BSE-2E by meeting the Collapse Prevention performance level, and preserving function at lower, but still significant hazard levels by targeting the Immediate Occupancy performance level at the ASCE/SEI 41 (ASCE 2017) BSE-1E or ASCE/SEI 7 (ASCE 2021) Design Earthquake hazard intensity.
- Consider retrofitting nonstructural components and systems that are critical to the building's function or whose failure could impede recovery of function. ASCE/SEI 41 (ASCE 2017) assesses and improves the seismic performance of existing nonstructural components and systems. As

discussed in earlier sections, these components are often the most critical in preventing a critical facility from quickly returning to function. Many of the nonstructural components and systems are changed on a semi-regular basis as facilities are renovated or technology necessitates replacement, such as new medical equipment or computer server technology. When this occurs, it should be replaced with seismically certified equipment per I_p = 1.5 requirements. However, even if many components are upgraded during renovations, the large-scale base building systems are often left unaltered. Components like elevators, chillers, cooling towers, and electrical switchgear can sustain damage that significantly impairs the functionality of a facility and many of these components have exceedingly long lead times for manufacture and delivery of replacement equipment, preventing the facility from quickly returning to function. While it may seem simple enough to recommend replacing critical equipment, replacement of these systems requires significant deconstruction of building interiors to provide access to remove and replace the systems. Additionally, many buildings were not designed with the level of redundancy in their MEP systems that would allow the building to continue operating while major system components are removed and replaced with seismically certified ones. An appropriate strategy to address these base building systems needs to be coordinated between the design team and the facility owner.

- One way to retrofit a critical facility to provide Operational performance per ASCE/SEI 41 (ASCE 2017) post-earthquake is to use seismic isolation. Seismic isolation systems reduce the accelerations imparted to the building above the plane of isolation, often reducing the accelerations to levels below the threshold that would damage existing nonstructural components and systems. Seismic isolation retrofits can be expensive, but there can be cost saving when compared against the cost of a conventional retrofit and the cost to replace all the base-building nonstructural components with more rugged, seismically certified, and properly anchored equipment.

- Like the overall building, critical equipment pieces can be placed on seismic isolation devices. Doing this has the potential to reduce the demands on the equipment to a level below the threshold where the component would sustain damage that would impede its function. When equipment is isolated, the distribution system components feeding the equipment or emanating from the equipment must be able to accommodate the additional relative displacement between the isolated equipment and the building and have adequate flexibility not to impact the performance of the isolated equipment.

Wind Hazards

Existing buildings have additional issues with dealing with the wind hazard because of the wind pressures used in the design of the building where typically lower than current required design pressures for the components and cladding and maintenance of the building envelope typically is not performed on a regular basis. Generally keeping the wind and the wind-driven rain out of the building is the key to reducing damage and downtime for these critical facilities. Below are some considerations to improve a facility's ability to keep wind, or wind-driven rain, from entering the building.

- Use recommended procedures for roofing and enclosure installations contained in the *ASCE/SEI Prestandard for Performance-Based Wind Design* (SEI 2019). These recommendations go beyond the current code provisions for the installation of enclosure elements to provide greater wind resistance.
- Provide coordination between the many elements of the building enclosure system to improve resistance to wind driven rain.

- Consider designing exterior cladding elements for Risk Category IV level wind pressures utilizing a directionality factor of 1.0, instead of the current code specified value of 0.85.
- Limit the use of gravel ballasted roofing systems on buildings in high wind areas. The roof gravel can become wind-borne debris penetrating the glazing on critical facilities.
- Provide additional construction inspections for the anchorage of rooftop equipment and critical equipment.
- Protect existing rooftop equipment and distribution system components critical to the building's function with screens that have been designed to resist windborne missiles.

Flood Hazards

Most existing buildings were designed before there were flood requirements and therefore have their basement and first floor below the flood elevation. Below are some considerations for flood-based retrofit of existing buildings.

General Statements

- Scour is a key consideration, but for a full-height basement the scour depth will never be deep enough to unseat the foundation elements. This should be carefully evaluated for soil or pile bearing buildings with no basements but need not be considered for this example.
- While ASCE/SEI 7 (ASCE 2021) dictates load factors for new construction, a performance-based design approach (reduced factor of safety) can be considered for any checks for what is a short-duration, exact load in an elective upgrade. The reason the load (hydrostatic and additive hydrodynamic) can be considered as exact is that once the resistive barrier height is exceeded, the building floods and unloads the structural elements in question.
- If the entire building is unable to meet the loads associated with dry floodproofing, consider partitioning to protect critical rooms or levels. For instance, if the basement slab-on-grade can

never meet the uplift pressure, consider letting the basement flood via venting and protecting the first floor (keeping in mind that this strategy will result in an uplift pressure on the underside of the first floor).

Basement Considerations

Foundation Wall

- Depending on the height of the ground water table (GWT), the wall may or may not be designed for saturated soil lateral earth pressure. In an above grade storm surge, the surface water may or may not seep down to meet the GWT. However, with the assumed 8-feet (2.4 m) of landscaping this is likely.
- Three feet of standing water means a surcharge load of approximately 200 psf (9.5 kPa). This may be higher than that considered in the wall design.
- The wall must be evaluated for the lateral pressure under the design flood and reinforced as required. Reinforcing options include synthetic fiber strips or bonded steel plates.
- All penetrations (utilities, structural cracks, expansion joints, etc.) through the wall should be evaluated for the adequacy of the seal. The seal should be intact and able to resist a submerged depth pressure up to or above the design flood depth.
- If possible, the adequacy of the exterior waterproofing should be validated. If unable to be easily viewed, the membrane should be replaced if near its expected lifespan.

Base Slab

- It is conservative to assume a hydrostatic uplift pressure equal to the depth of water (top of the design flood to the bottom of the base slab) times its unit weight. However, as previously mentioned, in an above grade storm surge, the surface water may or may not seep down to meet the GWT. This connectivity is a function of the duration, travel length, surface porosity, and soil porosity. In lieu of a detailed subsurface seepage analysis, full connectivity should be assumed, but an analysis may yield significant load savings.

- For this example, with an assumed 9-foot (2.7 m) depth to the bottom of the base slab, the uplift pressure is over 750 psf (35 kPa). Likely this value greatly exceeds the self-weight of the slab. If a reinforced pressure slab, consider reasonable, permanent superimposed dead loads and the self-weight as spanning between structural walls and columns. If pile supported, these can be considered as supports if an adequate tension connection is available. If overstressed, consider tie-down anchors (that are waterproofed after installation) or additional resistive dead load assuming the bearing pressure is not exceeded. If a traditional slab-on-grade, retrofitting may not be possible for dry floodproofing due to the magnitude of the uplift load.
- All penetrations (utilities, structural cracks, expansion joints, construction joints, etc.) through the slab should be evaluated for the adequacy of the seal. The seal should be intact and able to resist a submerged depth pressure up to or above the design flood depth.
- If possible, the adequacy of the exterior waterproofing should be validated. Since it is unable to be easily viewed, the evaluation may only be determined via lifespan. If near its expected lifespan, reflecting injection waterproofing can be considered, or the concrete can be evaluated for its own ability to control water flow in a short duration event.

First Floor Considerations

Façade

- The façade will need to be substantially impermeable to hydrostatic, hydrodynamic, debris impact, and small wave loads. In general, these will be substantially higher than the wind load that was used for the design of the façade, so reinforcing is required.

- Where a façade has a CMU back-up wall, it is possible to reinforce the CMU for the loads, considering the cladding as sacrificial. However, a curtainwall system does not use a structural back-up system that can be reinforced.
- Options to resist the 3-foot (0.9 m) flood load:
  - Install a cast-in-place upturned concrete wall behind the curtainwall, doweled into the concrete of the first-floor slab, up to the design flood elevation. This has challenges with floor space, electrical outlets, mechanical units, and service distribution.
  - Remove the lowest level of curtain wall, up to the second floor (if not stacked) and construct a cast-in-place upturned concrete curb in the plane of the curtain wall. Reinstall a shorter curtain wall on top of the concrete curb and reinsulate the system.
  - Replace the lowest level of curtain wall with a flood rated glass façade. The rating would only need to be up to the design flood depth, but the façade for the entire floor will need to be replaced because of the distinct types of mullions. Certainly, it may be aesthetically problematic to have different looking glazing systems, so a full height retrofit may be required.

Openings

- Barriers will need to be provided for each opening. In general, an office building would use a system of deployed (aluminum log or plank) barriers for the vestibules and personnel doors. The barriers must be sealed with inserts connected to the concrete flood walls to make a proper seal.
- It is possible to have vestibule barriers sit proud of the main building doors, and then tying back to the concrete flood walls, but this strategy requires a separate foundation and uplift slab or seepage cutoff.

- If there are loading docks present, many clients elect to install a self-activating (pop-up) flood barrier at the edge of the opening. Like a vestibule, these barriers would require a separate foundation and uplift slab or seepage cutoff for full perimeter protection. Alternatively, a 3-foot flood (0.9 m) depth may be below the loading dock platform, such that the loading area could be allowed to flood, assuming bounded by walls that can resist the loads.

5.3 Potential Code Changes

In developing the recommendations in this report, one item rose to prominence such that a potential code change should be considered.

- There are very few instances where the IEBC (ICC 2021a) requires a full evaluation or retrofit for wind, flood, or earthquake. There is a provision for structures assigned to Seismic Design Category F that requires seismic and wind evaluation and, if needed, retrofit if more than 50% of the building area is altered. Only structures assigned to Risk Category IV and nearest to the most active faults would be classified as Seismic Design Category F. Consideration should be given to extend this retrofit trigger to Risk Category IV structures in Seismic Design Category D and to add high wind regions to this. To help ensure that these requirements are followed consider extending the length of time that renovations on an individual building structure are considered for this trigger to a five-year period, or even longer.
- When retrofit is triggered or when it is specified voluntarily, there are no structural observation or special inspection requirements for retrofit. The engineer is left trying to extrapolate the structural observation and special inspection requirements for new construction to existing buildings. Structural observation and special inspection provisions for this should be developed, specifically around the connection of the new components to the existing structure.

- There are many existing structures within the FEMA defined ‘100-year’ flood zone. While a full flood retrofit is the best option, this is not mandated often. However, these buildings can have characteristics with significant performance and life-safety repercussions if not addressed. For instance, rainfall flood waters during Hurricane Ida trapped several residents in basement apartments. In addition, there can be significant risks due to low level heating and electrical systems, improper breakaway walls, soils highly susceptible to erosion and scour, and improper foundation anchorage. The IEBC (ICC 2021a) should consider requirements for a proper Flood Hazard Vulnerability Assessment for structures located in designated FEMA hazard areas.

5.3.1 Research Needs

Most of the research needs discussed in the preceding sections for new construction are also applicable to existing buildings. A key component to the evaluation of existing buildings is the ability to accurately model the behavior of structural components that do not meet new code detailing requirements. There has not been a lot of testing of non-conforming components both in their original state and altered as part of a retrofit. Even the SAC Joint Venture dedicated most of its focus to testing new beam-column connections as opposed to existing connections to understand the failure or retrofit measures to improve existing connections (FEMA 355d, 2000).

5.4 Climate Impacts

Climate change impacts on environmental loads need to be considered in the design of critical facilities. Provisions for these Future Conditions should be considered in our standards for proper use in the design of buildings and other structures. Some of the science is ready to be considered for implementation into standards, while the science is still in its infancy for other hazards. The understanding of sea level rise and the effects it will have on coastal communities is the climate impact that is the most understood at this time, however all impacts to the environmental loads are currently being studied. The upcoming 2023 Supplement 3 of ASCE/SEI 7 (ASCE 2021), for example, has included requirements for the future condition of sea level rise in the Chapter 5 Flood Load provisions. ASCE/SEI 7-16 already warns the user to consider sea level rise for Tsunami design. However, the other environmental loads are based on the available historical data and do not look at the future conditions caused by climate change.

The efforts to include provisions to account for all future climate impacts is a focus of the federal agencies and the standards writing organizations in the U.S. A method to include future conditions for environmental loading is currently being developed and is anticipated to be part of the 2028 edition of ASCE/SEI 7 and adopted into the 2030 International Building Code.

5.5 Recovery of Function

Because it may not be possible to design a critical facility to meet the Immediate Occupancy performance level for all hazards, an alternate approach is to design to control damage so the facility, or at least the critical parts of the facility, can be returned to function quickly. Determination of which specific functions are critical is a challenging task. This section discusses a few factors that should be considered to identify which components and systems are needed for critical function and which can be restored much later following the event.

When discussing return to function, there are two main components – repair time and time to initiate the repair. As discussed earlier in this document, estimating repair time is somewhat straightforward because performance-based engineering methods allow one to identify the structural members and nonstructural components that will likely sustain damage in a specific hazard event. Most of these procedures have been developed for earthquakes (ATC 58-1, 2018), but the underlying tenants are similar for wind and flood events.

Estimating the time between the event and the onset of repairs is more difficult. Several factors can delay the start of repair. Some of these impeding factors (ARUP, 2013 and ATC, 2022) are:

- Time for an engineer to inspect the facility and identify damage that requires repair.
- Time for an engineer to design the repairs.
- Time to obtain a building permit to permit a general contractor to construct the repairs.
- Time to abate environmental hazards, like mold from a flood event, before repair can commence.
- Time to obtain materials and long lead-time nonstructural components (such as elevators or electrical equipment).
- Time for the contractor to engage subcontractors and mobilize to begin the repair.

In general, structural damage challenges recovery of a facility. An engineer must inspect the structural damage to determine if it presents a safety issue that must be repaired before reoccupancy. If it needs to be repaired, a design must be completed, permitted, and then constructed. Sometimes environmental hazards, such as toxic mold, have occurred because of water intrusion and must be abated before repair work can begin. Even in the best situations, impeding factors will likely add several months to the recovery time, longer than a critical facility can be down. Therefore, preventing structural damage that triggers impeding factors and necessitates repair should be a component to the design or retrofit of a critical facility.

It is possible to develop a work-around for limited structural damage by installing temporary shoring to mitigate the immediate safety hazards posed by the structural damage. This can expedite reoccupancy and possibly functional recovery if the structural damage is limited and repairs can be conducted while the shoring is in place,

There are so many different nonstructural components in a building, many of which may not be required for a critical facility to function in the most basic sense. For example, in a data center, the only critical function is keeping the servers running, an act that only requires power and cooling to keep the servers from overheating. While in a hospital, almost every function is required to continue operations. While for a school, even one that is intended to be an emergency shelter, truly little may be required. Below is a list of components and systems with discussion about whether they are necessary to resume critical function or if temporary workarounds can be implemented for quick recovery.

- Building envelope: The building envelope provides protection against wind driven rain, flood waters, and thermal control. If the building is in a region where it is possible to go extended periods without any rain and there is no flood risk or need for infection control, the building envelop may be able to sustain damage that breaks its watertightness, but the facility can still resume its function. Depending on the level of damage a building envelope sustains, there could be significant impeding factors. Repairing seals that broke during drift requires skilled installers and façade access equipment. Replacing portions of the cladding that are damaged or have broken off from the structure often requires long lead-times.
- HVAC system: If the building is not situated in an area with temperature extremes and there are operable windows that can be opened to allow air exchange, the HVAC system may be able to be down. This may be permissible for a school that is serving as an emergency

shelter but will be unlikely in a hospital or data center. Most HVAC system components have significant lead times if they need to be replaced.

- Fire suppression system: While it may seem like the fire suppression system is critical to a building's function, there may be workaround with fire watches that can allow facility to resume function while the fire suppression system is repaired.
- Elevators: Depending on the population served by the facility (or lack thereof in the case of a data center), it may be possible for the building to resume function without fully operating elevators or all elevators in service. Elevator components have long lead times if they need to be replaced.
- Interior architectural finishes: Many interior architectural finishes, like partitions and ceilings, may not be essential to the operation of a facility. In a hospital they typically are because they are a key component of infection control. In a data center, only those partitions and ceilings that enclose the potions of the servers need to be air conditioned to keep them from overheating. However, damage to most common architectural finishes can be easily repaired without the need for highly specialized trades people or long lead time items.
- Lighting: Lighting may not be essential to resume function if alternate lighting can be arranged and brough to the facility in a very short time.
- Domestic water and wastewater: Workarounds are typically available for the water and wastewater systems in a facility.
- Stairs: Stairs are essential for people to get between levels in a building, especially to exit a building. Therefore, maintaining the stairs or repairing the stairs is essential to re-occupancy. There are potential workarounds if the interior stairs are damaged, such as providing temporary exterior egress stairs.

The ATC-138 (ATC, 2022) and ATC 58-7 (ATC, 2022) present discussion on how to determine which specific nonstructural components are required versus which are not needed or which can have workarounds. For hospitals, very few nonstructural components will not be needed or can have workarounds, while schools serving the shelter people may have more flexibility in having damaged nonstructural components.

Many MEP system components have long lead times or require specially trained professionals to repair them, creating a significant impeding factor. Even in normal times repair or replacement of these components can take months. Those lead times are amplified in the aftermath of a natural disaster. So, like structural system components, critical MEP system components should be protected against damage that would render them nonfunctional, so impeding factors related to them being fixed are minimized.

The only impeding factors that a facility owner can have control over is the time it takes an engineer to inspect the facility. San Francisco Department of Building Inspection partnered with the Structural Engineers Association of Northern California to pioneer the Building Occupancy Resumption Program (BORP) (SFDBI, 2001). BORP allows an owner to contract with an engineer to inspect their building following a major earthquake and authorizes that engineer to make an official declaration of the building's safety for reoccupancy. If the building is damaged, the owner of the facility already has a pre-existing relationship with an engineer who has conducted an inspection and can begin the repair design. Such arrangements can reduce the impeding factors of finding an engineer to inspect the damage or waiting on the local building officials to do so and to design any repairs, because engineering labor will be in high demand following a major event.

As discussed above, however, other impeding factors, like obtaining a building permit, mitigating environmental hazards, and procuring materials cannot be managed through preplanning. Therefore, the only way to control these impeding factors is to either find work arounds for the facility to function without the damaged components or systems or to design to prevent damage that would trigger an impeding factor.

5.6 Critical Dependencies

To restore their functionality, buildings must be supported by utility services (e.g., electric power, water, wastewater, telecommunications, natural gas, etc.). However, commercial utility systems are vulnerable to many of the same hazards as buildings. For example, an earthquake may damage an electrical substation, or a flood may damage a water pipeline that is hung from the underside of a bridge. Also, the national electrical code exempts electrical distribution structures under 60’ in height from being designed for “extreme winds”, which are interpreted to be hurricane design level winds. Thus, many of these distribution systems fail in a large wind event.

If the timeline to restore commercial utility services is incompatible with the recovery timeline expectations for a building, it may be necessary to provide backup systems to mitigate these critical dependencies. However, it should be noted that the backup systems themselves may introduce additional dependencies. For example, backup generators rely on fuel that may be in limited supply after an event.

One approach that has been successfully implemented by the Beaverton School District was to conduct a series of workshops and meetings between the owner, the project’s resilience lead or integrator, project design team, utility service providers, and other stakeholders (SEFT, 2015). The key tasks completed during and as follow-up to these workshops and meetings included:

- Identification of commercial utilities serving the facility.
- Development of a holistic understanding of the expected performance and recovery timeframes of utility services in their current state and after systematic long-term investments in utility system performance improvements.
- Coordination with utility service providers to identify gaps between facility functional recovery needs and the expected recovery timeline for utility systems serving the facility in their current state and after future performance improvements are implemented.
- Development of strategic approaches to mitigate utility service dependencies.
- Design and construction of on-campus utility systems to minimize any potential damage to pipelines, conduits, etc. between the utility mainline and the facility; and
- Development of a response plan to address identified gaps that were not able to be mitigated through construction-based solutions due to project budget limitations.

This resilience workshop and meeting approach also provided an opportunity for the owner to establish relationships with key utility representatives that can be leveraged for future collaboration.

Other dependencies may also be critical to the functional recovery of buildings. For example, all buildings may rely on consultants and contractors for post-disaster safety inspections and implementation of any necessary repairs, hospitals rely on outside vendors for medical supplies, etc. It is important that all potential dependencies are identified and appropriately mitigated to ensure that functional recovery goals can be achieved.

5.7 Resilience Integration

Post-disaster resilience and functional recovery is an emerging area of practice that requires holistic thinking and cross-cutting integration between the owner, all design and construction team members, and potentially other stakeholders to ensure that the owner's resilience objectives will be achieved. Fundamentally, an owner's post-disaster recovery timeline goals (influenced by community expectations) drive the level of performance enhancement features that need to be incorporated into a given project. Sophisticated owners may already have resilience plans and general design criteria that establish performance and function recovery criteria for projects. When available, these plans and criteria should be holistically reviewed and modified, as appropriate, to develop project-specific design criteria. For owners that are considering resilience for the first time, it will be necessary for the owner's trusted advisor and/or design team to collaborate with the owner to establish post-disaster recovery timeline goals and associated design criteria.

At the beginning of a project the design team should develop a resilience implementation strategy based on the established project-specific design criteria. After which, it is recommended that a resilience workshop be conducted to ensure alignment between all project stakeholders on the resilience approach adopted for the project. One recent mega-project by Willamette Water Supply Program (2020) in Oregon benefitted from such resilience workshops that were conducted for the major components of the project. Completing a resilience workshop early in the design process permitted easy refinement of the architectural layout of the facility to reduce structural design challenges and enhance the expected earthquake performance of the facility. Once all parties are aligned on the project's resilience strategy, it is recommended that the owner, and/or the owner's representative review design milestone submittals to ensure alignment with the resilience strategy and project specific design criteria.

Once the project enters the construction phase, it is important that the owner and design team collaborate with the general contractor to ensure that the design and coordination of deferred submittals is consistent with the project resilience requirements. The coordination of the location of nonstructural bracing and routing of nonstructural components to avoid consequential damage is an important consideration that is sometimes overlooked, even for projects with established resilience goals. Figure 5-1 shows an example of electrical conduit that were installed too close to a sprinkler sprig. Earthquake-shaking could potentially result in the conduits and sprinkler sprig pounding into each other and potentially damaging the sprinkler system.

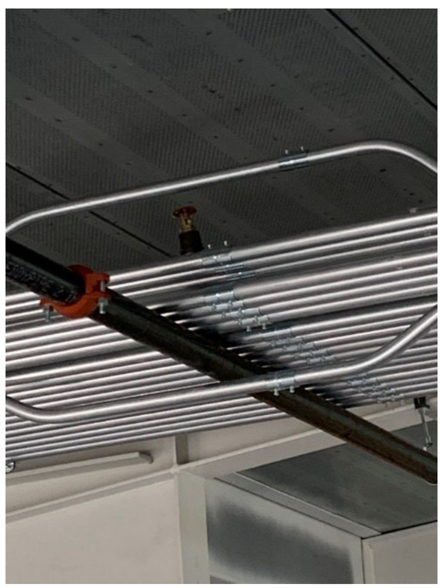


Figure 5-2. Conflict between Sprinkler Sprig and Electrical Conduit (Source: SEFT Consulting Group)

Resilience design principles bridge many different team disciplines. For this reason, resilience 'design' is not a singular training path in college programs. Experts in this area can come from other primary disciplines, like a project LEED coordinator. Resilience on a project is not a design component or a checklist, it is a comprehensive way of thinking that requires a champion to lead performance discussions with the owner, develop appropriate design criteria, deliver unifying guidance to the design team, and follow through to ensure resilience considerations are appropriately implemented during construction. It is recommended that all projects consider a Resilience Lead position to fulfill this role. Some of the roles and responsibilities of the Resilience Lead are as follows:

- Conduct a hazard performance workshop with the client and key stakeholders that discusses:
    - Comprehensive local hazard types
    - Client standards
    - Industry Codes and Standards
    - Site/project goals and challenges
    - Performance options per hazard
    - Operational resources
    - Lifecycle costs and maintenance
    - Community equity
    - Target metrics
- Work with the design team to produce a project Hazard Vulnerability Assessment (HVA) with options and cost-based recommendations for various levels of performance.
- Using the HVA, work with the client to finalize performance objectives for the project and how the project relates to the overall resilience of the community and document these goals.
- Disseminate and explain comprehensive goals to the project team and work with them as drawings, specifications, performance criteria, and calculations are developed.
- Cross-coordinate between different disciplines.
- Perform a quality review at each milestone submission.
- Work with the client on community outreach and education initiatives.
- Provide a final report to the client on how the design has met the project resilience goals.

- Provide bidding support to answer resilience related inquiries and ensure that the system is not compromised by a question response.
- Work with the contractor and owner through submittal review (especially for deferred design items), commissioning, and project completion to ensure goals are achieved.

Most areas of the Unites States require structural design for multiple environmental hazards. While a single hazard generally controls the design of the primary structural system, with other hazards being performance checks, it is possible for the design of the non-structural systems to be controlled by different hazards for the same project. And, with the fact that codes and standards are currently backwards looking in terms of hazard definition, every project can benefit from a Resilience Lead that can help the team and owners understand the comprehensive risks and available mitigation strategies for current, future, and evolving hazards.

The importance of the Resilience Lead position also applies to the construction phase of a project. It is critical that the nuanced items presented by the design team in the drawings and specifications make it into the final product. At times even critical structural inspections are conducted in a shoddy manner or sidestepped altogether. This presents an even bigger challenge for secondary items like component hanger assemblies or water stops. However, it is the integrity of these details that determines the ultimate success of the project when the hazard strikes.

The Resilience Lead's role is also critical at the end of the project, when the design team is dispersing, to provide a comprehensive package to the owner containing operational manuals and training guides required for the owner to successfully operate and maintain the systems they selected.

Owners, design firms, and agencies providing guidance for communities must embrace the overarching role of the Resilience Lead as a required team leader that works alongside the Project Manager to ensure the overall success of all projects.

5.8 Facility-Specific Topics

5.8.1 Hospital Facilities

The typical design of a new hospital facility looks at the building to function for the next 50 years and not beyond, however many of the existing hospitals in the U.S. have been in operation beyond this 50-year time horizon. The formation of hospitals started in the early-1700's in the United States, with the oldest continuously operating hospital being Bellevue Hospital Center in New York that started in 1731. The Pennsylvania Hospital was established in Philadelphia in 1751 and is still in operation today, with the hospital's main building dating back to 1756. So even though modern design codes use a 50-year design life for the basis of their provisions, many of these critical facilities continue to be utilized for many years beyond that period. Each of these hospitals noted will have gone through many of the anticipated design level events over their lifetime and will continue to be utilized for many years into the future. Thus, existing building standards should be developed for the retrofit of these types of facilities for the effects of the wind and flood hazards. These standards would need to consider how to incorporate resilience design principles into these retrofits to provide continuity of services to their respective communities.

Bellevue Hospital and the Pennsylvania Hospital are in large metropolitan areas with many other hospitals in the area to help serve the community during and following a large hazard event. However, other hospitals, such as the St. John's Regional Medical Center in Joplin, Missouri was one of two hospitals that was serving the community when it was struck by the Joplin Tornado in May of 2011. The St. John's hospital suffered severe damage and was shut down and had to be reconstructed after the event.

The hospital's building structure survived intact, but the non-structural elements in the facility received significant enough damage that it made it not economically feasible to operate the existing facility. Much of the damage to these buildings was caused by the gravel roof ballast on the buildings being lifted off and breaking the buildings glazing. This allowed the high winds into the building destroying many of the interior partitions within the facility. The only glazing in the facility that was not damaged was the impact resistant glazing provided in the behavioral health wing of the facility.

The new VA Hospital in New Orleans, The Southeast Louisiana Veterans Health Care System hospital opened in 2016, replacing the existing facility that was shut down due to flooding during Hurricane Katrina in 2005. Following Hurricane Katrina, seven of the sixteen hospitals serving the New Orleans area were still closed two-years after the hurricane. The VA Hospital in New Orleans at the time of Hurricane Katrina was flooded and lost power because the electrical service and mechanical systems were in the basement of the facility.

The new hospital is described as "the upside-down hospital" because the electrical system and plumbing systems are now located on the fourth floor. Other features adding to making the facility perform better are that the Emergency Department is located on the second level of the hospital, which is twenty-one feet (6.4 m) above the base flood elevation for the site. The Emergency Department drop off ramp can also serve as a boat launch in the event of flooding at the facility. The exterior walls of the facility are hardened to resist impact from wind-borne debris from high winds and the facility has enough electrical generation and water capacity to operate for five days without connection to the city power and water grid systems.

As these new facilities were being designed the owner and design team looked understood the issues of having these facilities offline for years following the event and thus used the currently available "best practices" to make these facilities more resilience to events that will happen in the future.

5.8.1.1 Criticality of Facility to Community

Hospitals are one of the most important facilities in a community's response and recovery from a disruptive event and are expected to remain operational during and after a significant event. Consideration of the types of events that occur in the region of these facilities needs to be considered and designed for, above code, to adequately perform during an event and provide the services that are expected of them after.

5.8.2 K-12 Education Facilities

5.8.2.1 Design Life

The building code typically assumes a 50-year design life for a structure. However, many school buildings have been in service for significantly longer than 50 years. With this extended service life, the likelihood of experiencing a design level hazard event significantly increases (e.g., the exposure window to a hazard is doubled for a 100-year versus 50-year design life).

5.8.2.2 Criticality of Facility to Community

The size of a community and the number of facilities in a school districts portfolio influence the criticality of an individual facility. For example, the Vernonia School District (discussed earlier) has one school building that serves all the district's students in grades K-12, where-as the Beaverton School District has thirty-four elementary schools, nine middle schools, and six high schools. If Vernonia's school building was to experience damage in a major disaster, the impact to the community would be more significant than if a few Beaverton School District school buildings were to experience damage. The holistic community level impact of K-12 school building clusters and the number of facilities associated with this cluster is not currently considered in building codes and standards.

5.8.2.3 Facility Expansion

Increasing enrollments and expanded programming options often requires school districts to expand their facilities over time. These building additions are often designed based on building code requirements that are significantly different than the original structure and are forced to conform to site constraints that may result in a less than ideal structural configuration. These factors make it challenging for the expanded facility to achieve the beyond-code-level performance that is often necessary to achieve improved facility performance.

5.8.2.4 Funding

Schools are dependent on public funding and voter-approved bond measures for implementation of major construction projects. Passing bond measures to perform necessary deferred maintenance is often challenging, let alone achieving approval for implementation of community resilience enhancements. There were formerly four public schools located within the tsunami inundation zone in

Oregon, three of these schools were in Seaside, Oregon. In 2013, a $128 million bond measure was defeated by Seaside voters that included relocating these three schools outside of the tsunami inundation zone. A $99.7 million bond measure was approved by voters in 2016 and construction of three new schools outside of the tsunami inundation zone was completed in 2021.

5.8.2.5 Earthquake Relief Shelter Code Change Proposal

Schools are often used as emergency shelters following a major disaster, but they are not typically designed for Immediate Occupancy structural performance. In Oregon, the Beaverton and Lake Oswego School Districts have voluntarily elected to design and construct portions of their new schools to Risk Category IV requirements and integrate selected resilience features, so that they may more reliably and efficiently used as emergency shelters following a major earthquake.

Encouraged by this voluntary action, the Oregon Seismic Safety Policy Advisory Commission (OSSPAC) developed a code change proposal for the 2019 Oregon Structural Specialty Code (OSSC) that would require selected portions of new schools constructed in high seismic regions in Oregon to be designated as earthquake relief shelters. The proposed requirements would apply to school gymnasiums, cafeterias, and large multi-purpose rooms with an area greater than 6,000 square feet (560 m^2) and require that these portions of a school building be designed and detailed as a Risk Category IV structure. Other performance enhancing features, including hook-ups for temporary electrical and water service, were also included as part of the code change proposal. It was estimated that the proposed changes would result in less than a 1% increase in construction costs. After debate by the State of Oregon Building Codes Division code review committee and public feedback from the construction industry, the OSSPAC earthquake relief shelter code change proposal was not adopted for implementation by the 2019 OSSC.

5.8.3 Data Center Facilities

If a data center is a single point of failure, the data center should be made extremely resilient. Designing for Risk Category IV requirements may be enough to prevent loss of function is significant events and a performance-based design with a target resilience goal. Some examples of target resilience goals are the ASCE 41 Operational building performance level in a very large return period hazard or a specific deterministic hazard. In considering retrofit or new design to such high performance, costs need to be considered. It may become prohibitively expensive to provide the desired performance objective, justifying the cost to build a second facility in another part of the country, ideally with lower or at least different environmental hazards. Having a redundant facility also protects against things that can cause a data center to go down, like a fire, accidental discharge of sprinkler systems, or loss of power due to issues with the local utility.

If the data center cannot be redundant, the new facility design or existing facility retrofit should consider enhanced resilience requirements in the structural and nonstructural design beyond what would be typically required for a Risk Category II building. Specifically, designers of new data canter facilities should consider designer for Risk Category IV requirements.

Because of the sensitivity of computers and electrical equipment to water, non-water-based fire suppression, such as inert gas fire suppression systems, should be used wherever possible in a data center.

Since it may not be possible to retrofit the entire building or the access floors in the server rooms, servers on isolated floors can be placed on individual isolations devices to reduce seismic shaking of the equipment to levels that will not damage the components.

6.0 Summary

The critical facilities that exist within our communities are essential to recovery following a hazard event. Their performance in these events depends on the current codes, regulations, and standards that are adopted and enforced by the local building officials. These codes and standards are life safety based and do not address how to improve the hazard performance of buildings. However, the adoption of the most current codes and standards by the local jurisdictions has improved the performance of typical buildings based on observations from recent events. A good example can be found in the damage levels found in structures following Hurricane Ian. For those structures impacted by the high winds only and not the storm surge, those designed using the 2005 or later Florida Building Code, which was developed with many higher wind design procedures following Hurricane Andrew, showed lower levels of damage than those designed to the earlier Florida Building Codes.

The critical facilities discussed in this report need additional design objectives and criteria because of their role in providing the community services needed for recovery. Designers of these critical facilities can improve the performance of their building by understanding the typical causes of building closure following these events and working with the entire design and construction team to use best practices that are currently being implemented into practice. Most of these best practices have been learned from past events and have been developed considering the work arounds that had to be done during these events to provide the services needed by the community. Elevating electrical equipment above the flood levels, providing alternative access to the facilities, providing redundancy of services are all practices that are being considered during the design phases of the projects. These considerations will result in more resilient construction and improve the recovery of these facilities to provide their necessary services to the community they serve.

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