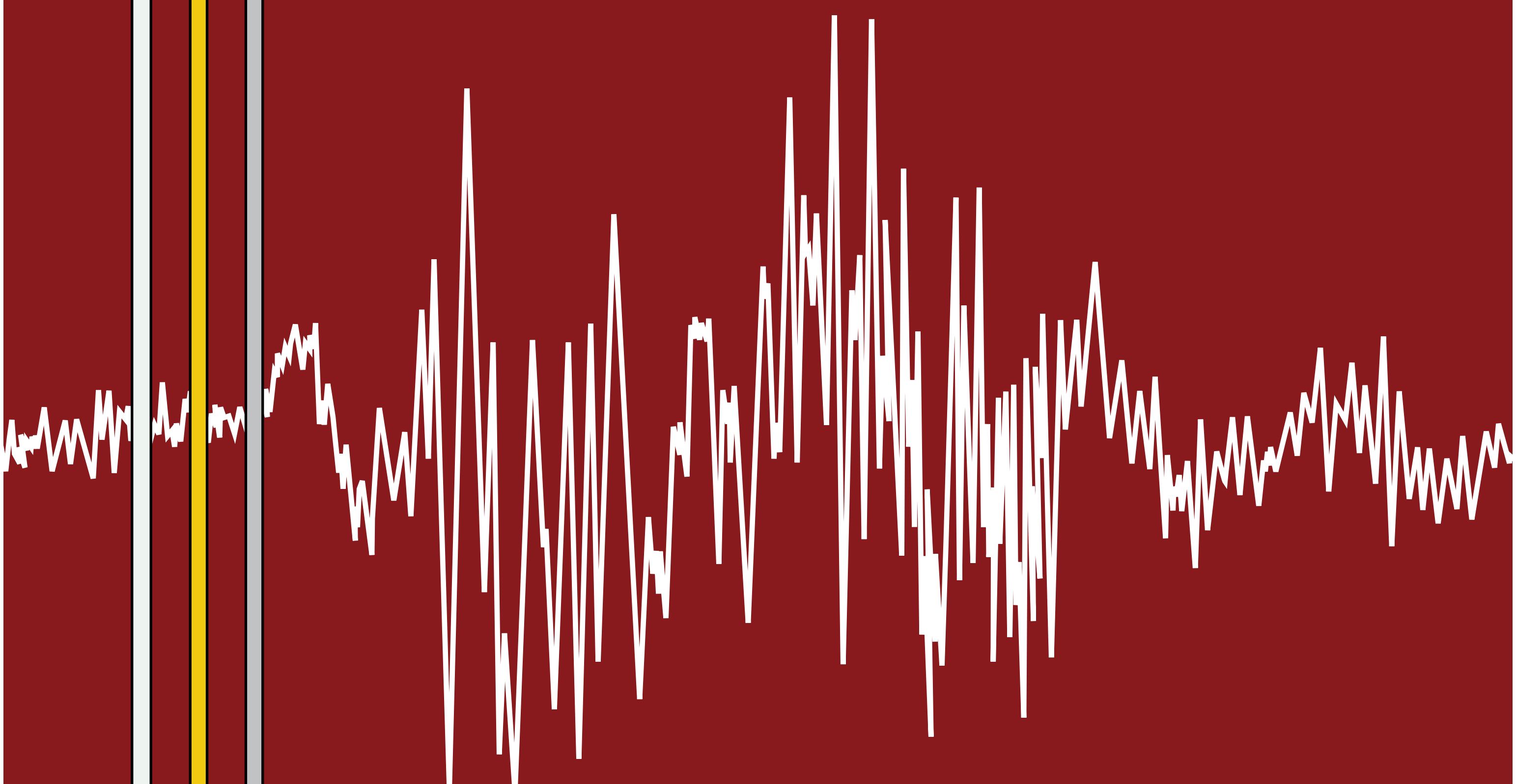
REDi™ Rating System

Resilience-based Earthquake Design Initiative
for the Next Generation of Buildings



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Front Cover: The REDi™ logo is the lotus flower, which rises out of muddy river bottoms to bloom. It can live for over 1000 years and can even revive after being dormant. Ancient Egyptians associate the lotus with resurrection while Hinduism associates it with eternity.

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Introduction

Motivation

Current building codes do not focus on earthquake resilience – the ability of an organization or community to quickly recover after a future large earthquake. The code objective is only to protect the lives of building occupants. Significant damage to the building structure, architectural components and facades, mechanical/electrical/plumbing (MEP) equipment and building contents is allowed as long as the code objective is met. It is therefore not surprising that when a major earthquake strikes an urban region the losses due to damaged buildings and infrastructure are immense. Direct losses include the financial costs of post-earthquake demolition, repair, and restoration of utilities.

But the most significant vulnerability may be indirect losses due to downtime - the inability of people to return to their homes or their jobs - which is much harder to quantify: loss of culture, sense of community, and quality of life can impact communities for years and even decades after an earthquake. While the building code provides reassurance that loss of life will be minimal after an earthquake, it does not address an equally important question - what type of life are we leaving for all of the survivors?

We believe it is time for a shift in thinking regarding the objectives for earthquake design and preparedness in modern society, in part because it is now possible to achieve far greater resilience at minimal additional investment. We created the Resilience-based Earthquake Design Initiative (REDi™) Rating System to provide owners and other stakeholders a framework for implementing "resilience-based earthquake design", a holistic "beyond-code" design, planning and assessment approach for achieving much higher performance.

Expectations for Code-Designed Buildings

Code design provisions have evolved over many years in response to improved knowledge from damage observed in real earthquakes and research test programs. The provisions are prescriptive, and assume that the intended earthquake performance is implicitly satisfied by meeting the minimum code requirements for design and detailing of structural and non-structural components. The historic objective has been to provide "life-safety" in "design level" earthquakes, but the ramifications of this have not been quantified until recently, and are still not clearly understood by building owners and occupants.

The code intent is that no more than 10% of new buildings should collapse in a very rare (MCE) earthquake (NEHRP, 2009). At the "design level" (ground shaking levels 2/3 of the MCE level) the intent is that new buildings should be "life-safe". This means that occupants should be able to escape from the building, but it does not imply that the building could be re-occupied or indeed whether repair would be economically feasible or not.

The direct financial losses for new code-designed frame buildings subjected to "design level" shaking have been recently estimated by several researchers at higher than 20% of total replacement value (Terzic et al. 2012, Mayes et al. 2013), and the expectation is that they may be unusable for more than 1 year (Terzic et al. 2012). These studies relied on a robust methodology for calculating losses originally developed by the Pacific Earthquake Engineering Research center (PEER) which has become the basis for state-of-the-art loss assessment outlined in FEMA P-58 (2013).

Ramirez and Miranda (2012) found that 4-story and 12-story concrete frame buildings in Los Angeles are estimated to suffer 42% and 34% direct financial losses in the "design level" earthquake. Their study explicitly included the probability that permanent (residual) drifts, which is an important indicator of reparability, would cause a total loss.

Performance-Based Design

Performance-based design (PBD) procedures are sometimes used to supplement code design. The intent of PBD is to demonstrate explicitly by performance prediction analysis that pre-identified earthquake performance objectives for the building structure are satisfied. This is generally done through advanced computer simulation which subjects a 3D mathematical representation of the structure to actual ground motions (typically scaled) recorded from past earthquakes.

On rare occasions, owners may voluntarily target performance objectives which exceed code objectives, but usually PBD is only used to verify that code-intended performance objectives are met, in order to circumvent certain code requirements (i.e. height limitations). In latter case, PBD provides higher confidence that the intended performance will be achieved during an earthquake. However, computer analysis alone is not necessarily a good predictor of actual damage when the structure is expected to sustain significant damage (i.e. code-intended performance). That is because the reliability of the models to capture the actual behavior of the building becomes more uncertain as the structure is pushed to its limits.

Neither code-based nor performance-based design approaches typically include explicit verification of non-structural component performance and neither consider other external factors that may affect functionality of the building after the earthquake.

Resilience-Based Design

Resilience-based earthquake design is a holistic process which identifies and mitigates earthquake-induced risks to enable swift recovery in the aftermath of a major earthquake - this exceeds code-intended performance objectives and typical performance-based design objectives. It requires integrated multi-disciplinary design and contingency planning (to address external threats to recovery) together with performance-based assessment to ensure that an owner's resilience objectives are met.

Designing buildings to sustain less damage in earthquakes is a key component of resilience-based design. This significantly decreases the uncertainty in the behavior of the building and increases the confidence that the building will perform as intended. Resilience-based design explicitly incorporates the design and performance verification of the structure and all non-structural components, including architectural components, facades, MEP equipment, and building contents. Several researchers have shown that base-isolating a building for example, can reduce the demands on both the structure and non-structural components, resulting in significantly decreased building damage and financial loss on the order of 2% or less (Terzic et al. 2012, Mayes et al. 2013).

One of the key differentiators of resilience-based design is preparedness for post-earthquake recovery to ensure continued operation (if desired) and liveable conditions immediately after the earthquake. This process considers the performance of the building (and contents) and threats posed by the post-earthquake environment which could hinder the primary functions of the organization. For example, damage arising outside the building envelope due to poor performance of adjacent buildings or utility disruption may not be in the control of the building owner, but contingency planning may be utilized to provide a degree of post-earthquake functionality and business continuity while these external factors are dealt with.

REDi™ Roadmap to Resilience

Overview

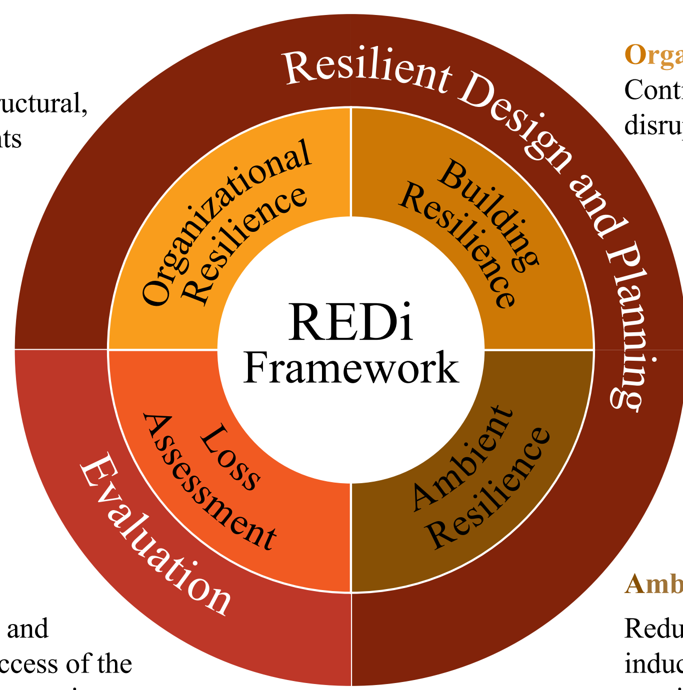
The REDi™ framework recognizes that resilient design and planning is the key to achieving a truly resilient facility. To qualify for a REDi™ rating, (Platinum, Gold, or Silver) it is necessary to satisfy mandatory criteria for that tier in each of three Resilient Design and Planning categories - Organizational Resilience, Building Resilience, and Ambient Resilience. In addition, a Loss Assessment must be performed to verify that a sufficient number of the non-mandatory recommendations have been adopted that the REDi™ resilience objectives associated with each rating (located on page 11) - measured in terms of downtime and financial loss - are achieved.

The general concepts which form the REDi™ Roadmap to Resilience are summarized in the figure below and described in more detail on the next page. To qualify for a REDi™ Rating, the criteria for the Resilient Design and Planning and Loss Assessment categories, located in their entirety in the REDi™ Guidelines and Criteria beginning on page 17, must be satisfied.

> The REDi™ roadmap to resilience will allow owners to resume business operations and provide liveable conditions quickly after an earthquake.

Building Resilience:
Minimize expected damage to structural, architectural and MEP components through enhanced design

Organizational Resilience:
Contingency planning for utility disruption and business continuity



Loss Assessment:
Evaluate financial losses and downtime to evaluate success of the design and planning measures in meeting the resilience objectives

Ambient Resilience:
Reduce risks that external earthquake-induced hazards damage building or restrict site access

REDi™ Roadmap to Resilience

Building Resilience

Reliable damage-control technologies such as base isolation and energy-dissipating systems have become well established over the past 15 years. Improved methods for detailing non-structural components have also been developed. At the same time, developments in computer simulation - based upon improved knowledge of structural behavior - now enable engineers to realistically predict the behavior of buildings in large earthquakes. These significant advances make it possible to design economically viable buildings which will suffer far less damage in strong earthquakes than conventional code-designed buildings. Incorporating enhanced design to minimize earthquake demands and to increase the capacity of non-structural components can protect owners' assets in addition to providing life safety.

Left: The San Francisco General Hospital employed base-isolation to protect the building from structural and non-structural damage in a major earthquake. Base-isolators substantially reduce the design seismic forces, allowing the superstructure to utilize less steel tonnage, which more than offset the cost of the base isolators and flexible connections required across the isolation plane.

Organizational Resilience

The time to achieve functional recovery of a damaged building is not just the time it takes to complete necessary repairs caused by earthquake damage. "Impeding factors" (see "Loss Assessment" below) can cause significant additional delays to recovery time. In addition, the effect of disruption to utilities must be considered to maintain liveable conditions and allow business to resume after an earthquake. Pre-earthquake contingency planning is the key to reduce these potential risks.

Ambient Resilience

One lesson from recent earthquakes is that hazards external to the building can impact recovery. Site planning is important. This is especially true of buildings in dense urban environments, where surrounding structures can collapse or shed debris onto roads or even onto the building. Ease of access to a building after an earthquake is a major factor in minimizing downtime. In susceptible areas tsunamis, liquefaction, slope failures or other earthquake-induced hazards can have a devastating effect on the time it takes the local community to recover. This could jeopardize the recovery of even the most structurally resilient buildings.

Loss Assessment

The success of the resilience-based design approach in satisfying the REDi™ resilience objectives (see page 11) is measured through a loss assessment which quantifies earthquake risk in terms of direct financial losses and downtime. PACT, a loss assessment tool developed by FEMA, allows the user to define the quantity and location of all building components and contents. The expected earthquake-induced responses (deformations, accelerations etc.) of the building structure are first predicted by computer simulation. The expected damage to each of the building components caused by the predicted responses is then computed. Finally, the consequences of the damage in terms of repair time and the cost of repairs is quantified and the risk drivers (those components causing the greatest proportion of the losses) are identified. We modified the loss assessment method used by PACT to incorporate more realistic repair strategies and delays due to "impeding factors" and estimated utility disruption times in order to predict the time required to achieve re-occupancy, functional recovery, or full recovery (see A4.3 "Downtime Assessment Methodology").

Avoid Cliff Edge effects…

The time to repair a building is essentially proportional to the severity of damage it suffers. If the building suffers only minor damage to non-critical components, then the repair time may be minimal and have little impact on functional recovery. But as the extent and severity of damage increases, the time required to achieve functional recovery may increase exponentially due to the amount of repairs required, but also due to "impeding factors" (see Glossary of Terms) that delay the initiation of repairs. These factors include completion of post-earthquake building inspection, securing financing for repairs, mobilizing engineering services, re-designing damaged components, obtaining permits, mobilizing a contractor and necessary equipment, and the contractor ordering and receiving the required components including 'long-lead time' items. See "Downtime Due to Delays" in A4.3.

REDi™ Resilience Objectives

The baseline seismic resilience objectives for the three tiers of the REDi™ rating system are outlined on the right. These refer to performance in the design level earthquake, defined in 2.1.1 of the REDi™ Guidelines and Criteria.

The Gold and Platinum tiers aim to achieve a step change reduction in the earthquake risks relative to code-designed buildings by targeting immediate re-occupancy status, quick functional recovery, and low levels of direct financial loss. The Silver tier does not necessarily achieve immediate re-occupancy, but the substantial reduction in damage caused and the planning measures in place enable the time required to achieve functional recovery to be limited to six months.

The terms used for defining the resilience objectives are located in Glossary of Terms.

REDi™ Resilience Objectives

Baseline Resilience Objectives

for Design Level Earthquake

Platinum

Downtime:
Immediate Re-Occupancy (Green Tag expected)
and
Functional Recovery < 72 hours

Direct Financial Loss:
Scenario Expected Loss < 2.5%

Occupant Safety:
Physical injury due to failure of building components unlikely

Gold

Downtime:
Immediate Re-Occupancy (Green Tag expected)
and
Functional Recovery < 1 month[1]

Direct Financial Loss:
Scenario Expected Loss < 5%

Occupant Safety:
Physical injury due to failure of building components unlikely

Silver

Downtime:
Re-Occupancy < 6 months (Yellow Tag possible)
and
Functional Recovery < 6 months[1]

Direct Financial Loss:
Scenario Expected Loss < 10%

Occupant Safety:
Physical injury may occur from falling components (but not structural collapse), fatalities are unlikely

[1] To achieve a Gold or Silver rating, it is permitted to assume that utilities would be restored within the timeframe corresponding to the functional recovery objective (i.e. utility disruption would not hinder functional recovery). Using this logic for Gold rated buildings, utilities may be assumed to be restored within 1 month after a design level earthquake. For Silver rated buildings, utilities may be assumed to be restored within 6 months after a design level earthquake. If there is evidence that any of the utilities would be disrupted for longer than the corresponding functional recovery timeframes, it must be reported to the Owner, but it will not disqualify the building from receiving either a Gold or Silver rating (see 1.2.1 in the REDi™ Guidelines and Criteria below).

Glossary of Terms

Design Level Earthquake The design level earthquake, defined for this methodology in more detail in 2.2.1 of the REDi™ Guidelines and Criteria, has a low chance (10%) of occurring in 50 years, the typical stated design life of new buildings. It can also be referred to as the 475 year return period earthquake - i.e. it is statistically expected to occur once every 475 years. This traditional definition (used in building codes for several decades prior to 1996) is different than the most current building code which defines the design ground motion as 2/3 MCE (NEHRP, 2009). The current code definition makes it difficult to understand the return period associated with the design ground motion and the return period could be significantly different at different locations across the United States. The 475 year return period earthquake was selected as the basis for the REDi ratings because it is traditionally accepted by the engineering and insurance industry and it enforces a uniformly defined earthquake hazard level independent of site location.

The design level earthquake is expected to cause moderate to significant damage to newer existing buildings designed to current or recent building codes - they may not be re-occupiable and will likely not be functional immediately following the earthquake (NEHRP, 2009) and will likely require significant repair or even replacement. Essential facilities like hospitals are likely to be re-occupiable and may remain operational (NEHRP, 2009). Utilities may be disrupted, roads and bridges may suffer moderate to significant damage, and a significant number of older buildings may collapse.

Maximum Considered Earthquake (MCE) The Maximum Considered Earthquake or MCE is defined by the building code. The MCE has a very low (2%) chance of occurring in 50 years (i.e. 2475 year return period) for most locations. However, for sites near to faults in seismically active regions, the code enforces an upper limit for shaking based on a deterministic earthquake scenario - one that accounts for the estimated maximum magnitude on a fault and a reasonable account of the uncertainty on the resulting ground accelerations. In some locations of coastal California for example, this upper limit governs and the associated return period is in general approximately 1250 years (SEAONC, 2009). Thus, the probability of occurrence associated with the MCE varies by region.

In either case, the MCE is expected to cause significant and widespread damage to newer existing buildings designed to current or recent building code - they will likely not be re-occupiable or functional following the earthquake and some may collapse (the design intent of the code implies that there is a 10% chance that a new building will collapse in an MCE (NEHRP, 2009)). Essential facilities like hospitals would likely be evacuated and would likely not be functional. Utilities would likely be disrupted, roads and bridges would likely suffer significant damage, and a significant number of older buildings would likely collapse.

Frequent Level Earthquake A "frequent level" earthquake is not defined in the building codes, but the implicit intent of code design is that frequent earthquakes should not cause significant damage (NEHRP, 2009). Recent non-codified guidelines for tall buildings require explicit demonstration of performance under frequent level shaking and have proposed return periods from 43 years (PEER-TBI, LATBSDC, SF-AB-083) to 72 years from the CTBUH (Willford et al. 2008).

The frequent level earthquake is expected to cause minor to moderate damage to newer existing buildings designed to current or recent building codes; typically they could likely be re-occupied soon after the earthquake with some loss of functionality. Essential facilities like hospitals are likely to remain operational. Utilities may be affected, roads and bridges may suffer minor to moderate damage, and some older buildings may be significantly damaged.

It should not be necessary to consider a frequent level earthquake for Platinum or Gold rated buildings

since the resilience objectives in the design level earthquake will likely govern. However, it may be prudent to consider the frequent level earthquake for Silver buildings, and target resilience objectives achieved by Platinum or Gold rated buildings.

Downtime Downtime is the time required to achieve a defined recovery state after an earthquake has occurred. Three such recovery states were defined by the Structural Engineers Association of Northern California (Bonowitz, 2011): re-occupancy of the building, pre-earthquake functionality and full recovery. The downtime resilience objectives of the REDi™ rating system focus on the first two: re-occupancy and functional recovery.

Section 4.3 of this guideline provides the methodology for calculating realistic downtime estimates which account for the time required to undertake repairs to the building (see "Repair Time" below), the time before repairs can be started (see "Impeding Factors" below) and utility disruption (see "Utility Disruption" below). See also "Probabilities" below.

Repair Time Repair time is the total amount of time required to repair or replace all damaged building components to restore the building to a specific recovery state, either re-occupancy or functionality, assuming that the labor, equipment, and materials required is available (see "Impeding Factors" below). For example, the repair time required to achieve re-occupancy is the time it takes to repair major structural damage, but not the time it takes to repair slightly cracked partitions since that would not hinder the building from being re-occupied. The REDi™ methodology follows a realistic repair sequence likely to be followed by a contractor, in order to estimate the repair time (see A4.3).

Impeding Factors Downtime is not just the time necessary to perform repairs to a building to permit re-occupancy or to restore functionality. The delay between the earthquake event and the initiation of repairs may be very significant. These delays are referred to as 'impeding factors' and include the time it takes to complete post-earthquake building inspections, secure financing for repairs, mobilize engineering services, obtain permitting, mobilize a contractor and necessary equipment, and for the contractor to order and receive the required components including "long-lead time" items. Other considerations, such as the time it takes for a competitive bidding process for contractors is also included for heavily damaged buildings. The REDi™ downtime estimates assume that the Owner's decision-making process or regulatory uncertainty does not contribute to downtime.

Estimated delay times associated with "impeding factors" are provided in A4.3 "Downtime Assessment Methodology". The delay time estimates may benefit from the recommendations to minimize their effects (see 1.2.1 and 1.3 in the REDi™ Guidelines and Criteria for details).

Re-occupancy and Green Tag Re-occupancy can occur when the building is deemed safe enough to be used for shelter.

If damage is apparent, this typically requires an inspection (ATC-20) which the jurisdiction will undertake at the request of the Owner. Re-occupancy can occur once a Green Tag is awarded following inspection by a qualified professional on the basis that any damage to structural and non-structural components is minor and does not pose a threat to life safety and if egress paths are undamaged (ATC-20). If "life-safety" hazards to occupants (which may include significant structural damage, exterior falling hazards due to damaged cladding and glazing, interior hazards from damaged components hung from the floor above or severely damaged partitions, or all of the above) are evident, the must be removed or repaired before a Green Tag is awarded. A Green Tag allows unrestricted access and re-occupancy to all portions of the building. Clean-up and/or minor repairs to some non-structural components (such as fallen ceiling tiles) by unskilled personnel may be required so as not to impede egress in some areas of the building.

If visible damage is minor, the Owner could decide to forego inspection, allowing the building to be re-occupied almost immediately after the earthquake at his/her discretion. This is the scenario assumed by REDi™ for buildings that are predicted by the "Downtime Assessment" in Section 4.3 to suffer only aesthetic damage (Repair Class 1 or less). However, since occupants of a building may also submit a request for inspection after an earthquake (even in the event of minor damage), it is recommended that the Owner retains a qualified professional to perform post-earthquake inspection (see 1.3.1) to avoid long delays associated with inspections performed by the jurisdiction. The jurisdiction also has the power to require inspection if they feel it is necessary, but it is unlikely to be initiated if the damage is minor.

Re-occupancy can occur before functionality is restored. In this case lighting, heating/air-conditioning, and water may not be available so the use of flashlights, blankets/heavy clothing, operable windows, bottled water and some form of waste disposal may be needed. Re-occupancy of multi-story buildings can occur provided stairs provide safe egress from higher floors; elevators are not necessarily required to be operable but in this case patients or the elderly would need assistance accessing higher floors. Though some discrete portions of a building may be re-occupied before others (i.e. "Yellow Tagged", see below), the re-occupancy objectives in REDi™ are associated with the time to re-occupy the entire building.

Yellow Tag A Yellow Tag is awarded following inspection by a qualified professional if there is moderate damage that may pose a life-safety risk to occupants (ATC-20). Due to the extent of visible damage, the Owner or occupants of a building would likely submit a request for inspection after an earthquake in a potential Yellow Tag building, or the jurisdiction may require one otherwise.

Structural damage which may not necessarily indicate deterioration of lateral strength (such as spalling of a well confined concrete member), could also be interpreted by some inspectors as posing a risk. A building with little structural damage may receive a Yellow Tag due to hazards from non-structural components. In that case, entry might be allowed only to certain portions of the building with the intention of securing and repairing the building to make it safe for basic habitation. Re-occupancy would occur only after all of the repairs required to address the life-safety issues are completed. A Yellow Tag designation does not prevent a contractor from entering the building, only the occupants, and only to certain portions of the building.

Functional Recovery Functional recovery represents the time required to establish re-occupancy and regain the facility's primary function (it is analogous to 'operational' or 'operable' in some building codes). For all occupancy types, this would require restoring power, water, fire sprinklers, lighting, and HVAC systems while also ensuring that elevators are back in service. Back-up systems may also be used in the interim to provide a pre-defined state of functionality agreed by the Owner (potentially at reduced capacity, see "Back-up Systems" in Glossary of Terms) until the municipal utilities are restored and able to provide resources for full capacity.

In residences, functional recovery is related to regaining occupant comfort and livable conditions – the lights are on, water flows, heating and air conditioning are operating. Functional recovery also indicates the time required for resumption of specific functions particular to a certain occupancy. Examples include emergency services and typical services in hospitals, business activity in offices and retail, or classes in educational facilities.

Repairs to prevent deterioration of the building (such as sealing leaky pipes for mold prevention or making sure the building envelope is weatherproof) must also be completed to achieve functional recovery.

Utility Disruption Utility disruption is likely to occur in a design level earthquake and must be considered for Platinum rated buildings (utility disruption estimates are provided in A4.3). In most cases functional recovery will require utility services to be available. Back-up systems are required to achieve the 72 hours functional recovery target for REDi™ Platinum rated buildings. If it is not feasible to store on site the back-up capacity necessary for the duration of the estimated utility disruption, contingency plans for re-fueling generators, re-filling water tanks, and emptying wastewater tanks should be in place to allow continued functionality (see 1.2.1 for details).

Utilities may reasonably be expected to be restored within the functional recovery timeframe objectives for REDi™ Gold and Silver rated buildings so back-up systems are only recommended (see 1.2.1 for details).

Back-up Systems The capacity of back-up systems should be adequate to operate Owner-designated systems at Owner-designated performance levels. This capacity may be substantially lower than that required for normal full operation but must be reasonable. For example, the capacity of back-up power required while utilities are disrupted could be based on operating the lighting for a reduced number of hours or keeping the temperature within a broader but reasonable range than 'normal' conditions.

Full Recovery Full recovery follows functional recovery when repairs required primarily for aesthetic purposes (such as painting cracked partitions) restore the building to its original pre-earthquake condition. Since these repair measures are minor and do not hinder building function, they could be undertaken at a time best suited to the owner and occupants. For that reason, it is not included as a REDi™ baseline resilience objective.

Scenario Expected Loss The Scenario Expected Loss (SEL) is the mean estimated direct financial loss (it is also known as the 50% probability of non-exceedance or 50% confidence level) suffered by the facility for a given earthquake intensity level. There is therefore a 50% likelihood that the actual loss would not exceed the specified percentage of Total Building Value of the facility. The loss includes the cost of repair or replacement (including labor) of damaged building components and contents to achieve full recovery (see above). It does not include the cost of engineering or architectural design services.

Lenders and investors typically associate the SEL with the 475 year return period earthquake but the term may be used in association with any return period earthquake (ASTM 2026-07).

Total Building Value Direct financial loss is calculated by PACT where the losses are expressed as a proportion (%) of the Total Building Value at today's prices. The Total Building Value defined here are the hard costs (including labor) only required to replace the building. This is different than the definition in ASTM 2026 for Replacement Value which includes demolition, design, and management since REDi™ rated buildings are not expected to suffer damage which requires total replacement and addition of those items (and others) reduces the loss ratios substantially.

The hard costs should be obtained from a construction cost estimate (including at minimum all structural and non-structural components) plus the value of damageable building contents if they are known. Mark-ups such as liability, material cost uncertainty, demolition, design/management, and profit/overhead should not be included. The construction cost estimate used for loss calculations should be no more than 10% different than the final cost estimate.

Glossary of Terms

Life-safety Physical injury or fatalities associated with an earthquake are generally caused by collapse or by components falling on persons inside or outside a building. Non-essential facilities designed to meet minimum code design requirements are intended to protect occupants from 'life-threatening damage' (NEHRP, 2009) due to structural collapse or failure of non-structural components in a design ground motion (which has similar intensity to the design level earthquake defined in this methodology).

However, the code does not address building contents (e.g. storage systems) which can cause injury or even fatality if they fall on someone. The REDi™ framework includes provisions for securing building contents to mitigate hazards of this type as well as reducing damage to the building fabric relative to code-designed buildings.

Injuries (or even fatality) which could potentially occur independent of building damage are not considered in the code or in REDi™. Examples include someone falling simply due to the effects of the shaking of the ground or the building or panic-induced crowd injury as people head for exits.

Repair Class "Repair Classes" describe how the extent and severity of damage to particular types of building components may hinder specific recovery states. See Table 3 in Section A4.3 "Downtime Assessment Methodology".

Probabilities Various similar terms are used throughout the guideline to express the probabilities associated with the direct financial loss and downtime estimates.

Similar to the Scenario Expected Loss, the REDi™ downtime objectives are associated with 50% probability of non-exceedance. For example, Gold buildings have a 50% probability that the time required to achieve functional recovery would not exceed 1 month. Other terms to express 50% probability of non-exceedance in this guideline include "median", "mean", "average", "expected", "best-estimate", and "50% confidence".

The Owner is encouraged to discuss higher probability levels with the engineer and design team if desired to achieve even better performance than the REDi™ resilience objectives. For example, Probable Maximum Loss is the 90% confidence level of direct financial loss that many earthquake insurance policies are based upon.

REDi™ Guidelines and Criteria

Contents

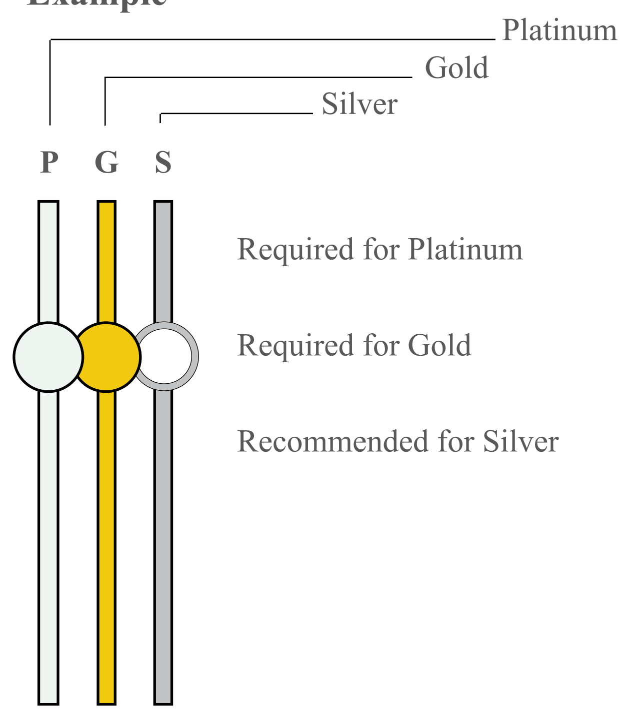
The REDi™ Guidelines and Criteria must be satisfied to meet the desired REDi™ Resilience Objectives found on page 11.

Key for Interpreting Criteria

Symbols

- Required for Platinum
- Required for Gold
- Required for Silver
- Recommended for Platinum
- Recommended for Gold
- Recommended for Silver

Example



Guiding Principles for Criteria

The prescriptive requirements contained in the REDi™ Guidelines and Criteria were developed to achieve the general intent for each rating tier, distinguished by the key guiding principles summarized below.

Platinum

* Enhance design of structure and architectural components such that the building and contents suffer only minimal (aesthetic) damage.

*Provide “beyond-code” provisions for egress systems and other improvements to occupant safety

* Protect MEP components and other critical systems. Provide back-up systems. This enables continued operations of primary functions in the absence of utilities.

* Pre-identify contingency plans to provide water and fuel and waste removal or employ alternative off-grid technologies in the event of extended utility disruption.

* Minimize risk of generally uncontrollable externalities which may affect functionality, including site access restrictions and potential damage from external hazards such as surrounding buildings.

Gold

* Enhance design of structure and architectural components such that the building and contents suffer only minimal (aesthetic) damage .

*Provide “beyond-code” provisions for egress systems and other improvements to occupant safety

* Protect MEP components and other critical systems or guarantee that they are replaced/repaired within 1 month. This enables normal operations to resume once utilities are restored

Silver

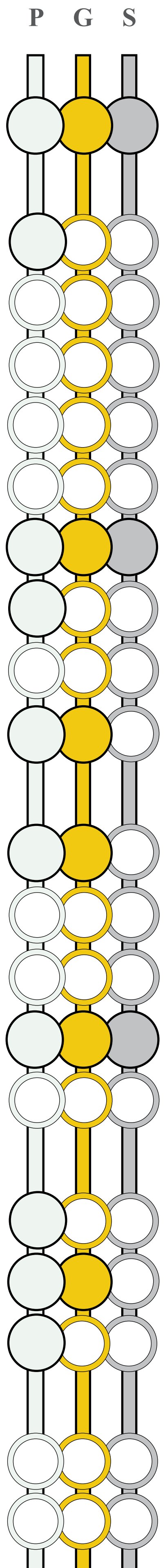
* Damage to the building may potentially result in a “Yellow Tag” which would prevent re-occupancy until the building is repaired.

*Provide “beyond-code” provisions for egress systems and other improvements to occupant safety

* A skilled contractor is required to make repairs to restore the building to a state which can support functional recovery within 6 months. It may be necessary to mitigate “impeding factors” (see Glossary of Terms) to meet this downtime objective.

* The building can resume normal operations only once the building is repaired and utilities are restored.

Summary of Criteria



1.0 Organizational Resilience

1.1 Resilience planning

1.1.1 Resilience Workshop

1.2 External Utility Supply Chain

1.2.1 Back-up for Utility Lines

1.2.2 Redundant Lines

1.2.3 Off-grid Technology

1.2.4 Passive Comfort

1.2.5 Low-use Fixtures

1.2.6 Gas Shut-off

1.2.7 Back-up Communication

1.2.8 Data Protection

1.2.9 Security

1.3 Mitigate Impeding Factors

1.3.1 Post-earthquake Inspection

1.3.2 Contractor/Engineer Mobilization

1.3.3 Access to Financing

1.3.4 Long-lead Time Items

1.3.5 Instrumentation

1.4 Business Continuity

1.4.1 Risk Assessment

1.4.2 Food and Water

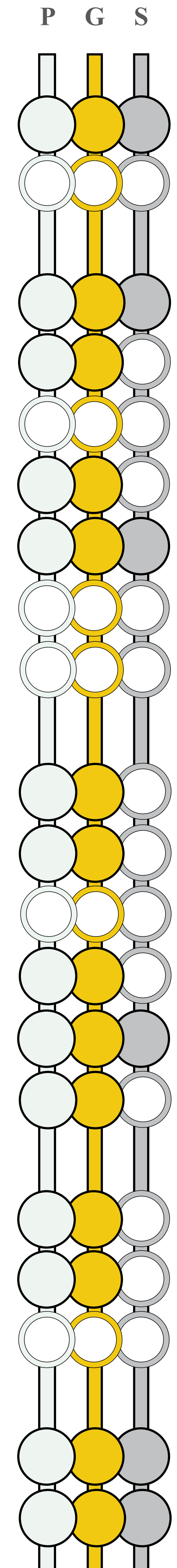
1.4.3 Preparedness Training

1.5 Advocacy for Resilience

1.5.1 Improve Infrastructure

1.5.2 Incentives

Summary of Criteria



2.0 Building Resilience

2.1 Seismic Hazard

2.1.1 Design Level Earthquake

2.1.2 Site Response Analysis

2.2 Enhanced Structural Design

2.2.1 Code Minimum Requirements

2.2.2 Design Demands

2.2.3 Vertical Earthquake

2.2.4 Minimize Structural Damage

2.2.5 Minimize Residual Drift

2.2.6 Expose Structural Elements

2.2.7 Symmetric Design

2.3 Enhanced Non-structural Design

2.3.1 Minimize Non-structural Damage

2.3.2 Equipment Functionality

2.3.3 Location of Critical Components

2.3.4 Protect Facades

2.3.5 Anchor Heavy Building Contents

2.3.6 Protect Other Building Contents

2.4 Capacity Design

2.4.1 Superstructure of Base-isolated Buildings

2.4.2 Capacity of Base Isolators

2.4.3 Capacity of Viscous Dampers

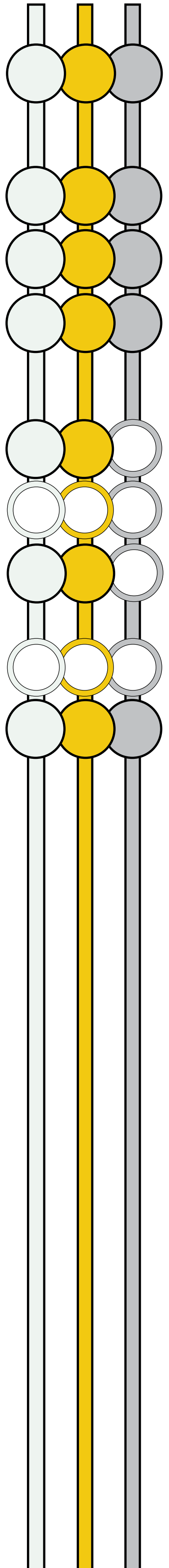
2.5 Safer Egress

2.5.1 Stairs

2.5.2 Doors

Summary of Criteria

P G S



2.0 Building Resilience (continued)

2.5.3 Elevators

2.6 Structural Analysis

2.6.1 Non-linear Response History Analysis

2.6.2 Simulation Model

2.6.3 Ground Motions

2.7 Peer Review & Quality Assurance

2.7.1 Structural Peer Review

2.7.2 Non-structural Calculations

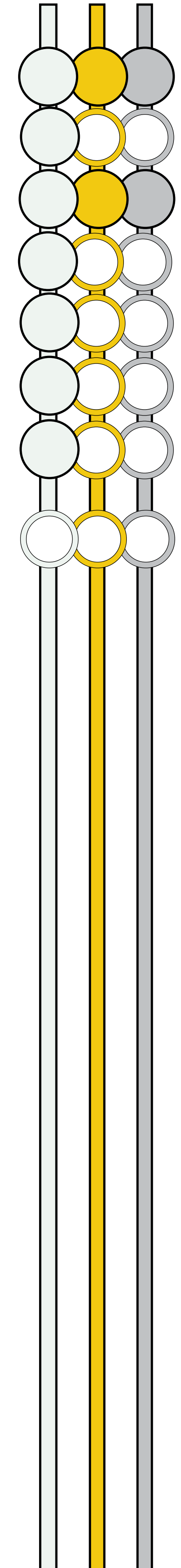
2.7.3 Installation of Non-structural Components

2.7.4 MEP Review

2.7.5 Design Build Components

Summary of Criteria

P G S



3.0 Ambient Resilience

3.1 Earthquake-induced Hazards

3.1.1 Design for Liquefaction

3.1.2 High Liquefaction Hazard

3.1.3 Other Ground Failures

3.1.4 High Tsunami Hazard

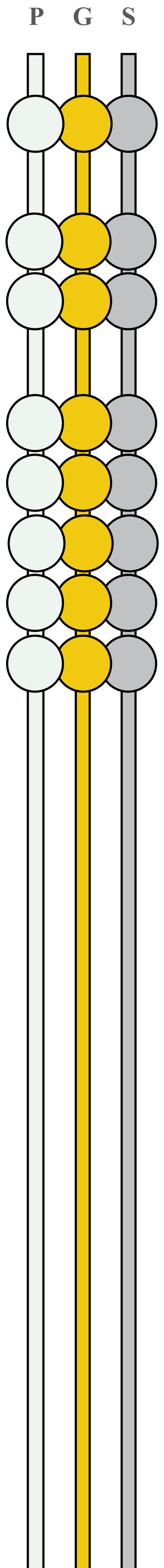
3.1.5 Assessment of Surrounding Buildings

3.1.6 High Hazard from Surrounding Buildings

3.1.7 Assessment of Surrounding Non-building Structures

3.1.8 Fire Sprinklers

Summary of Criteria



4.0 Loss Assessment

4.1 General Asssessment Guidelines

4.1.1 Guidelines for Loss Assessment

4.2 Direct Financial Loss Assessment

4.2.1 Direct Financial Loss Assessment

4.2.2 Valuable Building Contents

4.3 Downtime Assessment

4.3.1 Downtime Assessment

4.3.2 Impeding Factors

4.3.3 Utility Disruption

4.3.4 Long-lead Time Items

4.3.5 Critical Building Contents

1.0 Organizational Resilience

1.1 Resilience Planning

Intent:

Establish a resilience plan to identify risk drivers and ensure that all aspects of the design contribute to reducing the risk in accordance with the Owner's resilience objectives.

Criterion

P G S

1.1.1 - Resilience Workshop
Conduct a comprehensive workshop with the Owner, led by the engineer with at minimum, participation by the architect, facility manager (if applicable), and risk manager (if applicable), to agree on resilience objectives and to identify risk drivers and a resilience plan for the facility. Meeting minutes are taken and documented.

A formal Resilience Plan document which identifies how all resilience objectives have been achieved and identifies remaining potential risks at the completion of design is written by the Design Team and approved by the Owner.

Commentary

C1.1.1 - Resilience Workshop
The discussion would include but not be limited to the criteria in this guideline.

Some examples:

* Downtime goals for re-occupancy and functionality and financial loss objectives*
* Confidence levels for the above objectives (see "Probabilities" in Glossary of Terms)*
* Discuss structural solutions for minimizing demands and damage*
* Identify mechanical, electrical, and other components and equipment in the building which are critical to functionality and plan for protecting them from being damaged*
* Discuss architectural components and identify how they will accommodate expected earthquake demands*
* Identify mission-critical and valuable building contents and plan for protecting them*
* 'Externalities' that would affect business continuity and recovery and whether a formal business continuity and risk assessment is required. See 1.4.1.*
* For campuses, corporations, or other networked organizations, determine interdependencies of individual building performance on the overall resilience objectives*
* For developers, determine what should be written into fit-out contracts with tenants in order to satisfy the resilience objectives*

* Discuss any project-specific goals not explicitly covered by a particular rating*

1.2 External Utility Supply Chain

Intent:

Reduce risk that external utility disruption will hinder functional recovery of the facility.

P G S

Criterion

1.2.1 - Back-up for Utility Lines
For each utility listed below provide back-up systems (see Glossary of Terms) for the amount of time that the particular utility is estimated to be disrupted (minimum provide 72 hours capacity) if building functionality depends on it.

* Power
* Drinking water (see also 1.4.2)
* Non-drinking water
* Holding tank for wastewater
* Natural gas

See A4.3 "Downtime Due to Utility Disruption" for estimates of utility disruption times. These are based on data from previous earthquakes and hypothetical earthquake scenarios. These should be cross-referenced against region-specific forecasts by experts and local utilities if they exist and the most applicable predictions should be used. See also 1.2.3 and 1.2.4 for alternative design strategies.

Commentary

C1.2.1 - Back-up for Utility Lines
For Platinum rated buildings:
The physical capacity of back-up systems (e.g. size of tank) must hold enough supply (e.g. gallons of fuel) for 72 hours minimum. If the utility is expected to be disrupted for longer than 72 hours, the additional required supply must be located on-site, but may be capped by an additional 4 days (i.e. 7 days total supply on-site). If the utility is expected to be disrupted beyond 7 days, the Owner pre-identifies and pre-contracts resources to re-fuel generators (or stores additional fuel on-site), re-fill water tanks, and empty wastewater tanks to allow continued functionality for the time required. Consider whether this plan is feasible given the likely damage to roads/ bridges.

For Gold and Silver rated buildings:
Back-up systems for disrupted utilities are not required for Gold or Silver ratings (unless required by code for life-safety purposes - e.g. egress lighting) since it may be reasonable to assume that the utility would be restored within the timeframe corresponding to each of the functional recovery objectives (i.e. 1 month for Gold buildings). However, the utility disruption times must still be estimated per the Criterion. The estimated utility disruption may be capped by the timeframe corresponding to the considered functional recovery objective for the purposes of the "Downtime Assessment" in 4.3 but it must be reported to the Owner that such an assumption has been made.

Back-up Power:
guidelines in NFPA 110 for further guidance.

Back-up for Natural Gas:
Provide dual-fuel boilers which can run off an alternative back-up fuel supply such as propane.

Hospitals:
California Building Code Section 1615A.1.38 requires hospitals have 72 hours of on-site water and holding tanks for wastewater for emergency operation, integrated into the building's plumbing systems. Alternatively, they allow hook-ups for transportable sources of water and sanitary waste water disposal. The code requires 72 hours of back-up power only for critical care areas and radiological services. It is recommended that the back-up power be capable of serving other hospital functions as well.

1.2 External Utility Supply Chain

Criterion Commentary

P G S

1.0 Organizational Resilience

1.2.2 - Redundant Lines
Provide dual/multiple seismically-resilient utility lines to decrease risk that local damage to distribution systems causes utility disruption.

C1.2.2 - Redundant Lines
Route pipelines to avoid areas of large expected ground deformations (i.e. liquefaction and landslide zones and areas of lateral spreading). Use flexible pipelines and connect as close to the source of supply as possible.

See Chen and Scawthorn (2002) for more information.

1.2.3 - Off-grid Technology
Provide closed-loop systems and/or feed off microgrids so that water and energy supply is not reliant on the utility grid.

C1.2.3 - Off-grid Technology
The most resilient buildings are those that can continue to function without the support of the municipal utility grid, which may be vulnerable to earthquakes. The Living Building Challenge (ILFI, 2012), among others, outlines recommendations for closed-loop water and energy supply that may be followed. Water may be supplied through rainwater

1.2 External Utility Supply Chain

Criterion | Commentary

P G S

harvesting, on-site wells, or other natural closed-loop systems. Power may be supplied through on-site renewable energy such as wind turbines, PV panels, solar heating, etc. Additional resilience may be achieved through reliance on microgrids. Composting toilets and waterless urinals may be used to reduce solid waste and wastewater demands.

1.2.4 - Passive Comfort
Naturally daylight, ventilate, and temperature-condition the building through proper orientation, shape, and materal choice so it can continue to function without artificial lighting and air-conditioning.

C1.2.4 - Passive Comfort
Designing the building for occupant comfort in the absence of utilities provides livable conditions in the absence of utilities. Consider using manually operable windows for natural ventilation. See McGregor et al. (2013) for more details.

1.2.5 - Low-use Fixtures
Utilize appliances and fixtures that minimize water and energy use.

C1.2.5 - Low-use Fixtures
Low-flow water fixtures and energy efficient appliances (for example) would reduce the required capacity of back-up systems or elongate the duration that they could supply the required capacity.

See LEED V2.9 (2009) for New Construction for more details on low-use energy and water use fixtures and appliances.

1.2.6 - Gas Shut-off
The Owner has a contingency plan for natural gas shutoff. A shake-actuated shutoff system may be used but is not required.

C1.2.6 - Gas Shut-off
See ASCE-25 (2002) which outlines the benefits and disadvantages of implementing a shake-actuated automatic gas shutoff device. The disadvantages are mostly associated with resumption of natural gas service if it is shut off.

1.2.7 - Back-up Communications
For organizations which depend on communication for functionality, a back-up for the communication system is established in the event that cellphones, landlines, and internet are interrupted.

C1.2.7 - Back-up Communications
For additional information see Mitrani-Reiser et al. (2012)which details loss of communication for several days after the 2010 Chile earthquake.

1.2 External Utility Supply Chain

Criterion | Commentary

P G S

1.2.8 - Data Protection
Ensure that loss of power does not cause electronic data loss and a plan exists for quick re-booting of server systems.

C1.2.8 - Data Protection

1.2.9 - Security
Ensure that loss of power does not cause security systems to become inactive or ensure that manual over-ride is available (e.g. keys).

C1.2.9 - Security

1.3 Mitigate Impeding Factors

Intent:
Decrease delays to initiation of post-earthquake repairs required for re-occupancy and functional recovery.

P G S

Criterion

1.3.1 - Post-earthquake Inspection
Retain a qualified professional on an annual basis to inspect the facility immediately after an earthquake.

Commentary

C1.3.1 - Post-earthquake Inspection
See "Re-Occupancy" in the Glossary of Terms.

In San Francisco, the Building Occupancy Resumption Program (BORP) allows building owners to pre-certify post-earthquake inspection of their buildings using licensed engineers, which could limit delays to less than 24 hours. See www.seaonc.org/public/all/borp.html.

See A4.3 for estimates of delays due to post-earthquake inspection. These must be considered as an 'impeding factor' for the "Downtime Assessment" in 4.3 if more than aesthetic damage is predicted (i.e. for components with Repair Class > 1).

1.3 Mitigate Impeding Factors

P G S

Criterion

1.3.2 - Contractor/Engineer Mobilization
Retain a contractor and/or engineer on an annual basis if the estimated damage to the facility based on the "Downtime Assessment" in 4.3 would require their services.

1.3.3 - Access to Financing
Budget for the cost of the necessary repairs, calculated in the "Direct Financial Loss Assessment" in 4.2, to achieve at least functional recovery or have a plan that ensures quick access to private or other financing.

Commentary

C1.3.2 - Contractor/Engineer Mobilization
This is likely most applicable to Silver buildings which are expected to suffer damage requiring skilled contractors and potential engineering services. Contractors and engineers will likely be in scarce supply after a major earthquake and retaining them on an annual basis to perform post-earthquake repairs could save weeks of post-earthquake downtime. Also consider signing a pre-approval contract with the contractor, guaranteeing the contractor some pre-identified financial compensation to begin repairs, in case financing is not immediately available (see 1.3.3).

See A4.3 for estimates of delays due to contractor and engineer mobilization and for additional time for engineering re-design and review if required. These must be considered as an 'impeding factor' for the "Downtime Assessment" in 4.3 if more than aesthetic damage is predicted (i.e. for components with Repair Class > 1).

C1.3.3 - Access to Financing
The time to access financing may be the most uncertain 'impeding factor'. Financing from insurance claims or private-backed loans have varied considerably (several weeks to several months or longer). In addition, insurance companies often require insurance deductibles may be higher than the estimated losses. The most reliable method would be to limit the expected financial losses so that repairs necessary to achieve functional recovery can be financed within the normal operating budget of the facility. REDi™ rated buildings may not rely on government grants for funding sources.

1.3 Mitigate Impeding Factors

Criterion | Commentary

P G S

Since Platinum and Gold rated buildings are designed to sustain only aesthetic damage, component repairs would not hinder functional recovery and financing may not be required for the design level earthquake. However, it would be prudent to plan for the scenario in which higher than design level shaking occurs and causes unexpected damage.

For Silver, it would only be required if the estimated delay due to financing hindered the functional recovery objective (6 months) from being achieved. As above, it is always prudent to have access to financing.

See A4.3 for estimates of delays due to financing. These must be considered as an 'impeding factor' for the "Downtime Assessment" in 4.3 if more than aesthetic damage is predicted (i.e. for components with Repair Class > 1).

Note that the Scenario Expected Loss calculated herein is associated with Full Recovery of the facility, which will be higher than that associated with Functional Recovery. It woud be consevative to use the Full Recovery value. It is possible to calculate the losses associated with Functional Recovery instead for use in calculating the impeding factor for financing - this is explained in A4.3.

1.3.4 - Long-lead Time Items
For Platinum and Gold buildings, protect critical 'long-lead time' items which would hinder re-occupancy or building functionality (see 2.3.2) if they sustained irreparable damage.

For Silver buildings, either protect the 'long-lead time' items as described for Platinum and Gold or account for expected procurement times in the "Downtime Assessment" in 4.3 if they are expected to sustain damage requiring replacement.

C1.3.4 - Long-lead Items
Some critical equipment or custom components could take months to procure if they cannot be repaired - these are termed 'long-lead time' items. For this reason, Platinum and Gold rated buildings should protect these types of components - (i.e. allow no more than cosmetic damage) - to meet their short recovery objectives.
For Silver buildings, 'long-lead time' items which are expected to sustain damage requiring replacement (may be the case for Silver buildings), one strategy is to purchase redundant 'long-lead time' components and store them off-site (far enough away such that they would not be damaged by the same earthquake). Alternatively, these components may be allowed to be damaged if the time required to procure them does not prevent the downtime objectives from being satisfied.

The 'long lead-times' should be quantified from information provided by manufacturers, maintenence professionals, contractors, and/or cost estimators.

See A4.3 for guidelines to include the time required to procure 'long-lead time' items in the downtime calculations.

1.3.5 - Instrumentation
Instrument the building to measure earthquake response. The measurements can used to inform the Owner whether the facility has sustained damage to enable quick decisions regarding continuation of operations.

C1.3.5 - Instrumentation

1.4 Business Continuity

Intent:
Identify risks to aid owner in post-earthquake recovery planning.

P G S

Criterion	Commentary
1.4.1 - Risk Assessment A business impact assessment and risk assessment are conducted by the Owner or Owner's consultant as part of the corporate business continuity policy. Factors affecting downtime to be studied include (but are not limited to) availability of employees to return to work, site access, continuity of utilities and transportation/road networks, and dependence on products manufactured off-site (referred to as "third party suppliers") that would impede normal business operation/services. Also see 3.0 for other external earthquake-induced hazards including adjacent building damage.	***C1.4.1 - Risk Assessment*** *Though the focus of the rating system is to promote better design of buildings such that damage would be significantly reduced and downtime limited, many occupancies are dependent on off-site factors which would effect continuation of normal operation. These include how quickly employees are expected to return to work and anything that would hinder production or services. Additionally, the Christchurch earthquakes highlighted that many 'uncontrollable' externalities such as damage to adjacent buildings hindered building function. While it is difficult to mitigate such things, this criterion and those in 3.0 will help the Owner to be aware of all the risks to his/her facility.* *This requirement may not be applicable to some residential occupancies or for developer-owned buildings.*
1.4.2 - Food and Water Supply food and potable water, stored on site, for each employee or resident for at minimum 3 days. In hospitals, the supply of food and water should account for each hospital bed being filled.	***C1.4.2 - Food and Water*** *For immediate re-occupancy objectives, food and water should be available for at least the first 3 days after the earthquake. Developer-owned buildings may be exempt from this requirement but could ask commercial and residential tenants to consider it via their occupancy agreements.*
1.4.3 - Preparedness Training Provide earthquake preparedness training/information and supply earthquake preparedness kits, including medical supplies, to tenants and employees. Prepare employees for post-earthquake business resumption.	***C1.4.3 - Preparedness Training*** *See guidance on websites such as http://72hours.org.* *Developer-owned buildings may be exempt from this requirement but could ask tenants to consider it via their occupancy agreements.*

1.5 Advocacy for Resilience

P G S

Criterion	Commentary
1.5.1 - Improve Infrastructure Communicate to local and state representatives, utilities, and transportation departments the desire for improved/enhanced infrastructure to withstand the effects of natural disasters, including earthquakes.	***C1.5.1 - Improve Infrastructure***
1.5.2 - Incentives Request incentives from communities, cities, and states for building to 'beyond code' resilience objectives.	***C1.5.1 - Incentives***

2.0 Building Resilience

2.1 Seismic Hazard

Intent:
Identify site-specific ground shaking hazard.

P G S

Criterion

2.1.1 - Design Level Earthquake
The design level earthquake is represented by an elastic acceleration response spectrum having 10% probability of exceedance in a 50 year period based on a site-specific Probabalistic Seismic Hazard Analysis (PSHA). The spectrum shall have appropriate damping (e.g. less than 5% for tall buildings).

See 2.6.3 for development of earthquake ground motions used for non-linear response history analysis.

Commentary

C2.1.1 - Design Level Earthquake
General:
Follow the guidelines of Section 21.2 of ASCE 7-10 for the hazard analysis (Section 21.2.1 to 21.2.3 may be neglected).

Site Conditions:
Shear wave velocity and other soil parameters required for estimating surface ground motions should be determined from field measurements and laboratory tests. Site conditions should be accounted for via site amplification in ground motion prediction equations or via site response analysis (see 2.1.2).

Near-fault effects:
For sites located 20 km or closer to a fault capable of producing a M6.5, the site-specific seismic hazard calculations should account for near-fault directivity effects. For structures with short periods (T < 0.6 sec) and designed to remain elastic, near-fault directivity effects need not be considered. Consider using Somerville (1997) modified by Abrahamson (2000) or Shahi and Baker (2011) to augment the hazard for near-fault effects.

Directionality:
Note that the design response spectrum in ASCE 7-10 is based on Maximum direction demand instead of geomean (ASCE 7-05). While it is appropriate to account for Maximum direction demand response for designing the capacity of isolators (for example) or for in-plan symmetric structures, it is likely conservative to apply Maximum direction demand for structures which respond along specific axes or are

2.1 Seismic Hazard

Criterion | Commentary

P G S

dominated by several modes (Stewart et al, 2011). The latter may be addressed by using a CMS (see below). Consider using the geomean estimate for superstructure design and Maximum direction demand for isolator design. Note that applying near-fault effects and Maximum direction demand factors simultaneously may be conservative (see also 2.4.2).

Other effects:
Consider basin effects, topographic effects, and any other effects that may augment the hazard. Note that site response analysis does not capture these effects.

Conditional Mean Spectrum (CMS):
A CMS approach may be used if two or more suites of spectra are developed, the envelope of the spectra are not significantly below the UHS (no more than 25% below) across the period range of relevance to possible structural response including elongated periods, and responses are acceptable under each spectra considered. See also PEER TBI (2010).

2.1.2 - Site Response Analysis
For Site Class D, E, or F as defined in ASCE 7-10, Site Response Analysis is used to define the input response spectrum and input ground motions if required for non-linear response history analysis for the intensity levels above. See also 2.6.3.

C2.1.2 - Site Response Analysis
Follow the guidelines of Section 21.1.2 of ASCE 7 for the development of the Site Response Analysis model.

The average response spectra generated from a suite of acceleration records (or the envelope of the averaged suites if using CMS), used for design or non-linear response history analysis, shall not be lower than 80% of the response spectrum following 2.1.1 developed directly from ground motion prediction equations for the corresponding shear wave velocity at the input elevation considered.

2.2 Enhanced Structural Design

Intent:
Increase confidence in the building performance by designing for realistic earthquake demands

Criterion | Commentary

P G S

2.2.1 - Code Minimum Requirements
The design of the building conforms to the requirements of the local jurisdiction in which it is located but at minimum the seismic design requirements meets ASCE 7 - 10.

C2.2.1 - Code Minimum Requirements
A non-prescriptive approach, as outlined in Section 104.11 of the International Building Code, may be allowed by the jurisdiction to confirm compliance with the minimum intended performance objectives of the code. ASCE 7-10 Section 1.3.1.3 outlines "Performance-based Procedures".

2.2.2 - Design Demands
The earthquake loads (E, F_p) and displacement demands (δ) used to design structural and non-structural components according to ASCE 7-10 are, at minimum, based on the design level earthquake calculated in accordance with 2.1, or the code-defined Design Earthquake in Chapter 11, whichever is higher.

C2.2.2 - Design Demands
Also consider designing non-structural components for the floor spectra (if using a response-history analysis) from the design level earthquake if they are higher than the code-defined force demands.

2.2.3 - Vertical Earthquake
The effects of vertical earthquake motion are explicitly accounted for in the design of all structural (including gravity) and non-structural components (including joints between components, i.e. glazing, facades, partitions) if they are expected to increase damage and in the assessment of equipment functionality (see 2.3.2 below). The "Loss Assessment" in 4.0 considers the effects of vertical earthquake motion.

C2.2.2 - Vertical Earthquake
Codes require that vertical earthquake demands, typically approximated as $0.2S_{DS}$, where S_{DS} is the design spectral acceleration at T = 0.2 sec. are considered in load combinations for design of structural elements. However, it is not required to assess the effects of vertical earthquake demands on non-structural components and actual recordings indicate that vertical ground motions consistent with design level earthquakes can be significantly higher than the code approximated demand. Since vertical motions typically contain high frequency content, it is likely that the largest vertical demands would coincide with the largest moment and shear demands in the structure. It may be prudent to design structural and non-structural components for realistic vertical earthquake demands. This may be achieved through a Response

2.2 Enhanced Structural Design

Criterion | Commentary

P G S

Spectrum Analysis of the 3D model using a vertical response spectrum (consistent with the design level earthquake hazard) defined by Gulerce and Abrahamson (2011), Bozorgnia and Campbell (2004) or guidance in Appendix B.5 of FEMA P-58. Alternatively, vertical ground motions, matched to a spectrum produced by the methods above, can be incorporated explicitly in the non-linear response history analyses of 2.6.3.

2.2.4 - Minimize Structural Damage
The superstructure (and foundations) are designed to remain essentially elastic (e.g. cracking allowed) for the demands in 2.2.2

C2.2.4 - Minimize Structural Damage
This can be achieved by using expected (mean) strength properties and no strength reduction factors for ductile elements. For non-ductile elements, it may be more appropriate to use specified (nominal) strength properties and appropriate strength reduction factors.

Components that yield in self-centering systems, such as steel angles, are allowed only if they can be replaced within the desired functional recovery time objective.

2.2.5 - Minimize Residual Drift
Maximum residual drift is less than 0.5% in any story in the design level earthquake.

C2.2.5 - Minimize Residual Drift
There are considerable losses associated with large residual drifts. McCormick et al. (2008) suggest an upper limit of 0.5%. In addition, ATC-58 suggests that for 0.5% residual drift, there is a negligible chance that the structure would need to be demolished. Re-alignment for residual drifts less than 0.5% is expected to be difficult and unnecessary.

Relations are available in ATC-58 (Appendix C) between peak transient drifts and residual drifts. These may be used for Response Spectrum Analysis or in lieu of residual drifts obtained from NLRHA unless

2.2 Enhanced Structural Design

Criterion | Commentary

P G S

the NLRHA results are a better indicator of residual drift.

2.2.6 - Expose Structural Elements
Expose structural elements of the lateral resisting system if they are expected to be damaged so that they are easily replaceable or repairable.

C2.2.6 - Expose Structural Elements

2.2.7 - Symmetric Design
Place walls, braced frames, or moment frames in a symmetric and regular layout and allow them to be continuous up the height of the structure.

C2.2.7 - Symmetric Design
This is particularly important for buildings which are not expected to remain elastic. This is intended to promote designs which are vertically, horizontally or torsionally regular as defined by ASCE 7

2.3 Enhanced Non-structural Design

P G S

Criterion

2.3.1 - Minimize Non-structural Damage
For non-structural components (including architectural, mechanical, and electrical components) which are expected to contribute a significant proportion of the predicted losses, design the anchorage to remain essentially elastic (for earthquake loads calculated in accordance with 2.2.2 above) *and* design the components to accommodate relative displacements (calculated in accordance with 2.2.2 above) with minimal (aesthetic) damage.

Commentary

C2.3.1 - Minimize Non-structural Damage Demands:
While it is possible that non-structural components designed to standard code requirements for conventional buildings may perform well, an additional factor of safety such as used for essential facilities seems desirable. In addition, anchorage of non-structural components is designed to be damaged (R_p) - consider using an R_p factor close to 1. The losses associated with non-structural damage calculated explicitly using fragility curves in the "Loss Assessment" have significant dispersion. Designing non-structural components for higher forces and drifts will reduce the uncertainty in the expected losses.

Performance Objectives:
The code specifies that non-structural components accommodate relative displacements but it is generally understood that damage is expected - i.e. the component should accommodate relative displacements such that it does not pose a life-safety hazard. Therefore, non-structural components should be designed to accommodate relative displacements with minimal damage instead.

Interior Partitions:
Significant losses have been associated with damaged interior partitions (Mitrani-Reiser 2007 and Mayes et al 2013). Consider designing interior partitions to meet the requirements set for exterior partitions in ASCE 7 Section 13.5.3. See Araya and Miranda (2012) for resilient gypsum wall connection details.

2.3 Enhanced Non-structural Design

Criterion

Commentary

P G S

2.3.2 - Equipment Functionality
Mechanical and electrical equipment, back-up systems, or any other mission-critical components which are needed to maintain functionality of the facility, including those located in other buildings, should be shake-table tested or otherwise to prove they would remain operable in the design level earthquake.

C2.3.2 - Equipment Functionality
This can be achieved by meeting ASCE 7 Section 13.2.2 Special Certification Requirements for Designated Seismic Systems, which is generally only required for hospitals. Components necessary for quick functional recovery objectives (Platinum and Gold) should be held to the same standard.

For Silver rated buildings, if the components are identified as "standard" (rather than long-lead time, see item 1.3.4), then testing of that component may not be required if it takes less than 6 months to procure and install a replacement post-earthquake. In other words, the component could be allowed to be damaged as long as a replacement can be found and installed before the time functionality of the facility is desired.

OSHPD provides a list of pre-approved components which have been shake-table tested here: www.oshpd.ca.gov/fdd/Pre-Approval

2.3.3 - Location of Critical Components
Locate critical mechanical/electrical equipment, back-up systems, and mission-critical contents in the lowest level of a fixed base building and above the plane of isolation in a base-isolated building if floor accelerations are expected to be lower than the Peak Ground Acceleration.

C2.3.3 - Location of Critical Components
Accelerations are generally much lower at lower levels. Locate the equipment off of the floor if storm surge or tsunami can be expected to cause flooding in the basement. This can be achieved by placing equipment on platforms above the expected flood levels.

2.3 Enhanced Non-structural Design

Criterion / Commentary

P G S

2.3.4 - Protect Facades
Facades and curtain walls are designed and tested to accommodate relative displacements (calculated in accordance with 2.2.2 above) such that connections remain elastic and the building envelope remains effective in preventing air and water intrusion. Some damage at discontinuities such as corners and transitions may be allowed provided it is easily reparable.

C2.3.4 - Protect Facades
This objective is similar to performance requirements for Essential facilities found in AAMA 501.4 (2009).

2.3.5 - Anchor Heavy Building Contents
In addition to any code requirement, heavy building contents such as tall bookshelves, storage racks, server racks, file cabinets, appliances, and mounted televisions which are a potential life-safety hazard are anchored per FEMA E-74 (2011) or equivalent.

C2.3.5 - Anchor Heavy Building Contents
Developer-owned buildings may be exempt from this requirement but could ask commercial and residential tenants to consider it via their occupancy agreements.

2.3.6 - Protect Other Building Contents
Other building contents, including valuable, mission-critical, or priceless building contents such as lab specimens, microscopes, manufacturing equipment, medical equipment, computers, artwork, data storage devices and other inventory are protected or anchored per FEMA-74 (2011) or equivalent if they are expected to be damaged if left unprotected.

C2.3.6 - Protect Other Building Contents
Developer-owned buildings may be exempt from this requirement but could ask commercial and residential tenants to consider it via their occupancy agreements.

2.4 Capacity Design

Intent:
Increase confidence in the performance of base-isolated and viscously damped buildings.

Criterion / Commentary

P G S

2.4.1 - Superstructure of Base-isolated Buildings
The superstructure of base-isolated buildings should employ *special* brace, wall, or frame systems. If they employ *intermediate* lateral systems, they are designed to remain elastic in the code-defined MCE.

NOTE: This is not required if 2.4.2 below is met.

C2.4.1 - Superstructure of Base-isolated Buildings
The code intends that buildings have a 10% probability of collapse or lower in the MCE, though it is not required to verify this objective. Studies in FEMA P-695 (2009) have shown that new fixed-base buildings generally meet this objective. Buildings which achieve a rating are likely to perform better and have a lesser probability of collapse.

However, some isolated buildings may be more susceptible to collapse than their fixed-base counterparts and this requirement is to address this issue. The California Building Code 2010 (see 1613.6.2 and 1613A.6.2) has provided some exceptions which allows less ductile lateral systems compared to ASCE 7. FEMA P-695 (2009) indicates that these would not meet the code objectives for collapse. Their studies show that if provided higher strength, they perform as intended by the code or better (see 2.4.2).

2.4.2 - Capacity of Base Isolators
Design and test isolators and provide enough moat clearance to accommodate displacements associated with 84th percentile MCE demands.

NOTE: This is not required if 2.4.1 above is met.

C2.4.2 - Capacity of Base Isolators
Isolators are generally designed and tested for mean MCE displacements, including the effects of torsion, calculated based on lower bound stiffness/friction properties. For high confidence of good performance in MCE shaking (i.e. to reduce the likelihood of impact of the rim in friction pendulum bearings, instability in rubber bearings, and/or moat impact), it may be prudent to consider the effects of ground motion variability, in particular due to the effect of pulses on near-fault sites (this is not considered in the deterministic limit

2.4 Capacity Design

Criterion

Commentary

P G S

which often governs the code-defined MCE hazard) and maximum direction response (also known as Maximum Demand) for both near and far-fault sites.

Unless a more substantiated analysis is utilized to assess the effects of pulses and/or maximum orientation at the MCE level (see Almufti et al. 2013), a reasonable approach would be to use 84th percentile Maximum Spectral Demand factors published in Table C21.2-1 of NEHRP (2009) instead of the median Maximum Spectral Demand factors which are used in ASCE 7 - 10 maps. These are based on a study by Huang et al. (2008) for near-fault ground motions but NEHRP indicates that they can be used for far-fault ground motions as well. For long periods consistent with isolated structures, the table indicates that the 84th percentile Maximum Spectral Demand is 1.9x higher than that currently used for design. It is probably reasonable to either increase the spectral demands by 1.9 or increase the calculated code-defined isolator displacements in the MCE by 1.9. These results are consistent with a report by MCEER (Huang et al 2009) which found that isolators should be designed for as much as 3x the estimated mean demands when considering best estimate properties.

2.4.3 - Capacity of Viscous Dampers
For near-fault sites, design and test viscous dampers to accommodate story drifts associated with 84th percentile MCE demands.

C2.4.3 - Capacity of Viscous Dampers
Since viscous dampers are likely oriented along the building's principal axes, they may not be subjected to the maximum direction response. However, since the code-defined MCE does not consider the effect of pulses for near-fault sites (which are often governed by the deterministic limit), it may be prudent to consider this in design by providing larger damper strokes. See 2.4.2.

2.5 Safer Egress

Intent:
Reduce the probability that egress paths are damaged to increase safety and reduce expected downtime.

Criterion

Commentary

P G S

2.5.1 - Stairs
Stair framing elements and their connections are designed and detailed to maintain support of the design dead and live loads during the expected lateral drifts of the primary structure under the code-defined MCEearthquake event with limited damage.

C2.5.1 - Stairs
The Royal Commission Report (2012) based on lessons learned from the Christchurch earthquake highlighted the failure of stairs.

ASCE 7 - 10 treats stairways as architectural components with $R_p = 2.5$ and $I_p = 1.5$. Stairways are required to be designed for the forces from ASCE Chapter 13 (Design Earthquake demands) and it is implied but not explictly stated that they should be designed for relative displacements (since failure would "pose a life-safety hazard"). ASCE 7 - 05 has no requirements for stair design.

2.5.2 - Doors
Egress doors are designed to accommodate drifts (and residual drifts) such that they remain operable following the design level earthquake.

C2.5.2 - Doors
The possibility of doors jamming due to imposed drifts may be decreased by implementing similar connection details as used for interior partitions (see C2.3.1).

2.5.3 - Elevators
Elevator design meets the California Office of Statewide Health Planning and Development (OSHPD) special requirements detailed in Section 3009 of Title 24 (CBC 2010) or equivalent.

C2.5.3 - Elevators
Damage to elevators contributes significantly to downtime and can hinder functionality of the building.

PACT fragility curves for traction elevators indicate a 15% probability of damage for PGA = 0.25g. Therefore, if the PGA at the site for the MCE is less than 0.25g, the elevator design can be relaxed from the OSHPD standards. Instead, it should meet ASCE 7 - 10 and Section 1615.10.17 and 1615.10.18 in the 2010 California Building Code (CBC 2010).

2.6 Structural Analysis

Intent:
Increase confidence in the assessment of earthquake demands on stuctural and non-structural components.

P G S

Criterion

2.6.1 - Non-linear Response History Analysis
Non-linear Response History Analysis (NLRHA) is performed for structures where plastic deformations are expected and/or where it is required to properly assess energy dissipation from mechanical devices or rocking. Otherwise it is permitted to use Response Spectrum Analysis.

Commentary

C2.6.1 - Non-linear Response History Analysis
It is probably appropriate to use NLRHA when the ductility demand is greater than 2 for design level earthquake demands using expected (mean) strength properties and no strength reduction factors.

Wood-framed buildings are excluded from this requirement.

2.6.2 - Simulation Model
The mathematical model is 3D and all structural elements which contribute strength and stiffness to the lateral system of the the structure are modeled. Structural modelling assumptions follow ASCE 7, ASCE-41, FEMA P-58, PEER/ATC-72-1, PEER-TBI, CTBUH (Willford et al. 2008), or other equivalent performance-based design guideline.

C2.6.2 - Simulation Model
Damping:
Appropriate damping ratios should be applied (i.e. lower damping levels for tall buildings, buildings which experience drifts less than 0.5%, and for damping in the vertical direction). For Response Spectrum Analysis, response spectrum is modified to account for different damping ratio.

2.6.3 - Ground Motions
If NLRHA is employed, the selection, scaling, and matching of ground motions follow the guidelines in NIST (2012), FEMA P-58 or other accepted standard. The target spectrum is based on 2.1 above.

C2.6.3 - Ground Motions
In addition, the following should be followed:

Near-Fault Directivity:
If NLRHA is employed, for near-fault sites (typically within 20km of faults capable of producing an M6.5+) an appropriate proportion of the ground motions shall include velocity pulses with an appropriate distribution of pulse periods and pulse amplitudes. See Almufti et al (2013).

Criterion | Commentary

P G S

Duration:
Assess the effects of significant duration of ground motions if applicable (e.g. for tall buildings with multiple modes, peak moment and shear demands may not coincide if the ground motion is short) and if the structure is expected to undergo significant plastic deformation by incorporating long duration motions and components in the 3D simulation model which can capture low-cyclic fatigue.

Spectral Matching:
The non-stationary characteristics of the ground motions shall be preserved and the ground motions are baseline corrected if spectral matching is used.

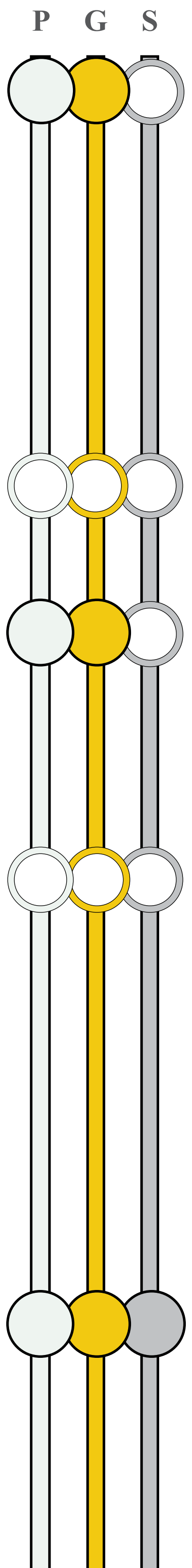
Spectral Shape:
The spectral shape of the seed motion should provide an adequate match to the target.

Kinematic Effects:
Kinematic effects are permitted but must be substantiated by a rational method such as a soil-structure interaction (SSI) analysis using continuum elements to represent the soil.. The kinematic effect in reducing the design level earthquake response spectrum in 2.1.1 is permitted.

SSI should always be employed if it increases the expected demands in the structure. See ATC-83 (report pending) guidelines.

2.7 Peer Review & Quality Assurance

Intent:
Improve structural and non-structural resilience by subjecting design and installation to scrutiny of independent experts.



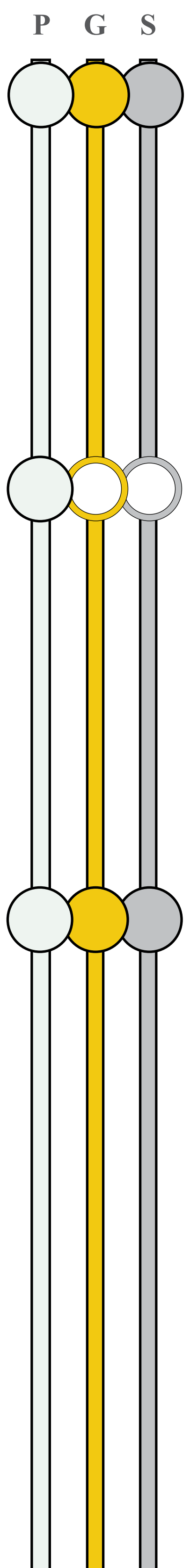
Criterion	Commentary
2.7.1 - Structural Peer Review Analysis and design is subject to formal structural peer review process and in addition: * Review of acceptance criteria for non-structural components and systems to withstand the calculated force and deformation demands * Review Resilience Plan detailed in 1.1.1 above	***C2.7.1 - Structural Peer Review*** *ASCE 7-10 Section 1.3.1.3 and Section 16.2.5 and other documents provide guidance on an appropriate scope for peer review.*
2.7.2 - Non-structural Calculations 3rd Party review of structural and non-structural component calculations.	***C2.7.2 - Non-structural Calculations***
2.7.3 - Installation of Non-structural Components Inspection instructions to verify the correct installation of non-structural components is included in the General Notes of the construction documents.	***C2.7.3 - Installation of Non-structural Components***
2.7.4 - MEP Review Design and redundancy of mechanical, electrical, and plumbing systems are peer-reviewed for conformance to the desired resilience objectives.	***C2.7.4 - MEP Review*** *This can be met by meeting Tier 3 or better of the Uptime Institute standards for Data Centers (Uptime Institute 2010).* *Peer review should focus on internal distribution strategies (such as dual distribution) that contribute redundancy to the MEP systems. Also consider enhanced commissioning to address the post-earthquake performance of MEP systems.*
2.7.5 - Design Build Components Engineer-of-record reviews all Design Build drawings and performance specification of non-structural components to ensure they conform with the performance criteria related to the desired resilience objectives.	***C2.7.5 - Design Build Components***

3.0 Ambient Resilience

3.1 Earthquake-induced Hazards

Intent:

Identify other earthquake-initiated hazards which may require mitigation.



Criterion	Commentary
3.1.1 - Design for Liquefaction Determine whether liquefaction or lateral spreading of the top 50 feet or other types of ground failure may occur in the design level earthquake using site-specific geotechnical data. If any of these failures is predicted to occur, ensure that the structural analysis accounts for these effects and demonstrate that the building and foundations are accordingly designed.	***C3.1.1 - Design for Liquefaction*** *The following guidelines may be used for liquefaction assessment: California Geological Survey (CGS 2008), Seed et al. (2003), Youd et al. (2001), and Boulanger and Idriss (2008).*
3.1.2 - High Liquefaction Hazard Building is not located on a site at which the analysis from 3.1.1 indicates that liquefaction will occur with predicted settlements of more than 6 inches or lateral spreading of more than 12 inches and surrounding buildings are generally supported by shallow foundations. Buildings that are located in rural areas or in suburban areas with heights generally less than 30 feet are exempt.	***C3.1.1 - High Liquefaction Hazard*** *While new buildings can be successfully designed to resist the effects of liquefaction, the impact on surrounding infrastructure including adjacent buildings, roads, and utilities can be extremely damaging. Platinum buildings may rely on transported back-up water and fuel for continued functionality. For that reason, site access is critical and likely debris in heavily liquefied zones could restrict site access.*
3.1.3 - Other Ground Failures If the building is located within a landslide zone or at the run-out of potential landslide, near an active fault rupture zone, avalanche zone, or downstream of a dam, the hazards are evaluated by licensed professionals and mitigation measures to prevent damage to structure or obstruction of egress are taken if required.	***C3.3.1 - Other Ground Failures*** *If the building is located on a known active fault (ruptured within the past 11,000 years), a detailed evaluation should be performed by registered engineering geologists experienced in assessing fault rupture hazards to assess the likely impact on expected earthquake performance.*

Criterion | Commentary

P G S

3.1.4 - High Tsunami Hazard

The building is not located within a tsunami inundation zone, delineated by tsunami inundation lines from available state tsunami inundation maps.

The building is permitted to be located within a tsunami inundation zone if a site-specific tsunami inundation study considering the governing earthquake scenarios determined from deaggregation of the site-specific hazard in 2.1.1 (or conservatively, from maximum credible earthquake scenarios from local/regional and/or distant faults), result in less than 1m of inundation depth (at mean higher high water) at the site and the ground floor level is above the inundation depth. Other mitigation measures should be taken to limit damage. No critical equipment should be located below inundation depth. Tsunami evacuation strategies should be practiced.

C3.1.4 - High Tsunami Hazard

While individual buildings can be designed to withstand tsunami effects, the impact on the surrounding area would likely be devastating. In addition, governments may not fund improvement projects in high tsunami zones. For example, the The Oregon Resilience Plan (2013) does not set targets to improve some infrastructure in the coastal tsunami zone, leaving those areas significantly more vulnerable. For these reasons, buildings can not receive a Platinum rating if they are located in a high tsunami zone.

California

California published tsunami inundation maps in 2009, available at: http://www.conservation.ca.gov/cgs/geologic_hazards/Tsunami/Inundation_Maps/Pages/Statewide_Maps.aspx. The maps represent the "maximum considered tsunami runup from a number of extreme, yet realistic, tsunami sources" including local and distant sources.

Oregon

Oregon published tsunami indundation maps in 1995 under Senate Bill 379 which limit construction of essential facilities in designated tsunami zones. These are available at: http://www.oregongeology.org/tsuclearinghouse/pubs-regmaps.htm. These maps consider only a large Cascadia Subduction earthquake (Mw 8.8 to 8.9) but run-up was assumed no less than that predicted for distant tsunamis with a 500 year recurrence or for historic distant tsunamis (Priest 1995). The maps are expected to be updated in 2014.

Washington

3.1 Earthquake-induced Hazards

Criterion | Commentary

P G S

Washington publishes various maps for some locations based on various earthquake scenarios, available at: http://www.dnr.wa.gov/Publications/ger_tsunami_inundation_maps.pdf. In general, they delineate zones which indicate inundation depth. The yellow zones (0.5m to 2m) should be considered high hazard.

General

See FEMA 646 for more information on available maps and for performing a tsunami hazard assessment.

Areas affected by tsunamis are not limited to CA, WA, and OR. Alaska, Hawaii, and parts of the east coast are also affected and available tsunami maps should be sought.

3.1.5 - Assessment of Surrounding Buildings

The engineer or other qualified professional provides a qualitative assessment of the earthquake performance of any adjacent buildings (including those close enough that potential falling debris could block site access) by the Rapid Visual Screening scoring methodology contained in FEMA-154 and potential impact on the rated building. This is documented and provided to the Owner. Buildings located adjacent to single family homes are excluded. The performance of any non-building structures should also be qualitatively assessed.

C3.1.5 - Assessment of Surrounding Buildings

The assessment should include qualititative assessment of external falling hazards and fire hazard when subject to the design level earthquake.

Buildings in dense urban settings are more susceptible to downtime caused by externalities such as adjacent building damage. This was evidenced in Christchurch, NZ where the Central Central Business District was cordoned off, restricting access to many undamaged buildings (EERI, 2011).

3.1.6 - High Hazard from Surrounding Buildings

The building is not adjacent to a building (or other structures) with major structural deficiences which may indicate likelihood of collapse, unless there is an established plan to demolish or retrofit the building or other

C3.1.6 - High Hazard from Surrounding Buildings

The Rapid Visual Inspection of FEMA 154 can not result in a score S less than or equal to 2.0.

3.1 Earthquake-induced Hazards

Criterion | Commentary

P G S

mitigation measures are taken.

3.1.7 - Assessment of Surrounding Non-building Structures
Identify any non-building structures located on the site which may compromise the resilience objectives of the facility if damaged and pursue migitation measures if required.

C3.1.7- High Hazard from Surrounding Buildings
This may include water tanks, heavy light posts, traffic lights, and retaining structures.

3.1.8 - Fire Sprinklers
Fire sprinklers are installed in accordance with ASCE 7 - 10 or equivalent, regardless of building height.

C3.1.8- Fire Sprinklers
ASCE 7 - 10 requires fire sprinklers for buildings of certain height. The recommendation here is to install fire sprinklers even in shorter buildings.

4.0 Loss Assessment

4.1 General Assessment Guidelines

Intent:

Ensure that the Loss Assessment is performed appropriately to most accurately estimate direct financial loss and downtime.

P G S

Criterion	Commentary
4.1.1 - Guidelines for Loss Assessment	***C4.1.1 - Guidelines for Loss Assessment***
* The *expected* loss results (50% probability of non-exceedance) are used as a minimum.	
* Loss calculations are performed using actual amount and location of damageable structural and non-structural components and contents where possible. Use 90% values provided in FEMA P-58 to estimate quantities if fit-out design is unknown at the time of the assessment.	
*Unattached building contents in residential buildings do not need to be included.	
* The assessment is performed for building demands resulting from analyses based on the 10% in 50 year hazard defined in 2.1. It is permitted but not necessary to calculate the losses using the code-defined Design Earthquake if it is higher than the hazard defined in 2.1.1.	
* Rugged components and contents as defined by FEMA P-58 Appendix I and the California Office of Statewide Health Planning and Development (OSHPD) CAN 2-1708A.5 do not need to be included. Other published literature, testing, or engineering judgment may be used to prove that a particular component is rugged.	** Rugged components are those components that are not expected to be damaged.* *See http://www.oshpd.ca.gov/FDD/Regulations/CANs/2007/2-1708A.5%20rev2.pdf for OSHPD CAN*
* Where the default fragility curves and consequence functions are not provided for a particular component or would not provide an adequate representation of the expected damage and consequence, they should be developed based on FEMA P-58 or obtained from peer-reviewed literature. The damage	

4.1 General Assessment Guidelines

Criterion

Commentary

P G S

indicated by the fragilities used for structural components should align with the level of damage indicated from the NLRHA.

* The PACT analysis should consider enough realizations such that the calculated loss does not vary by more than 5% when the number of realizations is increased.

* Use minimum dispersion factors per FEMA P-58 to model uncertainty in demands.

* Residual drift does not need to be considered since 2.2.5 limits the allowable residual drift.

4.2 Direct Financial Loss Assessment

Intent:

Evaluate the success of the resulting design in meeting the quantitative financial loss objectives associated with the desired REDi Rating.

Criterion

Commentary

P G S

4.2.1 - Direct Financial Loss Assessment
Direct financial loss is calculated by PACT where the losses are expressed as the repair cost divided by the Total Building Value (see Glossary of Terms).

This does not consider indirect financial loss such as business interruption.

C4.2.1 - Direct Financial Loss Assessment
The consequences in PACT for repair costs associated with severe damage (i.e. damage that would require replacement) to a particular component should reflect at minimum the original hard costs for that component. The consequence function should be adjusted if necessary.

4.2.2 - Valuable Building Contents
Where valuable building contents - including medical equipment and machines, servers, desktop electronics, art installations, and inventory - exceed more than 10% of the Total Replacement Value, they must be included in the Loss Assessment.

C4.2.2 - Valuable Building Contents

4.3 Downtime Assessment

Intent:

Evaluate the success of the resulting design and planning measures taken in meeting the quantitative downtime objectives associated with the desired REDi Rating.

P G S

Criterion	Commentary
4.3.1 - Downtime Assessment Use the "Downtime Assessment Methodology" contained in A4.3 to estimate the time to re-occupy the building and to achieve functional recovery (see Glossary of Terms).	***C4.3.1 Downtime Assessment***
4.3.2 - Impeding Factors Delays to initiation of post-earthquake repairs caused by 'impeding factors' - inspection, access to financing, engineering review or re-design, contractor mobilization, and permitting - are quantified based on estimates provided in the section "Downtime Due to Delays" in A4.3.	***C4.3.2 Impeding Factors*** *The benefit from implementing Recommendations to minimize the 'impeding factors' (see Section 1.3 for details) may be applied.*
4.3.3 - Utility Disruption Utility disruption must also be accounted in the downtime associated with functional recovery but a cap for Gold and Silver rated buildings may be employed). Utility disruption estimates are provided in the section "Downtime Due to Utility Disruption" in A4.3.	***C4.3.3 Utility Disruption*** *See also C1.2.1.*
4.3.4 - Long-lead Time Items The time associated with procuring any "long-lead time" components are included in the downtime calculations if they are expected to be damaged.	***C4.3.4 Long-lead Time Items*** *See 1.3.4 and A4.3 for more details.*
4.3.5 - Critical Building Contents Building contents, which if damaged, would hinder re-occupancy or functional recovery must be included.	***C4.3.5 Critical Building Contents*** *See also 2.3.5.*

A4.3 Downtime Assessment Methodology

Sean Merrifield and Ibrahim Almufti

INTRODUCTION

Despite the substantial consequences of downtime, the engineering community has struggled to develop a realistic downtime estimation method for individual buildings due to the overwhelming number of interdependent variables which need to be considered, the inherent uncertainties associated with each of those variables, and the lack of data that underlie robust estimates for how each of those variables contribute to downtime. The methodology provided herein is intended to provide a rational basis for estimating downtime for an individual facility, in light of the highly uncertain nature of such estimates, and to identify the specific and likely causes of downtime which can be mitigated in order to achieve the resilience objectives associated with the desired REDi™ Rating. Even though REDi™ rated buildings are designed to sustain minimal damage, the methodology also includes procedures to estimate downtime for conventionally-designed buildings which may be significantly damaged, allowing decision-makers to directly compare the benefits of resilience-based design.

MOTIVATION

FEMA (FEMA P-58) has recently published a methodology to quantify seismic risk in terms of losses for individual buildings. It represents a step-change for the assessment of site-specific facility risk because it allows users to identify specific building components which contribute the most significant proportion of losses through a large library of fragility curves and consequence functions. A Performance Assessment Calculation Tool (PACT) is included to facilitate the loss assessment. While FEMA P-58 provides estimates of direct financial loss and repair time due to earthquake damage, it does not calculate the facility's downtime which may be much longer than the repair time. There are several significant limitations to the FEMA P-58-based assessment in relation to calculating downtime which must be addressed:

- The repair time estimates are based on potentially unrealistic labor allocation and repair sequence logic.
- Repair time estimates are associated with the time required to achieve full recovery. However, most owners are primarily concerned with the time required to re-occupy the building and/or the time required to regain functionality.
- FEMA P-58 does not account for delays that prevent the initiation of repairs ('impeding factors' such as the time it takes to inspect the building, access financing, find and mobilize contractors/ engineers, and permitting) which could represent the largest contributor to downtime.
- FEMA P-58 does not account for the disruption to utilities.

The methodology described herein attempts to address these limitations by building on the FEMA P-58 damage state and repair time estimates as a basis for predicting downtime. Specifically, we provide:

- Definition of 'Repair Classes' which describe whether the extent of damage to and criticality of various building components will hinder achievement of specific recovery states like re-occupancy, functional recovery, and full recovery.

- A modified approach for allocating labor and sequencing repairs based on data from RS Means (Reed Construction Data Incorporated 2013) and anecdotal evidence from contractors and cost estimators.
- Estimates of delays to initiation of repairs ('impeding factors') based on lessons from past natural disasters and expert opinion.
- Estimates of utility disruption for electricity, water, and gas based on data from past earthquakes and predicted regional disruptions for hypothetical future earthquake scenarios published by experts.
- Sequential logic for calculating the time required to achieve re-occupancy, functional recovery and/or full recovery due to 'impeding factors', utility disruption, and building repairs (i.e. these must be considered in the order they will be initiated and completed).

Note that 'impeding factors' and utility disruption are 'controllable' in the sense that they can be mitigated by following the requirements and recommendations in Sections 1.0 and 3.0 (e.g. back-up systems can mitigate loss of functionality due to utility disruption). The methodology does not attempt to quantify downtime caused by some 'uncontrollable' externalities which include hazards from adjacent buildings, restricted site access, and availability of employees to return to work. Instead, these risks are intended to be minimized as much as possible by achieving the requirements (for Platinum) and recommendations (for Gold and Silver) in Sections 1.0 and 3.0.

The estimates for downtime do not consider damaged buildings that may need to be upgraded to a current code level to comply with the local jurisdictional requirements. This methodology may be used as a basis for calculating downtime in developed regions outside the United States but the user is cautioned as to the extent which FEMA P-58, the 'impeding factors' which delay repairs, and the utility disruption estimates are applicable. The methodology is applicable to almost all building types, occupancies, and functions.
The following terminology is used extensively throughout the paper:

- *Component type*: refers to groups of various building components including structural elements, pipes, HVAC ducts/drops, interior partitions, ceiling tiles, exterior partitions, cladding/glazing, mechanical equipment, electrical systems, elevators, and stairs.
- *Component*: refers to a sub-class of a component type category which provides more detail, such as cold water pipes (2.5" or less) or full-height gypsum board partitions.
- *Performance groups*: PACT uses this term to describe components which will experience the same demands depending on its location in the building. For example, full-height gypsum board partitions on the 2nd floor in the North-South direction are one performance group.

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- *Unit*: the quantity of measurement for each component. For example, piping units are measured in increments of 1000 linear feet (lf). Mechanical equipment is measured in number of units.
- *Quantity*: indicates the number of units. For example, 3 piping units is equivalent to 3,000 linear feet.

DEFINING DOWNTIME RECOVERY STATES

It is important to associate 'downtime' to a specific recovery state. Bonowitz (2011) identified three key milestones in a building's recovery timeline: re-occupancy, functional recovery, and full recovery. Our definitions for achieving these three recovery states are described in more detail below. The method described herein intends to estimate the time it takes to achieve one or more of these specific recovery states for the entire facility.

Re-occupancy can occur when the building is deemed safe enough to be used for shelter.

If damage is apparent, this typically requires an inspection (ATC-20) which the jurisdiction will undertake at the request of the Owner. Re-occupancy can occur once a Green Tag is awarded following inspection by a qualified professional on the basis that any damage to structural and non-structural components is minor and does not pose a threat to life safety and if egress paths are undamaged (ATC-20). If 'life-safety' hazards to occupants (which may include significant structural damage, exterior falling hazards due to damaged cladding and glazing, interior hazards from damaged components hung from the floor above or severely damaged partitions, or all of the above) are evident, the must be removed or repaired before a Green Tag is awarded. A Green Tag allows unrestricted access and re-occupancy to all portions of the building. Clean-up and/or minor repairs to some non-structural components (such as fallen ceiling tiles) by unskilled personnel may be required so as not to impede egress in some areas of the building.

If visible damage is minor, the Owner could decide to forego inspection, allowing the building to be re-occupied almost immediately after the earthquake at his/her discretion. This is the scenario assumed by REDi™ for buildings that are predicted by the "Downtime Assessment" in Section 4.3 to suffer only aesthetic damage (Repair Class 1 or less). However, since occupants of a building may also submit a request for inspection after an earthquake (even in the event of minor damage), it is recommended that the Owner retains a qualified professional to perform post-earthquake inspection (see 1.3.1) to avoid long delays associated with inspections performed by the jurisdiction. The jurisdiction also has the power to require inspection if they feel it is necessary, but it is unlikely to be initiated if the damage is minor.

Re-occupancy can occur before functionality is restored. In this case lighting, heating/air-conditioning, and water may not be available so the use of flashlights, blankets/heavy clothing, operable windows, bottled water and some form of waste disposal may be needed. Re-occupancy of multi-story buildings can occur provided stairs provide safe egress from higher floors; elevators are not necessarily required to be operable but in this case patients or the elderly would need assistance accessing higher floors. Though some discrete portions of a building may be re-occupied before others (i.e. "Yellow Tagged", see Glossary of Terms), the re-occupancy objectives in REDi™ are associated with the time to re-occupy the entire building.

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Functional recovery represents the time required to establish re-occupancy and regain the facility's primary function (it is analogous to 'operational' or 'operable' in some building codes). For all occupancy types, this would require restoring power, water, fire sprinklers, lighting, and HVAC systems while also ensuring that elevators are back in service. Back-up systems may also be used in the interim to provide a pre-defined state of functionality agreed by the Owner (potentially at reduced capacity, see "Back-up Systems" in Glossary of Terms) until the municipal utilities are restored and able to provide resources for full capacity. For example, the capacity of back-up power required while utilities are disrupted could be based on operating the lighting for a reduced number of hours or keeping the temperature within a broader but reasonable range than typical 'normal' conditions.

In residences, functional recovery is related to regaining occupant comfort and livable conditions – the lights are on, water flows, heating and air conditioning are operating. Functional recovery also indicates the time required for resumption of specific functions particular to a certain occupancy. Examples include emergency services and typical services in hospitals, business activity in offices and retail, or classes in educational facilities.

Repairs to prevent deterioration of the building (such as sealing leaky pipes for mold prevention or making sure the building envelope is weatherproof) must also be completed.

Full recovery follows functional recovery when repairs required primarily for aesthetic purposes (such as painting cracked partitions) restore the building to its original pre-earthquake condition. Since these repair measures are minor and do not hinder building function, they could be undertaken at a time best suited to the owner and occupants. For that reason, it is not included as a REDi™ baseline resilience objective.

BACKGROUND: FEMA P-58 REPAIR TIME ESTIMATES

The downtime estimation method proposed here is based on FEMA P-58, so a brief overview of the FEMA P-58 methodology will be presented first. The project was a significant 10-year effort funded by FEMA to develop a framework for performance-based seismic design and risk assessment of individual buildings. The FEMA P-58 framework is outlined in Figure 1.

PACT is the companion software to FEMA P-58 which estimates losses from damage to the structure, non-structural components, and building contents. PACT is available for free download at www.atcouncil.org. PACT uses fragility curves which relate the probability that various building components will sustain a particular severity of damage (called a damage state) to engineering demand parameters (EDP) such as peak floor accelerations and story drifts (determined from structural analysis). These damage states (DS) are then correlated to decision variables (DV) such as casualties, repair costs, and repair time using consequence functions. Thus, in order to appropriately capture the extent of losses, all structural components, non-structural components, and building contents that may significantly contribute to these DVs need to be identified and included in the PACT analysis model. Each building component has

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its own unique fragility curve, and each damage state within the fragility curve has a unique consequence function associated with it.

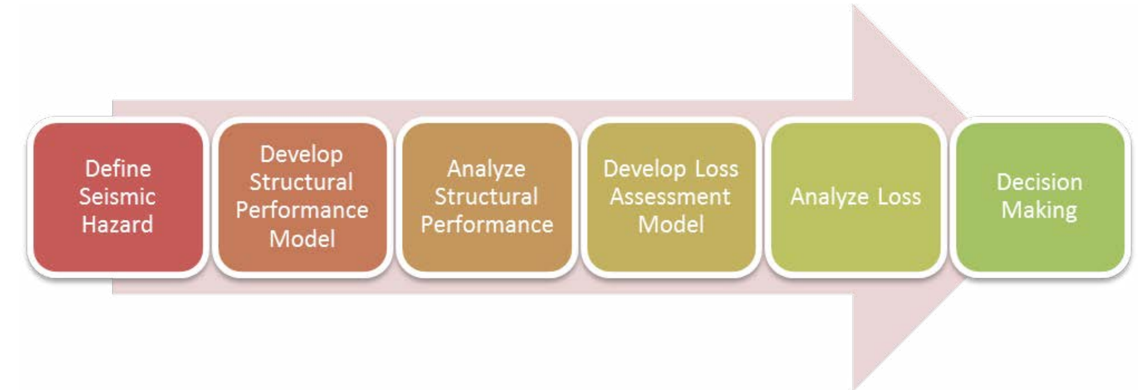

Figure 1. FEMA P-58 performance-based seismic assessment process

An example fragility curve is shown on the left of Figure 2. Each curve represents a possible DS of that component, where the damage extent is generally reflected by the DS number (i.e for a component with three damage states, DS1 is minor damage, DS3 is extensive damage). Some fragilities only have one damage state; in this case, the damage state usually represents failure or inoperability of that component. For a given level of EDP (in this case story drift), the probability that the building component is in a certain damage state (DS) is assessed. Using Figure 2 as an example, at 4% story drift, there is an 80%, 50% and 26% probability that damage would have exceeded the damage corresponding to DS1, DS2, and DS3, respectively (FEMA, 2013a) . Another way of interpreting the fragility curve is that there is a 26% probability that the component is in DS3, 24% probability that it is in DS2 (50% minus 26%), 30% probability that it is in DS1 (80% minus 50%) and a 20% probability that the component is undamaged.

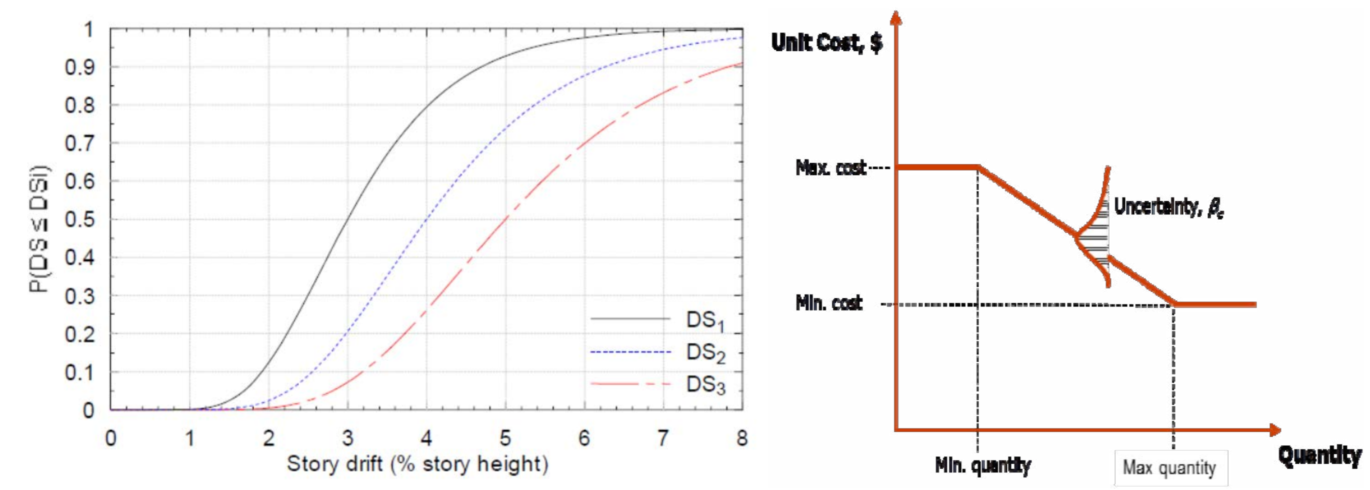

Figure 2. Example PACT fragility curve (left) and consequence function (right) (FEMA, 2013a)

The losses resulting from the repair of damaged components in each damage state is calculated through a consequence function, shown on the right of Figure 2. It expresses the unit cost to repair each component as a function of the quantity of each component which requires repair; this is a reflection of the increased efficiency of labor when working with larger quantities. Although the unit cost is expressed in financial terms here, it can be expressed in other loss parameters as well, such as repair time (in this case, the number of ‘worker-days’ required to repair a damaged component). The losses are determined by multiplying the number of components within each damage state by the corresponding unit costs given in the consequence function.

These calculations are performed using a large number of simulations (Monte Carlo) to represent uncertainty in the ground motion characteristics, modeling assumptions and structural response, damage state, and consequence function. One of these simulations is referred to as a ‘realization’. The losses from each realization are aggregated to determine a total loss for the building. These distributions are expressed in probabilistic terms such that the user can report losses based on probability of non-exceedance (typically reported as 50% (expected) and 90% (probable maximum) values, which are often casually referred to as confidence levels). More detailed information on the loss assessment process can be found in FEMA P-58 (FEMA, 2013a).

PACT REPAIR TIME

PACT provides the required repair time for each type of damaged component on each floor in terms of ‘worker-days’. The process for obtaining this information is outlined in Table 1 and Figure 3 which will be necessary to perform the downtime calculations presented below in “Downtime Due to Repairs”.

The total repair time estimates are computed by dividing the total number of ‘worker-days’ per floor by the number of workers allocated to each floor (based on square footage) and then repairs across all floors are assumed to occur either simultaneously (all floors repaired in parallel), or only once the repairs on another floor are completed (all floors repaired in series), starting from the lowest level. The difference in repair time estimates for a parallel vs. series assumption can be significant. For instance, the parallel estimates may be in the order of months, and the series estimates may be in the order of years, depending on the number of floors in the building. The results diverge as the number of stories increase. This large range between the lower and upper bounds is not useful for decision making or contingency planning. An alternative method was sought to address these limitations.

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Table 1. Instructions for disaggregating PACT repair time data

1.	Click on the ‘Examine Results’ tab on the PACT Control Panel, then ‘Data Drill Down and Exports’ tab.
2.	Select ‘I prefer one file for all the data’ and then click on ‘Export Repair Times’. This will create a spreadsheet of repair times for each building component, as a function of floor level, direction, and each realization.
3.	Add direction 1 and 2 repair time values for each drift-sensitive component for each realization.
4.	Obtain median (or desired probability of non-exceedance) loss for each component at each floor level.
5.	At this point the data has been filtered such that repair times are displayed for each component at each floor level only.

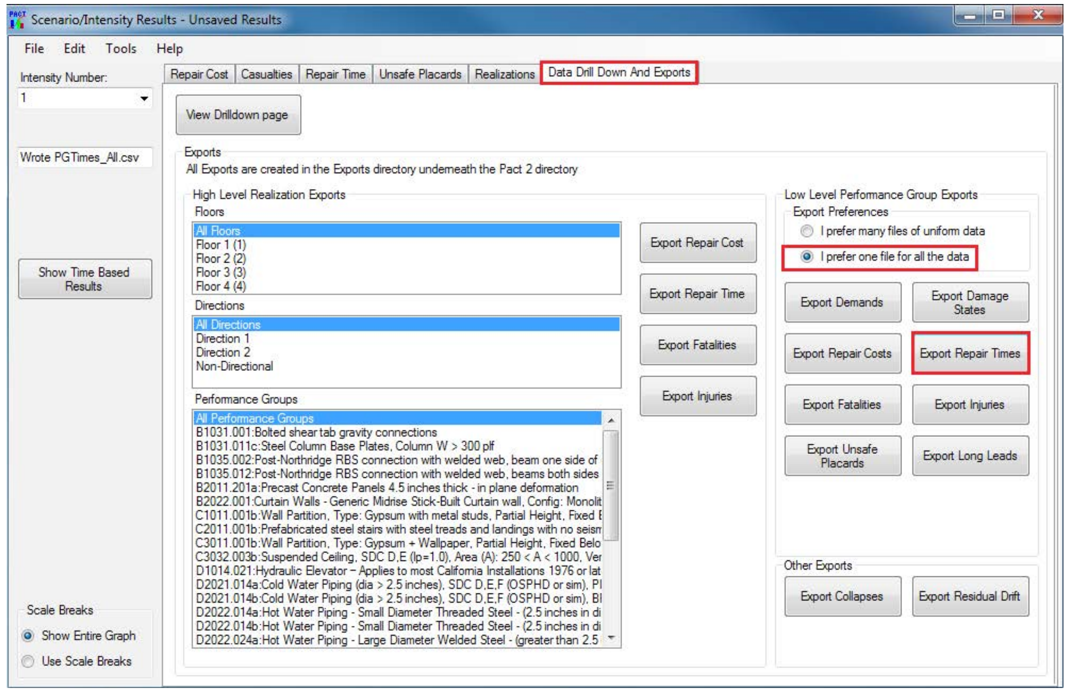

Figure 3. Disaggregating repair time data from PACT

AVERAGE DAMAGE STATES FOR EACH BUILDING COMPONENT

The methodology presented below incorporates the use of average damage states ($\overline{DS}$). The average damage state ($\overline{DS}$) weights the number of components that are damaged on a particular floor in a particular direction (i.e. performance group) against the extent of their damage, calculated using the following equation (FEMA, 2013a):

$$\overline{DS} = \frac{\sum_{i=1}^{n} i \cdot DS_i}{n}$$

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Where DS_i represents the quantity of a component in the ith damage state on a particular floor in a particular direction, and n is the total number of components on that floor in that direction. To illustrate this calculation, say there are 10 braces on a particular floor level in the North-South direction, where there are 2, 5, 3 braces in DS1, DS2, and DS3, respectively. The average damage state for the braces in the North-South direction at that floor level is:

$$\overline{DS} = \frac{\sum_{i=1}^{n} i \cdot DS_i}{n} = \frac{(1 \cdot 2) + (2 \cdot 5) + (3 \cdot 3)}{10} = 2.1$$

Although the distribution of damage is lost when calculating the average damage state ($\overline{DS}$), it provides a reasonable indication of the extent of damage for a certain component at a particular floor level. Unfortunately, this parameter is not normalized across all components, since components with 3 levels of damage would have a maximum of 3, whereas components with only 1 damage state would have a maximum state of 1. Therefore, components with 3 damage states indicate extensive damage around ($\overline{DS}$) = 3, whereas components with 1 level of damage would indicate extensive damage around an ($\overline{DS}$) = 1. This necessitated the need to define 'Repair Classes' which are defined below.

The procedure for obtaining average damage state values for each component type at each floor is outlined in Table 2.

Table 2. Instructions for disaggregating PACT average damage state data

1. Click on the 'Examine Results' tab on the PACT Control Panel, then 'Data Drill Down and Exports' tab.
2. Select 'I prefer one file for all the data' and then click on 'Export Damage States'. This will create a spreadsheet of average damage states ($\overline{DS}$) for each building component, as a function of floor level, direction, and each realization.
3. Take maximum of direction 1 and 2 for the average damage state values for each drift-sensitive component for each realization, since the more severely damaged component would govern the repair on that floor.
4. Obtain median (or desired probability of non-exceedance) loss for each component at each floor level.
5. At this point the data has been filtered such that average damage states are displayed for each component at each floor level only.

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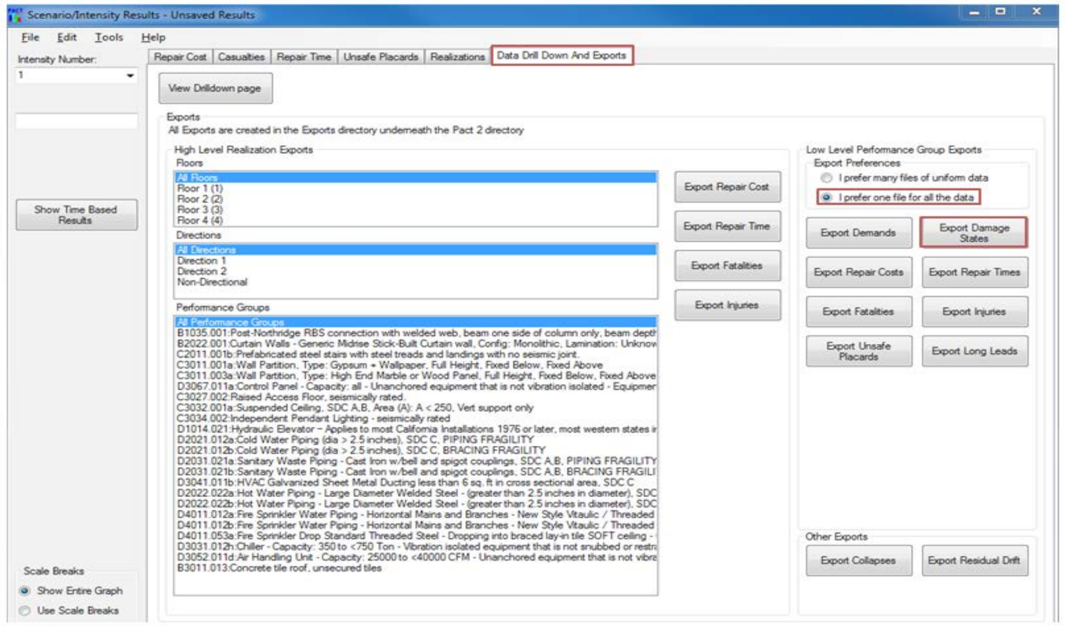

Figure 4. Disaggregating average damage state data from PACT

DEFINING REPAIR CLASSES FOR DAMAGE ASSESSMENT

In order to calculate downtime associated with achieving specific recovery states, we introduce a parameter called 'Repair Class'. Repair Classes describe whether the extent of damage to each component (measured by the average damage state for that type of component) would hinder specific recovery states. In addition, Repair Classes are used to help determine the extent of delays to initiation of repairs ('impeding factors') which are described below in "Downtime Due to Delays". The definition of the Repair Classes is provided in Table 3 and the logic for assigning a Repair Class to each component in PACT is described in more detail below. If user-defined fragilities are included, the Repair Class assignment for these components is left to the user's judgment but must be based on the same logic as described here.

Repair Classes were assigned to all of the default components in PACT's fragility database, shown in Table 4 and Table 5 (along with the description of each damage state for each type of component) for structural and non-structural components, respectively. Some components may require long-lead times if replacements need to be procured (see 'Downtime Due to Delays' below) - these are indicated with (LL) in Table 4 and Table 5. Long-lead items were identified from PACT's fragility database, but others were indicated as long-lead based on the author's judgment. Therefore, the user is encouraged to confirm that long-lead times are in fact required for these components and to confirm that they are not needed for any other components.

For *structural* components, the Repair Class is determined based on whether the extent of damage described by the damage state would hinder re-occupancy or not. That is, if the damage described poses a life-safety hazard or would likely result in a "Yellow Tag" (see Glossary of Terms) or worse as defined by ATC-20, it is assigned Repair Class 3. This may also include damage that may not necessarily indicate significant

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deterioration of lateral strength (such as spalling of a well confined concrete member). Otherwise, they are assigned to Repair Class 1 (cosmetic damage) since damaged structural components would never only hinder functionality (Repair Class 2).

For *non-structural* components, the Repair Class is also determined based on whether damage to that component is severe enough to pose a 'life-safety' hazard. In that case, it is assigned Repair Class 3. Otherwise, it may be assigned to Repair Class 2 if damage to that component would hinder functionality (e.g. damaged HVAC equipment) or Repair Class 1 if the damage is only cosmetic (e.g. cracked partitions).

Table 3. Repair Class Definitions

Repair Class	Repair Description
3	Heavily damaged *structural* or *non-structural* components which pose a risk to 'life-safety' and must be repaired to achieve **Re-occupancy**. Consequently, these components must also be repaired to achieve Functional Recovery and Full Recovery, since by definition they follow Re-occupancy.
2	Damaged *non-structural* components which do not pose a 'life-safety' risk or otherwise hinder Re-occupancy but must be repaired to achieve **Functional Recovery**. Consequently, the component must all be repaired to achieve Full Recovery, since by definition it follows Functional Recovery.
1	Minimal or minor cosmetic damage to *structural* or *non-structural* components which do not hinder Re-occupancy or Functional Recovery but must be repaired to achieve **Full Recovery**.

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Table 4. Assigned Repair Classes for structural components in PACT

Component	Average Damage State ($\overline{DS}$)			DS Description		DS Consequences	
	$0 < \overline{DS} \le 1$	$1 < \overline{DS} \le 2$	$\overline{DS} \ge 2$				
Steel							
Post-Northridge Moment Connections	3	3	3	DS1	Local beam flange and web buckling	DS1	Heat straightening of buckled web and flange
				DS2	DS1 plus lateral torsional buckling in hinge region	DS2	Remove and replace portion of beam
				DS3	Low cycle fatigue fracture in buckling region of RBS	DS3	Same as DS2
Non-BRB Braces (Seismic)	1	3	3	DS1	Brace buckling has initiated but does not exceed brace depth. Initial yielding in gusset place and adjacent framing.	DS1	Heat straightening of brace and gusset (largely for aesthetic reasons)
				DS2	Brace buckling beyond brace depth. Out-of-plane deformation of gusset, cracking at gusset welds, yielding of adjacent beams and columns.	DS2	Replacement of braces and gusset is likely required, and possible straightening of adjacent beams and columns.
				DS3	More severe case of DS 2	DS3	Same as DS 2
Non-BRB Braces (Non-seismic)	3			DS1	Fracture of brace or gusset. Buckling of gusset. Yielding and local buckling of adjacent beams and columns.	DS1	Replacement of braces and gusset. Straightening of adjacent beams and columns.
BRB Braces	3 (LL)			DS1	Fracture of brace or gusset. Buckling of gusset. Yielding and local buckling of adjacent beams and columns. Severe loss of lateral resistance.	DS1	Replacement of braces and gusset. Straightening of adjacent beams and columns.
Gravity Connections	3	3	3	DS1	Yielding of shear tab and elongation of bolt holes, crack initiation around bolt holes or shear tab weld.	DS1	Welded repair to any cracks, replacement of shear tabs if deformations are excessive.
				DS2	Partial tearing of shear tab or bolt shear failure.	DS2	Welded repair or full replacement of shear tab, installation of new bolts.
				DS3	Complete separation of shear tab	DS3	Full replacement of shear tab, installation of new bolts
Column Base Plates	3	3	3	DS1	Crack initiation at fusion line between column flange and base plate weld.	DS1	Partial removal of grade slab, gouging out material around weld and re-welding, and repair of grade slab.
				DS2	Propagation of crack into column and/or base plate.	DS2	Partial or full replacement of base plate.
				DS3	Complete fracture of column (or column weld) and dislocation of column.	DS3	Replacement of entire base plate assembly and most of column in the story above the base plate.
Column Splices	3	3	3	DS1	Cracking of weld at flange splice	DS1	Welded repair to cracks.
				DS2	Failure of web splice plate and dislocation of column segments	DS2	Realignment or replacement of column segments and rewelding of splice (repair may not be feasible).
				DS3	More severe case of DS 2	DS3	If feasible, repair would involve replacement of column base plate and most of column above.
Concrete							
Moment Frame B-C Joints	1	3	3	DS1	Beams or joints exhibit residual crack widths < .06 in	DS1	Patch residual cracks
				DS2	Residual crack widths > .06 in plus spalling of concrete which exposes beam and joint transverse reinforcement only.	DS2	Shore damaged members at least 1 level below, patch spalled concrete and cracks.
				DS3	Residual crack widths > .06 in plus spalling of concrete which exposes beam and joint transverse reinforcement only.	DS3	Shore damaged members at least 1 level below (more levels may be required), remove and replace damaged components.
Slender Shear Wall	3	3	3	DS1	Spalling of cover, vertical cracks greater than 1/16 in.	DS1	Epoxy inject cracks and patch spalled concrete.
				DS2	Exposed longitudinal reinforcing	DS2	Shore wall and replace concrete.
				DS3	Concrete core damage, buckled/fractured reinforcing, web failure, bond slip	DS3	Shore and replace wall or reinforce with R/C jacket if possible. Replace reinforcing.
Squat Shear Wall	1	3	3	DS1	Cracks with max. widths > .04in but < .12in	DS1	Patch residual cracks
				DS2	Crack widths > .12in, crushed core concrete, and buckling of vertical rebar	DS2	Inject grout, remove and recast damaged sections of wall, replace buckled rebar.
				DS3	Crack widths > .12in, sliding of wall resulting in large residual displacement, fracture of rebar	DS3	Remove damaged wall in 5ft lengths. Replace rebar.
Floor Slabs	3	3		DS1	Yielding of flexural reinforcement has initiated,large residual crack widths, possible spalling of concrete.	DS1	Patch residual cracks and spalled concrete
				DS2	Punching occurs, causing significant concrete spalling	DS2	Shore damaged area for two stories below, remove concrete without removing reinforcement, lap splice new rebar, recast concrete. If shear reinforcing was provided, epoxy inject cracks and fabricate new column capital underneath the slab.
Link Beams	1	3	3	DS1	Crack widths less than 1/16in. Cracks mainly at beam to wall interface, limited flexural cracking.	DS1	Epoxy inject cracks.
				DS2	Residual cracks greater than 1/8in, minor spalling of concrete.	DS2	Epoxy inject cracks, replace spalled concrete.
				DS3	Buckling or fracture of diagonal reinforcing, crushing of conrete.	DS3	Replace damage or fractured reinforcing. Replace damaged concrete.
Timber							
Shear Wall (Gyp. Board)	3	3	3	DS1	Slight separation of sheathing or nails which come loose	DS1	Replace loose nails, reinstall siding.
				DS2	Permanent rotation of sheathing, tear out of nails or sheathing.	DS2	Remove sheathing and install new ones. Reinstall siding.
				DS3	Fracture of studs, major sill plate cracking.	DS3	Remove and replace siding, sheathing, studs and plates.
Shear Wall (Stucco)	1	3	3	DS1	Cracking of stucco.	DS1	Fill cracks with cement compound and repaint.
				DS2	Spalling of stucco, separation of stucco and sheathing from studs.	DS2	Patch spalled areas with stucco and repaint.
				DS3	Fracture of studs, major sill plate cracking.	DS3	Remove and replace studs, plates, sheathing, and stucco.
Braces	3			DS1	Failure of diagonal bracing.	DS1	Replace sheathing studs, plates, bracing.
Masonry							
Slender Reinforced Wall	1	3	3	DS1	Few flexural or shear cracks with hardly noticable residual widths. Slight yielding of vertical reinfrocement.	DS1	Patch cracks and paint each side.
				DS2	Numerous flexural and shear cracks with residual widths < 1/64in. Mild crushing or spalling at wall toes. Small residual deformation.	DS2	Patch spalls with grout, epoxy injection for cracks, and paint each side.
				DS3	Severe flexural cracks with crack widths < 1/32in. Severe toe crushing or spalling. Fracture of buckling or buckling of vertical reinforcement. Large residual deformation.	DS3	Shore, demolish existing wall, construct new wall.
Squat Reinforced Wall	1	3		DS1	Cracks remain closed with hardly noticable residual cracks after load removal.	DS1	Grout wall, epoxy injection, paint each side.
				DS2	Wide diagonal cracks, crushing or spalling at wall toes.	DS2	Shore, demolish existing wall, construct new wall.

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Table 5. Assigned Repair Classes for non-structural components in PACT

Component	Average Damage State ($\overline{DS}$) $0 < \overline{DS} \le 1$	$1 < \overline{DS} \le 2$	$\overline{DS} \ge 2$	DS Description	DS Consequences	Repair Class Logic
Cladding/Glazing						
Glazing	2	3 (LL)	3 (LL)	DS1 Gasket seal failure.	DS1 Remove glass panel and replace damaged gaskets.	DS1 Not a hazard to occupants, but building enclosure is comprimised and inhibits building functionality.
				DS2 Glass cracking	DS2 Replace cracked glass panel.	DS2 Cracked glass is a hazard to occupants.
				DS3 Glass falls out	DS3 Replace cracked glass panel; cover exposure in meantime.	DS3 Broken glass is a hazard to occupants.
Architectural Cladding (Precast Concrete Panels)	3 (LL)			DS1 Cladding units damaged by impact at corners and at column covers (in-plane deformation) Cladding units damaged by out of plane anchorage failure (out-of-plane acceleration).	DS1 Replace cladding panel	DS1 Damaged cladding is a falling hazard on occupants.
Curtain Walls[1]	3 (LL)	3 (LL)		DS1 Glass cracking	DS1 Repair cracked glass panel	DS1 Cracked glass is a hazard to occupants.
				DS2 Glass falls out	DS2 Repair cracked glass panel; cover exposure in meantime	DS2 Broken glass is a hazard to occupants.
Exterior Partitions						
Exterior Partitions (Gyp. Board)	2	2	3	DS1 Slight separation of sheathing or nails which come loose	DS1 Remove exterior pliable siding, replace loose nails, reinstall siding.	DS1, DS2 Repairs will necessitate a temporary removal of the building closure, thus repairs will hinder functional recovery.
				DS2 Permanent rotation of sheathing, tear out of nails or sheathing.	DS2 Same as DS1	
				DS3 Fracture of studs, major sill plate cracking.	DS3 Remove and replace siding, sheathing, studs and plates.	DS3 Fractured elements can pose a hazard to occupants.
Exterior Partitions (Stucco)	2	2	3	DS1 Cracking of stucco.	DS1 Fill cracks with cement compound and repaint.	DS1, DS2 Repairs will necessitate a temporary removal of the building closure, thus repairs will hinder functional recovery.
				DS2 Spalling of stucco, separation of stucco and sheathing from studs.	DS2 Patch spalled areas with stucco and repaint.	
				DS3 Fracture of studs, major sill plate cracking.	DS3 Remove and replace studs, plates, sheathing, and stucco.	DS3 Fractured elements can pose a hazard to occupants.
Exterior Partitions (Flat Strap X Bracing)	2	3		DS1 Local buckling of chord studs	DS1 Replace gyp board, metal stud framing, and X bracing.	DS1 Not a hazard to occupants, but building enclosure is comprimised and therefore inhibits building functionality.
				DS2 Failure of many framing members and collapse.	DS2 Replace gyp board, metal stud framing, boundary elements, and X bracing.	DS2 Collapsed partition is a hazard to occupants.
Stairs						
Stairs (Steel & Hybrid)	1	3	3	DS1 Local steel yielding.	DS1 Patch, paint.	DS1 Repairs are for aesthetic purposes.
				DS2 Buckling of steel, weld cracking.	DS2 Removal and replacement of damaged components. Field repair of welds.	DS2 Vertical and lateral strength is comprimised and is a hazard to occupants.
				DS3 Loss of live load capacity. Connection and or weld fracture.	DS3 Replace stair.	DS3 Loss of live load is a hazard to occupants
Stairs (Concrete)	1	3	3	DS1 Local cracking, local spalling, and local rebar yielding.	DS1 Patch, paint, epoxy injection.	DS1 Repairs are for aesthetic purposes.
				DS2 Structural damage but live load capacity remains intact. Extensive concrete cracking, crushing, and buckling of rebar.	DS2 Remove damaged components, install replacement components.	DS2 Vertical and lateral strength is comprimised and is a hazard to occupants.
				DS3 Loss of live load capcaity. Extensive concrete crushing, connection failure.	DS3 Replace stair.	DS3 Loss of live load is a hazard to occupants
Elevators						
Elevator (Traction & Hydraulic)	2 (LL)			DS1 Elevator does not work (due to various types of damage).	DS1 Repair elevator (depending on type of damage).	DS1 Elevators need to be operational for building functionality. For re-occupancy, occupants will have to endure the inconvenience of having to use the stairs instead. Although elevators are also needed to transport workers, materials, and equipment such that other re-occupancy repairs can be made, it is assumed that temporary elevators are set up such that these repairs can be made (taken into account as an Impeding Factor).
Pipes						
Pipes	2	3		DS1 Small leakage at joints - 1 leak per 1000ft of pipe.	DS1 Retighten leaking joints.	DS1 Molding concerns would inhibit building functionality.
				DS2 Large leakage with major repair - 1 leak per 1000ft of pipe.	DS2 Replace 20ft section of pipe at leaking joints.	DS2 Major leakages will likely render the floor inoccupiable, and therefore needs to be repaired for re-occupancy.
Pipe Braces (Vertical Bracing Only)	3			DS1 Vertical Brace Failure - 1 failure per 1000ft of pipe	DS1 Replace failed vertical braces	DS1 Failed vertical braces mean pipes are a falling hazard on occupants.
Pipe Braces (Vertical & Lateral Bracing)	3	3		DS1 Lateral Brace Failure - 1 failure per 1000ft of pipe	DS1 Replace failed lateral braces	DS1 Failed lateral braces are not an immediate hazard, but lateral braces need to be repairs need to be repaired for re-occupancy such that pipes do not fall down in subsequent aftershocks.
				DS2 Vertical Brace Failure - 1 failure per 1000ft of pipe	DS2 Replace failed vertical braces	DS2 Failed vertical braces mean pipes are a falling hazard on occupants.
HVAC Distribution						
HVAC Ducts	3	3		DS1 Individual supports fail and duct sags - 1 support fail per 1000 ft of duct.	DS1 Replace failed supports and repair ducting in vicinity of supports	DS1 Failed supports are a hazard to occupants.
				DS2 Several supports fail and sections of ducting fall.	DS2 Replace section of failed ducting and supports.	DS2 Failed supports are a hazard to occupants.
HVAC Drops/Diffusers	3			DS1 Drops or diffusers dislodge and fail.	DS1 Replace diffusers/drops, as well as the ceiling and ducting in the vicinity.	DS1 Damaged drops/diffusers are a falling hazard to occupants.
Fire Sprinkler Drops	2	3		DS1 Spraying and leakage at drop joints	DS1 Replace sprinkler drop and minor water cleanup	DS1 Molding concerns would inhibit building functionality.
				DS2 Drop joints break, major leakage	DS2 Replace sprinkler drops and major water cleanup	DS2 Damaged drops are a falling hazard to occupants.

Table 5 cont'd. Assigned Repair Classes for non-structural components in PACT

Component	Average Damage State ($\overline{DS}$) $0 < \overline{DS} \le 1$	$1 < \overline{DS} \le 2$	$\overline{DS} \ge 2$	DS Description	DS Consequences	Repair Class Logic
Interior Partitions						
Full-height partition (Gyp. Board & Finish)	1	1	3	DS1 Screws pop out, minor cracking of wall board, warping or cracking of tape.	DS1 Retape joints, paste and repaint.	DS1 Repairs are for aesthetic purposes.
				DS2 Moderate cracking or crushing of gypsum wall boards.	DS2 Remove wall board and install new ones, tape, paste, and repaint.	DS2 Repairs are for aesthetic purposes.
				DS3 Significant cracking and crushing of gypsum wall boards, buckling of studs and tearing of tracks.	DS3 Remove and replace stud wall and wall board, tape, paste, and repaint.	DS3 Sharp edges may pose a hazard for occupants, or occupants may be reluctant to re-enter the premises because of a misunderstanding that damaged partition walls show comprimised structural integrity.For these reasons DS3 is repaired for re-occupancy.
Partial-height partition (Gyp. Board & Finish)	1	1	3	DS1 Screws pop out, minor cracking of wall board, warping or cracking of tape.	DS1 Retape joints, paste and repaint.	DS1 Repairs are for aesthetic purposes.
				DS2 Buckling or connection failure of top braces.	DS2 Replace top brace members and connections.	DS2 Repairs are for aesthetic purposes.
				DS3 Tearing or bending of top track, tearing at corners with transverse walls.	DS3 Remove and replace stud wall and wall board, tape, paste, and repaint.	DS3 Sharp edges may pose a hazard for occupants, or occupants may be reluctant to re-enter the premises because of a misunderstanding that damaged partition walls show comprimised structural integrity.For these reasons DS3 is repaired for re-occupancy.
Suspended Ceiling						
Lighting Fixtures	3			DS1 Disassembly of rod system at connections with horizontal light fixture, low cycle fatigue failure of the threaded rod, pullout of rods from ceiling assembly.	DS1 Replace damaged lighting components.	DS1 Damaged lights are a falling hazard on occupants.
Acoustic Tiles	1	3	3	DS1 5% of tiles dislodge and fall.	DS1 Reinstall new acoustic tile for damaged area.	DS1 Few ceiling tiles dislodged is likely not a hazard and is repaired for aesthetic purposes.
				DS2 30% of tiles dislodge and fall and t-bar grid damaged.	DS2 Same as DS1 and reinstall ceiiling grids.	DS2, DS3 Severe amount of dislodged tiles and damaged ceiling grid is a falling hazard to occupants.
				DS3 Total ceiling collapse.	DS3 Totally replace ceiling and grid.	
Stairs						
Stairs (Steel & Hybrid)	1	3	3	DS1 Local steel yielding.	DS1 Patch, paint.	DS1 Repairs are for aesthetic purposes.
				DS2 Buckling of steel, weld cracking.	DS2 Removal and replacement of damaged components. Field repair of welds.	DS2 Vertical and lateral strength is comprimised and is a hazard to occupants.
				DS3 Loss of live load capacity. Connection and or weld fracture.	DS3 Replace stair.	DS3 Loss of live load is a hazard to occupants
Stairs (Concrete)	1	3	3	DS1 Local cracking, local spalling, and local rebar yielding.	DS1 Patch, paint, epoxy injection.	DS1 Repairs are for aesthetic purposes.
				DS2 Structural damage but live load capacity remains intact. Extensive concrete cracking, crushing, and buckling of rebar.	DS2 Remove damaged components, install replacement components.	DS2 Vertical and lateral strength is comprimised and is a hazard to occupants.
				DS3 Loss of live load capcacity. Extensive concrete crushing, connection failure.	DS3 Replace stair.	DS3 Loss of live load is a hazard to occupants
Mechanical Equipment						
Chiller	2 (LL)			DS1 Chiller does not work (due to various types of damage)	DS1 Repair Chiller (depending on type of damage)	DS1 Mechanical equipment need to be operational for building functionality.
Cooling Tower	2 (LL)			DS1 Cooling tower does not work (due to various types of damage)	DS1 Repair Cooling Tower (depending on type of damage)	DS1
Compressor	2 (LL)			DS1 Compressor does not work (due to various types of damage)	DS1 Repair Compressor (depending on type of damage)	
Air Handling Unit	2 (LL)			DS1 AHU does not work (due to various types of damage)	DS1 Repair AHU (depending on type of damage)	DS1
HVAC Fan	2 (LL)			DS1 Fan does not work (due to various types of damage)	DS1 Repair Fan (depending on type of damage)	DS1
Variable Air Volume Box	2 (LL)			DS1 VAV Box does not work (due to various types of damage)	DS1 Repair VAV Box (depending on type of damage)	DS1
Anchorage	3			DS1 Anchorage Failure	DS1 Repair anchorage and remount equipment,	DS1 All equipment need to be anchored for re-occupancy such that they are not a hazard in future aftershocks.
Electrical Systems						
Switchgear	2			DS1 Switchgear does not work (due to various types of damage)	DS1 Repair Switchgear (depending on type of damage)	DS1 Electrical systems need to be operational for building functionality.
Motor Control Center	2			DS1 Motor Control Center does not work (due to various types of damage)	DS1 Repair Motor Control Center (depending on type of damage)	DS1
Transformer	2			DS1 Transformer does not work (due to various types of damage)	DS1 Repair Transformer (depending on type of damage)	DS1
Distribution Panel	2			DS1 Distribution Ppnel does not work (due to various types of damage)	DS1 Repair Distrubution Panel (depending on type of damage)	DS1
Anchorage	3			DS1 Anchorage Failure	DS1 Repair anchorage and remount equipment,	DS1 All equipment need to be anchored for re-occupancy such that they are not a hazard in future aftershocks.
Emergency Backup						
Battery Rack	3			DS1 Battery rack collapses, batteries fall, crack cases, dislodge conductors.	DS1 Replace battery rack, clean up spilled acid.	DS1 Emergency backup systems need to be operational for building functionality to ensure tenant safety in future hazards.
Battery Charger	2			DS1 Battery Charger is damaged and inoperable	DS1 Service for intermittent voltage output or for blown surge protector	DS1
Diesel Generator	2			DS1 Diesel Generator is damaged and inoperable	DS1 Repair Diesel Generator	DS1
Anchorage	3			DS1 Anchorage Failure	DS1 Repair anchorage and remount equipment,	DS1 All equipment need to be anchored for re-occupancy such that they are not a hazard in future aftershocks.
Critical Building Contents						
Contents critical to functionality	2 (LL)			DS1 Irreparable damage to the component (this fragility would be user-defined)	DS1 User-defined	DS 1 User-defined

[1] Default curtain wall fragilities in PACT do not include a DS for gasket seal failure, which is important for functionality. A user-defined fragility which includes this damage state should be included with Repair Class = 2.

[1] Default curtain wall fragilities do not include a DS for gasket seal failure. User-defined fragilities should include this DS with Repair Class 2.

SUMMARY OF FRAMEWORK FOR MODIFIED DOWNTIME METHODOLOGY

The process begins by assigning Repair Classes to each type of component based on the PACT average damage state results using Table 4 and Table 5. Once the user determines the specific recovery state for which downtime will be calculated (either re-occupancy, functional recovery, or full recovery), then only those components in Repair Classes which hinder the selected recovery state from being achieved are considered in the calculation. Figure 5, Figure 6, and Figure 7 show the general methodology for calculating downtime associated with each recovery state.

'Impeding factors' which delay the initiation of repairs required to achieve a certain recovery state must be estimated and included. A description of each impeding factor considered and the corresponding estimated delay is described in the "Downtime Due to Delays" section. Most impeding factors are influenced by the degree of building damage (such as financing, engineering review, and contractor mobilization); for these, the Repair Classes are used to determine the estimated delay. Since some impeding factors can occur in series or simultaneously, the sequence which produces the greatest delay must be used before building repairs are initiated.

Building repairs can begin once the impeding factors are addressed. The required component repairs for each floor are organized into logical repair sequences which are based on the number of workers allocated to each floor and the entire building. The sequence with the maximum repair time represents the necessary repair time for that floor. The downtime for the entire building can be assessed by following a logical repair sequence across floors. The detailed procedure is explained in the "Downtime Due to Repairs" section below.

Utility disruption affects functional recovery and full recovery (but not re-occupancy) for the entire building but does not hinder the initiation of building repairs. The estimated utility disruption should thus be considered in parallel to the other impeding factors and repair times when determining the time associated with both functional and full recovery. Estimates for utility disruption are described in the section "Utility Disruption".

An example of how each of these is calculated follows each section. An example of how the impeding factors, building repairs, and utility disruption are aggregated to calculate the time required to achieve functional recovery is provided in the section "Calculating Total Downtime".

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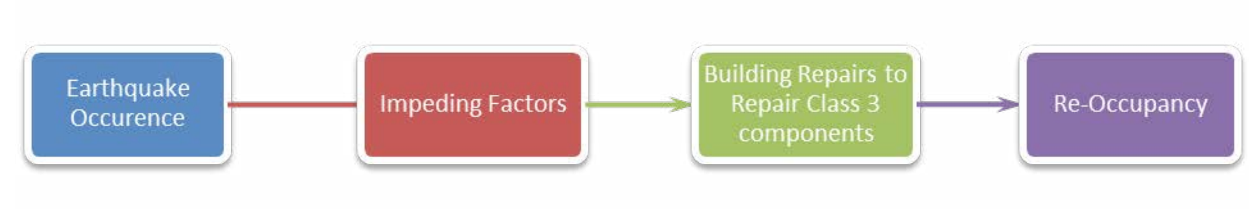

Figure 5. Downtime framework for Re-Occupancy

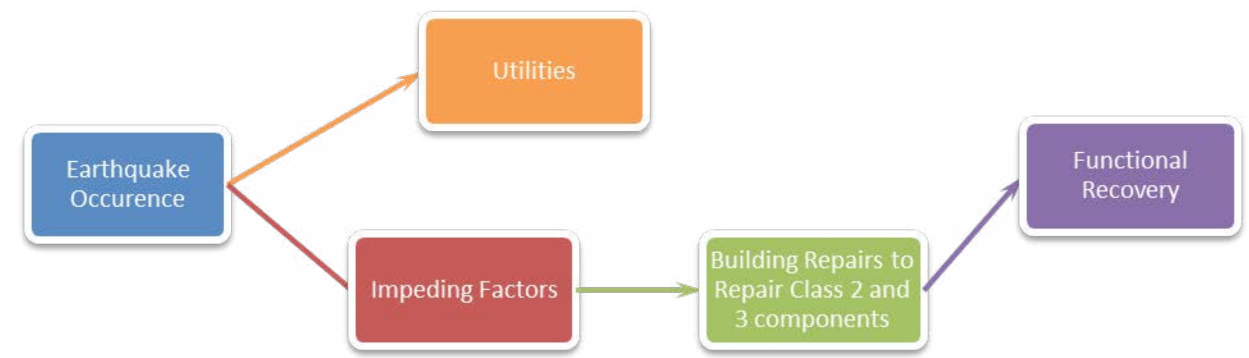

Figure 6 Downtime framework Functional Recovery

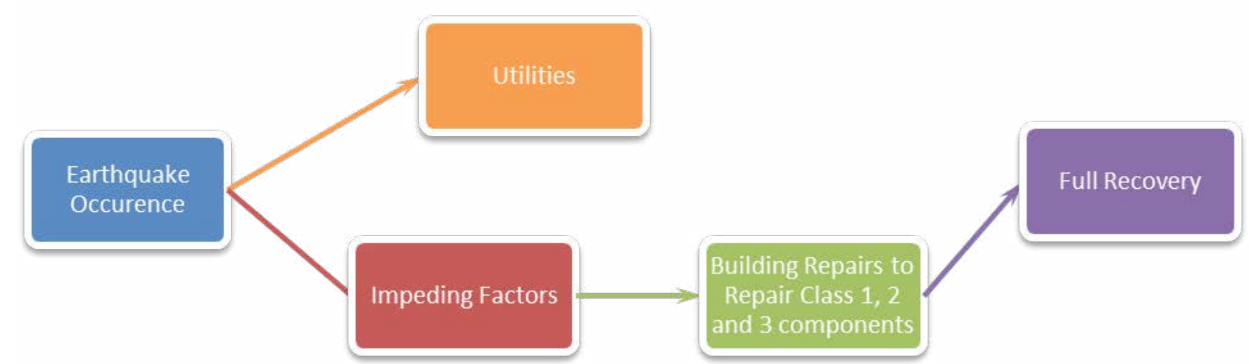

Figure 7 Downtime framework for Full Recovery

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DOWNTIME DUE TO REPAIRS

This chapter presents a method for determining downtime due to repairs for each recovery state. The methodology borrows from widely accepted methods in construction scheduling in order to create a realistic repair schedule. The building repair schedule is graphically represented by a Gantt chart, which depicts the various repairs that occur at every floor in the building as a function of time. The initial time represents the time at which building repairs commence (once impeding factors have been addressed), and the final time represents the total repair time of the building for the recovery state under consideration.

There are several factors that are considered in order to construct a realistic repair schedule:

- The sequence of repairs that will be undertaken.
- The number of workers that are available to work on the same component type on each floor and simultaneously across multiple floors.
- The total number of workers that are able to work on-site simultaneously.

These factors will be discussed in further detail in the following sections, and need to be considered when developing a repair schedule for a specific recovery state.

IDENTIFY REPAIRS FOR EACH RECOVERY STATE

As described above, Repair Classes can be assigned to each type of component based on the PACT average damage state results using Table 4 and Table 5. Once the recovery state for which the downtime is to be calculated is selected, the relevant Repair Classes can be considered. For example, to calculate the downtime associated with functional recovery, all damaged components in Repair Class 2 and 3 must be considered. Repairs to damaged components in Repair Class 1 need not be considered since they only hinder full recovery. The sections below describe the sequencing of repairs of only the components in the relevant Repair Classes.

FLOOR REPAIR SEQUENCES

A repair sequence defines the order of repairs that are to be conducted. For example, partitions can be replaced only once pipes and HVAC ducts have been repaired. Some repairs can occur simultaneously. For instance, a building envelope repair sequence would not interfere with an interior repair sequence. Component repairs at a particular floor level need to be ordered in a manner that reflects the sequence of repairs that are likely to be undertaken by the contractor. The suggested repair sequences at a particular floor is labeled *Typical Repair Sequences*, and presented in Figure 8.

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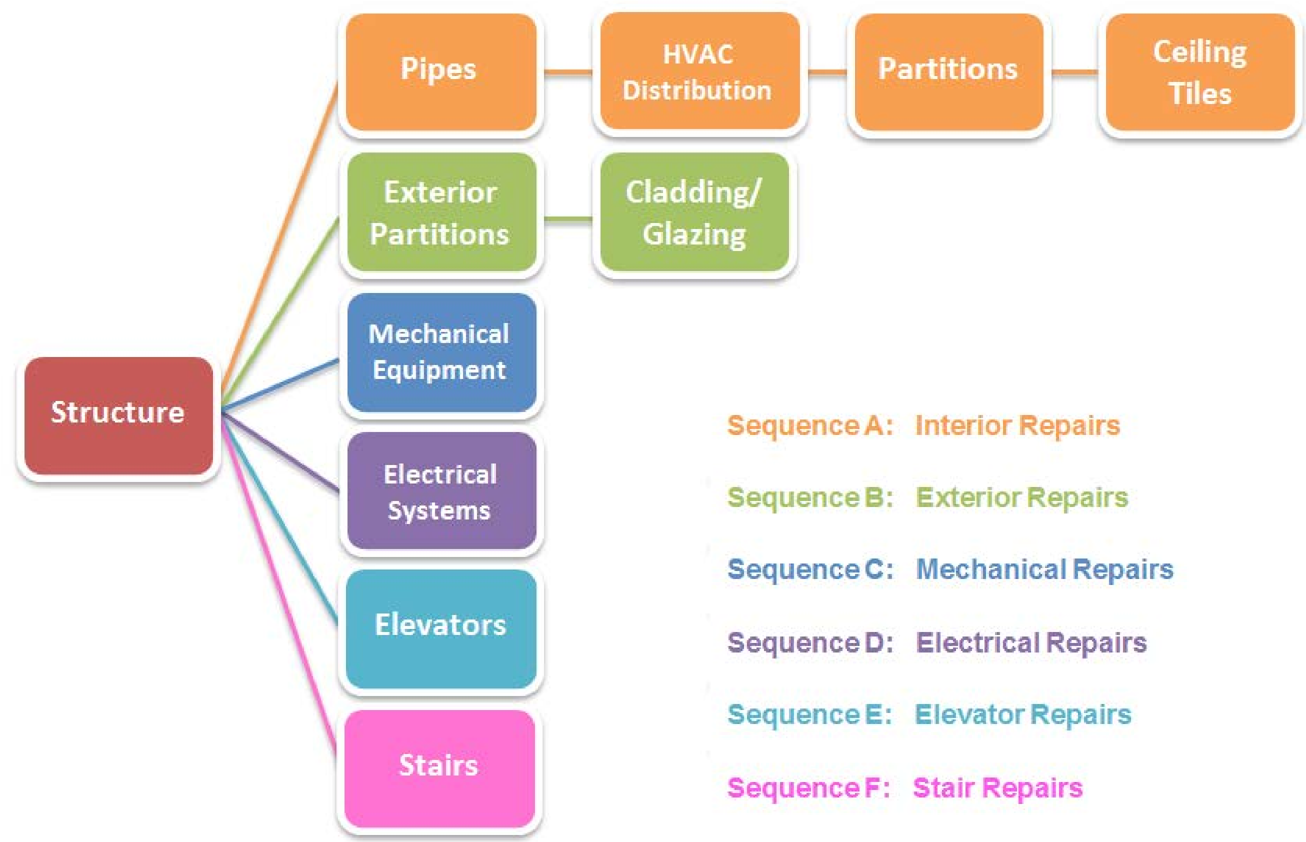

Figure 8. Typical repair sequences at each floor level

All floor repair sequences initiate only after the repair of the entire damaged structure, since the structural integrity of the building must first be ensured for occupant safety. We assume that the structure is repaired *only one floor at a time starting from the bottom*, since the structural integrity of the lower floor must first be guaranteed before the upper floor can commence repairs. Note that this assumes that residual drift is not significant and therefore the building is reparable – this may not be the case for significantly damaged buildings, but this assumption should hold for REDi™ Platinum and Gold buildings which should have negligible residual drift and for Silver buildings which are limited to less than 0.5% residual drift. Once repairs to the structure at all floor levels are complete, repair of various non-structural components can begin.

Each box in Figure 8 represents a component type. For example, 'Mechanical Equipment' represents all types of heavy mechanical machinery, such as cooling towers, chillers, and air handling units. Thus, repair times are summed for every component in each box to represent the repair time of that component type.

Each repair sequence is assumed to be repaired simultaneously (in parallel) with all other repair sequences. Sequence A repairs will generally occur throughout the interior of the floor, while Repair Sequence B repairs can occur simultaneously on the building perimeter. Sequence C to F repairs occur at select locations within the floor level, and it is assumed that Sequence A repairs can make accommodations around these locations.

Note that elevators are shown to be repaired after the structural repairs are complete but in parallel with repairs to non-structural components. It is assumed that temporary elevators would be set up by the contractor to transport the materials and equipment to carry out the structural repairs and then non-structural repairs if the elevators are damaged. The time required to do this is accounted for in the impeding factors for contractor mobilization which are located in the section "Downtime Due to Delays". Thus, damage to permanent elevators does not hinder either repairs to the structure or other components.

The *Typical Repair Sequences* encompass the vast majority of components that are likely to exist in a building. Repairs of other components not listed should be added according to engineering judgment.

LABOR ALLOCATION FOR EACH FLOOR

Labor allocation has a significant influence on the overall repair schedule, both within a floor level and across multiple floors. A larger labor force generally means that component repairs can be conducted faster and across more floor levels, but this needs to be balanced against the restrictions of labor availability, floor space, and site access. Numerous complexities arise when balancing repair demands and labor capacity, and certain assumptions are made (as will be discussed) to maintain the general applicability of this methodology.

The repair time for each component is currently expressed by PACT as the number of days for a single worker to complete the repair (i.e. 'worker-days'). Since it is expected that multiple workers are able to contribute to the repair of a particular type of component, the repair time estimate is lowered proportionally. Table 6 lists our recommended number of workers to be used for various component types.

For structural repairs and components that are distributed across or around the floor level (Repair Sequence A and B), the expected number of workers are computed based on floor area. FEMA P-58 indicates that the maximum number of workers per sq. ft ranges from 1 worker per 250 sq. ft to 1 worker per 2000 sq. ft (FEMA, 2013a). According to the *Typical Repair Sequence*, structural component repairs happen first, which means workers do not have to contend with other non-structural trades interfering with repairs. Thus, a metric of 1 worker per 500 sq. ft. is recommended, which falls within the higher range of FEMA P-58's suggestion. For non-structural repairs to Repair Sequence A and B we recommend using 1 worker per 1000 sq. ft. which falls within the mid-range of FEMA P-58's suggestion. Mechanical equipment, electrical systems, elevator, and stair repairs (Repair Sequences C through F) have workers assigned based on the number of damaged units. While we assume that these type of repairs would not hinder the Repair Sequence A and B repairs, we note that the recommended number of workers for Repair Sequence A and B was lowered relative to structural repairs to reflect that once all the workers are allocated for non-structural repairs, it would be roughly equivalent to assuming 1 worker per 500 sq. ft. Average crew sizes from RS Means (Reed Construction Data Incorporated 2013) were used to determine the number of workers assigned to repair each of the Repair Sequence C through F component types. It is important to note that these workers are assigned based on the average number of damaged units for a component type, so if Mechanical

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Equipment has three damaged chillers, 2 damaged cooling towers, and 1 damaged air handling unit, then the averaged damage units are 2, and thus two times the number indicated in Table 6 may be used.

Table 6. Recommended number of workers for adjustment of component repair times

Repair Sequences	Component Type	Number of Workers per Square Foot per Floor
-	Structure	1worker/500sf
A	Pipes/Sprinklers	1worker/1000sf
	HVAC Distribution	
	Partitions	
	Ceilings	
B	Exterior Partitions	1worker/1000sf
	Cladding/Glazing	

Repair Sequences	Component Type	Number of Workers per Damaged Unit[1]
C	Mechanical Equipment	3
D	Electrical Systems	3
E	Elevators	2
F	Stairs	2

[1]Number of damaged units = average number of damaged units across all components in the component type

MAXIMUM NUMBER OF WORKERS

The number of workers allocated to an individual floor is provided above, but the total number of workers across multiple floors must be capped by the total number of workers allocated to a project.

When constructing the repair schedule, the following restrictions apply at any given point in time:

1. The total number of workers on all levels repairing a particular component type shall not exceed the values listed in Table 7. This restriction accounts for the subcontractor's resource limitations, and their ability to provide the skilled crews to repair specific component types. The resource limitations are assumed to vary based on the height of the building, since contractors are likely to allocate a larger amount of resources on larger projects. The values listed in Table 7 represent approximately 3, 6, and 9 crews for each component type, for low-rise, medium-rise, and high-rise, respectively.

2. The total number of workers in the building at the same time, based on the gross square feet of the building, shall not exceed the value determined from Figure 9. This attempts to account for site restrictions by proxy of the maximum number of workers that can fit within a building. Figure 9 is based on the following equation, which was derived by consulting with contractors and cost estimators:

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$$N_{max} = 2.5 \times 10^{-4} A_{tot} + 10 \qquad 20 \leq N_{max} \leq 260$$

Where N_{max} is the maximum number of workers on site, and A_{tot} is the total floor area of the building (sq. ft.).

Floors can be repaired simultaneously as long as these requirements are met. If there are too many workers assigned to repairs across the floor levels, certain component repairs need to be delayed such that the above requirements are met.

Table 7. Maximum number of workers per component type

	Max. Number of Workers per Repair Sequence		
Repair Sequences	Low-rise (Less than 5 stories)	Medium-rise (Between 6 and 20 stories)	High-rise (Greater than 20 stories)
A	15	30	45
B	15	30	45
C	9	18	27
D	9	18	27
E	6	12	18
F	6	12	18

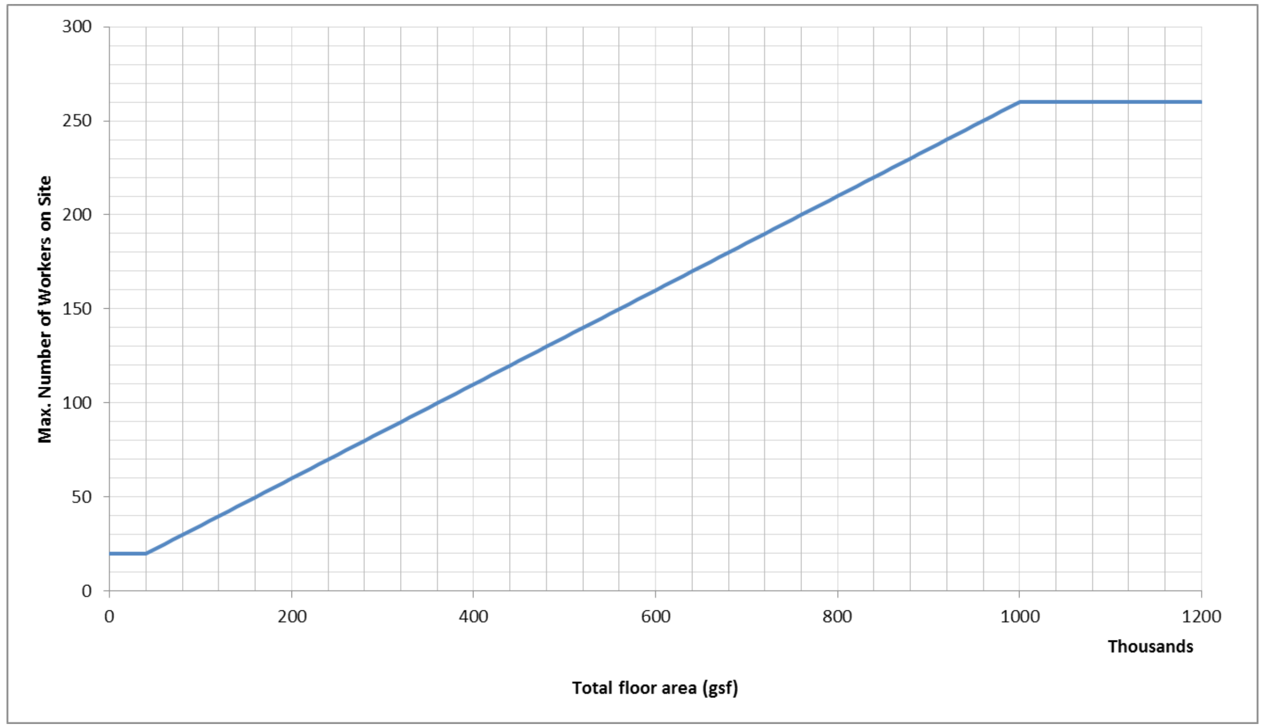

Figure 9. Maximum number of workers on site, based on total floor area

EXAMPLE: CREATING THE REPAIR SCHEDULE TO CALCULATE DOWNTIME

A repair schedule is constructed for each recovery state, based on the necessary repairs that were identified in the damage assessment process. The repair schedule can follow the user's preference, as long as the repair sequence and labor allocation constraints described above are met. This method allows a fair amount of flexibility in arranging the repairs and may require iteration.

The process of constructing a repair schedule using the concepts presented in this methodology is best illustrated through an example.

Summary:

The time associated with repairs only (this example does not include impeding factors or utility disruption which are jointly considered in the section entitled "Calculating Total Downtime") required to achieve *functional recovery* is sought for a typical three story steel office building used in Terzic et al (2012) located in Oakland, CA. The original building cost was estimated to be $16.2 million. The lateral structural system is a fixed-base steel Special Moment Resisting Frame (SMRF), and has a uniform floor area of 21,600 sq. ft across all floors. A non-linear response history analysis was performed using 40 three-component ground motion records, selected and scaled to represent ground motions at the DBE hazard level (10% probability of exceedence in 50 years) (Baker, 2011). More information on the case study building and the analysis method can be found in Terzic et al. (2012).

The loss analysis was performed in PACT, and the median component repair times and corresponding average damage states were extracted using the steps outlined in Table 1 and Table 2. In this example, we are interested in calculating 'best-estimate' repair times so the median values (50% probability of non-exceedance) are used – higher probabilities of non-exceedance can also be used if desired. Table 4 and Table 5 were used to assign Repair Classes to every component based on their average damage state. Only Repair Class 2 and 3 components were considered since only repairs to or replacement of these components are required to achieve functional recovery. The repair times for these components, organized by repair sequence, is summarized in Figure 10. These repair times represent the number of 'worker-days' to repair each component.

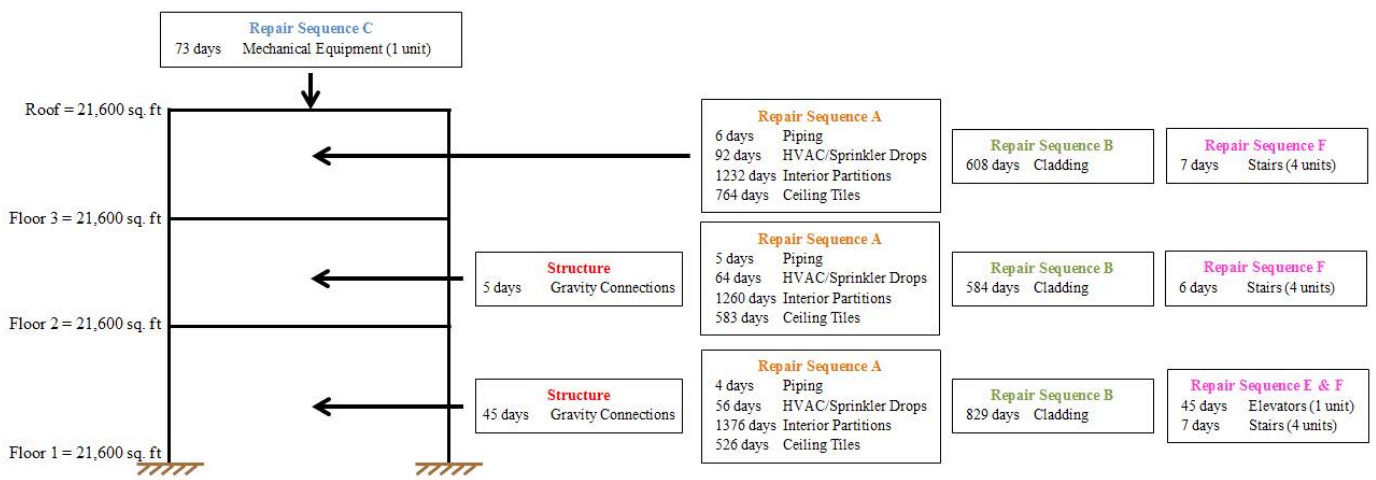

Figure 10. Floor by floor component repair times obtained from PACT analysis

Structural Repairs:

Repairs to the structure need to be completed before non-structural repairs can begin. According to Table 6, the desired number of workers to be allocated at each floor for structural repairs is 1 worker/500 sq. ft. Structural repairs can only occur 1 floor at a time, and since the floor area is the same at all floors, the number of workers allocated for structural repairs at a particular floor for any given point in time is:

$$\text{\# of workers} = (21{,}600\text{sq.ft})(1\text{worker}/(500\text{sq.ft})) = 44 \text{ workers}$$

The number of workers that are able to perform repairs in the building are constrained by site restrictions. Using Figure 9, the maximum number of workers that are allowed to be on site is 31 workers. Therefore, only 31 workers can be allocated to perform structural repairs at any time. Dividing the number of 'worker-days' to complete structural repairs at floor 1 and floor 2 by 31 workers yields a total repair time of 1.4 days and 0.1 days, respectively (floor 3 had no structural repairs). These floors need to be repaired sequentially, so the structure takes 1.5 days to repair in total.

The moment frame did not require repair for this particular example, though it is likely to have endured a significant amount of yielding (the PACT fragility curve for steel moment frames with an RBS connection indicates that the first damage state - initiation of local flange buckling - does not occur until a median demand of 3% drift. Yielding of the moment frame is not included as a damage state). Significant yielding of the moment frames is likely to result in large residual drifts, which were not considered in the Terzic study – the required structural repairs are therefore likely significantly underestimated. Nevertheless, the study still provides an adequate example for calculating repair time used in this methodology.

Non-structural Repairs:

Non-structural repairs can begin after all structural repairs are complete. Repairs may occur simultaneously across multiple floors as long as the labor allocation constraints are met. Repair Sequences that occur at

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multiple floor levels are Repair Sequence A, B, and F. The number of workers assigned to each Repair Sequence is usually assessed floor by floor, but in this case the building has a uniform floor area across the height, and the average number of damaged units for each component type is the same (see Figure 10). Thus, the number of workers assigned to a given Repair Sequence is the same for each floor:

	# of workers per floor	Max. # of workers per component type
Repair Sequence A	$\text{\# of workers} = (21{,}600sq.ft)\left(\frac{1worker}{1000sq.ft}\right) = 22\ workers$	$\mathbf{15\ workers}$
Repair Sequence B	$\text{\# of workers} = (21{,}600sq.ft)\left(\frac{1worker}{1000sq.ft}\right) = 22\ workers$	$\mathbf{15\ workers}$
Repair Sequence C	$\text{\# of workers} = (1\ damaged\ unit)\left(\frac{3\ workers}{damaged\ unit}\right) = \mathbf{3\ workers}$	$9\ workers$
Repair Sequence E	$\text{\# of workers} = (1\ damaged\ unit)\left(\frac{2\ workers}{damaged\ unit}\right) = \mathbf{2\ workers}$	$6\ workers$
Repair Sequence F	$\text{\# of workers} = (4\ damaged\ units)\left(\frac{2\ workers}{damaged\ unit}\right) = 8\ workers$	$\mathbf{6\ workers}$

At a given floor level, the number of workers per floor is constrained by the maximum number of workers available per Repair Sequence, determined from Table 7. Repair Sequence A, B, & F have a larger number of workers per floor than the maximum allowed per Repair Sequence. Thus the number of workers per floor is limited at 15 workers for Repair Sequence A and B, and 6 workers for Repair Sequence F. This also implies that these Repair Sequences cannot occur simultaneously at multiple floor levels, since the maximum number of workers allowed on the project for each Repair Sequence are being used at one floor level.

In the above calculation, the number of workers assigned to each Repair Sequence at each floor is bolded in red. The repair time for each repair sequence at each floor is calculated by summing their respective component repair times ('worker-days') and dividing by the number of workers assigned to that repair sequence:

Floor 1:

Repair Sequence A $$Repair\ Time = \frac{(1960\ worker\ days)}{15\ workers} = 131\ days$$

Repair Sequence B $$Repair\ Time = \frac{(829\ worker\ days)}{15\ workers} = 55.2\ days$$

Repair Sequence E $$Repair\ Time = \frac{(45\ worker\ days)}{2\ workers} = 22.5\ days$$

Repair Sequence F $$Repair\ Time = \frac{(7\ worker\ days)}{6\ workers} = 1.1\ days$$

Floor 2:

Repair Sequence A $$Repair\ Time = \frac{(1911\ worker\ days)}{15\ workers} = 128\ days$$

Repair Sequence B $$Repair\ Time = \frac{(584\ worker\ days)}{15\ workers} = 38.9\ days$$

Repair Sequence F $$Repair\ Time = \frac{(6\ worker\ days)}{6\ workers} = 1\ day$$

Floor 3:

Repair Sequence A $$Repair\ Time = \frac{(2092\ worker\ days)}{15\ workers} = 140\ days$$

Repair Sequence B $$Repair\ Time = \frac{(608\ worker\ days)}{15\ workers} = 40.5\ days$$

Repair Sequence F $$Repair\ Time = \frac{(7\ worker\ days)}{6\ workers} = 1.1\ days$$

Roof:

Repair Sequence C $$Repair\ Time = \frac{(73\ worker\ days)}{3\ workers} = 24.3\ days$$

Once the repair time for each Repair Sequence at each floor is known, the repair schedule to achieve functional recovery can be constructed. One possible repair schedule is shown in Figure 11. For this example, the repair time required to achieve functional recovery is about 401 days.

Although it is difficult to see, the red bars indicate the required duration of structural repairs, which occur at one floor level at a time, starting from the lowest level. After the structural repairs are completed, the non-structural repairs can begin. The locations where the bars overlap, whether within a floor or across floors, show where repairs are occurring in parallel.

For Repair Sequence A, B, and F, the maximum number of workers were being used for each Repair Sequence at each floor, so the repairs on the upper floors could not commence until the repairs of that same Repair Sequence was completed in the lower floors. Since Repair Sequence A controls the overall repair duration, the other Repair Sequences can be arranged in a variety of ways (keeping in mind the labor allocation constraints), but would have no impact on the overall repair time.

Figure 11 also shows an example of how the total number of workers on the site is tracked throughout the repair duration. The red-dashed line represents the maximum allowed capacity of 31 workers at the site. Although the site can accommodate more workers near the end of the project (15 workers being used

against the maximum allowed of 31), the limitation on the number of workers per Repair Sequence prevents additional workers from being added to Repair Sequence A repairs. Thus, the repair schedule can help identify the repairs that control the overall repair time.

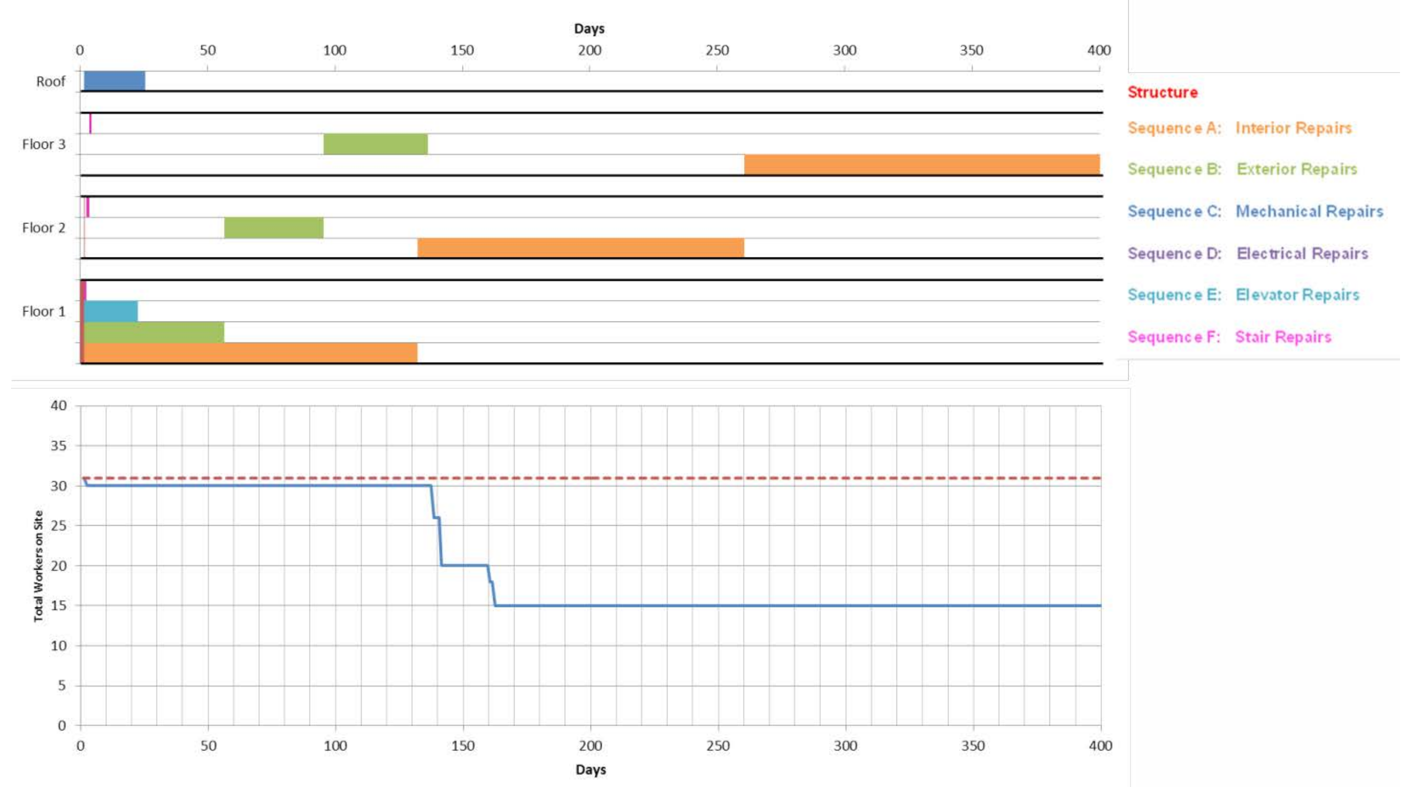

Figure 11. Example repair schedule (top) and schedule of total workers on site (bottom)

DOWNTIME DUE TO DELAYS

Downtime for a particular building is not limited to the time necessary to complete repairs. There are several delays that can occur which prevent repairs from initiating, which would consequently increase the time required to achieve any recovery state. Comerio (2006) labels these delays as 'irrational factors' due to their inherent uncertainty in downtime contribution. The factors she presents include financing, relocations of functions (surge), manpower, economic and regulatory uncertainty.

This methodology neglects some of these factors (relocation for example, since the primary concern was determining downtime for a specific building instead of business continuity for an organization), but includes some additional factors to Comerio's. We term them 'impeding factors' since they impede the ability to initiate repairs. Each impeding factor is described in the following sections, and estimates for delays due to each impeding factor are developed based on the conditions expected after an earthquake with intensity approximately equivalent to the design level or 475 year return period earthquake has occurred. Some of the delays associated with each impeding factor are largely based on the extent of damage sustained by the building itself. We note that buildings which are relatively undamaged (REDi™ Platinum and Gold) are likely to incur significantly less downtime due to delays than buildings that are damaged. The following impeding factors were considered:

- Post-earthquake Inspection
- Engineering Mobilization and Review/Re-design
- Financing
- Contractor Mobilization and Bid Process
- Permitting
- Procurement of Long-lead Time Components

The impeding factors are presented in the form of lognormal cumulative distribution functions (similar to PACT's fragility functions), but are coined 'impeding curves'. The impeding factors have a high degree of uncertainty, which is reflected in the dispersion of each impeding curve. However, since the upper bound consequence (in terms of delay time) may be infinite, the statistical population of the delays is not well-constrained and the typical assumption of lognormal distribution may not recognize the true dispersion. It is advised that these estimates be used only as a rational 'best estimate' approximation of the delays that could occur. At minimum, the median value (50% probability of non-exceedance) must be used to calculate delay times for REDi™. Often, probabilities of non-exceedance are used interchangeably with the term 'confidence' levels. For example, a 90% probability of non-exceedance could also be described as having a 90% confidence level that the losses would not exceed a specific amount. Higher probabilities of non-exceedance provided below may be used to estimate delays, but recognizing the limitations described above, these should still be described as 'best estimate' rather than 'confidence' levels.

The impeding curves are estimates developed by the authors of this paper, based on information provided by experts in various fields (including engineers, building owners, contractors, cost estimators, and bankers), as well as data collected from reconnaissance efforts in previous major disasters. FEMA P-58 outlines the development of fragility functions based on expert opinion, and this method was adopted and slightly

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modified such that these impeding curves could be developed. It is the authors' hope that the accuracy and uncertainties of these values are refined as more data becomes available. These estimates were developed for buildings located in the United States as other countries may have different emergency response plans. Table 8 provides a summary table of all the impeding factors considered, their median delays (θ), and dispersion factors (β). Each impeding factor is described in more detail below.

Table 8 Impeding factors median estimates and dispersions

Impeding Factor	Building	Mitigation Measure	Other Conditions	θ	β
Inspection	All Facilities	BORP Equivalent	-	1 day	0.54
	Essential Facility	-	-	2 days	0.54
	Non-Essential Facility	-	-	5 days	0.54
Engineering Mobilization & Review/Re-Design	All Facilities	Engineer on Contract	Max Structural RC = 1	2 weeks	0.32
			Max Structural RC = 3	4 weeks	0.54
			Max Structural RC = 3*	42 weeks	0.45
		-	Max Structural RC = 1	6 weeks	0.40
			Max Structural RC = 3	12 weeks	0.40
			Max Structural RC = 3 *	50 weeks	0.32
Financing	All Facilities	Pre-arranged Credit Line	-	1 week	0.54
		-	Insurance	6 weeks	1.11
		-	Private Loans	15 weeks	0.68
		-	SBA-backed Loans	48 weeks	0.57
Contractor Mobilization	Essential Facility < 20 Stories	GC on Contract	Max RC = 1	3 weeks	0.66
			Max RC = 3	7 weeks	0.35
		-	Max RC = 1	7 weeks	0.60
			Max RC = 3	19 weeks	0.38
	Non-Essential Facility < 20 Stories	GC on Contract	Max RC = 1	3 weeks	0.66
			Max RC = 3	7 weeks	0.35
		-	Max RC = 1	11 weeks	0.43
			Max RC = 3	23 weeks	0.41
	≥ 20 Stories	GC on Contract	Max RC = 1	3 weeks	0.66
			Max RC = 3	7 weeks	0.35
		-	Max RC = 1	28 weeks	0.30
			Max RC = 3	40 weeks	0.31
Permitting	All Facilities	-	Max Structural RC = 1	1 week	0.86
		-	Max. Structural RC = 3	8 weeks	0.32

*This curve should be used if loss analysis reveals a need for a complete re-design

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POST-EARTHQUAKE INSPECTION

Description: The building owner is expected to submit an inspection request if the structural integrity of the building is in question, or if there are other hazards that may pose a risk to the occupants' safety. Even without owner request or consent, the jurisdiction may require an inspection if they deem it necessary (i.e. if the building looks like it has sustained extensive damage). Tenants and insurance companies may also request an inspection regardless of the extent of visible damage. The estimated delays reflect that inspectors are expected to arrive earlier to essential facilities (Bruce, 2012).

Possible Mitigation: For expediting post-earthquake inspection, owners can pre-arrange for a qualified professional to inspect their building. They can also sign up for programs such as the Building Occupancy Resumption Program (BORP) (SEAONC, 2003) or other equivalents. This is essentially a contract between the building owner and pre-deputized engineers/contractors to immediately inspect the owner's building after an earthquake. Thus, the owner would not have to rely on city-appointed inspectors to obtain a tagging.

Impeding Curve: Represents the time between the end of the earthquake and conclusion of facility inspection.

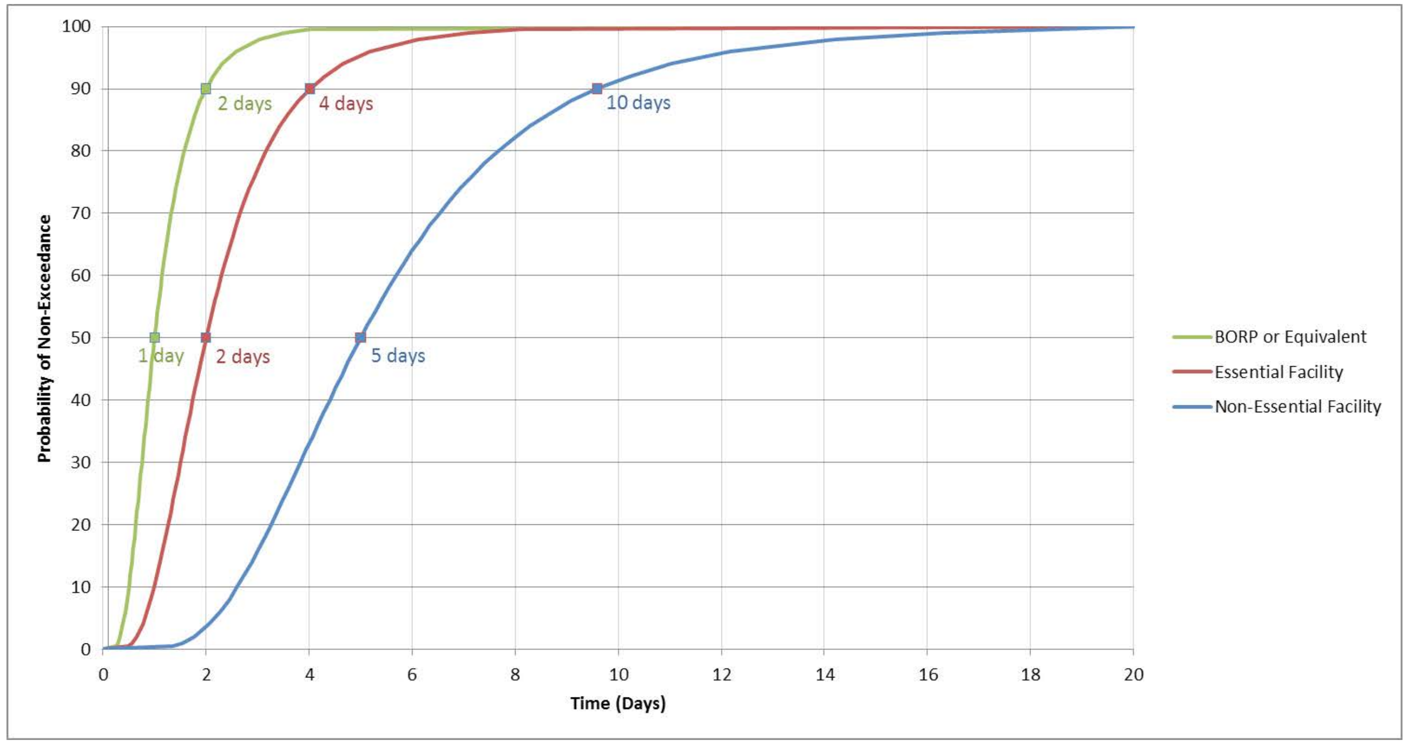

Figure 12. Impeding curve for post-earthquake inspection

Implementation: The delay due to post-earthquake inspection should be considered for all recovery states if the maximum Repair Class in the building is 3 for any component, otherwise delays due to post-earthquake inspection need not be included.

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ENGINEERING MOBILIZATION & REVIEW/RE-DESIGN

Description: An engineer would need to be consulted if there is structural damage to the building. The length of time to review/re-design depends on the degree of structural damage and may also depend on the size of the building.

Repair of minor structural damage (Repair Class 1) would likely require an engineer to stamp and approve the proposed repair strategy, but not necessarily perform any structural calculations. This may take some time for the engineer to review the damage and conclude that it is in fact only minor.

For significant structural damage (Repair Class 3) to some components, re-design (perhaps upgrading to current building code standards) of those components may be required. This would include a calculation package and drawings detailing the repairs to be issued. For this extent of damage, the review/re-design time should reflect the time required to complete the Construction Documentation (CD) phase of the project. This can be estimated by the actual CD phase if the building is currently in design or if it is an existing building, the likely CD phase for a project of similar size and occupancy.

If the loss analysis reveals significant structural damage (Repair Class 3) to a large number of components, this may require the building to be completely re-designed. Thus, the time required for engineering re-design should reflect the typical time required to complete a new construction project all the way from schematics to construction documentation.

While we have not considered architectural re-design explicitly as one of the impeding factors, since the project design phases are typically aligned, the impeding curves for engineering mobilization and review/re-design may be applied for architectural services as well.

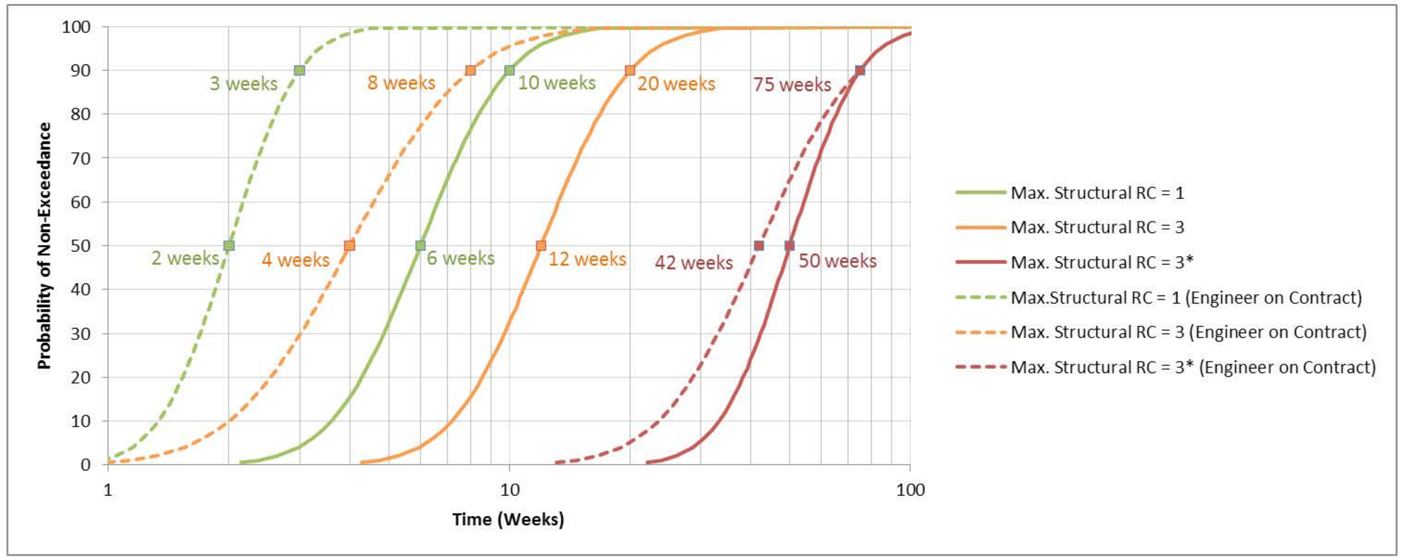
We note that scarcity of engineers after an earthquake accounts for approximately 4 to 8 weeks of additional delays.

Possible Mitigation: One mitigation strategy is to essentially eliminate the need for engineers by designing the building to remain essentially elastic (REDi™ Platinum and Gold).

The high demand for engineering services after a large earthquake creates a shortage in supply for these services. If damage requiring engineering review or re-design is expected, owners can avoid unnecessary delays due to these shortages by arranging contractual agreements with engineers to guarantee availability of their services immediately after an earthquake.

Impeding Curve: Represents the time required for engineering review and/or re-design, accounting for the time required to find available engineers due to scarcity. It is recognized that the project design schedule is different from project to project, and if the project design schedule is not in good agreement with the impeding curves presented below, it is left to the judgment of the engineer to determine the expected time for engineering review/re-design.

4.0 Loss Assessment



*This curve should be used if loss analysis reveals a need for a complete re-design

Figure 13. Impeding curve for engineering mobilization and review/re-design

Implementation:

Re-Occupancy and Functional Recovery: Delays due to engineering re-design need to be considered if the maximum structural Repair Class is equal to 3.

Full Recovery: Delays due to engineering investigation and review of proposed repairs need to be considered if the maximum structural Repair Class is greater than or equal to 1.

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FINANCING

Description: Significant delays can occur due to the inability to obtain financing to fund the necessary repairs. The amount of funding required is directly related to the expected financial losses calculated by PACT. If the financial losses calculated by PACT exceed the funds available to finance repairs, additional sources of funding need to be sought. The degree of delay due to financing is predicated on the method of financing. Financing may be procured through loans or insurance payments. Federal or other government grants should not be considered a viable financing option due to the uncertainty in securing these funds. The delay times indicated below assume that the borrower will qualify for the loan for which they apply. In addition, the ability of local smaller banks to process loans and disbursements is assumed to be unaffected, even if the banks are damaged, since most banks should have a comprehensive business continuity plan. We describe the available loans and related delays associated with disbursement of funds in more detail below.

Private Loans:
Owners may qualify for privately-financed loans (e.g. bank construction loans) if they meet certain loan qualifications which consider the following factors:

- Loan amount to value of property
- Source of re-payment/cash-flow
- Assets/collateral
- Borrower credit history
- Borrower experience
- Market conditions

For smaller enterprises, the source of all the cash-flow and assets may be housed in the building itself. If significantly damaged, this would hinder the ability to obtain a loan to make repairs. Some banks may be willing to qualify the borrower based on historical and future cash-flow or through other debt vehicles (Loftus, 2013).

SBA-backed Loans:
The Small Business Administration (SBA) has provided billions of dollars of disaster loans in federally-declared disaster areas to repair or replace property, equipment, and inventory. Businesses may qualify for up to $2M and homeowners up to $200K.

The SBA approved approximately $1.5BN worth of loans in the 5 months after Hurricane Sandy (Velasquez, 2013). Loan processing times averaged 30 days and 46 days for homeowners and businesses, respectively. This was an improvement over Hurricane Katrina (average response time was 76 days) which saw approximately 4 times the number of applications but worse than smaller hurricanes like Ike (56,000 applications) and Irene (28,000 applications) which averaged 12 days of processing time. Loan approval rates after Sandy were only 24%, causing a third of businesses to withdraw their applications. Even after loans were approved, it took months to disburse the money. As of the end of the first quarter of 2013 (5 months after the storm), only approximately 15% of the approved money had been disbursed. After

Hurricane Irene, 40% of the approved money had been disbursed in the same timeframe.
The estimates for delays associated with SBA-backed loans are largely based on the response times from Hurricane Sandy since the total losses (and therefore number of loan applications) may be more similar to those expected from a design level earthquake. In addition, the response times from Hurricane Sandy likely reflect some improvements in loan applications made after Hurricane Katrina (Klein, 2012).

Insurance:
Recent earthquakes have resulted in a large number of insurance claims resulting in significant delays to secure funds (New Zealand Parliament, 2011). In the United States, the last earthquake to cause significant insured losses is the 1994 Northridge earthquake. However, the insurance industry in California has changed drastically in that time and it is not possible to predict future claims approval delays from the experiences of Northridge. More recent natural disasters such as hurricanes and wildfires provide a better reference for how long it would take for claims payments to be made after a significant earthquake. New York State posted a 'report card' of various insurance companies' performance including their response times (New York Insurance Assistance, 2013) to Hurricane Sandy. The response of insurance companies after Sandy was much faster than other recent disasters including the 2003 Cedar fire in San Diego, 2007 Southern California wildfires, and 2005 Hurricane Katrina (Insurance Information Institute). These disasters were also considered in the development of the impeding curve for insurance claims delays. After Hurricane Sandy, approximately 18% of all claims closed without payment (New York Insurance Assistance, 2013). The impeding curve for insurance assumes that claims will be successfully awarded and that the insurance purchased covers the type of losses expected to be sustained.

Note that most insurance policies for residential buildings require a deductible on the order of 10 to 15% (EERI 1997), which in some cases could represent a substantial portion or the entire cost of repairs. Commercial policies typically require a deductible of 5% to 10% at minimum. For this reason, having earthquake insurance does not protect the owner from all liability. They will have to secure funds to cover any losses within the deductible in some other manner (e.g. loans) if they do not have the funds on hand. Insurance claims would not be initiated unless the losses exceed the deductible; there is no need to utilize the impeding curve for insurance claims delay in this case.

Possible Mitigation: One mitigation strategy is to essentially eliminate the need for financing by limiting the amount of financial losses to something within the organization's operating budget. An alternative to having funds in a reserve account, readily available in the case of a disaster, is to obtain a secured credit line as a contingency plan. This is not a typical bank product but it may be arranged on a case-by-case basis. The success for qualifying for such a product is based on a number of factors, including whether the owner has built up enough equity in the building (Delucchi and Funkhouser, 2013). The impeding curve for pre-arranged credit line shown below may only be used if such an arrangement is already in place at the time the loss assessment is conducted or assurance has been provided that it will be in place by the time construction is completed.

Impeding Curve: Financing represents the time needed to secure funds if the building owner does not have sufficient funds readily available.

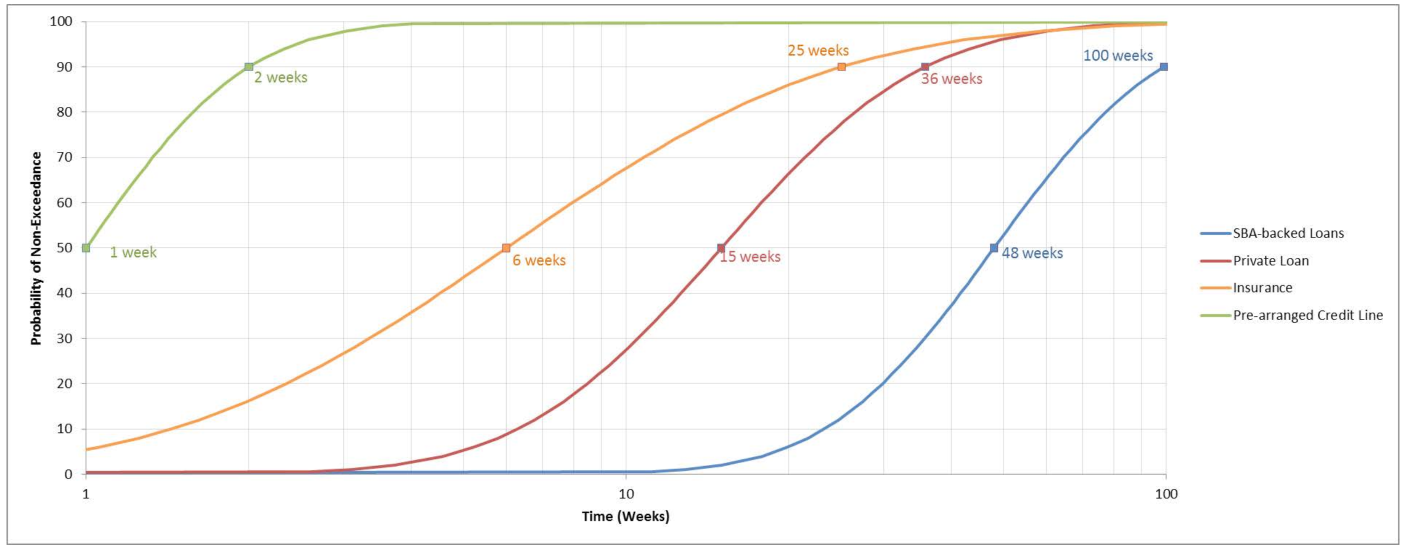

Figure 14. Impeding curves for financing repairs

Implementation:
The process of determining the appropriate delay due to financing for a particular recovery state is outlined below:

Re-Occupancy: Delays due to financing need to be considered if the maximum Repair Class is equal to 3 unless the Owner can guarantee availability of funds to cover the repair costs.

Functional Recovery: Delays due to financing need to be considered if the maximum Repair Class is greater than or equal to 2 unless the Owner can guarantee availability of funds to cover the repair costs.

Full Recovery: Delays due to financing need to be considered if the maximum Repair Class is greater than or equal to 1 unless the Owner can guarantee availability of funds to cover the repair costs.

The following additional guidelines are provided:

- **Calculate total repair cost for the recovery state considered.** Conservatively, the PACT financial loss estimates may be used since they represent the costs to achieve full recovery. Alternatively, component repair costs for a particular recovery state may be obtained by considering only the repair costs associated with the corresponding Repair Class.

- **Determine delay based on method of financing.** If the available funds are insufficient to cover the repair costs, then the appropriate impeding curve is selected based on the expected method of financing. Special consideration is needed for financing through insurance. If available funds are sufficient to cover the insurance deductible, then the impeding curve for insurance may be used. If there is insufficient funds to cover the insurance deductible, then funding for the deductible needs to be sought and the impeding curve for either the private loan or SBA-backed loan should be used. Unless the Owner qualifies for the borrowing criteria outlined above for private loans (which is much more difficult for small business owners), the impeding curve for the SBA-backed loan should be used. Note the funding limits for SBA-backed loans below. If the repairs and the deductible exceed $2M, it may be possible to obtain the additional necessary funding from alternative bank loans which consider future cash-flow, for example. If multiple sources of funding are used, the time associated with the longest delay should be used as the impeding factor.

- **Funding Limits.** SBA-backed loans are limited to $2M for business and $200k for residences. In addition, ensure that the insurance coverage is adequate for the repair costs considered.

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CONTRACTOR MOBILIZATION

Description: There are several factors which are critical contributors to the overall time required to mobilize a contractor:

- *Shortage of contractors* – After an earthquake there may be a demand surge for contractors to perform the necessary repairs. The lack of availability of contractors, materials, and equipment becomes a critical contributor to repair delays.
- *Severity of damage* – The amount of equipment, material, and labor that needs to be located and transported to the site would depend on the extent of damage.
- *Bidding* - Heavily damaged buildings would likely require a bidding phase for contract procurement since the losses are high and competitive bids would be sought.
- *Essential facilities* – Heavily damaged buildings that are essential to the post-disaster recovery process would likely take precedence.
- *Building height* – Heavy damage to tall buildings would require additional time to find and set up tower cranes.

The delay estimates for contractor mobilization do not account for long-lead time items (long-lead time items are accounted for as a separate impeding factor below). Note that the impeding curves for buildings taller than 20 stories are independent of whether the building is essential or not. This reflects the assumption that contractor mobilization delays for taller buildings are governed by the mobilization time for tower cranes.

Possible Mitigation: One mitigation strategy is to essentially eliminate the need for skilled contractors by designing the building to remain essentially elastic (REDi™ Platinum and Gold).

Otherwise, owners can avoid unnecessary delays due to contractor shortages by arranging contractual agreements with contractors to guarantee availability of their services immediately after an earthquake.

Impeding Curve: Represents the time required to find an available contractor in light of scarcity, complete the bidding process, secure site access, and transport necessary labor, equipment, and materials to the site.

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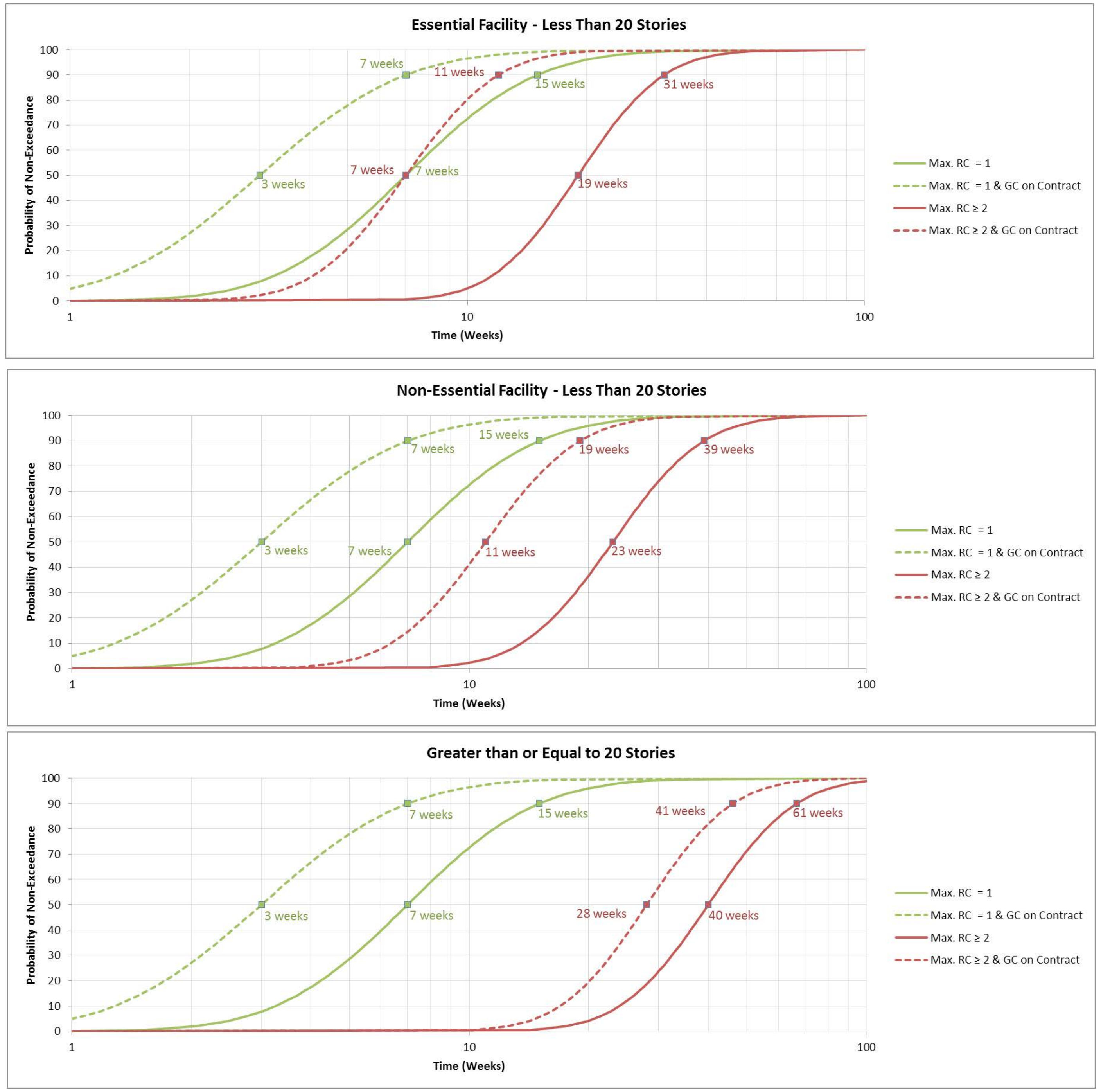

Figure 15. Impeding curves for contractor mobilization

Implementation:

Re-occupancy: Delays due to contractor mobilization should be considered if the maximum Repair Class of a component is equal to 3.

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Functional Recovery: Delays due to contractor mobilization should be considered if the maximum Repair Class of a component is greater than or equal to 2.

Full Recovery: Delays due to contractor mobilization should be considered if maximum Repair Class of a component is greater than or equal to 1.

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PERMITTING

Description: A permit approval from the local building jurisdiction would likely be required for buildings that exhibit structural damage, although the review process may be expedited in a post-earthquake recovery scenario to speed up recovery. The time required for review depends on the extent of structural damage. More complications arise for extensive repairs, and the re-issued drawings would need to be carefully evaluated, much like a typical permitting process. Repairs of certain non-structural components may also require permits, but these can usually be obtained 'over the counter' and do not account for significant delays (Kornfield, 2013).

Possible Mitigation: One mitigation strategy is to essentially eliminate the need for permits by designing the building to remain essentially elastic (REDi™ Platinum and Gold).

Impeding Curve: Represents the time needed for the local building jurisdiction to review and approve the proposed repair or re-issued drawings.

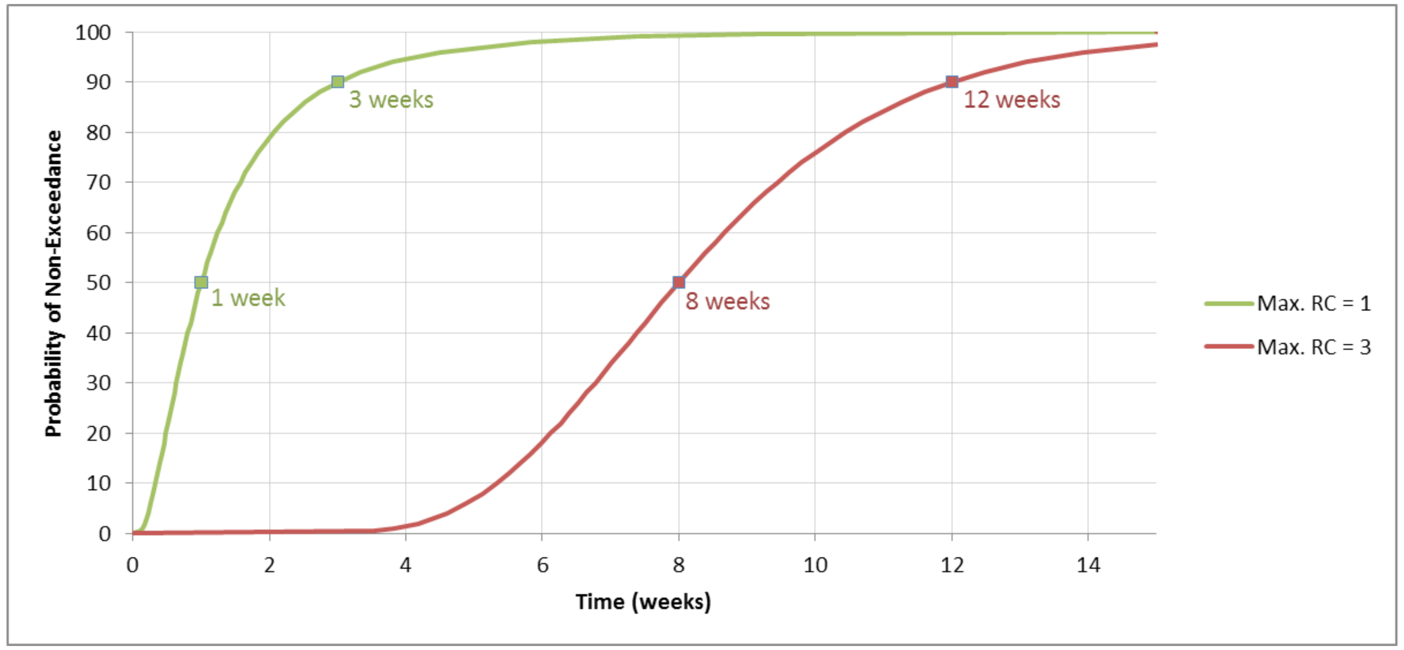

Figure 16. Impeding curve for permitting

Implementation:
Re-occupancy and Functional Recovery: Delays due to permitting should be considered if the maximum structural Repair Class is equal to 3.

Full Recovery: Delays due to permitting should be considered if the maximum structural Repair Class is greater than or equal to 1.

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LONG-LEAD TIME COMPONENTS

Description: There are some building components which require long procurement lead times – they are not readily available even in normal circumstances. These components include elevators, mechanical equipment, non-standard steel sections, buckling-restrained braces (BRB's), and other custom made components including facades, mission-critical contents, etc.

PACT's fragility database includes a long-lead flag for elevators and mechanical equipment, and additional components that are recommended to be treated as long-lead were identified in Table 5. Lead times vary on a case by case basis, so the user must identify the expected lead times for any components which must be replaced – that is, they are predicted by the loss analysis to suffer significant damage such that they are irreparable.

The contractor will order the replacements of long-lead components once they have been selected. The replacement of these components cannot be initiated until the long-lead items arrive on site so the repair schedule described above in "Downtime Due to Repairs" should be delayed accordingly.

Possible Mitigation: Protect long-lead time components from being damaged or store redundant long-lead time components off-site away from the expected earthquake-affected area.

Implementation: The delay due to the procurement of long-lead items is included at the end of the contractor mobilization phase. This long-lead time may hinder the repair of the corresponding component only, which would be applied at the start of the repair schedule for that component. Long-lead times do not hinder repairs of other components. The amount of time that must be accommodated at the beginning of the repair schedule is calculated by:

$$t_{LL,i} = t_{PR,i} - \left[t_{impeding} - \left(t_{inspect} + t_{CM}\right)\right] > 0$$

Where $t_{LL,i}$ is the long-lead time duration of component *i* applied at the start of the repair schedule, $t_{PR,i}$ is the time needed to procure the long-lead component *i*, $t_{impeding}$ is the total downtime due to delays (calculated in the following section), $t_{inspect}$ is time needed to perform building inspections, and t_{CM} is the time needed to mobilize a contractor. If $t_{LL,i}$ is negative, then the long-lead time will not hinder the initiation of repairs to that component.

See Table 4 and Table 5 for components which may require long-lead times. The user should confirm from the damage state description if the component can be repaired or if it must be replaced – if it requires replacement, the long-lead time delays must be considered.

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DELAY SEQUENCE

Once the delays for each impeding factor have been determined, these factors need to be combined. These values cannot simply be aggregated, since it is likely that these delays would occur simultaneously during the recovery period. Figure 17 depicts the expected sequence in which the delays would occur. The combination which yields the largest value would represent the delay to the initiation of repairs. Immediately following the earthquake, inspection may be necessary to determine if there is damage that could be possibly hazardous to the occupants.

From the observed damage during inspection, enough information would be available to determine whether a contractor, engineer, and financing is required. The owner is expected to start mobilizing a general contractor and if there is structural damage, to locate an engineer after the inspection has taken place. According to ATC-20, the inspection report may also estimate the financial loss of the building, at which point the owner could begin to secure sources of funding (ATC-20, 1989). These are assumed to occur simultaneously.

If structural repairs are necessary, permitting would occur following the re-issuance of drawings and/or calculations. If long-lead time components are damaged and require replacement, the delays for procuring them should be added after Contractor Mobilization as described above. In this case, replacement of the long-lead time components only would be delayed if that sequence represents the longest sequence of delays; other repairs can initiate once the next longest sequence of delays is concluded.

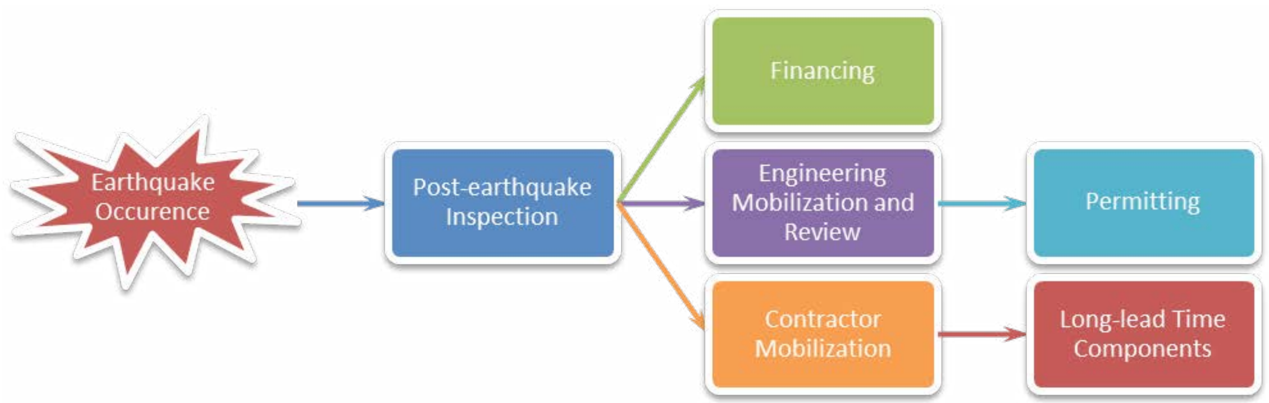

Figure 17. Sequence of delays due to impeding factors

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EXAMPLE: CALCULATING DOWNTIME DUE TO DELAYS

The calculation of downtime due to delays is illustrated using the example office building introduced in the "Example: Creating the Repair Schedule to Calculate Downtime" section. The example below assumes that no mitigation measures were undertaken by the owner to reduce the delay times.

Summary:
Additional building information is provided such that the contributions due to each impeding factor can be calculated:

- *Maximum Repair Class.* Figure 10 identified the building components that need to be repaired for functional recovery, which shows that the Repair Classes for these components are either 2 or 3. The maximum structural Repair Class is 3 since gravity connections were damaged. For non-structural components, significant cladding damage indicates that the maximum non-structural Repair Class is also 3 (see Table 5).
- *Long-Lead Times.* Figure 10 shows that mechanical equipment and elevator damage is present. As shown in Table 5, these components may require an additional long-lead time for procurement (it is assumed for this example that this is in fact the case). For the purposes of this example, it is also assumed that the lead-time for elevators and mechanical equipment are both 12 weeks.
- *Method of Financing.* Terzic et al. (2012) finds that the design level earthquake results in a median (Scenario Expected Loss) financial loss $3.75 million, which is about 23% of the original building cost. This example building is located in Oakland, which is a region of high seismicity. It is therefore assumed that the owner had obtained earthquake insurance for this building with a deductible of 5% of the building replacement cost.

Impeding Factor Contributions:
The calculation process for downtime due to delays begins with determining the contribution of each impeding factor. For this example, the 50% probability of non-exceedance values are used to determine the contributions from Figures 12 to 16, since this is consistent with the median repair times that were obtained for the example office building. The contribution due to each impeding factor is shown in Table 9.

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Table 8. Impeding factor contributions for example office building

Impeding Factor	Impeding Curve	Median Delay
Post-Earthquake Inspection	Non-Essential Facility	5 days
Financing	Insurance *SBA-backed Loans	6 weeks *48 weeks
Contractor Mobilization	Non-Essential Facility Less Than 20 Stories Max. RC = 3	23 weeks
Engineer Mobilization/Review	Max. Structural RC = 3	12 weeks
Permitting	Max. Structural RC = 3	8 weeks

*If reserve funds are not available for the deductible then it is assumed that SBA-backed loans are used to finance the deductible (deductible is 5% of the original building cost, which is $810,000. Since this is less than the $2 million limit for SBA-backed loans, the entire deductible can be financed through SBA-backed loans).

Delay Sequence:
We consider two examples below which consider two different methods of financing: one with no funds to finance the deductible, and one where funds are readily available (e.g. in a bank account). The one with no funds to finance the deductible is investigated first.

Figure 17 is used to sequence the delays due to impeding factors, and the total delay from each path is calculated. The longest delay path will represent the overall delay:

Path 1→Inspection + Financing(SBA-backed loans) = 5 days + 48 weeks = ***341 days***

Path 2→Inspection + Engineering Review & Mobilization + Permitting = 5 days + 12 weeks + 5 weeks = ***100 days***

Path 3→Inspection + Contractor Mobilization = 5 days +2 3 weeks = ***166 days***

Thus, Path 1 represents the critical delay path and the total downtime due to delays is 341 days. Note that this delay was assessed specifically for functional recovery, and delay downtime may be different for re-occupancy and full recovery.

Figure 10 indicates that elevators and mechanical equipment were damaged, which are long-lead components. Thus, the repair time of these components need to be increased by the anticipated delay

due to procuring these long-lead items. To illustrate this calculation process, it was assumed that all these components have a procurement time of 12 weeks. Thus, the time added to the repair time of these components is calculated as follows:

$$t_{LL,i} = t_{PR,i} - [t_{impeding} - (t_{inspect} + t_{CM})] = 12weeks - [341days - (47days)] = -304$$

This value is negative, so $t_{LL,i}$=0 days. Therefore, long-lead items have no impact on the repair schedule. The total delay downtime of 341days represents the delay downtime for the case where financing for the deductible was not readily available. If the owner does have adequate funds ($810,000) available, then the total downtime due to delays is revised to be:

Path 1→Inspection + Financing (Insurance only) = 5 days + 6 weeks = ***47 days***

Path 2→Inspection + Engineering Review & Mobilization + Permitting = 5 days + 12 weeks + 5 weeks = ***100 days***

Path 3→Inspection + Contractor Mobilization = 5 days + 23 weeks = ***166 days***

Thus, financing no longer controls the overall delay, and the critical delay path is now Path 3, with a delay of 166 days.

The overall delay time has changed, so the impact due to long-lead items need to be revised as well.

$$t_{LL,i} = t_{PR,i} - [t_{impeding} - (t_{inspect} + t_{CM})]$$

And in this case $t_{impeding} = t_{inspect} + t_{CM}$. Thus:

$$t_{LL,i} = t_{PR,i} = 12\ weeks$$

Therefore, repairs to elevators and mechanical equipment cannot commence until 12 weeks after the building repairs have begun. The repair schedule is updated to reflect this, and an example is shown in Figure 18.

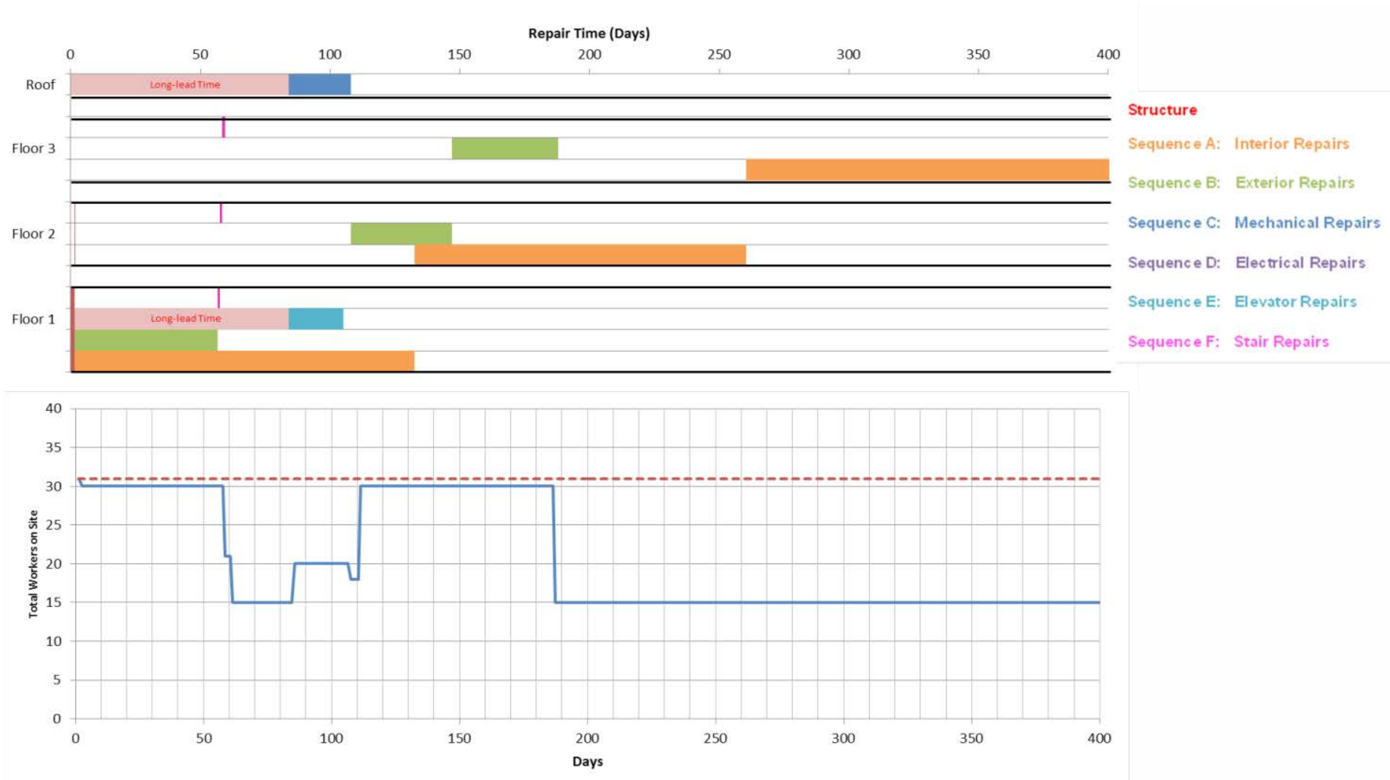

Figure 18. Updated example repair schedule to reach functional recovery with long-lead time included (top), schedule of number of workers on site (bottom)

The long-lead time needed for elevator and mechanical equipment repairs results in a delay of these component repairs. The repair schedule was altered from the previous example by initiating the Repair Sequence B (exterior repairs) on Floor 1 immediately after the completion of structural repairs. Due to the limitations of the total workers on site, this also meant that elevator, mechanical equipment, and stair repairs had to be delayed until Repair Sequence B repairs were completed on Floor 1. The repair schedule can be adjusted in this manner to accommodate for long-lead delays. It is also important to note that the long-lead delays to elevator and mechanical equipment repairs did not result in an overall repair delay, since it had no effect on the critical repair path.

DOWNTIME DUE TO UTILITY DISRUPTION

Electrical, water, wastewater, gas, and telecommunications systems are likely to be disrupted after a design level earthquake. Data from past earthquakes show that disruption times to electrical, water, and gas systems can be significant while disruption to telecommunication systems were found to be not as significant. Wastewater systems were found to principally cause sewage release into the environment rather than service disruption to customers.

Since utility service is required for functional and full recovery, delays due to utility disruption need to be considered for these recovery states, particularly if the recovery objectives are quick (i.e. Platinum). REDi™ Platinum buildings must use back-up systems to ensure continued functionality until utilities are restored and the predicted utility disruption times can be used to determine the extent of back-up capacity that is required to maintain functionality until the utilities are restored. While telecommunication and wastewater systems are not likely a significant source of disruption, contingency plans must still be made for REDi™ Platinum buildings (e.g. 72 hours minimum capacity for wastewater holding tank).

The methodology presented below was developed to provide engineers a simplified and rational approach for estimating utility disruption times for the purpose of contingency planning to satisfy the functional recovery resilience objectives in REDi™.

ACKNOWLEDGEMENT OF LIMITATIONS

The ability to predict utility disruption times is desirable, but there are several complications that make accurate predictions difficult to achieve. Utility systems are comprised of many components that form a complex network. These networks have varying degrees of redundancy, as well as interdependencies with other utility systems, which further complicates the overall network. All utility systems are widely distributed geographically, so the systems endure a wide range of seismic intensities and local site effects such as soil liquefaction.

Seismic resilience of the networks can also significantly differ geographically, and even between utility companies within the same region. If post-earthquake repairs are required, the number of available workers would strongly influence the disruption time. In addition, past earthquakes have shown that traffic disruption due to infrastructure damage can impede workers from reaching the damaged sites (Giovinazzi, 2011). These are just some of the factors that make determining utility downtime with reasonable accuracy a difficult task.

PURPOSE OF STUDY

Acknowledging these various limitations, a study was conducted to compare the measured disruption of utility systems in various past earthquakes. The purpose of the study was:

- To provide predictions of 'best estimate' utility disruption times.
- To identify whether individual components within the network show a pattern of vulnerability which govern the overall disruption of the system. This can be used to narrow down the causes and

extent of utility disruption.

- To create utility disruption curves for each utility system, based on restoration data acquired from utility companies that were exposed to a strong level of shaking and predicted disruption times from various published reports.

EARTHQUAKES CONSIDERED
Several moderate to large magnitude earthquakes which impacted regions with modern infrastructure were studied. The studied earthquakes include Loma Prieta (1989), Northridge (1994), Kobe (1995), Niigata (2004), Maule (2010), Darfield (2010), Christchurch (2011), and Tohoku (2011). Although some of these earthquakes did not necessarily represent 'design level' scenarios at most locations of the impacted regions, the utility disruption values were obtained such that lower-bound estimates could be made.

In addition, we also included estimated utility disruption times from studies that considered future earthquakes. These include The Oregon Resilience Plan (2013), Resilient Washington State (2012), LA Shakeout Scenario (Davis & O'Rourke, 2011), and San Francisco Lifelines Council (Johnson, 2013).

UTILITY PERFORMANCE ASSESSMENT FROM PAST EARTHQUAKES
Damage to various utility systems and associated disruption documented by a variety of sources were analyzed, including published journal papers and reports written by utility companies and/or their representatives. Disruption times, speed of recovery, component damage, and critical observations were recorded. A summary of findings is presented in Table 10. For each utility system, the severity of damage to service-critical components , primary source of overall disruption, and the time required to achieve various levels of restoration were recorded. Restoration does not necessarily indicate that pre-earthquake redundancies are restored. In addition, water system restoration refers to restoration of water delivery, but not necessarily restoration of water quality (boiling water notices removed), and quantity (water rationing removed). For all utilities, the extent of damage to service-critical components is assessed qualitatively (such as minor, moderate, or severe damage). These assessments were usually provided in the analyzed reports, and if not explicitly stated, qualitative assessments were made by the authors based on the description of damage. For distribution systems, such as water and gas mains, it is common practice for damage to be quantified by repair rate, which is the number of repairs conducted on distribution mains divided by the total length of mains.

Based on the findings of the study, the following observations were made for each utility system:

- **Electrical** – Electrical systems recover quickly, ranging from 2 to over 14 days for full service restoration for the earthquakes studied. Electrical systems generally perform better than other utility systems because of their high level of redundancy; power can be re-routed to bypass damaged facilities, and can even supply additional power through other utility companies outside the earthquake impact area. Power generating stations and transmission lines performed well in all earthquakes that were studied, as they suffered minor to no damage in all cases. Substations, on the other hand, have shown vulnerability in almost all earthquakes, and governed the disruption times in the Loma Prieta and Northridge earthquakes (Schiff and Matsuda, 1998; Lund et al., 1995). However, electricity was restored in less than 3 days in both of those earthquakes, indicating that damage to substations may not be a contributor to lengthy disruption. Severe damage to distribution systems, which is particularly evident in cases with severe liquefaction, caused the longest disruption times within the earthquakes that were studied. Therefore, the extent of damage to distribution systems likely govern the electricity disruption times.

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- **Water** – Water system disruption times are extensive in all earthquakes, ranging from 6 days to 10 weeks for full service restoration in the earthquakes studied. Water reservoirs tend to perform well, with the exception of a failed reservoir after the Christchurch earthquake, which serviced the central business district (CBD). However, water delivery was not needed in the cordoned CBD, so there was no impact in the overall water serviceability after the earthquake (Eidinger et al., 2012). Water treatment plants, storage tanks, and transmission lines have shown varying performance in all earthquakes. However, past earthquakes have shown extensive failures in distribution pipes, particularly smaller diameter pipes that traverse through liquefaction zones, which have shown to comprise the bulk of earthquake damage to water systems (Eidinger, 2012). The extent of disruption shows some correlation with the average repair rates of distribution mains. The Loma Prieta, Northridge, and Niigata events had repair rates less than 0.2 repairs/km, and complete service restoration was achieved within 2 weeks. The Kobe, Maule, and Christchurch events, which had repair rates greater than 0.4 repairs/km, had significantly higher disruption times, ranging from 4 to 10 weeks. The exception to these trends was the Darfield event, where the Kaiapoi and Christchurch water systems had average repair rates of 1.62 repairs/km and 0.42 repairs/km, respectively, but had complete service restoration achieved within 6 days. The high restoration rates in the Darfield event could be attributed to the relatively small size of the towns of Kaiapoi and Christchurch, where less distance would need to be covered to reach each repair.

- **Natural Gas** – Natural gas systems saw the most scatter in disruption and recovery time between earthquakes. Gas restoration ranged from 7 to 84 days for full service restoration. Service-critical components in the natural gas system performed well, but the major cause of disruption for most earthquakes was re-lighting and re-pressurizing the gas services to individual buildings after the gas was shut off for safety purposes. In the earthquakes studied, this took between 2 weeks to a month. The distribution systems tend to perform well, which could be attributed to the material type used in gas pipelines. Some gas systems, particularly newer or retrofitted systems, utilize polyethylene piping, which has shown superior performance in past earthquakes, even in areas of severe liquefaction (Eidinger, 2012). The Darfield and Christchurch earthquakes highlight this, as their gas network of 100% medium density polyethylene piping (MDPE) had no necessary repairs after both seismic events. However, events such as the Kobe earthquake highlight the potential vulnerability of distribution systems that do not utilize polyethylene piping – Kobe water distribution system mainly consists of ductile iron with threaded joints– which can lead to a substantial amount of disruption. For the Kobe earthquake the density of the urban environment also was a significant factor, as damaged buildings and infrastructure limited accessibility to repair locations (Chung, 1996).

- **Wastewater** – Damage to wastewater treatment plants and loss of power frequently resulted in raw sewage being released into the environment. However, damaged treatment plants typically

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do not result in loss of service to building occupants. Severe damage to sewage pipes can result in loss of service, but portable toilets are installed as a temporary solution. The response after the Christchurch earthquake illustrates a severe case, where significant damage to the sewage treatment plant led to heavy reliance on portable toilets for several months (Giovinazzi, 2012).

Wastewater systems can suffer extended durations of service disruptions, but the principal consequences of loss of service is waste discharge into the environment and temporary portable toilets set up for building occupants. Thus, occupants still have access to wastewater service even in these circumstances.

- **Telecommunication** – Telecommunication systems typically experience problems due to heavy call volume and insufficient backup power. However, telecommunication systems are available once power is restored, and in most cases core networks are operable and are available immediately after the earthquake if backup generators at the utilities are available. We recommend using the restoration curves developed for electricity as a proxy for telecommunication disruption.

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Table 10. Summary of utility system performance in past earthquakes

	Loma Prieta 1989	Northridge 1994	Kobe 1995	Niigata 2004	Maule 2010	Darfield 2010	Christchurch 2011
Magnitude M_w	6.9	6.7	6.9	6.6	8.8	7.1	6.3
Range of PGA	0.07 - 0.65[1] (0.33 in SF)[1]	.17 - .94[1]	-	-	0.3 in Concepcion[3]	0.18 - 0.35 (Urban) 0.5-0.9 (Epicenter)	-
Liquefaction	Minor	Minor[3]	Severe	-	Severe	Severe[1]	Severe[1]
Electrical Systems							
Power Generating Stations	Minor	Minor	Minor	-	-	-	-
Substations	Severe	Moderate	Moderate	-	Minor	Minor	Moderate
Transmission Lines	No Damage	Minor	Moderate	-	Minor	No Damage	Minor
Distribution Lines	Minor	Minor	Severe	-	Severe	Severe in Liquefaction Zones	Severe
Duration to Complete Service Restoration	2 days	3 days	6 days	Over 8 days	14 days	4 days	Over 14 days
Primary Source of Overall Disruption	Substations[1]	Substations[2]	Distribution	-	Distribution[2]	Distribution	Distribution[1]
Water Systems							
Water Reservoir/Wells	Undamaged[1]	Minor[2]	Minor[1]	No Damage	-	Moderate Damage to Wells	Failure of 1 Reservoir
Water Treatment Plant		Minor[2]	Moderate[2]	Moderate	Severe[3]	-	-
Water Storage Tanks	Damaged[1]	Severe[2]	Minor[1]	Minor	Severe[4]	Minor[1]	Minor[1]
Pumping Plants		Lost power	Lost power[2]	-	Severe[4]		
Water Transmission	Undamaged[1]	Severe[3]	Severe[2]	-	Severe	-	-
Distribution Main Repair Rate (Repairs/km)	0.02	0.10	0.44	0.20	0.83	0.42	0.96
Duration to Complete Service Restoration	2 weeks[1]	1 week[3]	10 weeks	2 weeks[1]	5 weeks[4]	6 days	Over 1 month
Primary Source of Overall Disruption	Distribution	Transmission & Distribution[3]	Distribution	Distribution	Transmission & Distribution[4]	Distribution	Distribution

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	Loma Prieta 1989	Northridge 1994	Kobe 1995	Niigata 2004	Maule 2010	Darfield 2010	Christchurch 2011
Gas Systems							
Gas Storage Field/Distribution Stations	Out of Impact Zone	Moderate	No Significant Damage[1]	-	-	-	-
Gas Transmission	Virtually Undamaged[1]	Minor[2]	Moderate	-	-	-	-
Gas Distribution Repair Rate (Repairs/km)	Nearly 0	0.011	0.60	-	-	0	0
Duration to Complete Service Restoration	1 month[1]	Over 1 month[1]	84 days	28 days[1]	-	No Disruption[1]	14 days[2]
Primary Source of Overall Disruption	Re-lighting[1]	Re-lighting[2]	Distribution[1]	-	-	-	Re-pressurizing[1]
Wastewater							
Treatment Plants	Lost power	Lost power	-	-	Severe[1]	Severe	Severe
Sewage Lines	Similar damage as Water Systems	Severe in liquefied areas	-	-	Severe[1]	Severe	Severe
Waste Discharge into Environment	Minor during power loss	-	-	-	Yes[1]	Yes[1]	Yes[1]
Duration to Complete Service Restoration	No disruption	No disruption	No disruption	-	Over 6 weeks[1]	-	-
Primary Source of Overall Disruption	-	-	-	-	Reclamation Plants and Sewage Lines[1]	-	-
Telecommunications							
Building Damage	-	Minor	-	-	Severe[1]	No Damage	No Damage, but inaccessible in CBD[1]
Equipment	-	-		-	Severe[1]	Minor	Minor
Cable	-	-	-	-	Severe[1]	Severe	Severe
Duration to Complete Service Restoration	Congestion lasted for 4 days[2]	Within 1 day	Congestion lasted for 5 days	-	Over 17 days[2]	2 days[1]	
Primary Source of Overall Disruption	Congestion	Switch Failures	Congestion	-	Power Failure	Power Failure	Power Failure
References							
Sources	[1] NRC, 1994 [2] Schiff, et al., 1990	[1] Schiff, et al., 1997 [2] Lund L. V., et al., 1995 [3] Davis, et al. 2012	[1] Chung, et al., 1996 [2] Kuraoka & Rainer, 1996	[1]Scawthorn, et al., 2006	[1] EERI, 2010 [2] Evans & McGhie, 2011 [3] TCLEE, 2011 [4] Eidinger J. M., 2012	[1] Eidinger, et al., 2012 [2]Knight, et al., 2011	[1] Eidinger, et al., 2012 [2] Giovinazzi, et al., 2011

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UTILITY DISRUPTION CURVES

Utility disruption curves for electric, water, and gas systems were developed, for a design level earthquake, based on qualitative fitting of restoration curves obtained from previous earthquakes and predicted disruptions from several studies of hypothetical design level earthquakes noted above. These are presented in Figure 19.

The utility disruption curves are plotted based on the number of days required to restore service to customers that lost service immediately after the earthquake. It is assumed that utility disruption will occur. The left axis (% Recovery) can be interpreted as the likelihood that the utility will be restored to your building within the corresponding timeframe. They are largely based on the performance of distribution systems, which our studies indicate governed the disruption times for utilities. That is, even in the case where generation stations, sub-stations, or plants were damaged, the repairs required to distribution or transmission lines governed the disruption times. Restoration of water services only includes recovery of water delivery (water quality and quantity restoration is not considered).

Utility disruption curves for water and gas are based on the average repair rate of buried distribution pipe mains, which indicate the severity of damage and hence, the expected disruption. Repair rates for electric distribution systems were not tabulated in the reports studied so the restoration curve for electricity is independent of repair rate. HAZUS determined repair rates for buried water pipelines based on O'Rourke & Ayala (1993). Their work has been updated in O'Rourke & Deyoe (2004), and is independent of pipeline material and is consistent for ground deformations measured in either wave propagation speed or permanent ground displacement. We use their work as the basis for calculating average repair rate. For cases where contributing earthquake scenarios (from deaggregation of the design level earthquake hazard) have a ratio of epicentral distance to focal depth of 5 or larger, R waves (a.k.a. surface waves) are assumed to control the ground strains. For ratios of epicentral distance to focal depth of smaller than 5, S waves (a.k.a. body waves) are assumed to control the ground strains. O'Rourke and Deyoe (2004) provide the following relationship to calculate repair rate (in repairs/km) based on peak ground velocity (Vmax in cm/s):

$$RR_R = 0.034 V_{max}^{0.92} \quad \text{for R waves}$$

$$RR_S = 0.0035 V_{max}^{0.92} \quad \text{for S waves}$$

The plots on the left of Figure 19 should be used if RR ≤ 0.2 repairs/km, and the one on the right should be used if RR > 0.2 repairs/km. We assume that the repair rate calculated at the building site can reasonably represent the local damage to the distribution system and therefore represents a good indicator of utility disruption times since utilities cannot be restored until the local distribution system is repaired.
The estimated utility disruption times should be cross-referenced against region-specific forecasts by experts (see "Earthquakes Considered" above) and local utilities if they exist and the most applicable predictions should be used.

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It was previously mentioned that polyethylene piping has shown superior performance in past earthquakes. If it is known that the utility company servicing the building under consideration uses more than 80% polyethylene piping for the network servicing the building, then the average repair rate can automatically be assumed to be less than 0.2 repairs/km.

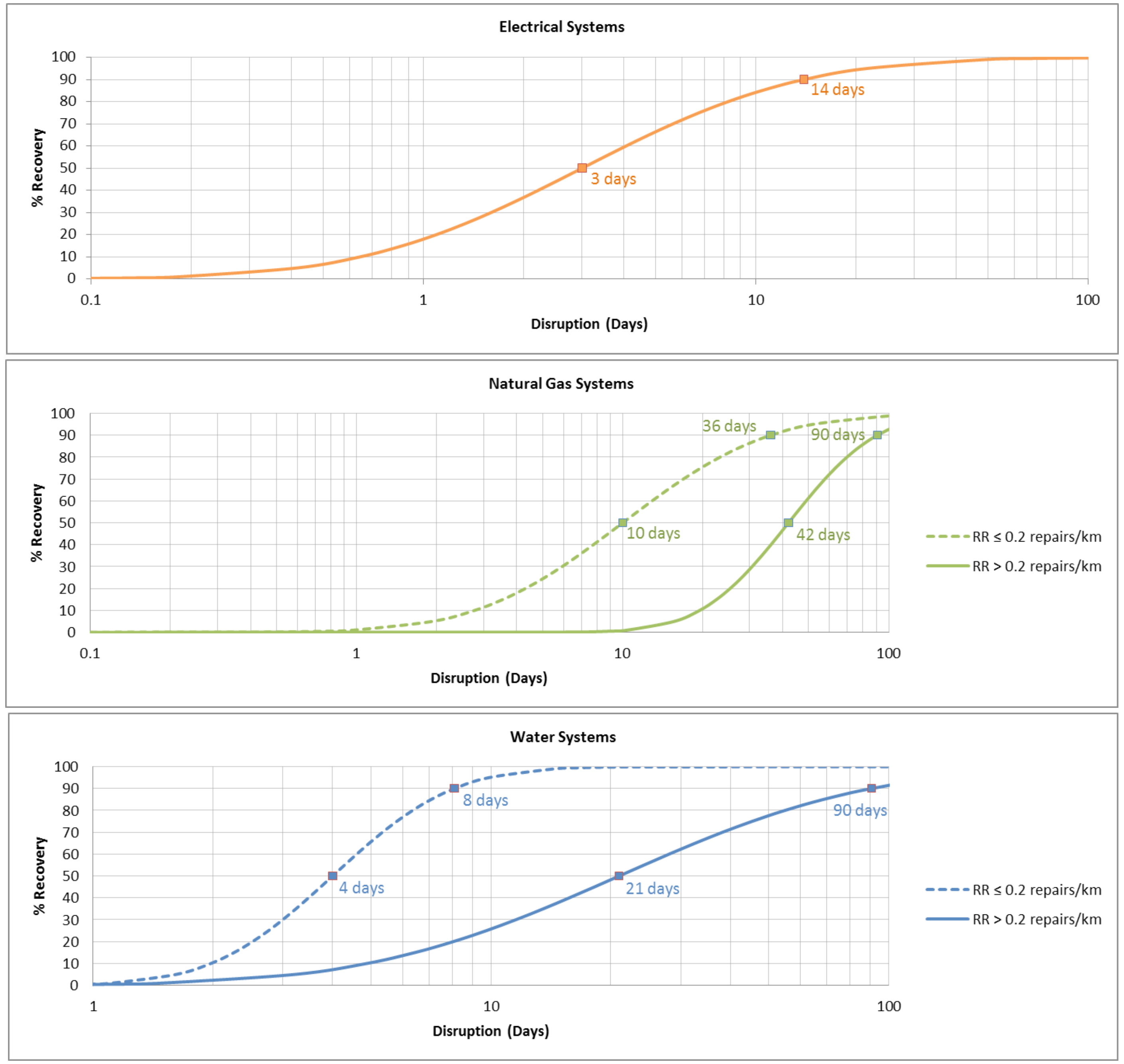

Figure 19. Utility disruption functions - electrical (top), water (middle), gas (bottom)

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EXAMPLE: CALCULATING UTILITY DISRUPTION

Summary:
The process for calculating the expected utility disruption for the example office building will be presented. Here, downtime due to utilities is governed by the extent of damage sustained by the utility provider, and is therefore independent of the damage sustained by the building under consideration. Note that utility disruption only needs to be considered for functional and full recovery. The calculation for the example office building is for downtime to reach functional recovery, so utility disruption needs to be considered. Also note that for Gold and Silver buildings, the utility disruption times may be capped by 1 month and 6 months, respectively.

Terzic et. al (2012) specifies that ground motions were selected for a building located in Oakland, California on stiff soil (site class D with V_{s30} = 180 to 360 m/s). The building is assumed to be located about 5 km from the Hayward fault. The hazard is therefore likely dominated by M_w 7.0 earthquakes (the characteristic maximum magnitude on the Hayward fault). Based on the Next Generation Attenuation (NGA) relationships, the PGV can be calculated for this scenario to be V_{max} = 50 cm/s. Since the ratio of the epicentral distance to the focal depth is approximately 1 (less than the given limit of 5), the ground strains are assumed to be controlled by R waves.

Utility Disruption:
To be consistent with the other examples, the 50% probability of non-exceedance values for utility disruption are selected for each utility system. For a peak ground velocity V_{max} = 50 cm/s with R wave dominance, the average repair rate RR for water and gas systems is calculated to be:

$R_{RR}=0.034V_{max}^{0.92} = 1.24$ repairs/km

Thus the disruption curves with RR > 0.2repairs/km need to be used.

From Figure 19 the utility disruption for each system is found to be:

Electrical Systems: ***4 days***
Water Systems: ***21 days***
Gas Systems: ***42 days***

CALCULATING TOTAL DOWNTIME

The downtime due to delays, repairs, and utility disruption are combined to represent the total downtime for the building. Downtime due to delays and utility disruption occur simultaneously after the earthquake occurrence, and downtime due to repairs follows the downtime due to delays. The time needed to complete all three sources of downtime represents the total downtime to achieve the recovery state under consideration.

The flow chart for downtime calculation of each recovery state is presented in Figure 22 through Figure 24.

EXAMPLE: TOTAL DOWNTIME CALCULATION

The overall schedule showing the chronology of delays, utility disruption, and building repairs which contribute to achieving functional recovery for the example office building presented previously is shown in Figure 20 for the case where the insurance deductible was financed through SBA-backed loans, and Figure 21 for the case where the owner had sufficient funds available to pay for the deductible. In both cases, utility disruption does not govern the time required to achieve functional recovery. The downtime due to delays and building repairs amount to 742 days for the first case (where the deductible is financed through SBA-backed loans) and 567 days for the second case (where funds are available to finance the deductible).

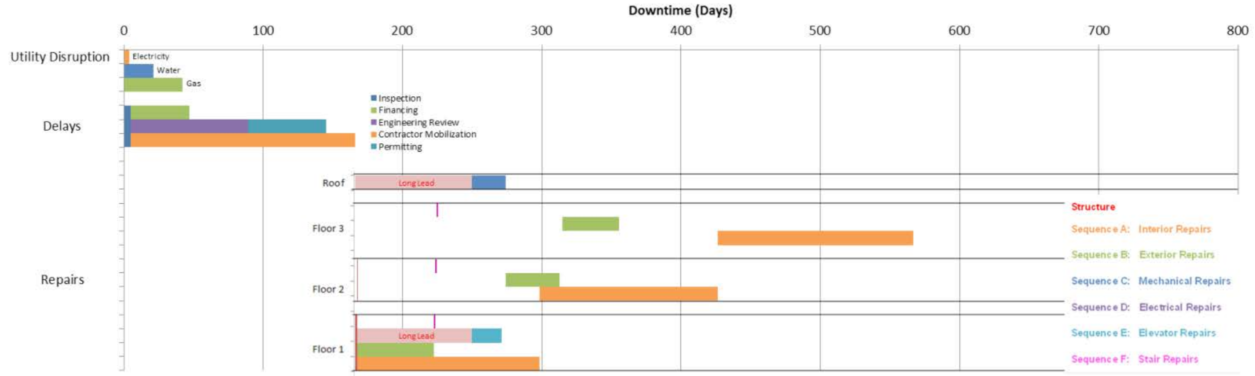

Figure 20. Total downtime timeline - insurance deductible is financed through SBA-backed loans

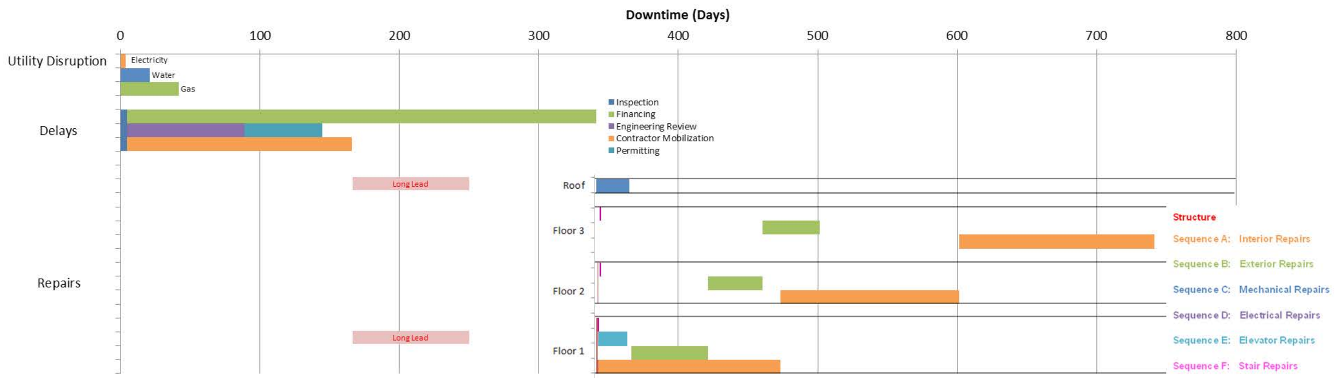

Figure 21. Total downtime timeline - pre-arranged funds are available to finance deductible

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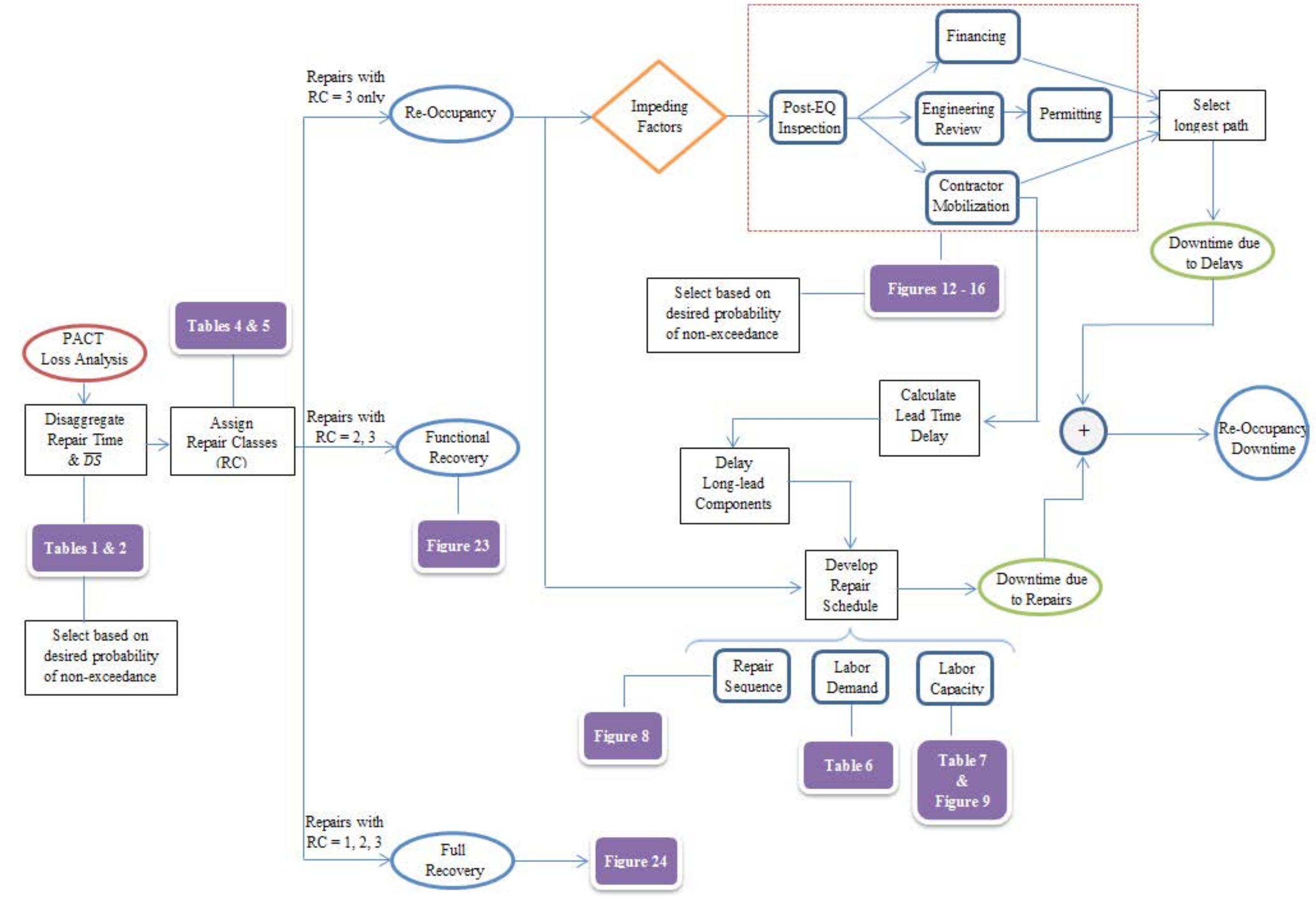

Figure 22. Flow chart for calculating the time required to achieve Re-Occupancy

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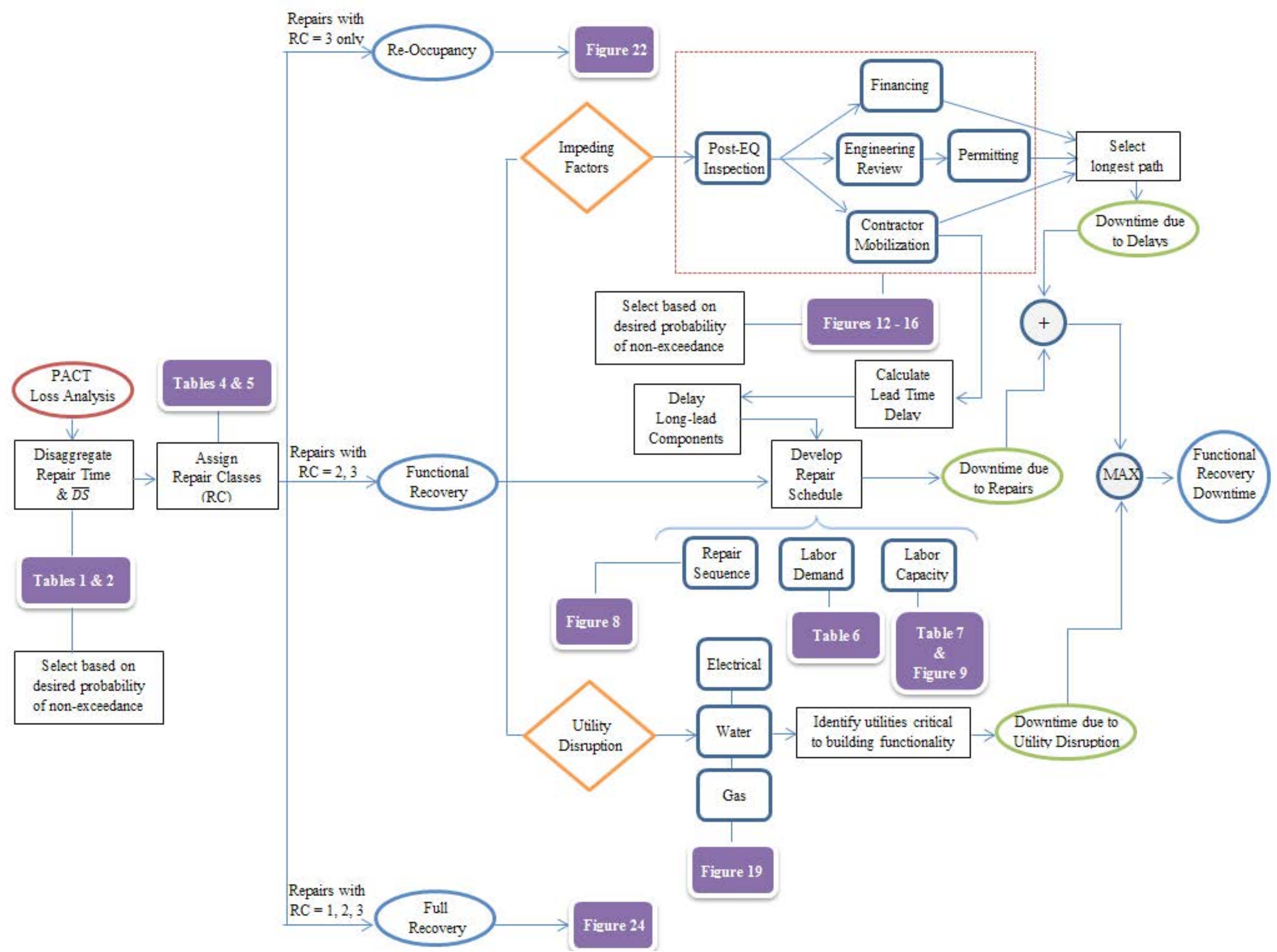

Figure 23. Flow chart for calculating the time required to achieve Functional Recovery

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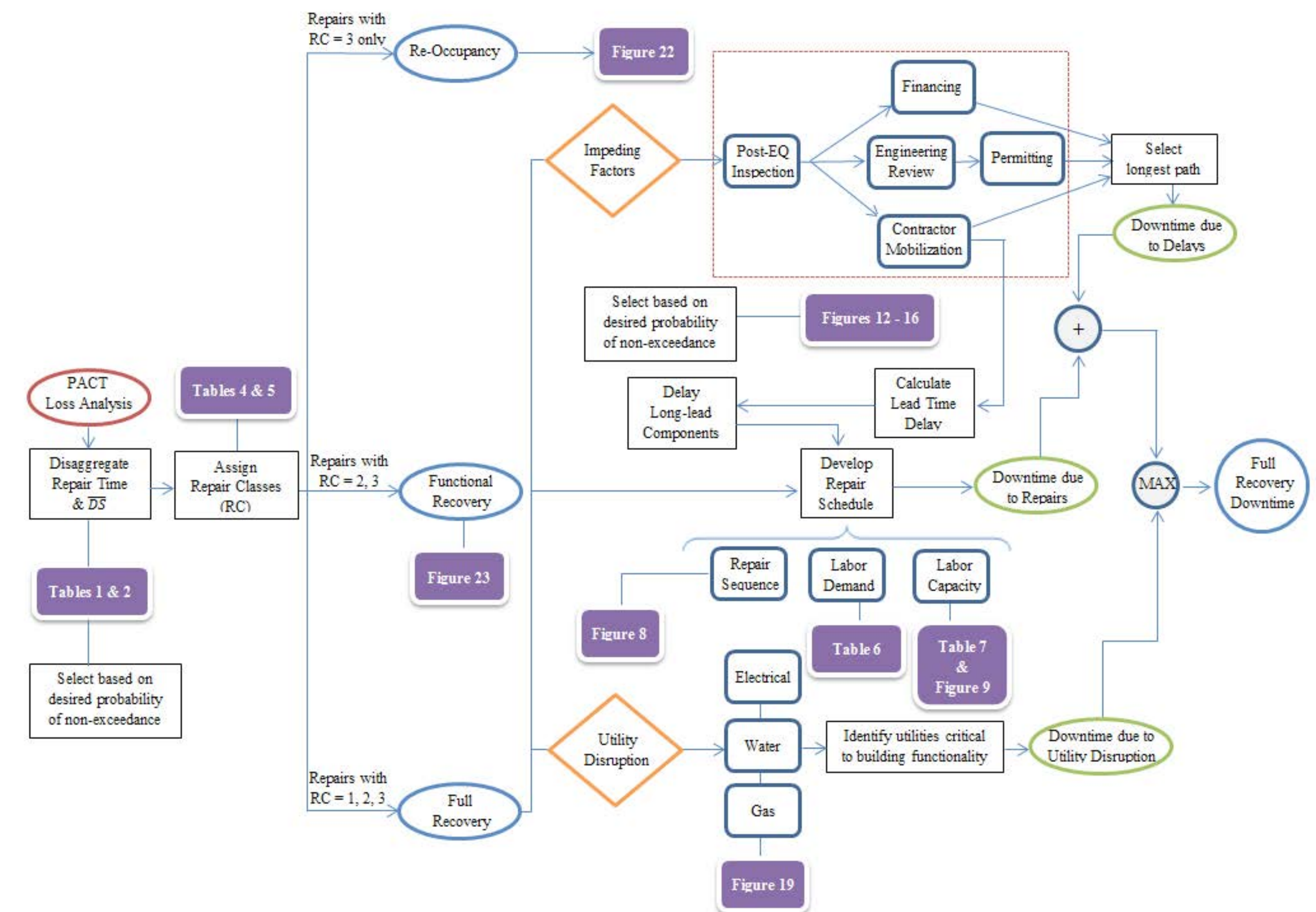

Figure 24. Flow chart for calculating the time required to achieve Full Recovery

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CONCLUSIONS

The methodology presented in Section A4.3 was specifically developed to enable the calculation of the time required to achieve re-occupancy and functional recovery after a design level earthquake, in order to satisfy the resilience objectives associated with the desired REDi™ rating.

While the REDi™ resilience objectives correspond to 'best estimate' (50% probability), the authors note that given the uncertainty, it may be prudent to use the 90% values for contingency planning purposes.

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