THE REDi™ RATING SYSTEM: A FRAMEWORK TO IMPLEMENT RESILIENCE-BASED EARTHQUAKE DESIGN FOR NEW BUILDINGS

I. Almufti\(^1\) and M. Willford\(^2\)

ABSTRACT

The earthquake performance objective of national building codes for the vast majority of buildings is to provide “life-safety” for building occupants in design level earthquake shaking. The code accepts that damage to the building structure, architectural components and facades, mechanical/electrical/plumbing (MEP) equipment, pipes, ducts and building contents may occur and that damage may not be economically repairable. Damage leads to direct economic losses (cost of earthquake repairs) and indirect losses (due to downtime while the building is non-functional). This can impact the recovery of communities for years or even decades after an earthquake.

It is time we shift our thinking in terms of what is desirable and acceptable building performance in major earthquakes, in part because it is now possible to achieve far greater resilience at minimal additional investment. In recognition that the recovery of entire communities and organizations may be compromised by the “life-safety” performance of individual buildings, we believe it is time for a step-change in the way building design is approached. With the support of a group of stakeholders and multi-disciplinary design professionals, we have developed the REDi™ rating system \([1]\) to provide owners, architects and engineers with a framework for implementing “resilience-based earthquake design”, a holistic design, planning, and verification approach for achieving “beyond-code” seismic resilience. It is written as a set of guidelines with specific criteria (based on the rating desired - Platinum, Gold, or Silver) which aim to minimize building damage and promote contingency planning for utility disruption and other threats to recovery. The success of the resulting design in meeting quantitative financial loss and downtime resilience objectives corresponding to each rating tier is then demonstrated by performing a modified FEMA P-58 loss assessment developed specifically for REDi™.

\(^1\)Senior Structural Engineer, Arup, San Francisco, CA 94105
\(^2\)Principal and Arup Fellow, Arup, San Francisco, CA 94105

THE REDi™ RATING SYSTEM: 
A FRAMEWORK TO IMPLEMENT RESILIENCE-BASED 
EARTHQUAKE DESIGN FOR NEW BUILDINGS

I. Almufti¹ and M. Willford²

Abstract

The earthquake performance objective of national building codes for the vast majority of buildings is to provide “life-safety” for building occupants in design level earthquake shaking. The code accepts that damage to the building structure, architectural components and facades, mechanical/electrical/plumbing (MEP) equipment, pipes, ducts and building contents may occur and that damage may not be economically repairable. Damage leads to direct economic losses (cost of earthquake repairs) and indirect losses (due to downtime while the building is non-functional). This can impact the recovery of communities for years or even decades after an earthquake.

It is time we shift our thinking in terms of what is desirable and acceptable building performance in major earthquakes, in part because it is now possible to achieve far greater resilience at minimal additional investment. In recognition that the recovery of entire communities and organizations may be compromised by the “life-safety” performance of individual buildings, we believe it is time for a step-change in the way building design is approached. With the support of a group of stakeholders and multi-disciplinary design professionals, we have developed the REDi™ rating system [1] to provide owners, architects and engineers with a framework for implementing “resilience-based earthquake design”, a holistic design, planning, and verification approach for achieving “beyond-code” seismic resilience. It is written as a set of guidelines with specific criteria (based on the rating desired - Platinum, Gold, or Silver) which aim to minimize building damage and promote contingency planning for utility disruption and other threats to recovery. The success of the resulting design in meeting quantitative financial loss and downtime resilience objectives corresponding to each rating tier is then demonstrated by performing a modified FEMA P-58 loss assessment developed specifically for REDi™.

Introduction

The basic objectives for “code” seismic design of buildings have not changed since the first SEAOC Blue Book introduced performance objectives in 1960 [2]. These remain that buildings should resist minor earthquakes without damage but that damage (but not collapse) to both the structure and non-structural elements is permitted in major earthquakes. Therefore the code intent for the vast majority of buildings is to provide “life-safety” for building occupants; but not to ensure functionality after a large earthquake. Earthquake engineering practitioners and

¹Senior Structural Engineer, Arup, San Francisco, CA 94105
²Principal and Arup Fellow, Arup, San Francisco, CA 94105

academics have largely focused on developing ductile structural systems which can sustain high levels of damage before collapsing in order to achieve the “life-safety” objective more economically. It is therefore not surprising that when a major earthquake strikes an urban region the losses due to damaged buildings and infrastructure are immense. Typically losses are measured in terms of repair or rebuilding costs, but the indirect losses due to downtime - the inability of people to return to their homes or their jobs - which include loss of economic activity, culture, sense of community, and quality of life may be even greater. These losses are harder to quantify but typically impact communities for years and even decades after an earthquake. Modern building codes have contributed tremendously to protecting against loss of life but they are also part of the problem; they have contributed to a false sense of security among the public, building owners and tenants that building performance in a major earthquake will be much better than what the code actually provides [2]. The achievement of “life-safe” buildings is a major accomplishment of 20th century research and code development. But we should be aiming for better still in the 21st century, aligning objectives with public expectations.

It is now possible to design resilient buildings that will suffer little damage in major earthquakes at minimal cost premium. This is made possible by the availability of reliable proven seismic protection devices, and through the use of computer simulation (based upon improved knowledge of structural behavior) enabling engineers to realistically predict the earthquake demands on buildings. Very modest changes to conventional non-structural details can greatly reduce their susceptibility to damage. The consequences of damage in terms of financial loss and repair time can ultimately be used to benchmark performance. Components that contribute significantly to the losses can be re-designed to improve performance and in combination with contingency planning, allows designers to protect owners’ assets and business continuity in addition to providing life safety.

We have developed guidelines and criteria to facilitate a beyond best-practice design, planning, and verification approach based on lessons learned from past earthquakes and by identifying limitations in the traditional code approach. We packaged these into a single integrated and actionable framework named the REDi™ Rating System which can be used as a tool to communicate earthquake risk to stakeholders and to implement resilience-based earthquake design. The purpose of this paper is to summarize the motivation for resilience-based seismic design and to describe the framework and resilience objectives which form the basis for the REDi™ Rating System. A detailed description of all the provisions and methods is beyond the scope of this paper but the reader is referred to [1] where the full provisions are available for download.

**Code-based Design and Predicted Consequences**

Code design provisions have evolved 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 current seismic provisions [3] intend that the probability of collapse for new buildings should not exceed approximately 10% in the risk-targeted Maximum Considered Earthquake (MCE_R). In many regions the MCE_R corresponds to the 2475 year return period, but many near-fault sites are
governed by a deterministic limit which implies that the collapse probability is higher than 10% for buildings located there. At the “design level” (ground shaking levels 2/3 of the MCEq level) the intent is that new buildings should be “life-safe”. This means that occupants should be able to egress from the building, but it does not imply that the building could be re-occupied or be operational, or indeed whether repair would be economically feasible or not. The ramifications of this have not been quantified until recently, and are still not clearly understood by building owners and the public.

The direct financial losses for code-designed frame buildings subjected to “design level” shaking have been recently estimated by several researchers at higher than 20% of total replacement value [4,5,6]. Ramirez and Miranda [7] found that code-designed 4-story and 12-story concrete frame buildings in Los Angeles are estimated to suffer 42% and 34% direct financial losses, respectively, in the “design level” earthquake. Their study explicitly included the probability that permanent (residual) drift, which is an important indicator of reparability, would cause a total loss. These loss studies adopted the robust methodology for predicting damage and calculating repair costs originally developed by the Pacific Earthquake Engineering Research center (PEER) which has become the state-of-the-art loss assessment outlined in FEMA P-58 [10].

While there are few data points currently available for downtime, the expectation is that code-designed buildings may be unusable for more than 1 year [4,8], though empirical evidence suggests these may be underestimated [9]. Downtime is arguably more important than direct financial loss because it relates directly to actual recovery, which is intuitively understood by stakeholders. In the past direct financial loss has been the de facto measure of earthquake risk because it is used to price insurance. Downtime has been more difficult for engineers to predict than financial loss since there has not been a consensus approach adopted by the industry. An improved downtime methodology which builds upon FEMA P-58 repair times and considers delays to initiation of repairs has been developed for implementation in the REDi™ guidelines (see “Improved Downtime Methodology”).

The expected performance of essential facilities has not been quantified using a FEMA P-58 approach. The intended performance, described in the 2012 International Building Code [11], is for these facilities to remain operational after a design level earthquake. But the NEHRP [12] commentary seems to contradict this – a performance matrix shows it to be only “immediate occupancy” in a design level earthquake. Nevertheless, essential facilities are expected to perform better than ordinary buildings. However, it is far from certain whether the seismic design requirements for essential facilities, which include consideration of higher design forces, lower drift limits, and verification of MEP equipment performance, would result in operational performance since performance is typically not explicitly verified. It is also not clear whether the code design requirements for essential facilities result in the most cost effective solutions for achieving high performance [13].

**Motivation: Observed Consequences of Code-based Design**

There has not been a “design level” earthquake in the United States in recent memory. Northridge and Loma Prieta produced design level intensity shaking in discrete locations but in general these would not be categorized as “design level” earthquakes. Perhaps the best recent example of what “life-safety” performance looks like on a citywide scale is in Christchurch, New
Zealand. Christchurch is a city containing buildings of various ages. The code seismic design provisions in New Zealand and the USA are similar both in terms of performance objectives and the structural systems that are employed. Christchurch was struck by two major earthquakes approximately 6 months apart. The second earthquake which occurred in February, 2011 was located closer to the city and therefore produced more intense ground shaking. The loss of life in Christchurch was relatively minor; 185 people died, 115 of them in the collapse of the Christchurch TV building which was an older building (constructed in the 1980s). By and large, newer buildings met the “life-safety” performance objectives of the code, and suffered significant damage due to the intense shaking. The Royal Commission [9] studied the performance of many existing buildings including a representative set of five buildings which were designed to the most recent New Zealand code. Four of those buildings required demolition or major repair; the fifth one was base-isolated. While some may argue that the shaking (which was generally observed to be greater than the design level earthquake) makes the devastation an outlier and therefore not indicative of future performance of the building stock in design level shaking, we note that the observed damage is entirely consistent with the code-intended performance objectives for the design earthquake.

In some respects Christchurch was a success story which validated the effectiveness of modern building codes. According to many engineers, the majority of buildings performed “well” – meaning that they did not collapse. But for the general public, there was a shocking realization that buildings designed to modern standards were not as “earthquake-proof” as they believed. Perhaps this is a product of society’s belief in government regulation – that would never knowingly allow us to own and occupy buildings which are intended to suffer significant damage in an earthquake. Or perhaps it is the belief that “modern science” – mentioned by interviewees in Holmes et al. [2] - would prevent such widespread damage. In Christchurch, the central business district (CBD), was cordoned off for more than two years and in large part, Christchurch has yet to begin rebuilding nearly three years after the earthquake sequence. Many businesses were forced to move to the suburbs, likely never to return. Christchurch is an example of what could happen anywhere in seismically active regions of the developed world. While loss of life was limited, Christchurch confirmed that the most significant vulnerability is not people’s safety (thanks to the building code), but rather the economic losses due to direct earthquake damage and the indirect losses due to downtime including loss of community and culture, and the loss of quality of life. The building code may be doing a good job of saving lives, but we must ask ourselves: what kind of life does it leave for the many survivors, and could much better outcomes be achieved for minimal additional construction cost?

In response to the devastating consequences of the earthquakes, a Royal Commission was established to assess whether the current legal and best-practice design requirements in New Zealand are adequate given the known earthquake risks [14]. The Commission provided useful recommendations to generally improve building (mostly structural and geotechnical) performance. However, given almost carte blanche the opportunity to significantly influence and improve the future direction of building code earthquake performance objectives, they concluded:

• “...it would not be sensible, in our opinion, to conclude that the performance of buildings in the February earthquake demonstrates a need for wholesale change.”
…the objective should be incremental improvement, rather than a change of direction…"

“…once the objective of life-safety is achieved, the question of the extent to which buildings should be designed to avoid damage is a social and economic one, and the answer depends on choices that society as a whole must make.”

“In the circumstances, our concept of “best practice” is one that reflects the existing objective of life-safety, and looks to ensure that building damage is minimized within the limits established by the existing knowledge about earthquake risk and our understanding of the cost implications of more onerous requirements.”

“Any other approach would be a radical change that we do not consider would be justified by the experience of the Canterbury earthquakes.”

In our view, these are disappointing conclusions considering the public sentiment and governmental willingness to make changes. The argument appears to be based upon a belief that “more onerous requirements” would be excessively costly to implement and that earthquake performance objectives are a decision for public policy makers, not design professionals. This has been cited in other reports in the US including Holmes et al. [2] and could explain why building code changes are incremental in nature and often lag several years behind state-of-the-practice. However, the cost argument goes against the evidence of numerous studies and many completed projects which show that it is possible to design new buildings, using modern seismic protection technology, that would allow owners to resume business operations and provide livable conditions quickly after an earthquake for additional investment of approximately 5% of building cost or less (see “Costs of Resilience-based Design” below).

Performance-based Design and Earthquake Rating Systems

In recognition that code “life-safety” objectives are vague in terms of actual risk (particularly financial and downtime risks), performance-based design (PBD) has evolved as a process to communicate seismic risk to building owners in terms of direct consequences such as Deaths, Dollars, and Downtime [15]. It allows owners to select pre-identified seismic performance objectives for different earthquake intensity levels in terms they can actually understand.

Unfortunately, PBD is often used only to verify that code-intended seismic performance objectives are met, typically in order to circumvent certain code requirements (e.g. height limitations). For example, most PBD guidelines for tall buildings target “collapse prevention” as a suitable performance objective for the maximum considered earthquake [16], which is in line with the current code intention. In this case, the only distinction between code design and PBD is that PBD provides more confidence that the building will achieve the code-intended performance. In this paradigm, the performance of the building is quantified based on the relation of certain engineering demand parameters (EDPs) to code limits for structural components expressed in terms such as “Life Safety” and “Collapse Prevention”. That is to say, in current practice, PBD is not always used as intended to communicate performance in terms of direct consequences.

The concept of PBD does provide a basis for communicating earthquake risk, but perhaps the most accessible method for public understanding is through an earthquake rating system. This is
not a new proposal - many have previously called for a rating system including SPUR [13], interviewees in Holmes et al. [2], the Oregon Resilience Plan [17], and others in the community. The SEAONC Existing Buildings Committee has proposed an assessment/rating system for existing buildings, based on compliance with ASCE 31 requirements [18] and have proposed that future versions use FEMA P-58. In contrast, the rating system we are proposing is a design/rating tool, which assists in the achievement of better performing buildings through better design and planning. SPUR [13] argued for two separate rating systems, one for new buildings and one for existing, mainly because for new buildings “it is possible to tie the certification to a set of seismic design provisions with which the structural engineer and owner volunteer to comply” leading to a “more objective certification system than could ever be developed for existing buildings”. In recognition that building codes may only increase earthquake performance objectives incrementally (if at all), our rating system is a voluntary guideline to promote a step-change reduction in earthquake risks relative to the traditional code objectives. It clearly articulates risks in layman’s language and presents design approaches for those stakeholders who realize that they do not wish to be vulnerable to a range of risks.

Resilience-based Earthquake Design

Resilience-based earthquake design is a holistic approach which seeks to identify all earthquake-induced risks (including those outside the building envelope) and mitigate them using integrated multi-disciplinary design and contingency planning to achieve swift recovery objectives in the aftermath of a major earthquake. Achievement of the REDi™ resilience objectives, which exceed code-intended performance objectives and by corollary, typical performance-based design objectives, is explicitly verified through a FEMA P-58 based assessment.

The REDi™ framework establishes three rating tiers, each with resilience objectives which aim to substantially reduce earthquake risks relative to the code objectives for ordinary buildings. We denote the rating tiers as Platinum, Gold, and Silver, based on the success of LEED in elevating the relation of these classifications with higher building performance among stakeholders. The resilience objectives associated with the “design level earthquake” (which we define as producing 475 year return period ground shaking) are shown in Table 1. We chose the 475 year return period as our reference because it is traditionally accepted by the engineering and insurance industry and it enforces a uniformly defined earthquake hazard level which is less ambiguous than the current definition of the design ground motion (2/3 MCE_R). The functional recovery objectives for Platinum are generally consistent with code-intended performance objectives for essential facilities. The Gold functional recovery objectives reflect that downtime of one month “can be enough to force a business to close, relocate, or leave the state entirely” [17]; this prompted recovery targets in Oregon of 30 days for banks, retail centers, government facilities, and schools. Platinum and Gold ratings can only be satisfied if building repairs are not required since it is unlikely that they could be undertaken within the functional recovery timeframes; one of the key differences therefore is that Platinum buildings require back-up systems in case of utility disruption while functionality in Gold buildings is achieved only once utilities are restored. The considerable gap in recovery objectives between Platinum/Gold and Silver reflect that any damage requiring repair will likely take months to complete, and only if planning measures are in place prior to the earthquake to address “impeding factors” which delay initiation of repairs (see “Improved Downtime Methodology” below). Note that functional
recovery relates to regaining normal occupant comfort and livable conditions (pre-defined by the owner) together with the resumption of the intended functions of the building. Examples include emergency services and typical services in hospitals, business activity in offices and retail, or classes in educational facilities. The financial loss limits for each tier were selected based on several studies of various structural systems subjected to a range of earthquake intensities [4,5,8] which showed that recovery timeframes of 6 months or less were related to financial losses below 10% (see Figure 1).

Table 1. REDiT™ baseline resilience objectives for design level earthquake

<table>
<thead>
<tr>
<th>Rating</th>
<th>Re-occupancy</th>
<th>Functional Recovery</th>
<th>Financial Loss</th>
<th>Occupant Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platinum</td>
<td>Immediate</td>
<td>&lt;72 hrs</td>
<td>&lt;2.5%</td>
<td>Injuries unlikely</td>
</tr>
<tr>
<td>Gold</td>
<td>Immediate</td>
<td>&lt;1 month</td>
<td>&lt;5%</td>
<td>Injuries unlikely</td>
</tr>
<tr>
<td>Silver</td>
<td>&lt;6 months</td>
<td>&lt;6 months</td>
<td>&lt;10%</td>
<td>Injuries possible</td>
</tr>
</tbody>
</table>

Figure 1. Financial loss vs downtime from various studies

To qualify for a REDiT™ rating, it is necessary to satisfy the mandatory requirements for that tier in each of three Resilient Design and Planning categories: Non-mandatory recommendations are also proposed to reduce potential losses.

1. **Organizational Resilience**: Pre-earthquake contingency planning is the key to restoring functionality within a desired timeframe and to maintain livable conditions directly after an earthquake. Guidelines and criteria in this category introduce measures to reduce downtime due to factors that could delay initiation of repairs (such as access to post-disaster financing, and contractor and engineer mobilization) and to maintain business continuity including contingency planning for utility disruption.

2. **Building Resilience**: The key principle in resilience-based earthquake design is to limit expected damage to structural, architectural and MEP components and egress systems (including elevators, stairs, and doors) since any damage greater than cosmetic could hinder re-occupancy or otherwise prevent a speedy return to functionality. Reliable damage-control technologies such as base isolation and energy-dissipating systems have become well established over the past 15 years and allow the building structure to remain essentially elastic in intense earthquake shaking. Improved methods for detailing non-structural components to accommodate the anticipated building displacements and accelerations with very minor damage have also been developed. In addition, MEP
components and other critical systems should be seismically qualified by shake-table testing (or otherwise pre-approved) to ensure they remain operable after experiencing design level accelerations to allow functionality once utilities are restored.

1. **Ambient Resilience**: In recognition that the recovery of even the most resilient buildings could be jeopardized by threats external to the building envelope, the criteria and guidelines in this category aim to minimize the risk that external earthquake-induced hazards could damage the building, restrict site access, or otherwise hinder re-occupancy or functional recovery. 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. 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.

Following the adoption of the mandatory and selected non-mandatory REDiT™ recommended measures, a formal Loss Assessment must be performed to verify that the quantitative REDiT™ resilience objectives - measured in terms of downtime and financial loss - are achieved. Financial losses are estimated using the Performance Assessment Calculation Tool or PACT [10]. Downtime is calculated using a FEMA P-58 based approach enhanced specifically for the REDiT™ Rating System [1] to enable calculation of the time required to achieve three distinct recovery states: re-occupancy, functionality, and full recovery (see “Improved Downtime Methodology” below).

**Improved Downtime Methodology**

FEMA P-58 provides estimates of repair time for earthquake damage, but it does not calculate the facility’s downtime - which may be much longer than the repair time. We developed an improved method to enable benchmarking against the REDiT™ resilience objectives and to reflect the holistic resilience-based design approach which attempts to identify almost all earthquake-induced threats to recovery.

Specifically, the enhancements provided by the REDiT™ downtime methodology include:

- Definition of “Repair Classes” which describe whether the predicted damage will hinder achievement of specific recovery states (re-occupancy, functional recovery, full recovery) depending upon damage extent and criticality of various building components
- Estimates of delays to initiation of repairs (which we term “impeding factors”) such as the time required to complete post-earthquake building inspection, secure financing for repairs, mobilize engineering services, re-design damaged components, obtain permits, mobilize a contractor and necessary equipment, and the contractor ordering and receiving the required components including “long-lead time” items.
- 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).
The reader is referred to the REDi™ [1] guidelines to view the full methodology. The methodology does not attempt to quantify downtime caused by certain “uncontrollable” externalities which include hazards from adjacent buildings, restricted site access, and availability of employees to return to work.

**Costs of Resilience-based Design**

One of the most cited arguments for not building to “beyond-code” standards is the cost implication, (e.g. the Royal Commission conclusions regarding Christchurch). But we believe these are overstated. Terzic et al. [4] calculated the cost premium for a base-isolated building is on the order of 3 to 7%. There was virtually no cost premium for the San Francisco General Hospital, designed by Arup with base-isolation (personal comm. Eric Ko) since the lower force demands resulted in a savings of approximately 3,000 tons of steel in the superstructure [19]. Recently, Almufti et al. [20] found that the cost premium for achieving a REDi Gold rating for a 43-story concrete core residential building in San Francisco was no more than 2% relative to a conventional PBD design; however, the conventional design was estimated to be unusable for approximately 2 years after a design level earthquake.

Regardless, it seems likely that many modern business owners would view a minor added initial cost as a valuable investment to protect their asset and the survival of their business. Developers are savvy enough to recover additional first costs through marketing the additional value of seismic resilience. In fact, a group of interviewees considered 5 to 10% as an acceptable cost premium for enhanced seismic performance [2]. A recognized rating system would help considerably in giving traction to such initiatives. The cost premiums associated with resilience-based design could also be potentially offset through incentive programs organized by city governments who stand to benefit [13].

**Conclusions**

Resilience-based earthquake design recognizes that buildings and organizations play an important role in the ability of a community to recover. Designing to achieve “beyond-code” earthquake performance objectives can substantially decrease the time required to achieve recovery after a major earthquake. The REDi™ Rating System is not just an assessment tool – it is a vehicle for the practical holistic implementation of resilience-based earthquake design. The REDi™ framework is suitable for future adaptation to achieve resilience against any type of extreme event, including floods, hurricanes, terrorism, and climate change.

The full benefits of the adoption of resilience-based design will not be realized on a city wide scale in the short term; it is necessary for a critical mass of new resilient buildings to be constructed as older less resilient ones are replaced. However, there is no reason not to start now. The engineering community can promote this change by re-focusing its efforts on damage prevention rather than on ductility alone. We also need to re-frame the way in which we communicate with the public and with ourselves. For example, it is time to stop equating “good performance” with “low probability of collapse”. We can, and should, set ourselves higher targets worthy of the 21st century.
Acknowledgments

The authors would like to thank everyone who contributed to the REDi™ Rating System (see [1] for the full list) and the Investment in Arup program for research funding.

References