PROBABILISTIC ASSESSMENT OF THE BENEFITS OF RETROFITTING NONDUCTILE CONCRETE BUILDINGS IN TERMS OF REGIONAL LOSSES

by

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above-mentioned discipline.

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Probabilistic Assessment of the Benefits of Retrofitting Nonductile Concrete Buildings in terms of Regional Losses

Thesis directed by Associate Professor Abbie Liel

ABSTRACT

Los Angeles, California, is a densely populated city located in an area of high seismic hazard. The region's aging building stock has contributed to concerns about the seismic resilience of the community. Recent research has highlighted the vulnerability of nonductile concrete buildings and their associated risk to safety and post-disaster recovery. Currently, there are approximately 1500 nonductile concrete buildings in the city of Los Angeles, motivating discussions for retrofit policies to mitigate the risk stemming from these buildings. While the understanding of individual building retrofit is important for the building owner, investor, and/or tenants, the evaluation of structural retrofit on an entire community can help influence policy decisions.

This thesis combines advances in probabilistic regional seismic risk assessments with new assessments of retrofit performance of nonductile concrete buildings designed according to ASCE 41 to assess the benefits of retrofit policies in Los Angeles, considering a representation of the existing pre-1980 concrete buildings. Using the Seismic Performance Prediction Program (SP3) and the FEMA P-58 methodology, seismic losses for each building are presented in terms of economic losses, repair times, and fatalities. Sixty-seven different regional retrofit strategies are subsequently evaluated in terms of their ability to satisfy retrofit objectives addressing reduction in displacement of residents, in loss of occupiable building space, in earthquake-induced fatalities, and in earthquake-induced repair costs.

The results show that retrofitting a minimum of 60% of the buildings to the Immediate Occupancy performance level fulfills a number of possible regional retrofit strategies and objectives for the City of Los Angeles. Design retrofits to Collapse Prevention and Life Safety performance levels require retrofitting a larger number of buildings to achieve the same improvements in regional performance, and in some cases cannot achieve the overall goals.

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CHAPTER 1

INTRODUCTION

Los Angeles (LA), California is a highly seismically-active region due to its proximity to numerous faults, including the Whittier Fault, Hollywood Fault, the Simi Fault, and the San Andreas Fault, among others. As a result, a recent USGS study estimated a 36% likelihood of one or more M7.5 events occurring within the next 30 years in the Southern California region, and a 93% likelihood of one or more M6.7 events occurring in the next 30 years (USGS, 2015b). LA is also one of the most populated areas in the world, with almost 4 million people residing in the city, and over 10 million in the metropolitan area (United States Census Bureau, 2016).

Nonductile reinforced concrete (NDC) buildings make up a substantial portion of the vulnerable buildings in the United States, and are among one of the most seismically-dangerous building types (Comerio & Anagnos, 2012; Lynch et al., 2011; SEAOSC, 2016). California alone is estimated to have over 20,000 of these buildings, most of which are privately-owned industrial, office, or multi-family residential buildings (Anagnos et al., 2016; Comartin et al., 2011; Concrete Coalition, 2011; Liel & Deierlein, 2013). Despite the known vulnerabilities in these structures, building codes are not retroactive and, as a result, many of these buildings have likely not been retrofitted. Moreover, there are a number of challenges to retrofitting these structures, including the large number of these potentially-susceptible buildings (Anagnos et al., 2016). In addition, seismic upgrades are expensive, disruptive to tenants, and time consuming. Local or municipal retrofit ordinances can encourage or mandate building owners to make necessary structural upgrades, but without that push, retrofit decisions are left in the hands of building owners.

State and local policies addressing seismic safety of existing buildings have been motivated in part by observed damage in past earthquakes. For example, the 1933 Long Beach earthquake triggered the enactment of the Field Act, in reaction to the damage of 75% of the school buildings in Long Beach, California (Jephcott, 1986; Liel & Deierlein, 2012). The Field Act was the first statewide regulation of structural design, requiring all structural plans and specifications for new school buildings to be reviewed by the State (Jephcott, 1986; Liel & Deierlein, 2012), and was later amended to include retrofit of pre-Field Act school buildings. In addition, starting with the 1933 Long Beach earthquake, concerns were voiced about the dangers of unreinforced masonry (URM) buildings (Liel & Deierlein, 2012). Finally, after the 1983 Coalinga earthquake that caused collapse of unreinforced masonry (URM) buildings resulting in deaths and injuries, URM ordinances were adopted across California and eventually a state-wide ordinance mandated action by all local jurisdictions (SEAOSC, 2016). More recent earthquakes at Northridge, Christchurch New Zealand, and Mexico City all identified many limitations of the past building codes and existing building inventories, including NDC, soft first-story, and steel moment frame structures (City of Los Angeles, 2015; SEAOSC, 2016). Although some of these vulnerabilities were identified over 20 years ago, ordinances requiring structural upgrades of these deficiencies were not implemented until recently (City of Los Angeles, 2015). The city of LA is one of the first jurisdictions to proactively address retrofit of NDC buildings, and other communities are following this lead.

Previous studies have primarily examined retrofit design and performance of individual buildings. This understanding is important for the building owner, investor, and/or tenants. However, policy makers may be more interested in the influence of retrofit for an entire community to assess benefits of various retrofit policies from the perspective of community safety and resilience. Indeed, many stakeholders, including government agencies, city planners, insurers, may be concerned about the collective risk of a community or portfolio of buildings. The problem many jurisdictions currently face is trying to mitigate multiple seismic risks that affect a potentially large number of vulnerable buildings in their community.

This thesis combines advances in probabilistic seismic regional loss assessments with new assessments of retrofit performance of NDC buildings to assess the benefits of retrofit policies for the city of Los Angeles, California. Chapter 2 begins with the background of the problem faced, and motivation for this study. Chapter 3 describes the methods utilized to assess the regional loss and the performance of retrofitted buildings. Chapter 4 presents community-level economic, time, and fatality losses for various retrofit cases in the region, as well as evaluates potential retrofit goals to strengthen the built environment for the city of LA. The conclusions and limitations are presented in Chapter 5.

CHAPTER 2

POINTS OF DEPARTURE

2.1 Introduction

Many researchers, such as Liel & Deierlein (2012), Anagnos et al. (2008), and Galanis & Moehle (2014), have identified collapse vulnerabilities of NDC buildings. Seismic deficiencies in these structures include weak-column to strong-beam arrangements, shear critical columns, and inadequate anchorage of longitudinal and transverse reinforcement. In the U.S., the 1971 San Fernando earthquake, among other events, revealed critical vulnerabilities in reinforced concrete (RC) buildings, eventually leading to significant changes in the building code in the late 1970s (Liel & Deierlein, 2012; SEAOSC, 2016). Since this time, the provisions for RC buildings have required increased shear reinforcement in columns and joints, ductile detailing, and strong-column weak-beam implementation. However, building code standards are not retroactive and therefore, existing buildings are not affected by new regulations, and the vulnerability of existing reinforced concrete buildings remains (SEAOSC, 2016).

The Structural Engineers Association of Southern California (SEAOSC) and the Dr. Lucy Jones Center for Science and Society (DLJCSS) disseminated the *2016 Safer Cities Survey* with the goal of identifying existing vulnerable buildings, which included NDC structures, in built Southern California communities and determining what strategies, if any, municipalities are using to address those structures (SEAOSC, 2016). Vulnerable building data was collected through phone calls and emails with Building Officials, in addition to review of online city codes (SEAOSC, 2016). The survey showed that a number of jurisdictions in the region have acted to implement retrofit ordinances for some of these building types, whether they are mandatory, voluntary, or in development. However, in many jurisdictions, retrofit is left in the hands of the building owners, who are responsible for deciding how and when to structurally upgrade their buildings, if at all. The exception to this is that owners may also be required to retrofit if extensive architectural or other renovations change their building (ICC, 2015).

2.2 Retrofit Ordinances

The benefits of retrofitting NDC buildings have been studied by a number of researchers (Anagnos et al., 2016; Bonstrom & Corotis, 2015; Harrington, 2016; Kim & Hagen, 2014), and it is clear from the outcome of the *2016 Safer Cities Survey* that existing pre-1976 RC buildings pose great risk to Southern California communities. Benefits of retrofitting vulnerable buildings include reduced risk of injuries or fatalities, reduced repair costs, and reduction in other social impacts of earthquakes (Harrington, 2016; Liel & Deierlein, 2013).

However, significant barriers to retrofit remain, and these often discourage the voluntary retrofit by building owners. Factors influencing owner willingness to retrofit include the cost of designing and constructing the retrofit upgrades, retrofit triggering of other building renovations, and possible displacement of residents (Anagnos et al., 2016; Bonstrom & Corotis, 2015; Liel & Deierlein, 2012, 2013). In opposition, voluntary retrofit in California is encouraged by larger tech companies and financial institutions interested in the safeguarding of critical facilities, as well as building owners concerned about their refinancing qualifications (Holmes, 2009).

A few cities in California, including the city of LA and the city of West Hollywood, recently passed mandatory retrofit ordinances for NDC and soft-story buildings (City of Los Angeles, 2015; SEAOSC, 2016). The goal of these retrofit ordinances is to improve the performance of vulnerable buildings and decrease the risk of injury, loss of life, and building damage (City of Los Angeles, 2015; City of West Hollywood, 2017).

2.2.1 Implementation of Mandatory Retrofit Ordinances

In November 2015, the city of LA Department of Building Safety implemented Ordinance No. 183893, addressing existing NDC buildings. The ordinance applies to all RC buildings designed under building codes enacted before 1977, with the exception of single-family homes. Building owners will be served documentation if their building falls into this category of structure. Once served notice, the building owner has three years to submit a checklist to the Department to determine if the building is considered a NDC building (City of Los Angeles, 2015). The owner then has ten years (after being served documentation) to submit plans to retrofit or demolish the building, document previous retrofit actions to the building, or provide a structural analysis report that the building meets basic engineering and safety requirements during a seismic event (City of Los Angeles, 2015). If plans of retrofit or demolition are submitted, the owner has 25 years (after served documentation) to complete the retrofit or demolition (City of Los Angeles, 2015).

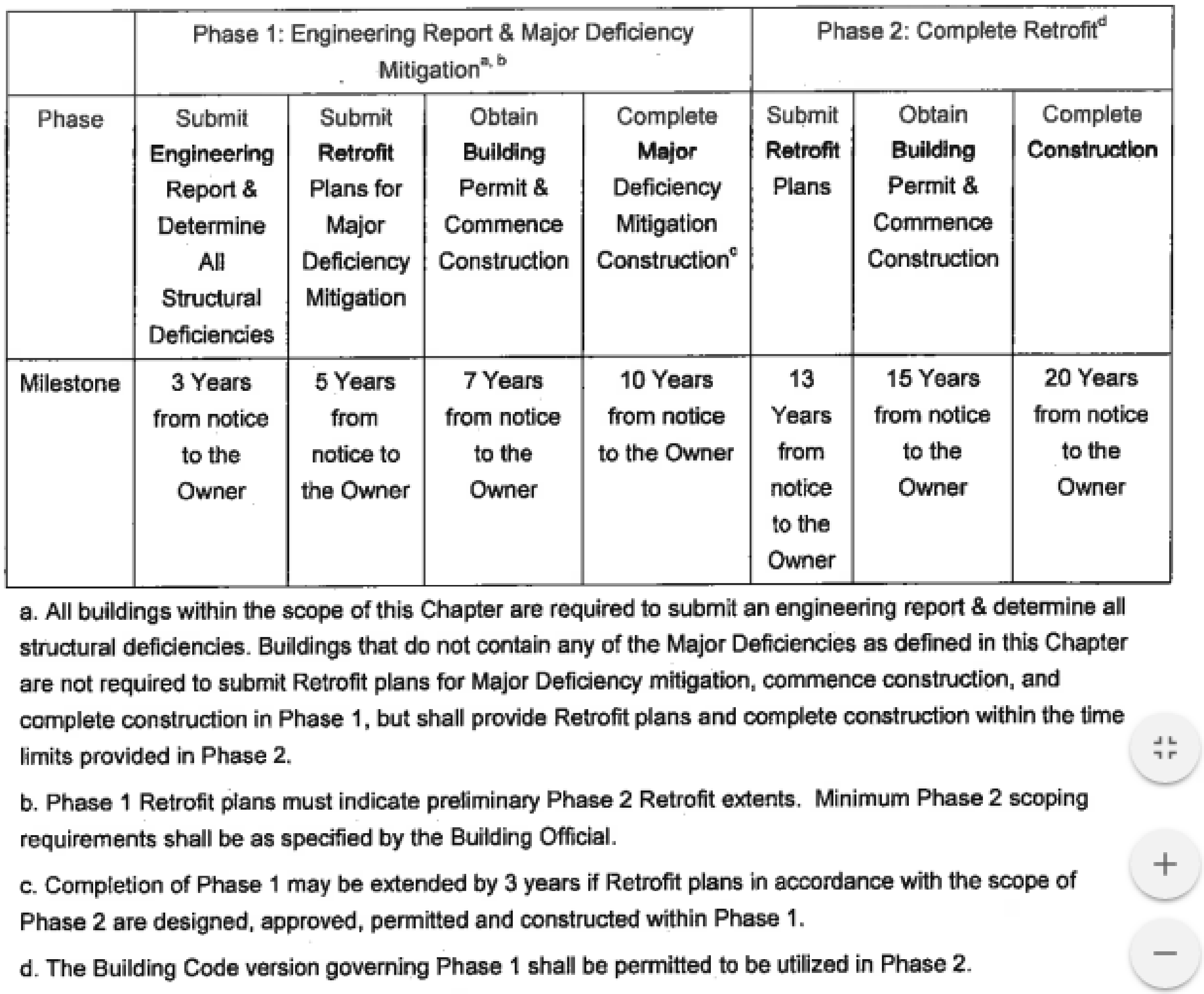
In order to determine if a building does not require retrofit, the owner must submit a structural analysis and evaluation of the existing building proving that it meets minimum criteria. The building can pass the minimum requirements one of three ways. The first method, which represents 75% of current code, ensures that the strength of the lateral-force resisting system is equal to at least 75% of the base shear of a modern building at that site according to ASCE 7, and any component that is not a part of the lateral-force-resisting system can resist gravity loads and 100% of the design story drift, per the current LA Building Code seismic provisions (City of Los Angeles, 2015). The second method is to show that the building meets the “Basic Safety Objectives” of ASCE 41 (City of Los Angeles, 2015). The third method allows for the building owner to obtain a structural evaluation using another method of equivalent standards of the two previous criteria that is approved by the Department (City of Los Angeles, 2015). If the building does need to be retrofit, the building owner must follow the “75% of ASCE 7 and ASCE 41” procedures to design the retrofit (City of Los Angeles, 2015).

In August 2017, the City Council of West Hollywood adopted Ordinance 17-1011, provisions for existing NDC buildings, effective August 7, 2018. Like the city of LA retrofit ordinance, the city of West Hollywood identifies the dangers and deficiencies of NDC buildings. This ordinance also applies to RC structures designed under building codes enacted before 1977, with the exception of: RC frames with flexible diaphragms, single story buildings (unless the lateral force resisting system is a concrete moment frame), and frames with concrete-encased steel lateral force resisting systems (City of West Hollywood, 2017).

If the building is affected by the ordinance, and the building owner confirms plans to upgrade the building’s structural system, they must follow the retrofit requirements. The city of West Hollywood retrofit ordinance separates the retrofit requirements into two phases, “Phase 1: Engineering Report and Major Deficiency Mitigation” and “Phase 2: Complete Retrofit.” In Phase 1, the building owner must submit an engineering report to the Building and Safety Division. The report will identify all structural deficiencies according to ASCE 41 (ASCE, 2013), and describe how Major Deficiencies will be mitigated. Major Deficiencies include insufficient load path, weak or soft story, vertical irregularity, torsion, and captive column (City of West Hollywood, 2017). Phase 1 also dictates the upgrades made to the structure will not increase the demand-to-capacity ratio by over 10 percent of any existing lateral load component, unless the component is proven to be able to handle the increased load (City of West Hollywood, 2017). Phase 2 requires the full completion of the building retrofit. The ordinance presents a timeline for building owners of vulnerable NDC buildings located in West Hollywood, reproduced in Table 2.1. All buildings are required to meet the structural performance level at an earthquake hazard level based on Risk

Category, per ASCE 41 (City of West Hollywood, 2017). Other analysis methods may be used but need to be approved by the Building Official.

Table 2.1 – From the city of West Hollywood retrofit Ordinance 17-1011, time period for compliance of various phases (Table from City of West Hollywood, 2017).



	Phase 1: Engineering Report & Major Deficiency Mitigation[a, b]				Phase 2: Complete Retrofit[d]		
Phase	Submit **Engineering** Report & Determine All Structural Deficiencies	Submit **Retrofit** Plans for Major Deficiency Mitigation	Obtain **Building** Permit & Commence Construction	Complete **Major** Deficiency Mitigation Construction[c]	Submit **Retrofit** Plans	Obtain **Building** Permit & Commence Construction	Complete **Construction**
Milestone	3 Years from notice to the Owner	5 Years from notice to the Owner	7 Years from notice to the Owner	10 Years from notice to the Owner	13 Years from notice to the Owner	15 Years from notice to the Owner	20 Years from notice to the Owner

a. All buildings within the scope of this Chapter are required to submit an engineering report & determine all structural deficiencies. Buildings that do not contain any of the Major Deficiencies as defined in this Chapter are not required to submit Retrofit plans for Major Deficiency mitigation, commence construction, and complete construction in Phase 1, but shall provide Retrofit plans and complete construction within the time limits provided in Phase 2.

b. Phase 1 Retrofit plans must indicate preliminary Phase 2 Retrofit extents. Minimum Phase 2 scoping requirements shall be as specified by the Building Official.

c. Completion of Phase 1 may be extended by 3 years if Retrofit plans in accordance with the scope of Phase 2 are designed, approved, permitted and constructed within Phase 1.

d. The Building Code version governing Phase 1 shall be permitted to be utilized in Phase 2.

2.3 Previous Regional Studies of Seismic Retrofit

Regional seismic loss analysis provides potentially-useful information not only to engineers, but also to policy makers, community planners, and insurance providers. While seismic losses computed on a building-by-building basis are important for individual building owners, seismic losses calculated on a regional level can help communities plan for upcoming natural disasters, and prioritize mitigation strategies. Regional risk assessments have been conducted for cities all over the world, as well as in the U.S., to assess seismic risk on the community level with varying degrees of detail (e.g., Anagnos et al., 2016; Bonstrom & Corotis, 2015; Chang et al., 2000; DeBock & Liel, 2015b; Manzour et al., 2015; Salgado-Gálvez et al., 2014; Smyth et al., 2004).

Smyth et al. (2004) evaluated the housing stock in Turkey, using a benefit-cost analysis to evaluate different seismic retrofit options. The residential buildings represented in the study were RC moment frame buildings built to the 1967 code. The purpose of the study was to provide the benefits and costs of different mitigation strategies for residential buildings in this study area in Istanbul. The authors calculated the benefits to different mitigation strategies by determining losses to the region with and without mitigation. They concluded that the costs associated with retrofitting the structures was relatively low compared to the potential risks of these buildings to life safety (i.e., the benefits).

Bonstrom and Corotis (2014) utilized a reliability-based regional assessment to prioritize retrofit strategies to reduce regional earthquake risk. The study applied a regional loss assessment to a neighborhood in San Francisco, California using the first-order reliability method (FORM), and accounting for spatial correlations in building performance through the region. The building inventory was located in the Embarcadero area of San Francisco, and comprised of 36 different building types, 33 HAZUS occupancy types, and differing seismic design eras (i.e. pre- and low-code) (Bonstrom & Corotis, 2015). Seismic retrofit options are provided from FEMA 156 as typical cost estimates to upgrade the seismic design code level for groups of buildings. The case study uses a deterministic earthquake scenario, a magnitude 7.2 earthquake on the San Andreas Fault, although the study framework can be carried out probabilistically. The results compared retrofit spending by building type, as well as retrofit spending per square foot by building type. The study uses a number of retrofit budgetary constraints to retrofit the most vulnerable building types in the region and produce loss exceedance curves. The authors also demonstrate that spatial correlation has a great influence on the reliability assessment. By including spatial correlations, the likelihood of very low losses and very high losses increase, thus decreasing the probability of moderate losses. The results of this case study conclude that, given a fixed retrofit budget, the greatest portfolio loss reduction per dollar spent on retrofit stems from reinforced masonry buildings and concrete frame structures with unreinforced masonry walls.

Salgado-Gálvez et al. (2014) conducted a fully probabilistic regional loss assessment for the existing building inventory of the city of Medellin in Colombia. The study considered regional characteristics including building types, building heights, building-use categories, replacement costs, and socio-economic levels. Analysis results of the existing building portfolio are presented in a number of loss exceedance curves and risk maps, as well as tables describing regional losses as total loss amounts and annualized loss amounts.

Anagnos et al. (2008, 2012, 2016) conducted a study on the NDC building stock in LA to determine regional losses based on scenario events of M7.8 and 7.15 on the southern San Andreas and Puente Hills Faults, respectively (Anagnos et al., 2016). The San Andreas scenario has a recurrence interval of about 150 years, which is relatively short compared to the Puente Hills scenario (recurrence interval of about 3000 years). The study used the NEES Grand Challenge NDC building inventory (same inventory as used in the current thesis, described below in Section 3.3). Building damage and losses were estimated using the HAZUS Advanced Engineering Building Module and assigned to one of the three concrete model building types: C1 – concrete moment frames, C2 – concrete shear walls, and C3 – concrete frames with URM infill walls

(Anagnos et al., 2016). For both earthquake events, each building was considered for four building design performance cases: deficient, baseline, targeted poor performer, and mitigated. Baseline buildings were modeled using HAZUS loss models altered to reflect vulnerabilities of NDC buildings by reducing the building strength. The strength was reduced to 60% of the HAZUS default value for high-rise buildings, 75% for mid-rise, and 90% for low-rise (Anagnos et al., 2016). Deficient buildings were modeled using the HAZUS loss models, but altered further to decrease the strength and ductility, and increase collapse probability, as well as incorporate one or more structural deficiencies. The strength of deficient buildings was reduced to 50% of the HAZUS default value for all buildings (Anagnos et al., 2016). Targeted poor performers combined specific baseline and deficient buildings to model a group of specific buildings with a high probability of having deficiencies including soft stories, shear critical columns, and torsion caused by stiffness irregularities, and is thought to represent a more realistic loss representation than the baseline or deficient cases (Anagnos et al., 2016). Mitigated buildings were modeled in HAZUS as modern (2013) buildings.

The method resulted in NDC losses ranging from \$1.8 to \$10.2 billion, as well as regional fatalities ranging from <50 to 2,700 people in the San Andreas scenario, and losses from \$5.9 to \$28.5 billion as well as fatalities from <65 to 8,300 people in the Puente Hills event for the full NDC inventory used. They proposed targeted building groups to be upgraded as policy implications including to retrofit high-rise buildings, pre-1930 buildings (excluding schools), pre-1930 4+ story warehouses and light manufacturing buildings, 4+ story warehouse and residential frames with URM infill, and 8+ story commercial frames with URM infill (Anagnos et al., 2016). The study concluded that 48% of the economic losses and 69% of the fatalities result from the combination of the pre-1930 4+ story warehouses and manufacturing buildings and the pre-1930

8+ story commercial buildings, which together only make up 18% of the value and 17% of the total area (Anagnos et al., 2016). These resulting differences in economic losses and fatalities for each of the groups contributing to the losses can provide policy-makers with a set of obtainable retrofit options.

CHAPTER 3

METHODS

3.1 Design and Modeling of Retrofit Nonductile Concrete Buildings

The buildings considered in this study are based on retrofit NDC buildings designed and modeled by Harrington (2016). These buildings are a 3-story, 6-story, and 9-story NDC space frame structures, designed according to the 1967 Uniform Building Code (UBC) and, as such, represent the strength, stiffness, and collapse capacities of typical NDC moment frames. Retrofits for each building were then designed using three common retrofit strategies to three performance levels, per ASCE 41 (ASCE, 2013). Specifically, each unretrofit model was subject to an ASCE 41 evaluation of the selected performance objective to determine critical members in the structure. Once the critical members were identified, one of three local retrofit strategies was applied to columns in each model: concrete column jacketing, steel column jacketing, and fiber-reinforced-polymer (FRP) column wrapping. Harrington (2016) then assessed the unretrofit retrofit buildings through the performance-based earthquake engineering (PBEE) procedure. In particular, economic losses were evaluated using the Seismic Performance Prediction Program (SP3), which is based on the FEMA P-58 methodology (FEMA, 2012). These buildings form the basis of this regional loss study and are described in more detail below.

3.1.1 Seismic Evaluation and Retrofit

The ASCE *Seismic Evaluation and Retrofit of Existing Buildings* (ASCE 41-13) is the U.S. standard for seismic evaluation and retrofit. The 2013 version of this ASCE standard was preceded two previous documents, ASCE 31-03 and ASCE 41-06, and has recently been updated by ASCE 41-17. *Seismic Evaluation of Existing Buildings* (ASCE/SEI 31-03) was published and intended to replace FEMA 310, *Handbook for Seismic Evaluation of Buildings – A Prestandard* (1998). ASCE 41 was a three-tiered seismic evaluation system of existing buildings. ASCE then published

Seismic Rehabilitation of Existing Buildings (ASCE/SEI 41-06), using the latest advancements in technologies and performance-based seismic rehabilitation of existing buildings. This Standard was intended to replace FEMA 356, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*. In 2013, ASCE released *Seismic Evaluation and Retrofit of Existing Buildings* (ASCE/SEI 41-13), hereafter referred to as ASCE 41, the new combined standard to merge and eliminate the inconsistencies that previously existed between the two previous documents. The combined ASCE 41 and the potential for a coordinated evaluation process was described by Pekelnicky and Poland (2012).

ASCE 41 begins with an evaluation of the building to determine if the building meets the objectives associated with a selected performance level. If the building does not comply with the performance objectives, the same ASCE 41 document may be used to design a retrofit. The three ASCE 41 performance levels (in order of increasing seismic resistance) are Collapse Prevention (CP), Life Safety (LS), and Immediate Occupancy (IO). From ASCE 41 Section 2.3, the "Collapse Prevention" performance level implies the structure has endured substantial damage to many components and is on the "verge of partial or total collapse" of the lateral-force-resisting system, but the gravity-resisting system must be able to support the continued gravity loads. The "Life Safety" performance level may indicate some severely damaged structural components, but there is no falling debris. The structure is damaged, but is not totally collapsed and, although injuries might occur, the risk to life safety is low. "Immediate Occupancy" implies the structure is safe to occupy after an earthquake, and still retains its initial strength and stiffness. Functionality of the structure may be limited by damage to nonstructural components, but not by structural components. Figure 3.1 represents a pushover illustrating the relative position of the three ASCE 41 performance levels for ductile and nonductile structures (reproduced from Harrington, 2016).

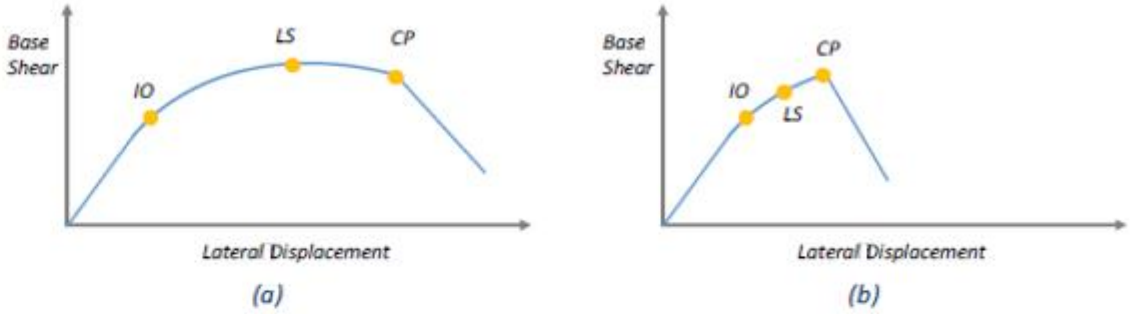


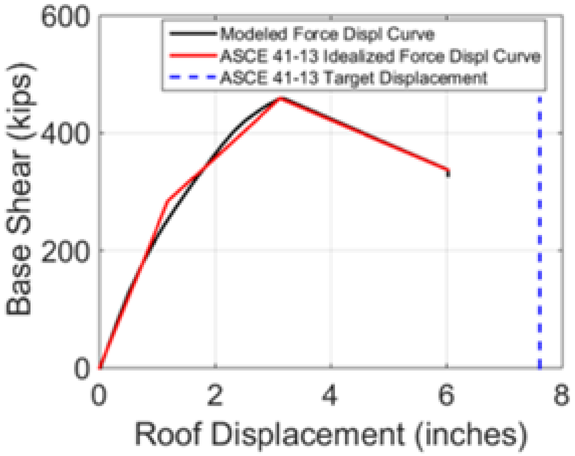
Figure 3.1 – Relative structural deformation demands between the three ASCE 41 performance levels: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) for (a) ductile and (b) nonductile structures (Figure from Harrington, 2016).

There are three tiers of evaluation allowed in ASCE 41. This study utilized Tier 3 (for evaluation and retrofit); Tier 3 is the most involved and, hence, least conservative and the most commonly used method in practice for retrofit design (Harrington, 2016). A Tier 3 involves comparing seismic demands on each component in a building to acceptance criteria (typically in terms of deformations for RC components). Nonlinear or linear, and static or dynamic, analysis procedures can be used. All elements in the structure must satisfy the acceptance criteria for the building to comply with the chosen performance level. If used to design a retrofit, the Tier 3 procedure is used to assess the retrofit, rather than original building. The retrofit design is modified until each component satisfies the performance level acceptance criteria. Harrington (2016) used the nonlinear static procedure, i.e. pushover, in ASCE 41's Tier 3.

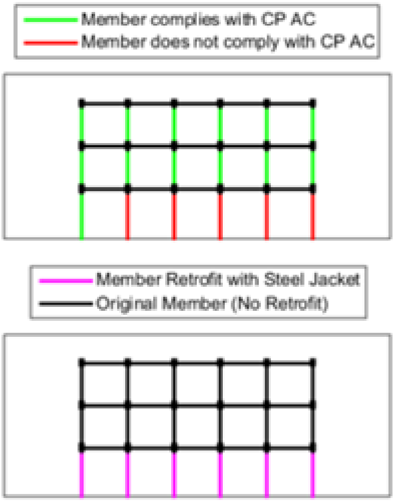
Searer et al. (2008) voiced concerns of "significant danger" ASCE 31-03 and ASCE 41-06 posed on the structural engineering community. According to those authors, these standards were overly conservative and required strengthening of elements that did not need to be upgraded, as well as reduced the creativity of engineers in design, compared to fully performance-based methods. In particular, ASCE 41is considered conservative because it claims the structure does not meet the performance objectives if a single primary structural element fails the acceptance criteria, rather than considering global structural performance. This element-based approach does not reflect the systematic performance of the structure, nor does it account for redundancy or load redistribution in the buildings (Searer et al., 2008)

3.1.2 Details about Retrofit Designs

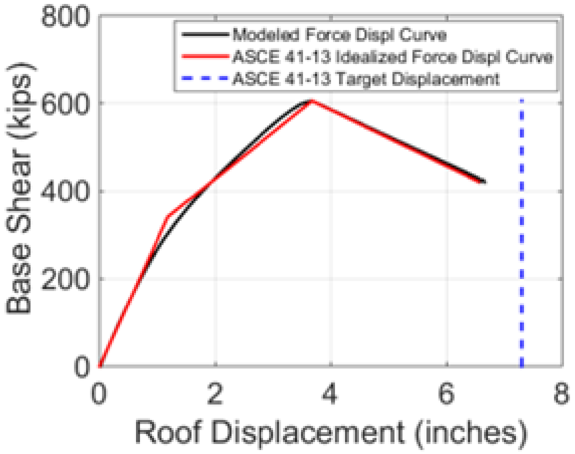
In total, Harrington (2016) designed 27 retrofit buildings (3 buildings x 3 performance levels x 3 retrofit strategies), as listed in Table 3.1. Buildings retrofit with steel jackets and concrete jackets both resulted in increased ductility capacity and strength (Harrington, 2016). presents the retrofit design process for a 3 story building retrofit with steel jackets to the CP performance level (all reproduced from Harrington, 2016). *(a)*, *(c)*, and *(e)* show the pushover plots for each iteration of retrofit and how the force-displacement relationship strengthens with increased retrofit. Buildings retrofit with FRP increased the deformation capacity (ductility) of the structure, but there was no significant change in strength. Building models retrofit with FRP wrapped columns to the IO performance level could not reach sufficient strength or stiffness requirements and are therefore not included in this study, leaving 24 retrofit buildings for analysis here.


Modeled Force Displ Curve
ASCE 41-13 Idealized Force Displ Curve
ASCE 41-13 Target Displacement
Base Shear (kips)
600
400
200
0
0
2
4
6
8
Roof Displacement (inches)

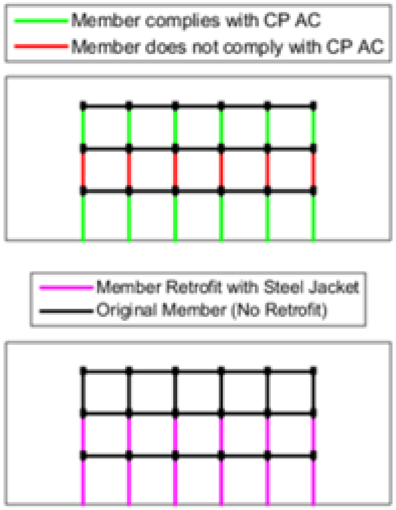
(a)


Member complies with CP AC
Member does not comply with CP AC
Member Retrofit with Steel Jacket
Original Member (No Retrofit)

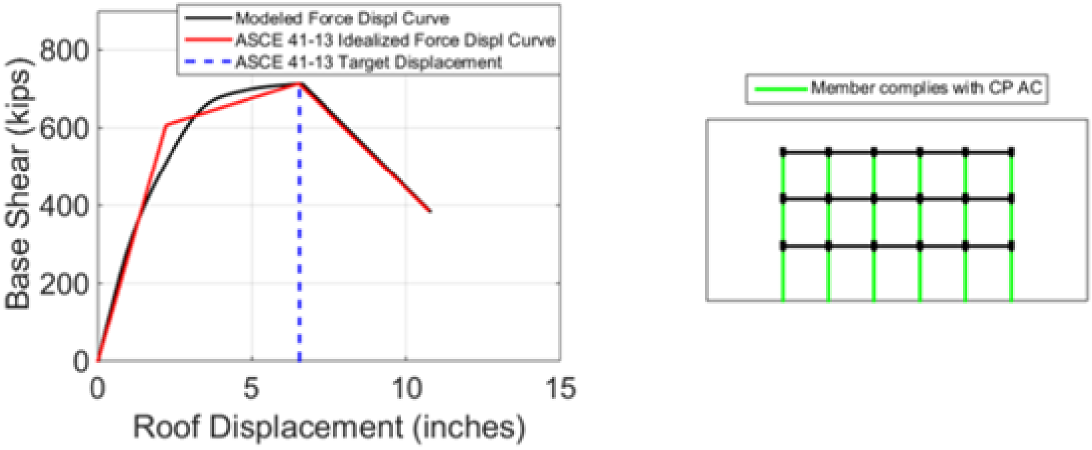
(b)


Modeled Force Displ Curve
ASCE 41-13 Idealized Force Displ Curve
ASCE 41-13 Target Displacement
Base Shear (kips)
800
600
400
200
0
0
2
4
6
8
Roof Displacement (inches)

(c)


Member complies with CP AC
Member does not comply with CP AC
Member Retrofit with Steel Jacket
Original Member (No Retrofit)

(d)



(e) (f)

Figure 3.2 – Retrofit design process for a 3 story building retrofit with steel jackets to the CP performance level: (a) Evaluation of original 1967 building using the NSP; (b) Members that are found not to comply with CP acceptance criteria (AC) under seismic hazard level and retrofit scheme implemented to address these deficiencies; (c) Evaluation of structure after the first retrofit iteration; (d) Members that are not compliant with CP under seismic hazard level, and the associated retrofit scheme;(e) Evaluation of the structure after the second retrofit iteration; (f) Showing that all members now comply with CP under the seismic hazard level (all from Harrington, 2016).

3.1.3 Modeling of Building Response using OpenSEES

Each building archetype was assessed using nonlinear models in *OpenSEES* for the pushover analysis used in the retrofit design process, as well as the modeling necessary for the PBEE assessment (determining structural responses and collapse capacities). Each beam is assumed to be controlled by flexure and, therefore, is modeled using distributed (“force-based”) plasticity elements that can capture initial stiffness, concrete crushing, steel yielding, and steel buckling (Harrington, 2016). All unretrofit columns are modeled as either flexure-critical or shear-critical columns. Flexure-critical columns are modeled with distributed fiber elements that capture axial-flexure interaction that is critical for columns, in addition to the behaviors previously identified for beam elements. Shear-critical columns have the fiber elements, but also shear and axial springs that can capture shear failure and subsequent loss of vertical load bearing capacity (Harrington, 2016). Columns retrofit with FRP jackets are modeled by altering the element's shear, axial, and flexural response to reflect the increase in shear strength and improved confinement of the concrete. Columns retrofit with steel jackets and concrete jackets are modeled by altering the element's fiber properties to account for the additional confinement and material in the jacket.

Further modeling considerations for the structures include modeling of the joints, foundation fixities, damping, and P-Δ effects. All joints in the structure are modeled using panel zones centered around elastic rotational springs to describe shear flexibility and deformation (Harrington, 2016). Ground floor columns are assumed to be fixed at their base (Harrington, 2016). Five percent Rayleigh damping is considered and anchored to each model's first and third modes, with damping only defined to elastic elements. Finally, *OpenSEES* "P-Delta" coordinate transformation is used in each model to account for geometric nonlinearities, or *P-Δ* effects, in the structural responses.

Peak floor accelerations (PFAs) and story drift ratios (SDRs) are presented to quantify the engineering demand parameters (EDPs), which were computed in the nonlinear dynamic multi-stripe analysis in Harrington (2016), with records selected according to the conditional mean spectrum approach. Collapse capacities were computed through incremental dynamics analysis (Harrington 2016) and are reported in Table 3.1.

3.1.4 Modeling of Building Damage and Losses using SP3

The Seismic Performance Prediction Program (SP3), created by Haselton Baker Risk Group, is a probabilistic seismic loss assessment tool based on the FEMA P-58 methodology (FEMA, 2012). FEMA P-58 is a building-specific method for predicting building losses through four main stages of analysis: hazard analysis, structural analysis, damage analysis, and building loss analysis. SP3 uses the USGS-defined hazard curve to compute the site specific earthquake hazard for each building model at the building's period and site soil class. In the structural analysis step, the EDPs from Harrington (2016) are used to define the structural response history, and then are used during damage analysis to evaluate each structural and nonstructural component's damage accumulation. The damage of each component is probabilistically derived using fragility functions, based on the EDPs. Finally, during loss analysis, component damage is related to decision variables including repair costs, repair time, and fatalities. This method relies on Monte Carlo simulations to represent a large number of possible earthquakes and their impact on building responses.

Table 3.1 – Characteristics of buildings designed and modeled by Harrington (2016) used for this study.

Retrofit Method	*Number Stories*	*Performance Level*	*Occupancy*	*Mean Loss (%)*[1]	*Median Collapse Capacity Sa(T_1) (g)* [2]
None	3	*None*	Commercial	78%	1.28
None	3	*None*	Residential	97%	1.28
None	3	*None*	Warehouse	76%	1.28
FRP	3	CP	Commercial	65%	2.11
FRP	3	CP	Residential	82%	2.11
FRP	3	CP	Warehouse	65%	2.11
FRP	3	LS	Commercial	65%	2.11
FRP	3	LS	Residential	82%	2.11
FRP	3	LS	Warehouse	65%	2.11
Steel J.	3	CP	Commercial	41%	1.72
Steel J.	3	CP	Residential	48%	1.72
Steel J.	3	CP	Warehouse	41%	1.72
Steel J.	3	LS	Commercial	40%	1.92
Steel J.	3	LS	Residential	46%	1.92
Steel J.	3	LS	Warehouse	41%	1.92
Steel J.	3	IO	Commercial	22%	2.04
Steel J.	3	IO	Residential	28%	2.04
Steel J.	3	IO	Warehouse	28%	2.04
Conc. J.	3	CP	Commercial	33%	2.02
Conc. J.	3	CP	Residential	37%	2.02
Conc. J.	3	CP	Warehouse	35%	2.02

Retrofit Method	*Number Stories*	*Performance Level*	*Occupancy*	*Mean Loss (%)*[1]	*Median Collapse Capacity Sa(T_1) (g)* [2]
Conc. J.	3	LS	Commercial	42%	1.77
Conc. J.	3	LS	Residential	49%	1.77
Conc. J.	3	LS	Warehouse	43%	1.77
Conc. J.	3	IO	Commercial	15%	2.96
Conc. J.	3	IO	Residential	18%	2.96
Conc. J.	3	IO	Warehouse	21%	2.96
None	6	*None*	Commercial	76%	0.93
None	6	*None*	Residential	75%	0.93
None	6	*None*	Warehouse	74%	0.93
FRP	6	CP	Commercial	53%	1.26
FRP	6	CP	Residential	51%	1.26
FRP	6	CP	Warehouse	50%	1.26
FRP	6	LS	Commercial	53%	1.26
FRP	6	LS	Residential	51%	1.26
FRP	6	LS	Warehouse	50%	1.26
Steel J.	6	CP	Commercial	36%	1.27
Steel J.	6	CP	Residential	38%	1.27
Steel J.	6	CP	Warehouse	39%	1.27
Steel J.	6	LS	Commercial	27%	1.36
Steel J.	6	LS	Residential	24%	1.36
Steel J.	6	LS	Warehouse	27%	1.36
Steel J.	6	IO	Commercial	7%	1.81
Steel J.	6	IO	Residential	8%	1.81
Steel J.	6	IO	Warehouse	12%	1.81
Conc. J.	6	CP	Commercial	45%	1.37
Conc. J.	6	CP	Residential	43%	1.37
Conc. J.	6	CP	Warehouse	43%	1.37
Conc. J.	6	LS	Commercial	45%	1.37
Conc. J.	6	LS	Residential	43%	1.37
Conc. J.	6	LS	Warehouse	43%	1.37
Conc. J.	6	IO	Commercial	6%	2.86
Conc. J.	6	IO	Residential	6%	2.86
Conc. J.	6	IO	Warehouse	11%	2.86
None	9	*None*	Commercial	49%	1.17
None	9	*None*	Residential	74%	1.17
None	9	*None*	Warehouse	47%	1.17
FRP	9	CP	Commercial	25%	1.44
FRP	9	CP	Residential	21%	1.44
FRP	9	CP	Warehouse	25%	1.44
FRP	9	LS	Commercial	25%	1.44
FRP	9	LS	Residential	21%	1.44
FRP	9	LS	Warehouse	25%	1.44
Steel J.	9	CP	Commercial	39%	1.57
Steel J.	9	CP	Residential	33%	1.57
Steel J.	9	CP	Warehouse	36%	1.57

Retrofit Method	*Number Stories*	*Performance Level*	*Occupancy*	*Mean Loss (%)*[1]	*Median Collapse Capacity Sa(T_1) (g)* [2]
Steel J.	9	LS	Commercial	40%	2.05
Steel J.	9	LS	Residential	35%	2.05
Steel J.	9	LS	Warehouse	37%	2.05
Steel J.	9	IO	Commercial	3%	3.70
Steel J.	9	IO	Residential	2%	3.70
Steel J.	9	IO	Warehouse	6%	3.70
Conc. J.	9	CP	Commercial	38%	1.58
Conc. J.	9	CP	Residential	33%	1.58
Conc. J.	9	CP	Warehouse	36%	1.58
Conc. J.	9	LS	Commercial	39%	2.37
Conc. J.	9	LS	Residential	33%	2.37
Conc. J.	9	LS	Warehouse	36%	2.37
Conc. J.	9	IO	Commercial	7%	3.58
Conc. J.	9	IO	Residential	2%	3.58
Conc. J.	9	IO	Warehouse	7%	3.58

[1] *Mean losses are presented as a percentage of the building value, at the 10% in 50-year event at a site in Southern California (33.996°N, -118.162°W).*

[2] *Median collapse capacities Sa(T_1) are computed as the structural response up to collapse using Incremental Dynamic Analysis of a set of far-field ground motions from FEMA P695 (Harrington, 2016).*

Each unretrofit and retrofit model is duplicated and rerun for three different occupancy types: commercial-, residential-, and warehouse-use buildings (see Table 3.1). These occupancy types were chosen to cover the majority of the building stock evaluated in this study. Each occupancy model differs in cost per square foot, and the assumed population of nonstructural components; structural components are identical regardless of occupancy.

Nonstructural components are populated using typical component inventories for each building model from quantities and fragilities published in FEMA P-58 (FEMA, 2012) and expanded by the Haselton Baker Risk Group. All structural components are explicitly-defined for each model based on the UBC-designed RC frame components and the retrofit RC frame components from Harrington (2016). These user-defined unretrofit elements were assigned as "non-conforming moment frame" components. Each retrofit column was assigned the Ordinary Moment Frame (OMF) fragility function because FEMA P-58 and SP3 do not have retrofit column fragility functions. The OMF fragility functions are reasonable substitutes for the retrofit columns because the columns in OMF systems are flexurally-governed and damage concentrates in the beams and joints, similar to jacketed columns, although repair costs may differ (Harrington, 2016). The number of OMF fragility functions at each story are based on how many columns were retrofit for each story.

Spectral acceleration at the building's effective fundamental period, $Sa\ (T_1)$, is the ground motion intensity measure used. This effective fundamental period comes from ASCE 41 Section 7.4.3.2.5, and is computed in from an idealized force-displacement curve (Harrington, 2016). SP3 uses a site-specific hazard curve based on the 2009 U.S. Geological Survey (USGS) probabilistic seismic hazard maps. Initially, each building model in SP3 is assumed to be located at a site in Southern California (33.996°N, -118.162°W).

Every structural and nonstructural component is associated with a fragility curve to determine the repair cost of that element, given the level of damage. The building losses are a summation of the repair costs of all the components that make up the building, for each earthquake simulation. Therefore, economic losses are calculated as the damage from the combined structural components, nonstructural components, and building contents, all normalized by the structure's replacement cost (without demolition), and are evaluated at the following hazard levels for the site coordinates provided above: 50% in 50 years (72-year return period (RP)), 50% in 100 years (144-year RP), 10% in 50 years (475-year RP), 5% in 50 years (975-year RP), and 2% in 50 years (2475-year RP). This produces a (vulnerability) curve relating ground motion intensity to loss that is site-independent for use in the regional loss assessment. Figure 3.3 shows median loss data for the buildings with commercial occupancy and retrofitted using steel jacketing. Selected economic loss values for all buildings are provided in Table 3.1. The loss values do not take into account the cost of business interruptions or possible increase of market values after an event (Haselton Baker Risk Group, n.d.).

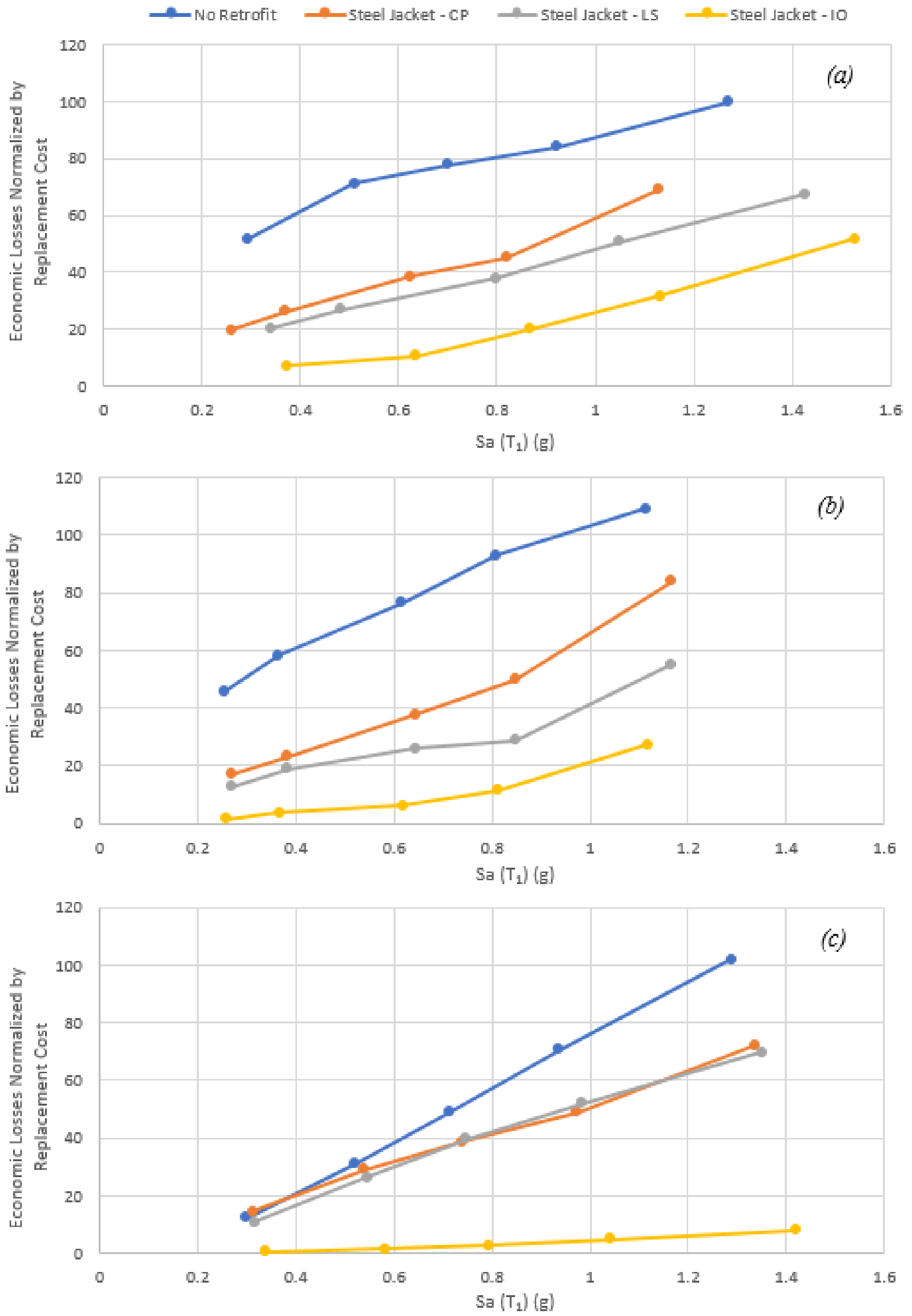


Figure 3.3 – Economic losses computed from SP3 for retrofit and unretrofit (a) 3-story models, (b) 6-story models, and (c) 9-story models at five levels of ground motion intensity, considering commercial occupancy, and retrofits were done with steel jackets. Note: Losses are presented as a percentage normalized by the replacement cost of the building without demolition.

In this study, SP3 is used to calculate the financial, time, and human losses for each of the retrofit buildings, as well as the unretrofit. Financial losses are calculated as the dollar value required to repair all the damaged building components (in Figure 3.3 are normalized by the replacement cost of the building). Serial repair time is computed as the time it takes to repair the structural and nonstructural elements in the building, assuming work can be completed only one floor at a time (FEMA, 2012), although this is more conservative for taller buildings. To compute human losses, we consider only fatalities associated with structural collapse, not falling objects. The collapse fatalities are derived by the building's collapse modes and the population of the building at the instance of simulated collapse (FEMA, 2012). The building collapse modes are built in to each component fragility based on the FEMA P-58 methodology, and building population is based on the time and day of each earthquake simulation, and the size and occupancy type of the building (FEMA, 2012).

3.2 Probabilistic Portfolio Seismic Risk Assessment

A group of spatially-distributed buildings in a region subject to earthquake damage and losses is represented by a building stock. The combined losses of the building stock are referred to as "regional losses". This regional retrofit study utilizes the advances made in probabilistic portfolio seismic risk assessments from DeBock & Liel (2015a). Probabilistic methods can be distinguished from scenario approaches, which are based on the occurrence of a specific earthquake scenario and possible outcomes from that earthquake.

3.2.1 Probabilistic Regional Loss Assessment Methodology

Most probabilistic regional loss assessments utilize a Monte Carlo simulation (MCS) method in sampling fault rupture using specific fault rupture scenarios (DeBock, 2013; DeBock & Liel, 2015b, 2015a). Thousands of fault rupture scenarios are selected to accurately represent the hazard of a particular region. For each fault rupture, a suite of ground motion intensity maps is calculated for the region using MCS. Building losses at each site are calculated from the resulting SP3 loss analysis for each building model and portfolio losses for each simulated map are computed by adding all the building losses in the region. (Alternatively, importance sampling can be used to reduce the number of maps to a more computationally efficient level.) The probability densities associated with each simulated rupture scenario can be combined with the region portfolio losses from the series of MCS to compute a mean rate of exceedance (MRE) curve for the region (DeBock & Liel, 2015b, 2015a). Figure 3.4 presents a flowchart of the regional loss assessment procedure.

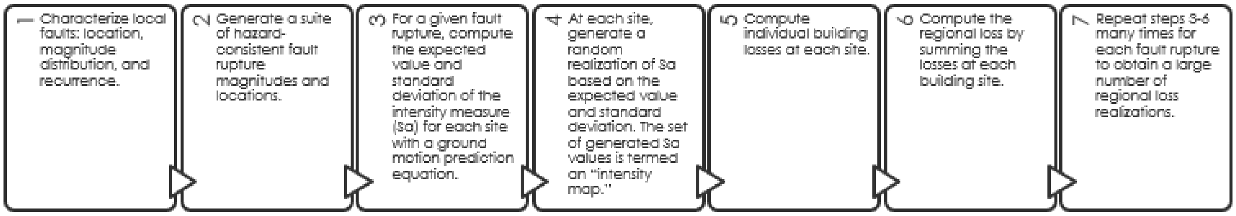


Figure 3.4 – Probabilistic portfolio seismic risk assessment procedure (DeBock & Liel, 2015a)

3.2.2 Types of Spatial Correlations

Crucially, the probabilistic regional loss assessment developed by DeBock (2013) incorporates two primary sources of spatial correlations in ground motion intensity measures. The first source of spatial correlation is the intra-event spectral acceleration residuals, which stem from the attenuation of the earthquake ground motion over distance, as captured by using ground motion prediction equations (GMPE, e.g. Boore & Atkinson 2008). As the intensity from the earthquake attenuates with increasing distance from the fault rupture, all sites in the region will feel the different intensities of ground shaking, but sites close to each other will all tend to experience shaking higher or lower than average (Goda & Hong, 2008a; Goda & Hong, 2008b; Jayaram & Baker, 2009; Loth & Baker, 2013). The spatial correlation stems from the amount the ground motion intensities differentiate from the expected values of intensity computed from the GMPE. Previous research has shown that neglecting the spatial correlations from ground motions intensities can lead to overestimation of regional losses in smaller and more frequent events, and underestimation in larger and less frequent events (e.g., DeBock & Liel, 2015a; Park et al., 2007). The second source of correlation is the inter-event spectral acceleration residuals, which is constant for each building period across all sites in each intensity map (DeBock, 2013; DeBock & Liel, 2015a). The inter-event residual represents the uncertainty in fault rupture characteristics and regional effects (DeBock, 2013; DeBock & Liel, 2015a).

DeBock et al. (2013) distinguished between two types of spatial correlations in building response: self-correlation and cross-correlation. Self-correlation is the spatial correlation of the same building's response at different site locations. Cross-correlation is the spatial correlation of different building's responses at different site locations. Both types are important in this study because our building stock consists of some identical building models at different sites, as well as many different buildings at different sites.

DeBock et al. (2013) created a distribution of spatial correlations for building responses by evaluating nonlinear structural responses of building models subject to a set of geographically distributed historical and simulated ground motions. Six building models of ductile and nonductile concrete structures, of varying height, ductility and strength, were used in the dynamic structural modeling to capture building behavior. Several EDPs were extracted from the nonlinear models and include peak floor acceleration, interstory drift ratio, and beam and column plastic hinge rotations (DeBock, 2013; DeBock & Liel, 2015a).The study found that regardless of which EDP is used in the evaluation, patterns in correlations, conditioned on an IM of $Sa(T_1)$, are all similar (DeBock, 2013).

Results in spatial correlations show that, as the inter-site distance between two sites increases, the correlation decreases, although it is dependent on building and earthquake characteristics. The cross-correlations are greatly impacted by specific building characteristics including differences in building period and ductility, and earthquake characteristics including event magnitude and soil conditions (Vs,30) (DeBock, 2013). For example, positive correlations in building responses for larger inter-site distances are seen in larger magnitude events. In addition, the use of absolute response quantities when calculating correlations results in sensitivity to the size of the earthquake event (DeBock, 2013). This probabilistic regional loss assessment (DeBock, 2013; DeBock & Liel, 2015b) is unique because it uses existing GMPEs and spatial correlation models to map a region with site-specific building responses and realistic correlation patterns.

3.3 Implementation of Probabilistic Regional Loss Assessment and Advanced Retrofit Models in this Study

3.3.1 Existing Building Portfolio

The building inventory used in this study was obtained from the Network for Earthquake Engineering Simulation (NEES) Grand Challenge (NEES, 2011). The NEES team compiled an inventory of 1451 pre-1976 reinforced concrete buildings in the city of LA. he building inventory provides the latitude and longitude of each NDC structure in the city of LA, as well as most addresses, occupancy types, building types, years built, and total building area. Note that only older (pre-1976) concrete buildings are included in the building stock, and tilt-up buildings are excluded. The inventory is not specific about which buildings have concrete and / or infill walls. The building inventory is mapped in Figure 3.5, showing only the subset of 1132 buildings used in this study for reasons described below.

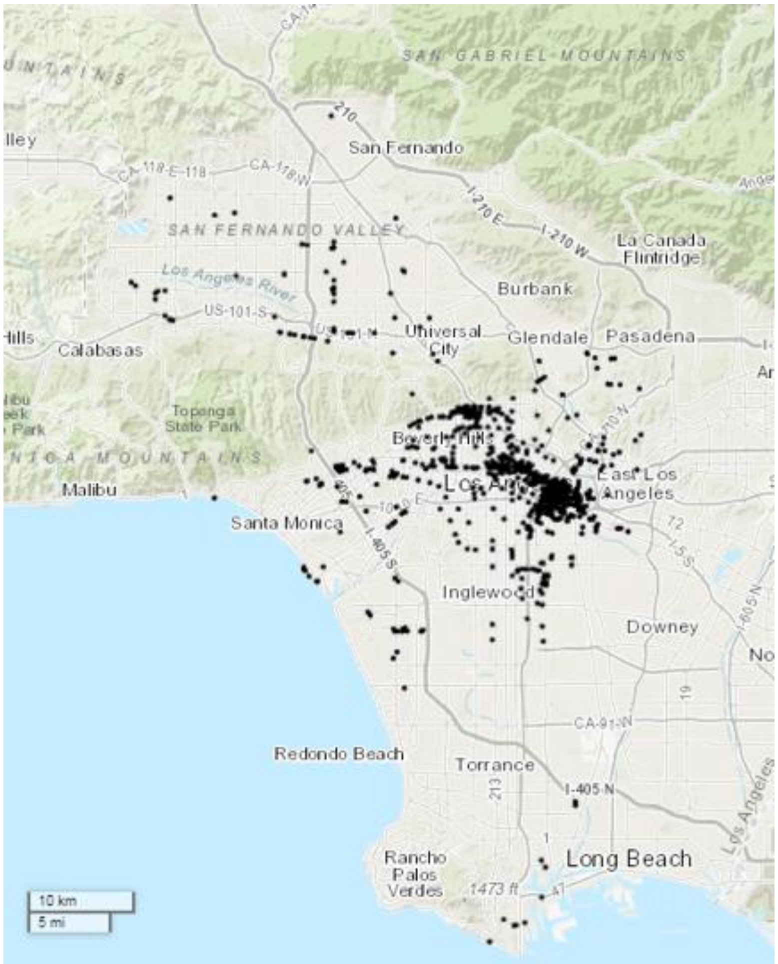


Figure 3.5 – Locations of NDC buildings in the city of LA included in this study.

The building models from Harrington (2016) are mapped to this building inventory by assigning one of our retrofit or unretrofit building models to each building in the inventory. To do so, we make a number of assumptions: (1) all NDC buildings in the inventory are assigned to our NDC frame models, although some buildings likely have walls; (2) commercial building models are assigned to buildings labeled as commercial and government occupancies in the inventory, warehouse building models are assigned to buildings labeled as warehouse and industrial occupancies, and residential building models are assigned to buildings labeled as all residential occupancies (including nursing homes and hotels), as reported in Table 3.2; (3) buildings 1 to 3 stories in height are assigned to a 3 story (low-rise) model, buildings 4 to 7 stories in height are assigned to a 6 story (mid-rise) model, and buildings 8 to 18 stories in height are assigned to a 9 (high-rise) story model (see Figure 3.7). All churches, educational buildings, and healthcare buildings are excluded from this inventory, because of differences in design procedures and in representing the nonstructural components and contents for these buildings, leaving 1132 total buildings for this assessment. Figure 3.6 and Figure 3.7 show the breakdown of the structures in the NDC building inventory by specific occupancy and number of stories, respectively.

Table 3.2 – Building stock breakdown by occupancy.

Grey Model Occupancy	*NEES Occupancy*	*No. of Buildings*	*% of Building Stock*
Residential	Residential	202	18%
Commercial	Commercial	575	53%
	Government	30	
Warehouse	Warehouse	125	29%
	Industrial	200	

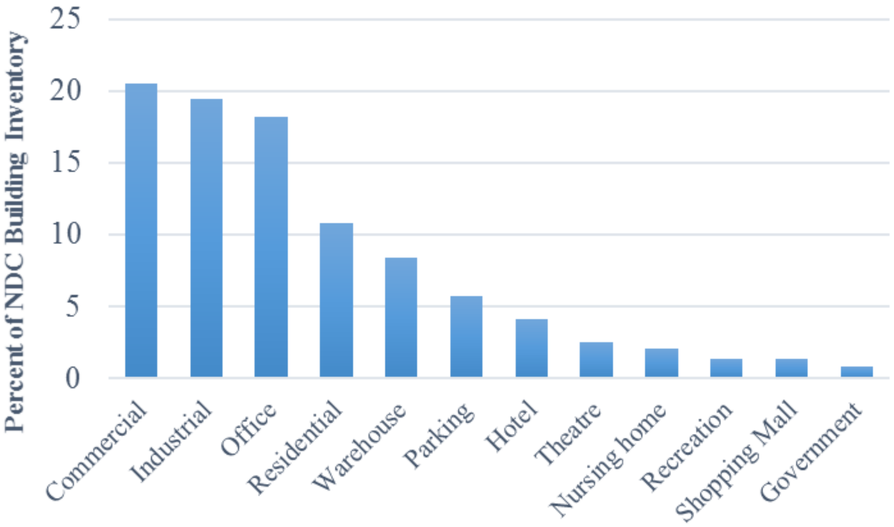


Figure 3.6 – Number of NDC buildings in the LA inventory used in this study, by NEES occupancy designation.

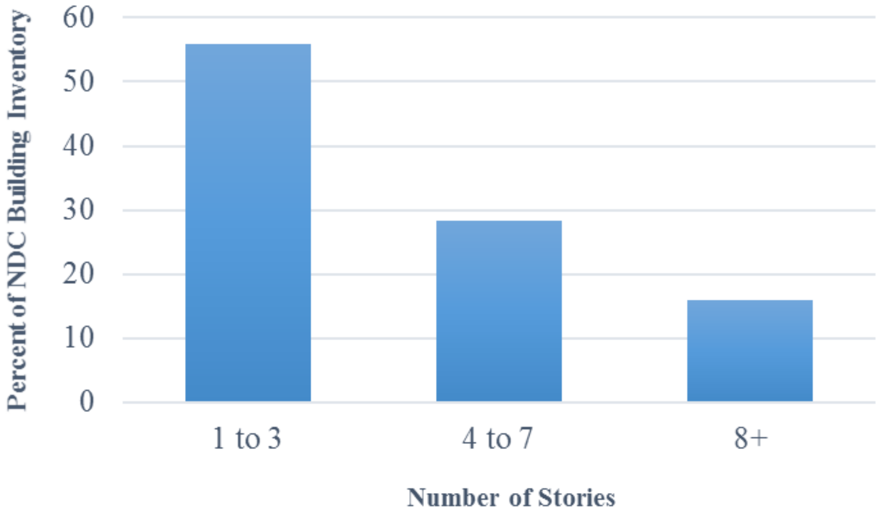


Figure 3.7 – Number of NDC buildings in the LA inventory used in this study, by story height.

3.3.2 Retrofit Cases to the Building Portfolio

For this regional retrofit study, we considered many different retrofit cases, presented in . Case 0 is the original, unretrofit building portfolio. The initial retrofit case starts with retrofitting 10% of building stock. When 10% of the NDC building inventory is retrofit, five different cases for level of retrofit, *i.e.*, combinations of CP, LS, and IO, are chosen. The buildings comprising the 10% selected for retrofit are random. The variability of the regional loss results was evaluated to determine how significant the losses changed based on which buildings were randomly selected for retrofit by running 100 MCS and plotting the resulting regional losses. Figure 3.8 presents the total economic losses against the return period for the region for 20 randomly selected iterations (red lines), as well as the median regional loss of all 100 iterations (blue line). From Figure 3.8, the total economic regional losses do not significantly change from any one iteration to the next, and therefore, the remainder of this study used only one iteration of random building selection for each regional retrofit case. In addition, for each case, the type of retrofit (concrete jacketing of the columns, steel jacketing of the columns, or FRP wrapping of the columns) are assigned at random to each building in the region through MCS, but evenly distributed between the types. Thus, Case 1.1 represents the minimum retrofit case considered (only 10% are retrofit, and to the CP level), and Case 11.3 represents the maximum retrofit case (90% are retrofit, and all the retrofits are to IO).

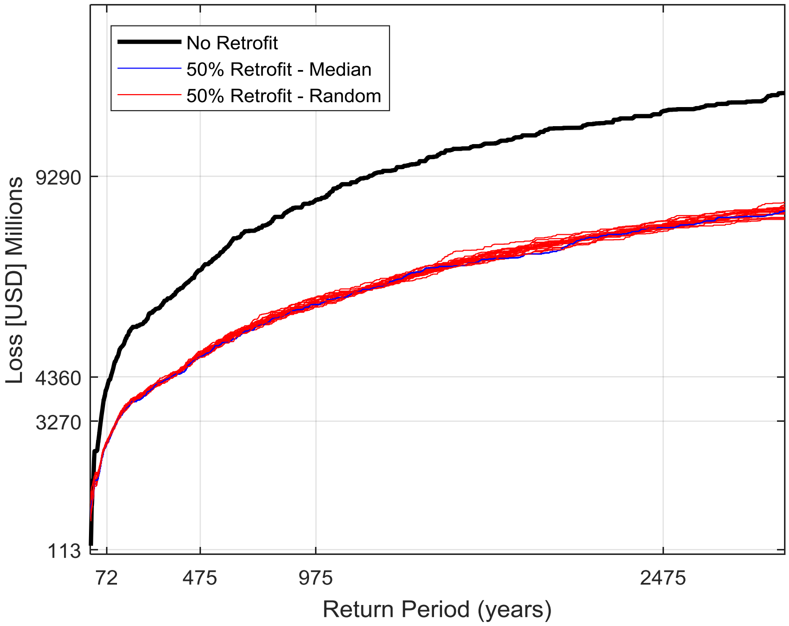


Figure 3.8 – Total regional economic losses presented against return period for 20 randomly selected iterations of Case 6.4 and the median of 100 total iterations.

Table 3.3 – Regional retrofit cases.

Case Number	*% of Region Retrofit*	*% Collapse Prevention*	*% Life Safety*	*% Immediate Occupancy*
0	0	0	0	0
1.1	10	100	0	0
1.2	10	0	100	0
1.3	10	0	0	100
1.4	10	33	33	33
1.5	10	60	30	10
2.1	20	100	0	0
2.2	20	0	100	0
2.3	20	0	0	100
2.4	20	33	33	33
2.5	20	60	30	10

Case Number	*% of Region Retrofit*	*% Collapse Prevention*	*% Life Safety*	*% Immediate Occupancy*
3.1	25	100	0	0
3.2	25	0	100	0
3.3	25	0	0	100
3.4	25	33	33	33
3.5	25	60	30	10
4.1	30	100	0	0
4.2	30	0	100	0
4.3	30	0	0	100
4.4	30	33	33	33
4.5	30	60	30	10
5.1	40	100	0	0
5.2	40	0	100	0
5.3	40	0	0	100
5.4	40	33	33	33
5.5	40	60	30	10
6.1	50	100	0	0
6.2	50	0	100	0
6.3	50	0	0	100
6.4	50	33	33	33
6.5	50	60	30	10
7.1	60	100	0	0
7.2	60	0	100	0
7.3	60	0	0	100
7.4	60	33	33	33
7.5	60	60	30	10
8.1	70	100	0	0
8.2	70	0	100	0
8.3	70	0	0	100
8.4	70	33	33	33
8.5	70	60	30	10
9.1	75	100	0	0
9.2	75	0	100	0
9.3	75	0	0	100
9.4	75	33	33	33
9.5	75	60	30	10
10.1	80	100	0	0
10.2	80	0	100	0
10.3	80	0	0	100
10.4	80	33	33	33
10.5	80	60	30	10
11.1	90	100	0	0
11.2	90	0	100	0
11.3	90	0	0	100
11.4	90	33	33	33
11.5	90	60	30	10

3.3.3 Implementation of Regional Loss Assessment

The regional loss assessment begins with the making of maps of spatially distributed spectral acceleration values at a variety of different fundamental periods to assess each building at each site. A total of 62,650 maps are created for this region. The spectral acceleration calculated at each site considers the correlations described above. The Ground Motion Prediction Equation (GMPE) used in this study is from Boore and Atkinson (2008), which is dependent on soil conditions ($V_{s,30}$). $V_{s,30}$ values were obtained for each site from Haselton Baker Risk Group, which are based on the USGS topographic-based $V_{s,30}$ (personal communication, 2018; USGS, 2015). Before beginning the losses assessment, the hazard implied by the maps is compared to USGS Hazard curves to ensure the mapped representation of future earthquakes adequately captures site seismicity.

After all the maps are created, losses are generated from median loss (vulnerability) curves (Figure 3.3) for each building described in Chapter 3.1.4 (Modeling of Building Damage and Losses using SP3). These curves were generated with SP3 at the five stripes of intensity levels for each building. The value of losses for each building are interpolated from the available points based on spectral acceleration from each map at each spectral acceleration demand at each site. Median losses are used because there is no significant change in regional loss results compared to using a MCS to pull losses from a loss curve for each building (DeBock & Liel, 2015a). This implies the variability in regional loss results is not dominated from the uncertainties in the vulnerability functions, and instead is dominated from the variability in the event-to-event ground shaking intensity (DeBock, 2013; DeBock & Liel, 2015a).

When calculating the losses, if the spectral acceleration demand of the simulated map at a site is greater than the maximum demand considered in the SP3-generated loss curve, the maximum SP3 loss for that building model is used. This assumption may produce a slight underestimation of individual building losses, but it is an attempt to control the unreasonable extrapolation of losses that could occur if extrapolated linearly, and it does not significantly change the regional loss results. In addition, the maximum spectral acceleration demand for which each building model in SP3 was evaluated was compared to the median collapse capacity to ensure each model was analyzed (for losses) past the collapse capacity. For models that were not assessed at a spectral acceleration level meeting or exceeding that building's collapse capacity, linear extrapolation was used to calculate another associated loss value for that model at a higher spectral acceleration value. These additional loss values were applied and used to calculate the losses of the building at each simulated map. We found no significant changes between the computed regional losses that incorporate the additional extrapolated loss value and the computed regional losses that use the maximum loss value at the previously highest spectral acceleration. If the spectral acceleration demand of the simulated map is less than the minimum acceleration demand considered in SP3, the simulated loss value is linearly extrapolated below the minimum SP3 loss value. These assumptions apply to the resulting economic, time-based, and fatality losses.

Regional economic losses are calculated as the summation of the losses from building damage or collapse for every building in the region at that seismic event. The repair time of each building at each map simulation is linearly interpolated between the median SP3 serial repair times, based on ground shaking intensity. Repair time for each building is used in this study to determine an average repair time per story, by dividing the resulting SP3 serial repair time for each building model by the number of stories for that model. Average repair time per story is then used to calculate the number of people displaced from their residence and the number of unoccupiable buildings. In this study, if the repair time per story for a building is 42 days or greater the building is deemed unoccupiable, and if the repair time per story is 21 days or greater the considered residents are (“long-term”) displaced from their home. Regional repair time is the summation of the “serial repair time,” from SP3 and the FEMA P-58 methodology, of every building for each event.

Regional fatalities are computed as the summation of fatalities for every building for each map (event). As with economic losses and repair time losses, collapse fatality losses calculated in this study for each building at each map are linearly interpolated between the median SP3 collapse fatality values. The model assumes the median collapse fatalities in each case, as function of intensity. However, larger fatalities would result from higher occupancy of the building based on the time and day of the simulation (i.e. values farther from the median), which are not directly accounted for here.

CHAPTER 4

REGIONAL LOSSES, FATALITIES AND REPAIR TIMES, ACCOUNTING FOR RETROFIT

Chapter 4 presents the results from the probabilistic regional loss assessment, incorporating a number of retrofit cases. The results are proposed as losses in community-level repair costs, savings from retrofit strategies, repair time, and fatalities. These results show probabilistically how the losses change on a regional scale as more buildings in the region are retrofit, and as the performance level of the retrofits change.

4.1 **Retrofit Effectiveness Metrics**

4.1.1 Motivation for Selected Results

Davis & Porter (2016), in collaboration with the National Institute of Buildings Sciences' Multihazard Mitigation Council, conducted a survey asking the public about the potential consequences of a large earthquake on the Hayward Fault in the San Francisco Bay Area, and their opinion on current and future building codes. The respondents of the survey were 814 adults from California, Missouri, and Tennessee in July 2015, although only the results from the 400 California respondents are used in this section. To exclude professional-interest bias from the survey, building professionals were asked not to participate in the survey.

One question on the survey asked respondents what their preferred code objective should be, with 21% responding Life Safety, 42% responding Occupiable, and 19% responding Functional. "Life Safety" was defined for survey respondents to mean that people would not be killed, although the building may not be occupiable after an event; "Occupiable" means the building would still be habitable during repairs to bring the building back to the fully-functioning state after an event; and "Functional" means the building would endure minimal repairs and be functional after an event (Davis & Porter, 2016). The survey also asked what building buyers would be willing to pay for a functional or occupiable building after a large event, most respondents answered with \$3 or \$10 per square foot (options included \$0, \$1, \$3, and \$10), suggesting they may be willing to pay for increased performance of their buildings (Davis & Porter, 2016). The goal of the current building code is to safeguard human lives; therefore, this study indicates the public might prefer an updated building code so that buildings are functional or occupiable after a large earthquake. Another question from the survey asked respondents if they thought the future of seismic building performance was important or not, and about 80% of respondents chose "important" or "very important." (Davis & Porter, 2016).

One final question the committee asked the public was about alternatives to the functional-occupiable-life-safe scale to measure seismic performance of buildings. The question asked which of the five measures are of most interest: (1) number of people injured or killed in the community, i.e. community casualties, (2) number of collapsed buildings in the community, (3) number of unoccupiable buildings in the community, (4) per-building collapse probability, or (5) total repair costs of damaged buildings in the community. Of the Californian respondents, 38% responded that number of community casualties was most critical, 23% expressed interest in per-building collapse probability, 12% wanted to see number of collapsed buildings, 11% found number of unoccupiable buildings to be important, 9% expressed interest in total repair costs, and 7% responded with something other than the above five options.

Here, we apply these results to study retrofit effectiveness in terms of interest to the community using four of these measures to assess retrofit alternatives for the city of LA. The seismic performance measure that is not resulted here is the per-building collapse probability, as that is a building-specific measure and does not fit into the scope of this thesis.

4.1.2 Number of Community Fatalities

From the public's response to the survey discussed in Davis & Porter (2016), one of the most important measures of buildings seismic performance is the number of people injured or killed after a large event. The current study evaluates the community fatalities (i.e. people killed) in the city of LA, shown in Figure 4.1 for various CP retrofit cases. Figure 4.1 and similar plots below are structured as follows. The x-axes correspond to the return periods associated with these regional consequences based on the seismic hazard for the region. The specific return periods chosen are values often used in engineering applications and code discussions. The number of fatalities experienced by the unretrofit city of LA with a 475 mean return period is 70 (of 96,500 total occupants in the 1132 NDC buildings in this study). (Later, we refer to this number of fatalities as the 475-year loss). If 50% of the region is retrofit to the CP performance level (Case 6.1), the city will experience about 50 fatalities at the 475-year loss. As expected, as the regional retrofit percentage increases, the number of community fatalities decrease at each return period loss.

Figure 4.2 shows the total community fatalities for the region retrofit to various LS cases, compared to the unretrofit region. At the 475-year loss, the city will endure about 45 fatalities if 50% of the region is retrofit to the LS level (Case 6.2). Figure 4.3 presents the total fatalities of the region, comparing the unretrofit region to the region is retrofit to various IO cases. If 50% of the region is retrofit to the IO performance level (Case 6.3), the city will experience about 40 at the 475-year loss.

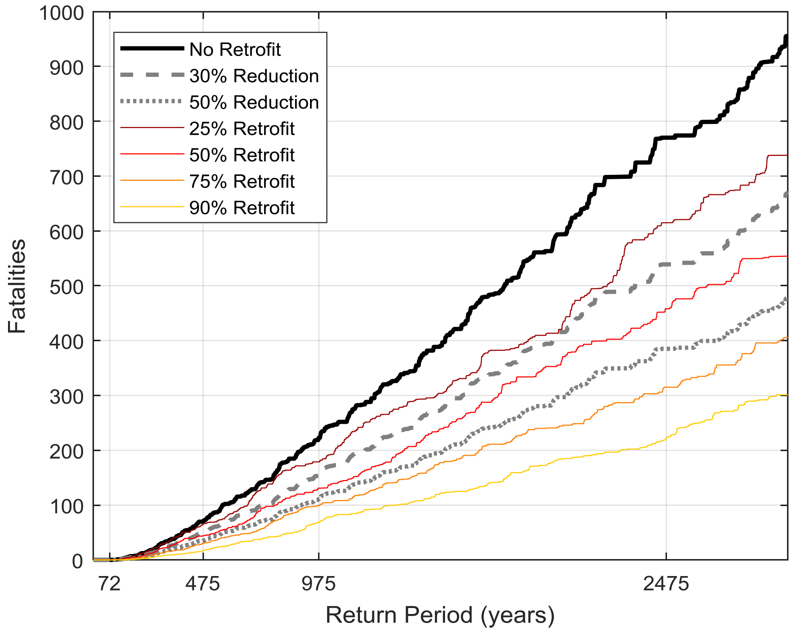


Figure 4.1 – Total regional fatalities presented against return period for buildings retrofit to the CP performance level (Cases 3.1, 6.1, 9.1, and 11.1).

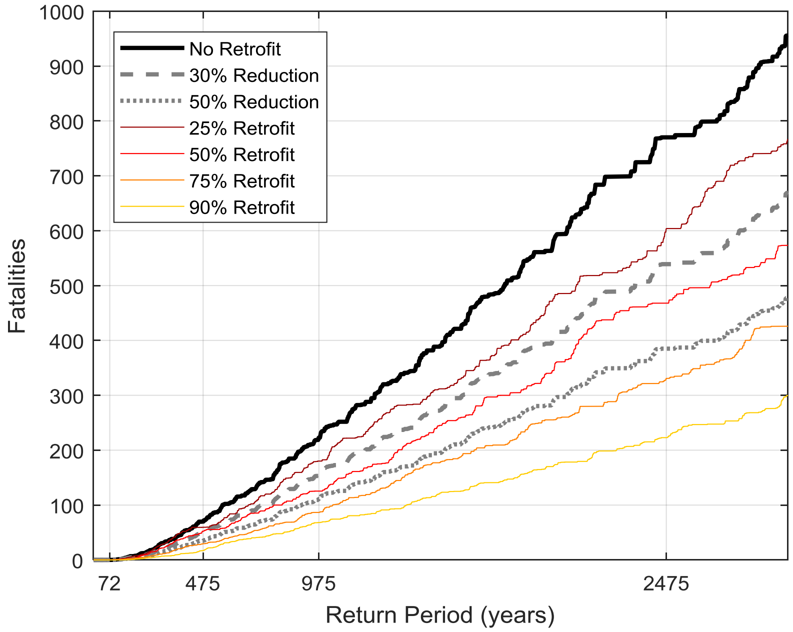


Figure 4.2 – Total regional fatalities presented against return period for buildings retrofit to the LS performance level (Cases 3.2, 6.2, 9.2, and 11.2).

In terms of community fatalities, unsurprisingly, the region retrofit to the IO performance levels results in the most significant reductions in deaths. While the region retrofit to CP or LS levels reduces the number of fatalities less than retrofitting the region to IO levels, the largest fraction of the gain is from the unretrofit region to the CP regions. Comparing the regional losses at each return period, there is not a significant difference between the loss results from the CP and LS retrofit cases. Although there are differences between the CP and LS regional losses, and the LS and IO regional losses, the most extreme differences are the between the CP and IO regional losses. As a result, the following figures will only be comparing the CP performance levels to the IO performance levels for significant differences in losses. All LS level results can be found in the Appendix. Figure 0.1 and Figure 0.2 in the Appendix show that the other retrofit cases evaluated both also reduce regional fatalities, but still not to the degree of the IO cases.

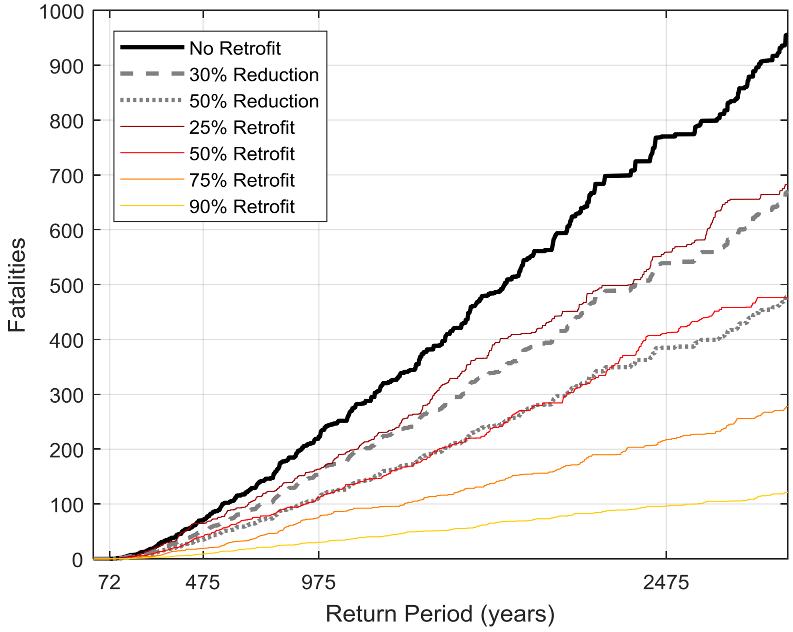


Figure 4.3 – Total regional fatalities presented against return period for buildings retrofit to the IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).

4.1.3 Number of Collapsed Buildings

The next seismic performance measure revealed as important to the public from the Davis & Porter (2016) survey is the number of collapsed buildings after a large event. Buildings are considered collapsed by comparing each building at that site in the assessment to their respective collapse capacity at its spectral acceleration demand as calculated in *OpenSEES.*

Figure 4.4 presents the number of collapsed buildings in the region for the unretrofit region, as well as the 25%, 50%, 75%, and 90% retrofit region, all to the CP performance level. In the unretrofit region, 41 NDC buildings (of 1132 total NDC buildings evaluated in this study) are predicted to collapse in the 475-year loss, which is about 3.6% of the buildings stock. When 50% of the region is retrofit to CP level, only 35 buildings collapse at the 475-year loss, which reduces the number of collapsed buildings to about 3.1% of the building stock. Of these 35 collapsed buildings, 22 of them are retrofit to CP.

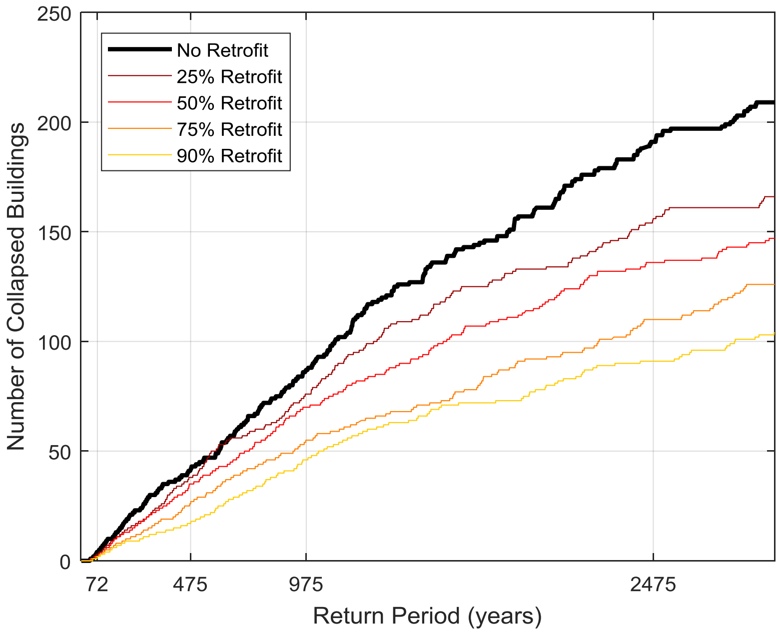


Figure 4.4 – Total number of collapsed buildings presented against return period for buildings retrofit to the CP performance level (Cases 3.1, 6.1, 9.1, and 11.1).

Figure 4.5 below shows the number of collapsed buildings in the unretrofit region, compared to the case regions when all buildings retrofit in that scenario are retrofit to the IO performance level. When 50% of the region is retrofit to the IO level, only 25 buildings collapse at the 475-year loss, which is about 2.2% of the building stock.

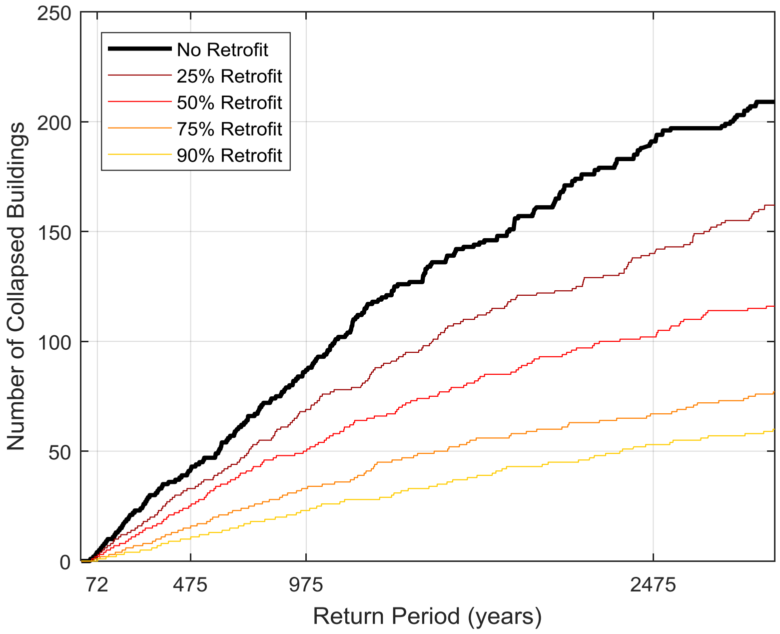


Figure 4.5 – Total number of collapsed buildings presented against return period for buildings retrofit to the IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).

4.1.4 Number of Unoccupiable Buildings

This section presents the number of unoccupiable buildings in the region, again motivated by the Davis & Porter (2016) survey. Buildings considered "unoccupiable" are individual buildings with an average repair time per story computed as 42 days (6 weeks) or more.

Figure 4.6 describes the number of unoccupiable buildings for the unretrofit region, as well as the region retrofit to the CP performance level. For the unretrofit region, there are 880 unoccupiable NDC buildings (of 1132 total NDC buildings) at the 475-year loss, which is 78% of the building stock. At the same 475-year loss for the region when 50% of the building stock is retrofit to CP, there are about 640 unoccupiable buildings, which is about 57% of the building stock. Of those 640 unoccupiable buildings, about 52% are retrofit to the CP performance level. Even at the 72-year loss, the unretrofit region consists of about 645 unoccupiable buildings (57%

of the building stock), whereas the 50% retrofit to CP region includes only about 360 unoccupiable buildings (32% of the building stock). Of those 360 unoccupiable buildings, about 52% are retrofit to CP.

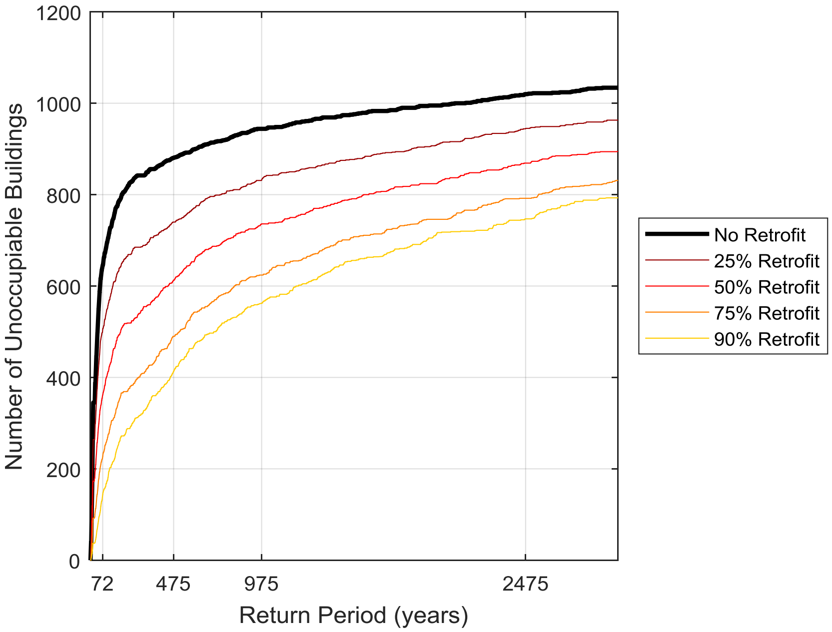


Figure 4.6 – Total number of unoccupiable buildings presented against return period for buildings retrofit to the CP performance level (Cases 3.1, 6.1, 9.1, and 11.1).

Figure 4.7 presents the number of unoccupiable buildings for the unretrofit region, as well as the region retrofit to the IO performance level. When 50% of the region is retrofit to IO, about 460 buildings are still considered “unoccupiable” at the 475-year loss (41% of the building stock). Of those 460 unoccupiable buildings, about 50% are retrofit to the IO performance level. At the 72-year loss, about 335 buildings are unoccupiable (30% of the building stock), and of those, 50% are retrofit to IO.

A significant reduction in unoccupiable buildings is observed between the 50% IO and CP retrofit levels at the 475-year loss resulting in 165 buildings that are occupiable when retrofitting to IO than when the region is retrofit to CP. In addition, the rate of reduction in the number of unoccupiable buildings decreases as the percentage of the region that is retrofit increases, observed in both Figure 4.6 and Figure 4.7. That is, the largest difference is between the unretrofit region and the 25% retrofit region, then between the 25% retrofit region and the 50% retrofit region, and so on. In comparison to the relative difference in CP fatality reductions to IO fatality reductions, the change in relative difference between CP unoccupiable buildings reduced and IO unoccupiable buildings reduced is about the same.

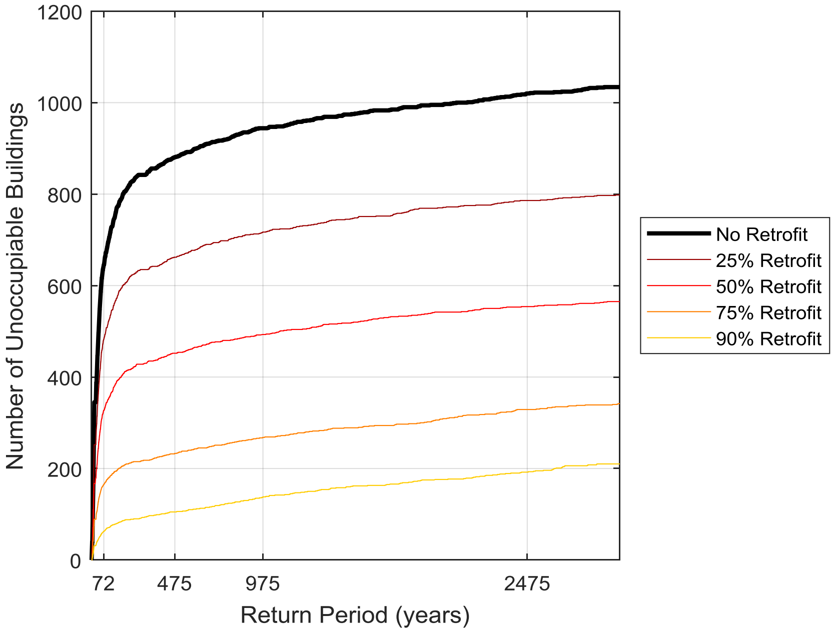


Figure 4.7 – Total number of unoccupiable buildings presented against return period for buildings retrofit to the IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).

The steep slope of the unretrofit regional loss lines in Figure 4.6 and Figure 4.7 also make a compelling argument for resilient design. While retrofit is a successful option to upgrade the safety of our communities from structural failures, occupiable buildings after an event are increasingly of interest, as shown by the Davis & Porter (2016) survey. The steep slope of the loss line before the 72-year return period loss indicates a significant increase in structural and nonstructural damages for each increasing step in hazard level. With this inflation of damage, buildings will become less occupiable after an earthquake. More recently, motivations in building design are to make structures resilient after an earthquake, not only to decrease the losses endured after an event, but also to allow residents and business to reoccupy their spaces faster.

4.1.5 Economic Losses

The figures presented in this section show the total regional losses (USD Millions) for different retrofit cases. On these plots, the y-axes tick marks are chosen to correspond to selected budget and damage values listed in Table 4.1 below. These values were chosen to display relatable values in order to give perspective on how much the city is forecasted to lose in damages after that hazard level loss. While this is a comparison to the losses from building damages in the 1994 Northridge Earthquake, this regional loss assessment and the Northridge event are constructed of different building portfolios. The Northridge event was also a single magnitude 6.7 earthquake in the valley of Southern California. The estimated Northridge loss displayed on the following plots is only to give reference for the loss values calculated in our study.

Table 4.1 – Selected comparison values for economic losses.

Category		*[USD] Millions*
2018 City of LA Total Expense Budget [1]	$	9,290
Total Estimated Regional Building Damage from the 1994 Northridge Earthquake (in 2018 USD) [2]	$	4,360
2018 City of LA "A Safe City" Expense Budget [1,4]	$	3,270
2018 City of LA "Building and Safety" Expense Budget [3,5]	$	113

[1] (City of Los Angeles, 2018)

[2] (EQE & OES, 1995)

[3] (City of Los Angeles, 2017)

[4] "A Safe City: Maintaining an innovative and accountable public safety workforce, improving LA's resiliency and ability to respond to crisis, and making our streets safe for all users." (City of Los Angeles, 2018)

[5] The "Building and Safety" department enforces all ordinances as well as structural plan checking, residential inspection, and code enforcement (City of Los Angeles, 2017)

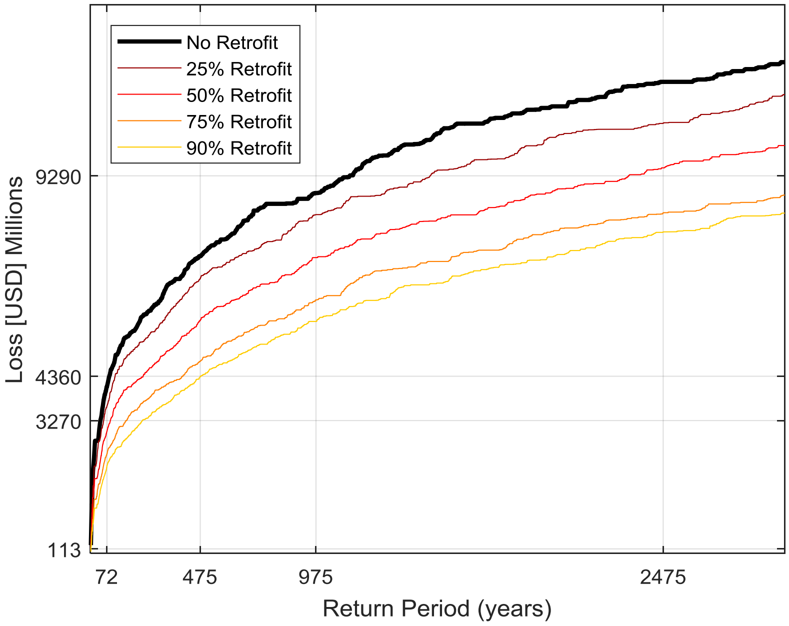


Figure 4.8 – Total regional economic losses presented against return period for buildings retrofit to the CP performance level (Cases 3.1, 6.1, 9.1, and 11.1).

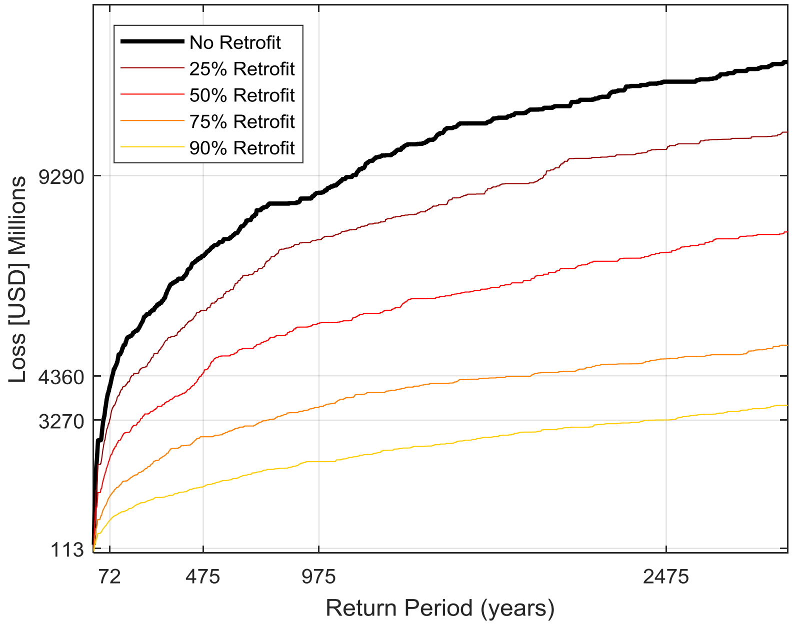


Figure 4.9 – Total regional economic losses presented against return period for buildings retrofit to the IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).

Figure 4.8 shows the total regional losses (USD Millions) when all the buildings in the selected retrofit cases are upgraded to the CP performance level. Figure 4.9 presents the total regional losses of selected retrofit cases updated to the IO performance level.

At the 475-year loss, the city of LA is estimated to lose approximately $7.5B solely from the current NDC building stock. If half of the NDC building stock is retrofit to only the CP performance level, the city could save about $2B in building losses at this level of event. If half of the original NDC buildings are retrofit to the more rigorous IO performance level, the city could save over $3B in building losses. From Table 4.1 above, the estimated regional building damage from the historic 1994 Northridge Earthquake totaled $4.36B (in 2018 USD).

Another interesting argument in favor of retrofit arises from the first sections of each curve in Figure 4.8 and Figure 4.9. By the 72-year loss, the unretrofit region already accumulated over $4B in building damage losses. By retrofitting 50% of the region all to the CP level, the city can save about one-third of the losses of the unretrofit region, and, additionally, the city can save about half of the losses if 50% of the region is retrofit all to the IO level.

4.2 Additional Regional Loss Results

This section presents results following the regional retrofit assessment that were not addressed as seismic performance measures in the survey discussed in Davis & Porter (2016). We feel these results may also offer compelling arguments in favor of retrofit of NDC structures for policy-makers and stakeholders to make collective risk-oriented decisions for the given portfolio of vulnerable NDC buildings.

4.2.1 Changes in Regional Losses per Building Map

The figures presented in this section show a map of the losses per building in the region as the level of retrofit, regional retrofit percentage, and selected map change. For each building, losses are calculated as structural and nonstructural repair costs, normalized by the replacement cost of the building. Colors are used to categorize buildings into three loss groups. Losses less than 20% of the replacement cost of the building are chosen as the bounding lower limit because typically buyers are concerned with property losses over 20% for mortgage risks, especially for new buildings, based on Probable Maximum Loss (PML) reports (Derhake, 2009). Losses greater than 40% are chosen as the bounding upper limit because losses above 40% may be a trigger for building replacement (FEMA, 2012).

Figure 4.10 maps the unretrofit (Case 0) regional losses for all buildings in the region for the event (map) corresponding to the *(a)* the 50th percentile loss based on ranking the maps considered in order, *(b)* the 75th percentile loss based on ranking the maps considered in order, and *(c)* and the 90th percentile loss based on ranking the maps considered in order. In Figure

4.10*(c)*, the majority of the dots, representing individual NDC buildings in the region, are black, representing these buildings endured more than 40% of the building's replacement cost in losses.

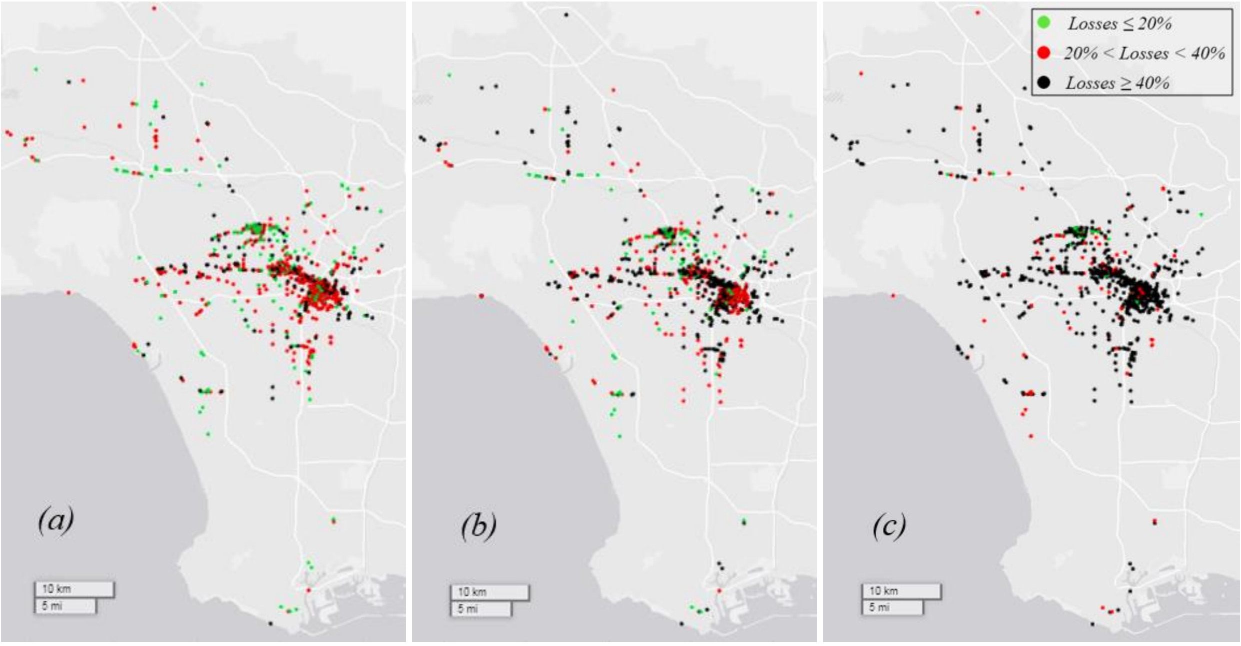


Figure 4.10 – Case 0, Losses normalized by replacement cost for each building in the unretrofit stock for a single realization for (a) the 50th percentile loss, (b) the 75th percentile loss, and (c) the 90th percentile loss. Note: the loss patterns in an equally costly event could be substantially different depending on the fault rupture.

Figure 4.11 maps the region if 25% of the buildings are retrofit to the CP performance level (Case 3.1) for the *(a)* 50th percentile loss map, *(b)* 75th percentile loss map, and *(c)* 90th percentile loss map. As the hazard decreases, the losses for individual buildings decrease, turning black dots in Figure 4.11*(c)* to green dots in Figure 4.11*(a)*. Similarly, black dots (buildings with more than 40% losses) in Figure 4.11*(c)* change to red or green dots (buildings subject to retrofit in this region) in Figure 4.11*(c)*.

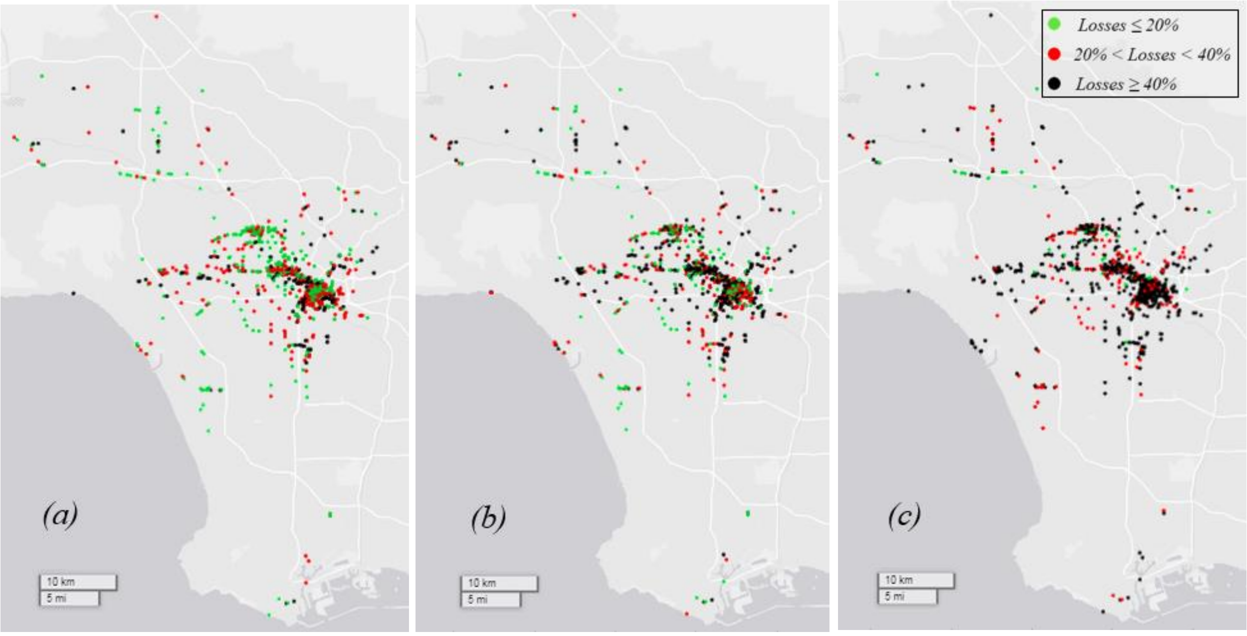


Figure 4.11 – Case 3.1, Losses normalized by replacement cost for each building in the 25% retrofit stock (all buildings retrofit to CP performance level) for a single realization for (a) the 50th percentile loss, (b) the 75th percentile loss, and (c) the 90th percentile loss. Note: the loss patterns in an equally costly event could be substantially different depending on the fault rupture.

Figure 4.12 presents the 90th percentile loss map for the region if 75% of the buildings are retrofit to *(a)* the CP performance level, or *(b)* the IO performance level. These figures show a significant decrease in overall building performance for the same percentile map by retrofitting the region to the more aggressive IO performance level. This shows a compelling example of the decreased regional losses for retrofitting to the IO performance level, rather than retrofitting 75% of the region to the CP level.

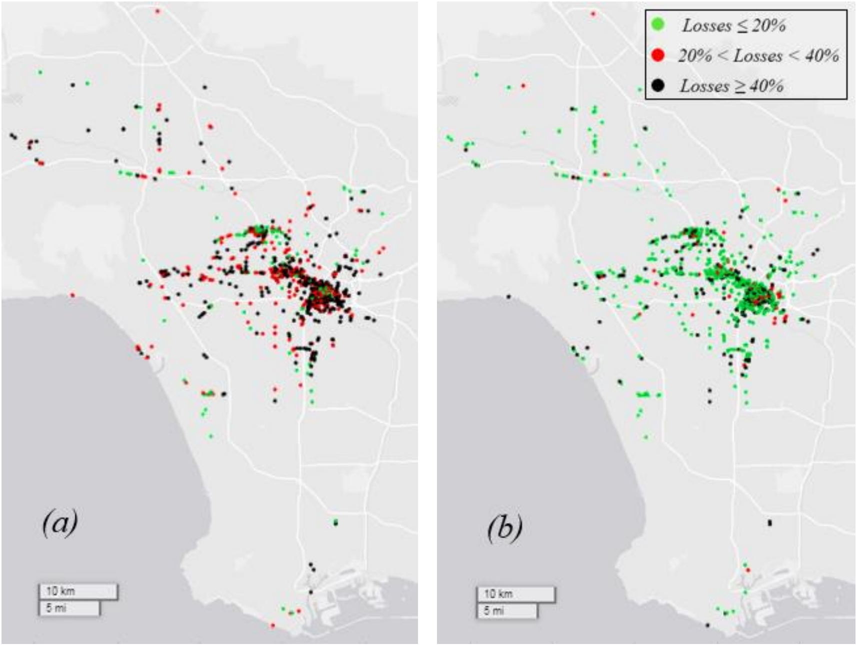


Figure 4.12 – Losses normalized by replacement cost for each building in the 75% retrofit stock for a single realization when all buildings are retrofit to the (a) CP performance level (Case 9.1) and (b) the IO performance level (Case 9.3), for the 90th percentile loss. Note: the loss patterns in an equally costly event could be substantially different depending on the fault rupture.

4.2.2 Total Regional Economic Savings

Figure 4.13 presents the regional savings (USD Millions) for the same CP performance level retrofit cases, and Figure 4.14 shows the regional savings for the IO cases. Regional savings are calculated as the difference in losses between the unretrofit region and each retrofit region. On the community scale, retrofitting the region to the IO performance level results in greater regional savings than retrofitting each building to the CP level, as apparent from comparing Figure 4.13 and Figure 4.14. For each percentage of the building stock retrofit, the regional savings approximately double from retrofitting to the CP level to retrofitting to the IO level at the 475-year loss.

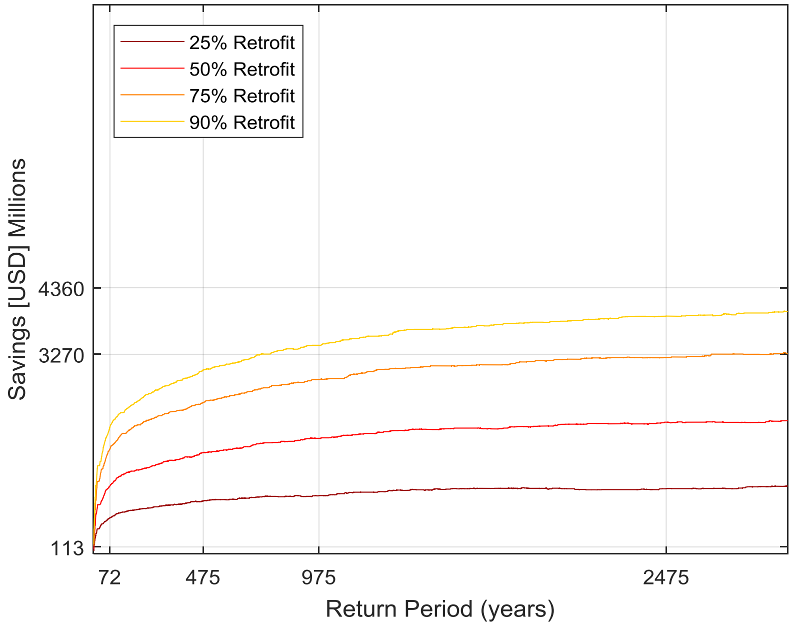


Figure 4.13 – Regional economic savings presented against return period for buildings retrofit to the CP performance level (Cases 3.1, 6.1, 9.1, and 11.1).

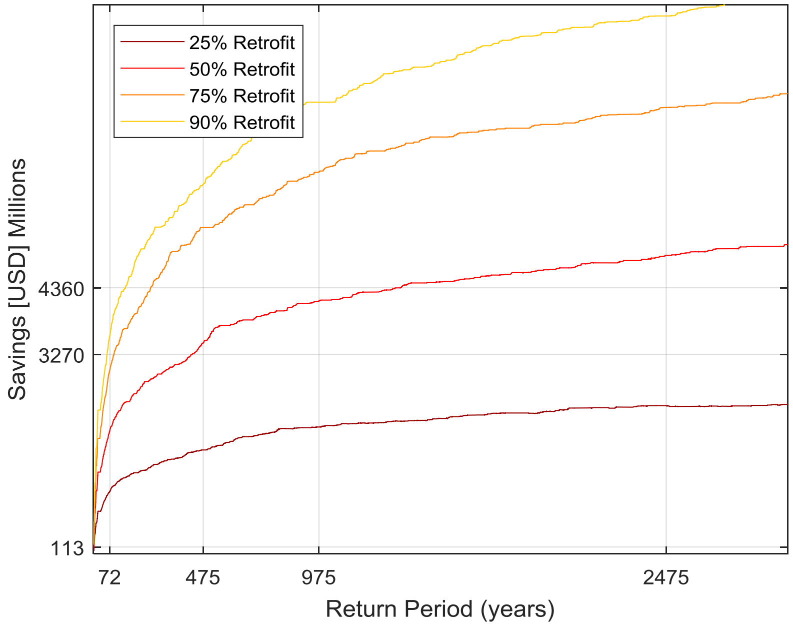
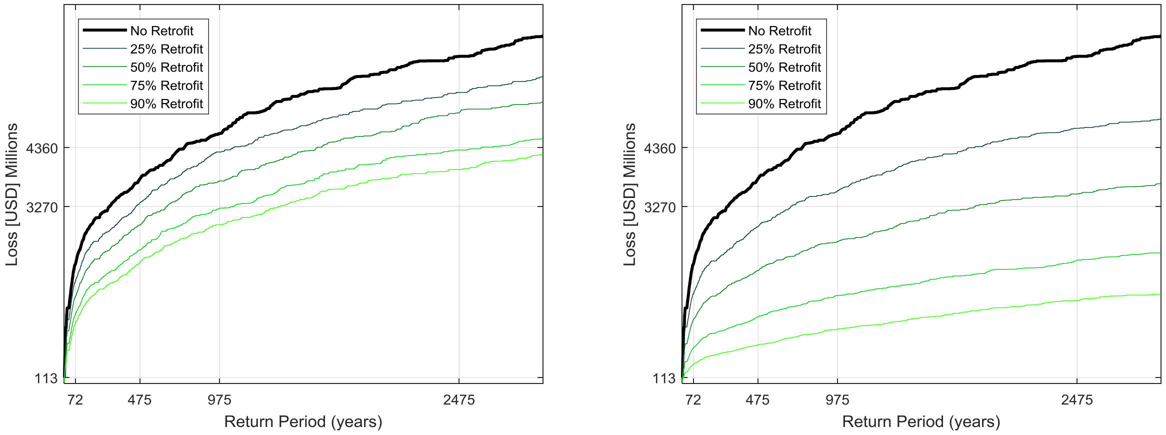


Figure 4.14 – Regional economic savings presented against return period for buildings retrofit to the IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).

4.2.3 Economic Regional Losses by Building Occupancy

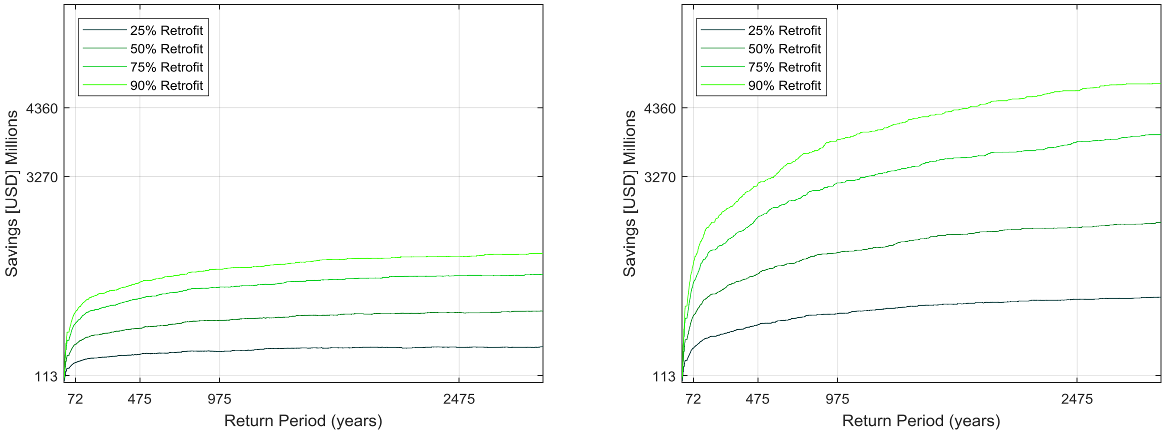
Figure 4.15 and Figure 4.16 show the regional losses and savings (USD Millions), respectively, for the commercial-use buildings in the region, all retrofit to the *(a)* CP and *(b)* IO performance level. Figure 4.17 and Figure 4.18 present the regional losses and savings for the residential-use buildings, and Figure 4.19 and Figure 4.20 for the warehouse-use buildings.

From Figure 4.15, the largest difference between retrofit cases seems to be between the unretrofit region and the 25% retrofit region (for both CP and IO performance levels). By retrofitting the region to only 25%, the losses can be significantly decreased. In addition, there is considerable differences between the CP retrofit cases and the IO retrofit cases. The regional savings of commercial-use buildings in Figure 4.16 also show the drastic difference between the CP retrofit cases and the IO retrofit cases. The IO retrofit savings almost double the CP retrofit savings in most retrofit cases. The IO retrofit savings also continue increasing as the hazard level also increases at a steeper rate than the CP retrofit savings, as the slopes of the curves in Figure 4.16 show.



(a) *(b)*

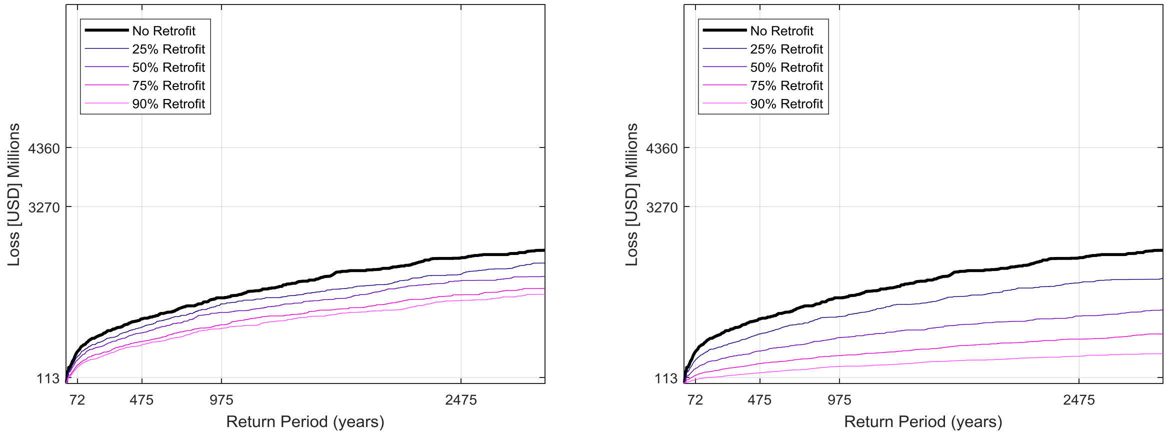
Figure 4.15 – Regional economic losses from commercial buildings only retrofit to the (a) CP performance level (Cases 3.1, 6.1, 9.1, and 11.1) and (b) IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).



(a) (b)

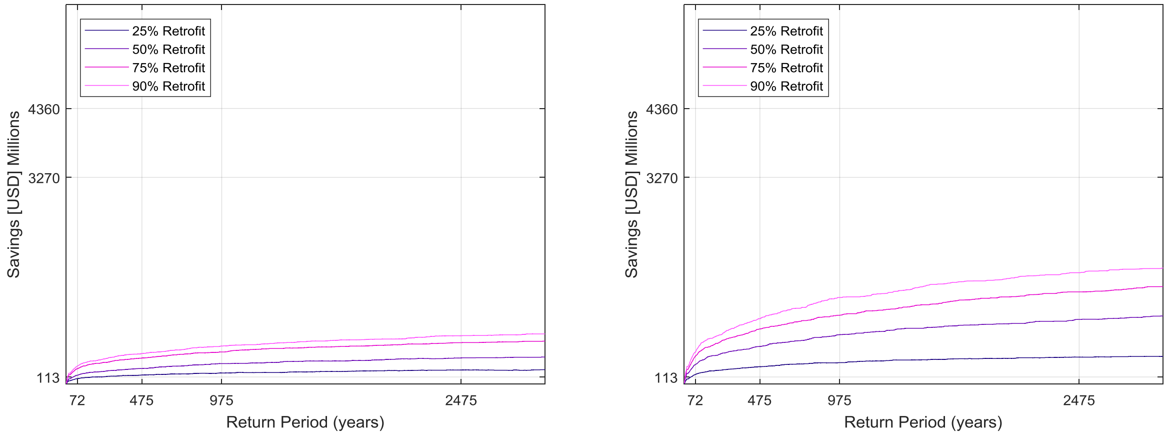
Figure 4.16 – Regional economic savings from commercial buildings only retrofit to the (a) CP performance level (Cases 3.1, 6.1, 9.1, and 11.1) and (b) IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).

Figure 4.17 through Figure 4.20 also present similar trends as discussed above. Regional losses are decreased more when retrofitting all buildings of that retrofit case to the IO level compared to the CP level. Commercial-use buildings make up the majority (53%) of the building inventory evaluated, and therefore contribute most to the losses on a regional level. Residential-use buildings form 18% of the building stock and warehouse-use buildings represent 29% of the building stock, which is 60% more buildings than residential.



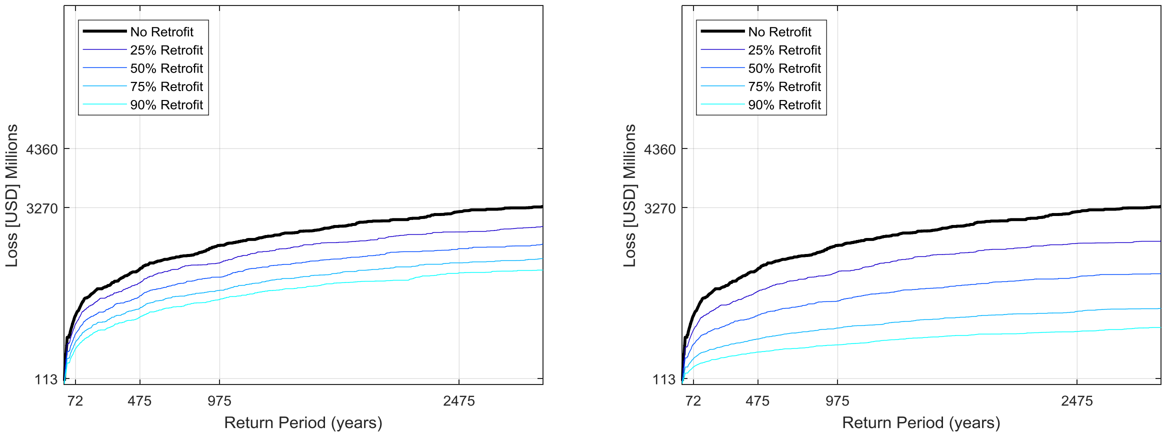
(a) *(b)*

Figure 4.17 – Regional economic losses from residential buildings only retrofit to the (a) CP performance level (Cases 3.1, 6.1, 9.1, and 11.1) and (b) IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).



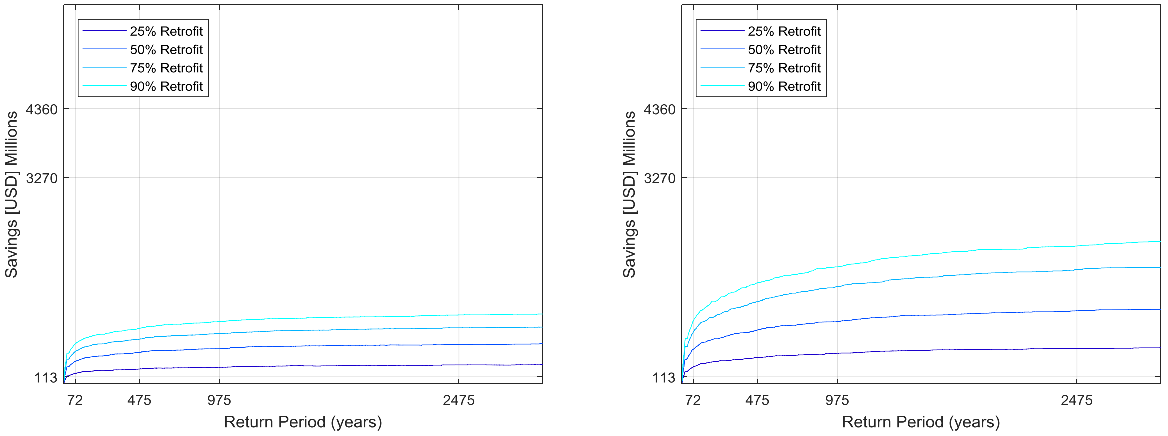
(a) *(b)*

Figure 4.18 – Regional economic savings from residential buildings only retrofit to the (a) CP performance level (Cases 3.1, 6.1, 9.1, and 11.1) and (b) IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).



(a) *(b)*

Figure 4.19 – Regional economic losses from warehouse buildings only retrofit to the (a) CP performance level (Cases 3.1, 6.1, 9.1, and 11.1) and (b) IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).



(a) *(b)*

Figure 4.20 – Regional economic savings from warehouse buildings only retrofit to the (a) CP performance level (Cases 3.1, 6.1, 9.1, and 11.1) and (b) IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).

4.2.4 Regional Economic Losses and Savings Presented Annually

Annualized losses for the entire region by retrofit case are presented in Table 4.2. Annualized losses are calculated by summing the product of the losses from each map by the portion of the probability density distribution that the loss represents, so they represent the expected losses to the building inventory if these losses were evenly distributed each year. Table 4.2 also presents the savings achieved by retrofitting the region to each percentage and performance level. Savings are calculated as the percent difference in losses between the retrofit region and the unretrofit region. The "% Annual Savings" is to be interpreted as the portion of the annual unretrofit cost saved by retrofitting the region to that retrofit case level, not accounting for the cost of the retrofit.

From Table 4.1, the portion of the 2018 City of LA Expense Budget for "A Safe City" is \$3.27B and the portion of the budget for "Building and Safety" is \$113M. The total annual loss for the existing and unretrofit NDC building stock in the city of LA is \$512M, from Table 4.2, which is about 4.5 times the amount of the 2018 "Building and Safety" budget allocation for the city of LA, and puts a significant dent in the 2018 "A Safe City" budget allocation.

From Table 4.2, the annual losses are significantly decreased by retrofitting the region to any IO percentage (Cases 3.3, 6.3, 9.3, and 11.3), saving at least 24% compared to the unretrofit region (Case 0). Case 3.3, the 25% retrofit region all to the IO level, decreases the annual losses \$125M, which is almost \$40M greater savings per year than Case 3.1, the 25% CP retrofit level. Cases 9.3 and 9.1 represent the 75% retrofit region, all to the IO and CP level, respectively. Retrofitting to Case 9.3 decreases the annual losses from the unretrofit region by \$356M, which is almost 70% the annual losses of the unretrofit region. Furthermore, selecting the 75% IO retrofit region (Case 9.3) over the 75% CP retrofit region (Case 9.1) decreases the annual losses by \$102M.

Table 4.2 – Total Annualized losses by regional retrofit case.

Case Number	*% of Region Retrofit*	*Retrofit Performance Level*	*Total Annual Loss [USD] Million*	*Total Annual Savings [USD] Million*	*Total % Annual Savings*
0	0	0	512	-	-
3.1	25%	All CP	426	71	17%
3.2	25%	All LS	423	74	17%
3.3	25%	All IO	387	94	24%
3.4	25%	33%CP 33%LS 33%IO	416	78	19%
3.5	25%	60%CP 30%LS 10%IO	422	74	18%
6.1	50%	All CP	347	112	32%
6.2	50%	All LS	332	116	35%
6.3	50%	All IO	269	128	47%
6.4	50%	33%CP 33%LS 33%IO	310	122	39%
6.5	50%	60%CP 30%LS 10%IO	331	117	35%
9.1	75%	All IO	156	109	69%
9.2	75%	All LS	235	127	54%
9.3	75%	All CP	258	128	50%
9.4	75%	33%CP 33%LS 33%IO	222	126	57%
9.5	75%	60%CP 30%LS 10%IO	228	126	55%
11.1	90%	All CP	208	123	59%
11.2	90%	All LS	139	101	73%
11.3	90%	All IO	88	73	83%
11.4	90%	33%CP 33%LS 33%IO	159	110	69%
11.5	90%	60%CP 30%LS 10%IO	186	118	64%

From Table 4.3, annual losses are presented at each regional retrofit case for each occupancy type. Percent annual savings are computed through the same procedure as before, but considering each occupancy class separately. Commercial-use buildings are the largest portion of the building stock and, accordingly, contribute the largest portion of the annual losses. Likewise, the residential-use buildings contribute the least losses to the total unretrofit annual costs, as they make up the smallest percentage of the building stock. Retrofitting the residential and commercial inventory to each percent region of IO performance level is approximately directly correlated to the percent that case observes in annual savings (Cases 3.3, 6.3, 9.3, and 11.3). IO retrofit of the 25% of the region results in 25% annual savings of the commercial building inventory as well as 25% of the residential building inventory, and so on and so forth for further percentages of the retrofit.

Table 4.3 – Annualized losses and savings by regional retrofit case for residential, commercial, and warehouse buildings.

Case Number	*Residential Annual Loss [USD] Million*	*Residential Annual Savings [USD] Million*	*Residential % Annual Savings*	*Commercial Annual Loss [USD] Million*	*Commercial Annual Savings [USD] Million*	*Commercial % Annual Savings*	*Warehouse Annual Loss [USD] Million*	*Warehouse Annual Savings [USD] Million*	*Warehouse % Annual Savings*
0	63	-	-	282	-	-	167	-	-
3.1	52	9	18%	234	40	17%	141	22	16%
3.2	50	10	21%	231	42	18%	141	21	15%
3.3	46	12	26%	211	53	25%	130	29	22%
3.4	52	9	17%	227	45	20%	137	25	18%
3.5	51	10	19%	233	40	17%	137	24	18%
6.1	45	13	28%	191	62	32%	111	37	34%
6.2	41	14	35%	180	65	36%	111	37	33%
6.3	30	16	53%	147	70	48%	93	41	44%
6.4	42	14	33%	166	68	41%	102	40	39%
6.5	43	14	32%	183	64	35%	105	39	37%
9.1	16	12	75%	80	57	72%	61	39	64%
9.2	30	16	52%	131	70	54%	74	41	55%
9.3	32	16	49%	140	71	50%	86	42	49%
9.4	23	15	63%	124	70	56%	75	41	55%
9.5	26	15	58%	137	70	51%	84	42	50%
11.1	27	15	57%	114	68	60%	67	40	60%
11.2	26	15	58%	108	67	62%	59	38	65%
11.3	7	7	88%	42	36	85%	39	30	77%
11.4	21	14	66%	86	60	70%	52	36	69%
11.5	23	15	64%	103	65	64%	61	39	64%

4.3 Targeted Vulnerable Buildings

The following section evaluates additional regional retrofit cases of only specifically vulnerable building types. The two vulnerable building types chosen are 6-story buildings and residential buildings, due to their increased individual building losses. These additional regional retrofit cases analyze the impact of targeting specifically identified vulnerable building types and retrofitting only those buildings in the region. The results are presented as different retrofit metrics, depending on which set of vulnerable buildings is being evaluated.

4.3.1 Targeted Vulnerable Buildings for Retrofit: 6-story only

This section evaluates the effectiveness of regional retrofit when targeting only mid-rise (i.e. those represented by 6-story structures) buildings in the region. These buildings are chosen because the mid-rise buildings are the most vulnerable building height category, in terms of individual building losses. Table 4.4 presents the additional regional retrofit cases when 10% and 25% of the region is retrofit, but targeting only the mid-rise buildings. In other words, 10% and 25% of the building stock is still retrofitted, but the selected buildings are all of the mid-rise category. These midrise buildings are chosen at random for retrofit, as well as the retrofit strategy (i.e. concrete jacketing, steel jacketing, or FRP wrapping of the columns).

Table 4.4 – Additional regional retrofit cases for 6-story buildings only.

Case Number	*% of Region Retrofit*	*% Collapse Prevention*	*% Life Safety*	*% Immediate Occupancy*
0	0	0	0	0
12.1	10	100	0	0
12.2	10	0	100	0
12.3	10	0	0	100
13.1	25	100	0	0
13.2	25	0	100	0
13.3	25	0	0	100

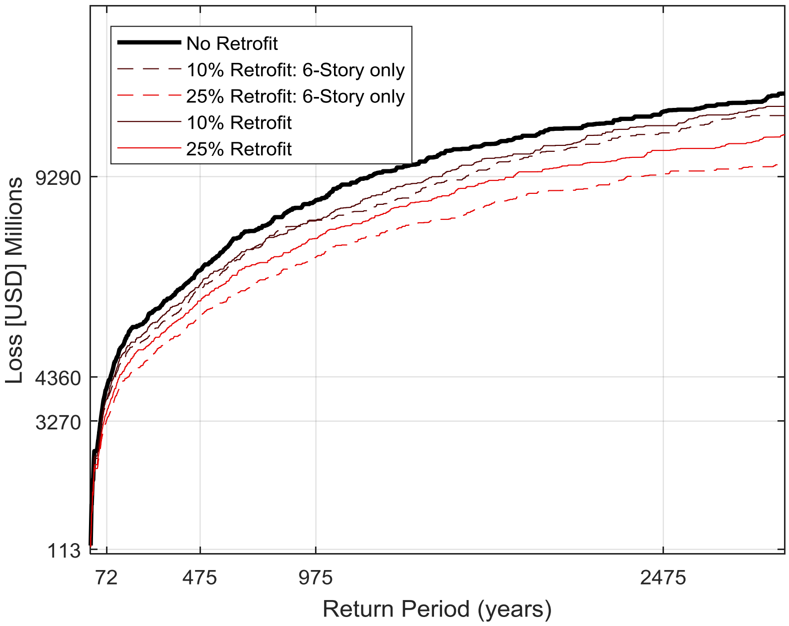


Figure 4.21 - Total regional economic losses presented against return period for buildings retrofit to the CP performance level (Cases 1.1, 3.1, 12.1 and 13.1).

Figure 4.21 shows the total regional economic losses against return period when 10% of the region is retrofit and when 25% of region is retrofit to CP, only for midrise buildings (Cases 12.1 and 13.1, respectively), as well as when 10% and 25% of the region is retrofit, regardless of which buildings are chosen for retrofit (Cases 1.1 and 3.1, respectively). For the unretrofit region, the total economic losses are approximately $4B and $7.5B at the 72-year loss and 475-year loss, respectively. At the 72-year loss, although there is not a significant decrease in the losses when retrofitting only 10% or 25% of the region, cases 12.1 and 13.1 (retrofitting only midrise buildings) do reduce the losses more than cases 1.1 and 3.1 (retrofitting all heights buildings). At the 475-year loss, there is a further decrease of the losses between the 6-story only retrofit cases and the previous random retrofit cases. When 10% of the region is retrofit to CP, but only targeting midrise buildings (Case 12.1), the losses decrease by an additional 2.3% compared to the 10% regional retrofit to CP, chosen at random (Case 1.1). Comparing the region when 25% is retrofit to CP only for midrise buildings and buildings chosen at random (Cases 13.1 and 3.1, respectively) the losses decrease by an additional 6.9% by retrofitting the targeted midrise buildings. This implies that the midrise buildings are more vulnerable, and by targeting the midrise buildings for retrofit, the city can effectively decrease the regional losses further.

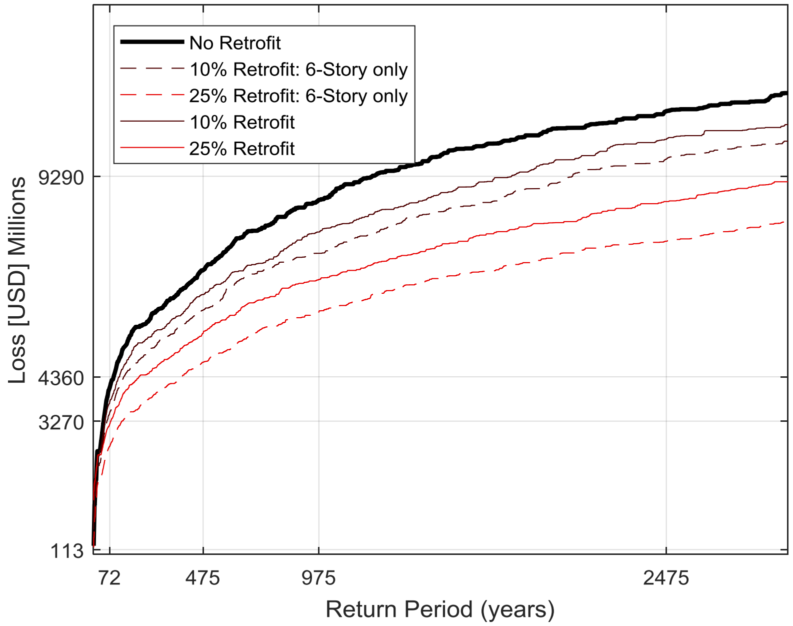


Figure 4.22 - Total regional economic losses presented against return period for buildings retrofit to the IO performance level (Cases 1.3, 3.3, 12.3 and 13.3).

Figure 4.22 presents the total economic losses for the region when 10% and 25% of the buildings are retrofit to IO, selecting only midrise buildings (Cases 12.3 and 13.3), and when 10% and 25% of the buildings are retrofit, selecting from all buildings at random (Cases 1.3 and 3.3). At both the 72-year loss and the 475-year loss, the targeted cases 12.3 and 13.3 clearly reduce the losses more than the previous cases 1.3 and 3.3. In addition, the losses are further decreased by retrofitting the region all to the IO performance level, instead of CP (Figure 4.21). When 10% of the region is retrofit to IO, only for midrise buildings (Case 12.3), the losses decrease by an additional 6.7% compared to the 10% regional retrofit to IO, chosen at random (Case 1.3). The losses decrease by 15% more when retrofitting 25% of the region to IO, only the midrise buildings (Case 13.3) instead of 25% of the region to IO at random (Case 3.3).

4.3.2 Targeted Vulnerable Buildings for Retrofit: Residential buildings only

This section analyzes the vulnerability of the residential buildings by targeting additional regional retrofit cases (in Table 4.5) where only the residential buildings are selected for retrofit. Residential buildings are selected as a targeted building type to evaluate the impacts of retrofitting only these buildings to decrease the number of displaced residents and residential fatalities in the city. While it is important to safeguard the occupants of all buildings, residential buildings pose an immediate threat to the homes and, hence, the community's viability. These additional cases target 10% and 25% of the building stock for retrofit, selecting only residential buildings at random for retrofit. As before, the retrofit strategies are chosen at random.

Table 4.5 – Additional regional retrofit cases for residential buildings only.

Case Number	*% of Region Retrofit*	*% Collapse Prevention*	*% Life Safety*	*% Immediate Occupancy*
0	0	0	0	0
14.1	10	100	0	0
14.2	10	0	100	0
14.3	10	0	0	100
15.1	25	100	0	0
15.2	25	0	100	0
15.3	25	0	0	100

The following figures plot the total number of residents displaced from their homes against the return period loss. Displaced residents are defined as any person occupying a residential building with an average serial repair time per story of 21 days or more. The number of residential buildings only makes up about 18% of the region, so the 25% retrofit case, only residential buildings (Case 15.1) is retrofitting all of the residential buildings in the region, as well as an additional 7% of buildings selected at random.

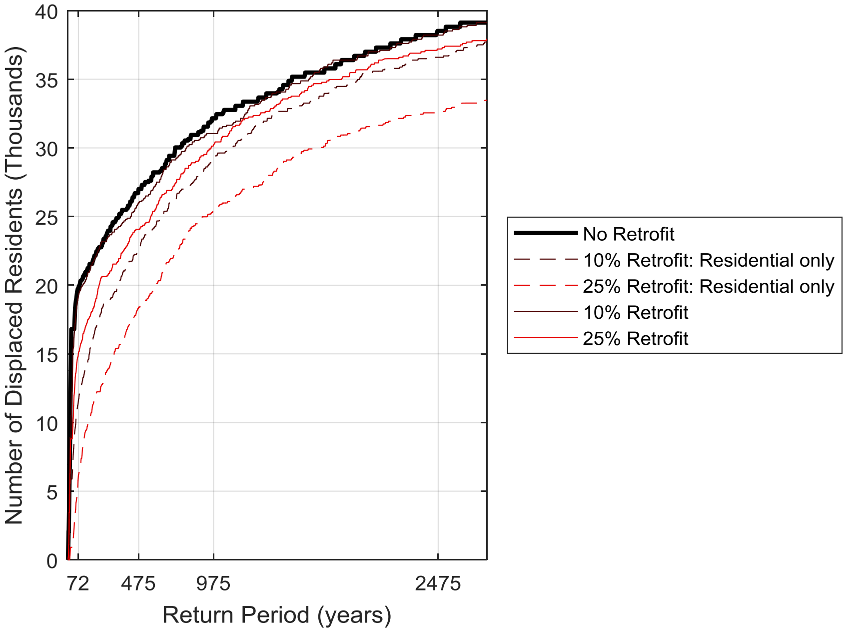


Figure 4.23 - Total number of displaced residents presented against return period for buildings retrofit to the CP performance level (Cases 1.1, 3.1, 14.1 and 15.1).

Figure 4.23 presents the number of displaced residents (thousands) for the region when 10% and 25% of the region are retrofit all to the CP performance level, only selecting residential buildings for retrofit (Cases 14.1 and 15.1), as well as 10% and 25% regional retrofit all to CP when buildings are selected at random (Cases 1.1 and 3.1). At both the 72-year and the 475-year losses, the only residential regional retrofit cases (14.1 and 15.1) clearly reduced the number of displaced residents more than the random regional retrofit cases (1.1 and 3.1). From this plot, the number of displaced residents is further reduced by only retrofitting the residential buildings than the random retrofit cases because in those cases the buildings chosen for retrofit are a combination of residential, commercial, and warehouse, and the number of displaced residents is only considering people occupying residential buildings.

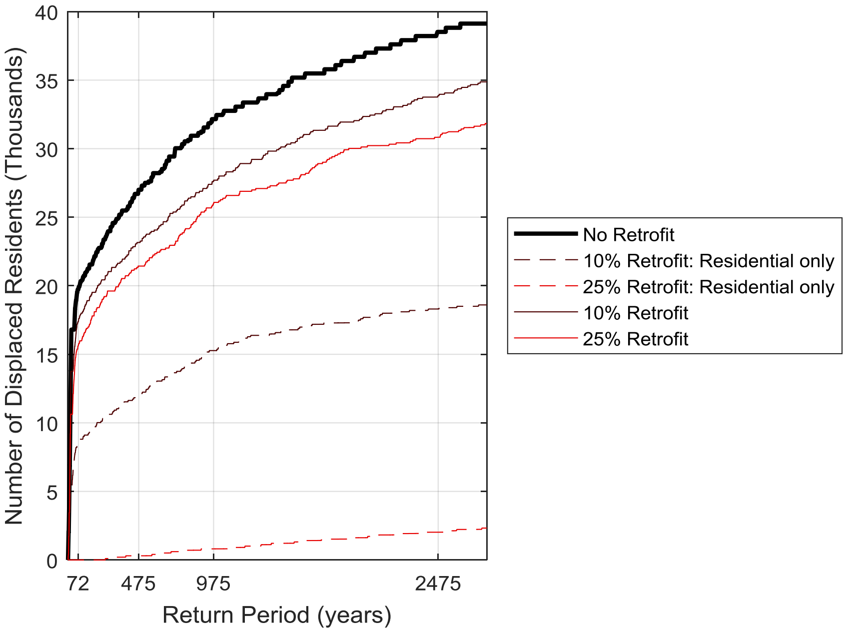


Figure 4.24 - Total number of displaced residents presented against return period for buildings retrofit to the IO performance level (Cases 1.3, 3.3, 14.3 and 15.3).

Figure 4.24 displays the number of displaced residents (thousands) for the region when 10% and 25% of the region are retrofit all to the IO performance level, only selecting residential buildings for retrofit (Cases 14.3 and 15.3), as well as 10% and 25% regional retrofit all to IO when buildings are selected at random (Cases 1.3 and 3.3). The decreases in displaced residents by retrofitting only the residential buildings (Cases 14.3 and 15.3) are significant because these cases target only the residential buildings, whereas the random regional retrofit cases (1.3 and 3.3) include residential, commercial, and warehouse buildings. The reduced number of displaced residents are extreme from retrofitting the region to the CP performance level (Figure 4.23) to retrofitting the region to the IO performance level (Figure 4.24).

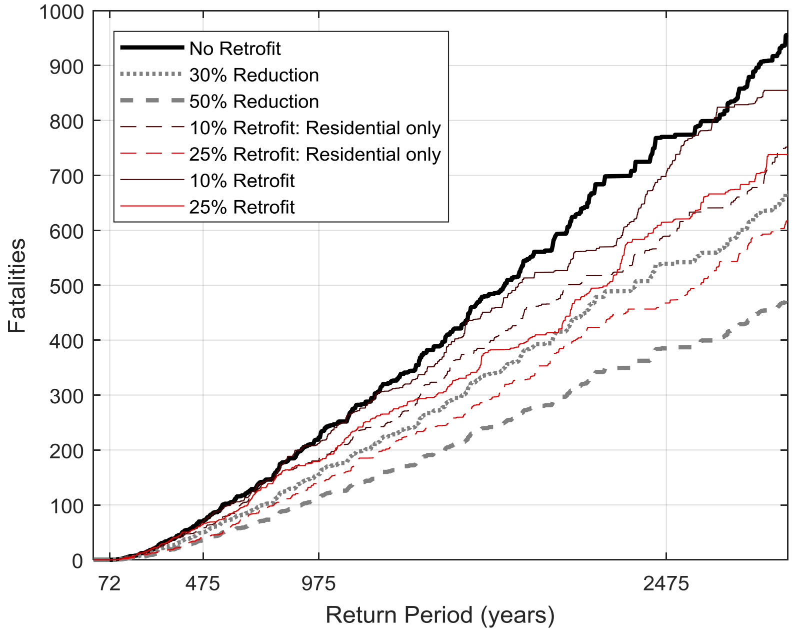


Figure 4.25 - Total regional fatalities presented against return period for buildings retrofit to the CP performance level (Cases 1.1, 3.1, 14.1 and 15.1).

Figure 4.25 presents the total number of fatalities in the region, comparing CP retrofit cases (14.1 and 15.1) when only residential buildings are selected for retrofit, and CP retrofit cases (1.1 and 3.1) when the buildings are selected at random for retrofit, regardless of the occupancy type. This shows the larger reduction in fatalities by targeting only the residential buildings in the region when retrofitting 10% and 25% of the region, than if you target all buildings at random. The mean population of residential buildings is greater than the population of commercial and warehouse buildings, which implies that by targeting only residential buildings for retrofit can be more effective at reducing the number of fatalities in the region, than selecting the buildings for retrofit at random, regardless of occupancy type.

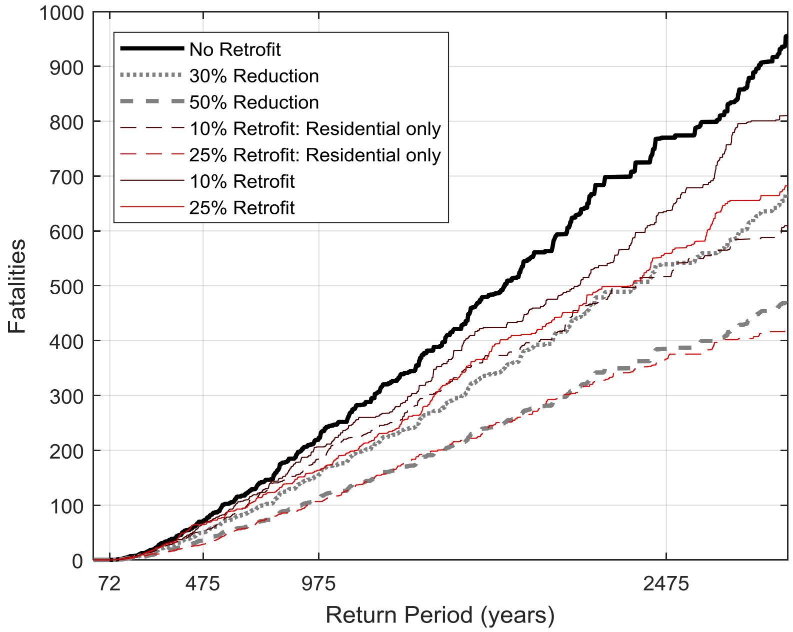


Figure 4.26 - Total regional fatalities presented against return period for buildings retrofit to the IO performance level (Cases 1.3, 3.3, 14.3 and 15.3).

Figure 4.26 instead plots the number of fatalities experienced in the city, comparing the IO retrofit cases (14.3 and 15.3) when only the residential buildings are selected for retrofit, and the IO retrofit cases (1.3 and 3.3) when the buildings selected for retrofit are selected at random. As before, the fatalities are further reduced when targeting only the residential buildings for retrofit. In addition, the reduction in fatalities are more dramatic in the IO cases than the CP cases.

4.4 Possible Retrofit Objectives: Which Retrofit Alternatives Meet These Goals?

This section next examines these regional retrofit outcomes in the context of possible goals for the city of LA. This section aims to present clear community retrofit strategies to reach a certain goal for the city. There are a sizable number of NDC structures in the state of California, many of which reside in LA, and often the problem can be too overwhelming to see a clear path to reduce seismic risk for the community. Therefore, by assessing retrofit outcomes in the context of specific goals, we can begin to attack the problem. The *2016 Safer Cities Survey* declares that Southern California should “sustain occupancy, provide shelter, and support economic stability following an earthquake” (SEAOSC, 2016). This language motivates the goals discussed here, though they may or may not align with the goals of LA or any other jurisdiction. These retrofit goals were chosen by the authors as ambitious but achievable goals for the city of LA.

4.4.1 Retrofit Goal #1: Reduce Residential Displacement by 30%

A major concern for communities after a large event is the number of people that will be displaced from their homes (Comerio, 2006). The objective of this regional retrofit goal is to reduce the number of people displaced from their residence by at least 30%, compared to the unretrofit region (at the 72-, 475-, and 2475-year losses). Here, residents are assumed to be displaced from any residential building if the average serial repair time per story of that building is 21 days or more. We take the term “residential building” to encompass apartments, condos, dormitories, and hotels.

Table 4.6 lists the different regional retrofit cases able to achieve the goal of 30% reduction in displaced residents. At the 72-year loss, 40% of the region needs to be retrofit to CP to achieve the 30% reduction of residents displaced from their homes. While only 20% of the region needs to be retrofit to IO at the 72-year loss to achieve a 30% reduction in displaced people, retrofitting to the IO performance level is assumed to cost more than retrofitting to the other performance levels. Therefore, it may be more economical to retrofit a higher percent of the region at a lower performance level.

From Chapter 4.3.2 (Targeted Vulnerable Buildings for Retrofit: Residential buildings only), the most efficient way to reduce the number of displaced residents is to first target the residential buildings for retrofit. Figure 4.25 and Figure 4.26 present a significant decrease in the number of residents displaced from their homes when retrofitting only the residential buildings, instead of randomly selecting buildings for retrofit.

Table 4.6 – Minimum retrofit cases to reduce residential displacement by at least 30%.

Event	*Case Number*	*% of Region Retrofit*	*Retrofit Performance Level*	*% Reduced Displaced Residents*
72-year loss	5.1	40%	All CP	34%
	4.2	30%	All LS	34%
	2.3	20%	All IO	30%
	3.4	25%	33%CP 33%LS 33%IO	32%
	5.5	40%	60%CP 30%LS 10%IO	34%
475-year loss	11.1	90%	All CP	33%
	7.2	60%	All LS	32%
	4.3	30%	All IO	34%
	5.4	40%	33%CP 33%LS 33%IO	33%
	9.5	75%	60%CP 30%LS 10%IO	38%
2475-year loss	*unable to reach 30% reduction*		All CP	-
	unable to reach 30% reduction		All LS	-
	4.3	30%	All IO	30%
	10.4	80%	33%CP 33%LS 33%IO	31%
	unable to reach 30% reduction		60%CP 30%LS 10%IO	-

4.4.2 Retrofit Goal #2: Reduce Community Fatalities by 30% and 50%

The next retrofit goal is to reduce the total number of fatalities in the region. Table 4.7 presents different retrofit cases to reduce the community fatalities by 30%. This 30% reduction can be achieved by retrofitting the smallest portion of the building stock if buildings are retrofitted to the IO performance level. The regional retrofit percentage increases as the case performance level decreases. For example, at the 72-year event, only 10% of the region needs to be retrofit to IO to reduce the number of community fatalities by 30%; whereas, 25% of the region needs to be retrofit to CP to reduce fatalities by 36%. Figure 4.1 and Figure 4.3 present the total regional fatalities for the unretrofit region, the 30% reduction of the unretrofit region, the 50% reduction of the unretrofit region, and all CP and IO retrofit cases, respectively.

Table 4.7 – Minimum retrofit cases to reduce community fatalities by at least 30%.

Event	*Case Number*	*% of Region Retrofit*	*Retrofit Performance Level*	*% Reduced Community Fatalities*
72-year loss	3.1	25%	All CP	36%
	4.2	30%	All LS	42%
	1.3	10%	All IO	30%
	3.4	25%	33%CP 33%LS 33%IO	31%
	4.5	30%	60%CP 30%LS 10%IO	30%
475-year loss	6.1	50%	All CP	37%
	4.2	30%	All LS	30%
	5.3	30%	All IO	35%
	6.4	50%	33%CP 33%LS 33%IO	31%
	5.5	40%	60%CP 30%LS 10%IO	37%
2475-year loss	6.1	50%	All CP	40%
	5.2	40%	All LS	36%
	4.3	30%	All IO	30%
	5.4	40%	33%CP 33%LS 33%IO	33%
	5.5	40%	60%CP 30%LS 10%IO	31%

Table 4.8 displays the retrofit cases that reduce the community fatalities by 50% of the unretrofit region. As expected, increased regional retrofit percentages are required to reach a higher goal of 50% reduction of community fatalities. In most cases, the regional retrofit percentage also increases as the year loss increases, from the 72-year loss to the 2475-year loss (see both Table 4.7 and Table 4.8). This is due to the decreased probability of that loss occurring and the increased number of fatalities in the region, requiring more of the region to be retrofit.

From Figure 4.25, comparing the number of fatalities from the targeted residential building retrofit cases to the randomly selected retrofit cases, the 30% reduction and 50% reduction lines are plotted to compare to the fatality reductions of the retrofit cases. As shown for the 2475-year loss, the targeted retrofit cases, only retrofit Case 15.1, when 25% of the region is retrofit to CP, reduces the number of fatalities greater than 30%. From Figure 4.26, again at the 2475-year loss, only the retrofit case (15.3) when 25% of the region is retrofit to IO and only selecting residential buildings reduces the number of fatalities greater than 30%. The other retrofit cases presented in Figure 4.26 show a further reduction in losses, but do not meet the 30% or 50% reduction goals.

Table 4.8 – Minimum retrofit cases to reduce community fatalities by at least 50%.

Event	*Case Number*	*% of Region Retrofit*	*Retrofit Performance Level*	*% Reduced Community Fatalities*
72-year loss	6.2	50%	All CP	60%
	6.2	50%	All LS	58%
	5.3	40%	All IO	50%
	7.4	60%	33%CP 33%LS 33%IO	67%
	8.5	70%	60%CP 30%LS 10%IO	64%
475-year loss	9.1	75%	All CP	57%
	9.2	75%	All LS	56%
	7.3	60%	All IO	58%
	8.4	70%	33%CP 33%LS 33%IO	50%
	9.5	75%	60%CP 30%LS 10%IO	58%
2475-year loss	8.1	70%	All CP	54%
	8.2	70%	All LS	56%
	7.3	60%	All IO	59%
	8.4	70%	33%CP 33%LS 33%IO	50%
	8.5	70%	60%CP 30%LS 10%IO	53%

4.4.3 Retrofit Goal #3: Reduce Regional Repair Time by 50%

The next retrofit goal of interest is to reduce the total repair time of the region with retrofit by 50%. Repair time is important in terms of community rehabilitation after an earthquake. Whether a damaged building requires one week of repair time or one year of repair time, occupants are still unable to use the space and are displaced from the structure. Table 4.9 shows the percent reduction in total repair time compared to the unretrofit region for each retrofit performance level option. As the year loss increases, the percentage of the region required for retrofit also increases due to the increased damage accumulation in the region.

Table 4.9 – Minimum retrofit cases to reduce regional repair time by at least 50%.

Event	*Case Number*	*% of Region Retrofit*	*Retrofit Performance Level*	*% Reduced Repair Time*
72-year loss	11.1	90%	All CP	50%
	11.2	90%	All LS	53%
	7.3	60%	All IO	55%
	9.4	75%	33%CP 33%LS 33%IO	52%
	11.5	90%	60%CP 30%LS 10%IO	55%
475-year loss	*unable to reach 50% reduction*		All CP	-
	unable to reach 50% reduction		All LS	-
	7.3	60%	All IO	53%
	11.4	90%	33%CP 33%LS 33%IO	52%
	unable to reach 50% reduction		60%CP 30%LS 10%IO	-
2475-year loss	*unable to reach 50% reduction*		All CP	-
	unable to reach 50% reduction		All LS	-
	8.3	70%	All IO	56%
	unable to reach 50% reduction		33%CP 33%LS 33%IO	-
	unable to reach 50% reduction		60%CP 30%LS 10%IO	-

From Table 4.9, the option that requires the least amount of the building inventory to be retrofit to achieve the 50% reduction is the IO retrofit case (in both the 72- and 475-year losses), by retrofitting 60% of the buildings in the region, and is the only retrofit option presented able to achieve the 50% reduction goal in the 2475-year loss. At the 72-year loss, retrofitting the region to CP or LS can also achieve this retrofit goal, although 90% of the region needs to be subject to retrofit. At the 475-year loss, retrofitting the region to CP or LS cannot reduce the repair time enough to reach the 50% reduction in regional repair time. Neither the targeted residential buildings or the targeted 6-story buildings satisfy the 50% repair time reduction goal at either the 10% regional retrofit or the 25% regional retrofit.

4.4.4 Retrofit Goal #4: Reduce Number of Unoccupiable Buildings by 30%

The final retrofit goal considered is to reduce the number of unoccupiable buildings in the region after an event. This section presents the retrofit cases that can reduce the number of unoccupiable buildings in the region by at least 30% compared to the unretrofit case. Unoccupiable buildings are defined in this study as any damaged building with an average repair time per story of 42 days or greater. Table 4.10 gives each retrofit case to achieve the 30% reduction goal for the 72-, 475-, and 2475-year losses, with increasing regional retrofit percentages increasing with increasing year losses. The most significant reductions are from the IO retrofit cases (Figure 4.7) compared to the reductions from the CP retrofit cases (Figure 4.6). Furthermore, retrofitting 40% of the region to the IO performance level can reach the 30% reduction goal at each year loss observed. In contrast, while all the retrofit cases analyzed are able to reduce the number of unoccupiable buildings by 30% at the 72-year loss, retrofitting the region to either CP or LS, or retrofit cases of lower percentages on IO, cannot achieve this retrofit goal at the 475- or 2475-year losses. Neither the targeted residential buildings or the targeted 6-story buildings satisfy the 30%

reduction of unoccupiable buildings goal at either the 10% regional retrofit or the 25% regional retrofit.

Table 4.10 – Minimum retrofit cases to reduce the number of unoccupiable buildings by at least 30%.

Event	*Case Number*	*% of Region Retrofit*	*Retrofit Performance Level*	*% Reduced Unoccupiable Buildings*
72-year loss	7.1	60%	All CP	36%
	6.2	50%	All LS	32%
	4.3	30%	All IO	31%
	6.4	50%	33%CP 33%LS 33%IO	33%
	7.5	60%	60%CP 30%LS 10%IO	34%
475-year loss	*unable to reach 30% reduction*		All CP	-
	unable to reach 30% reduction		All LS	-
	5.3	40%	All IO	37%
	7.4	60%	33%CP 33%LS 33%IO	31%
	unable to reach 30% reduction		60%CP 30%LS 10%IO	-
2475-year loss	*unable to reach 30% reduction*		All CP	-
	unable to reach 30% reduction		All LS	-
	5.3	40%	All IO	41%
	8.4	70%	33%CP 33%LS 33%IO	37%
	unable to reach 30% reduction		60%CP 30%LS 10%IO	-

4.4.5 Retrofit Goal Conclusions

The retrofit goals presented in this section are an attempt to guide policy-makers and other stakeholders in choosing retrofit options for NDC buildings to best benefit the community. Due to the number of vulnerable NDC structures in the city of LA, the problem posed in retrofitting all of these buildings can be overwhelming, and addressing this challenge is difficult due to the lack of funds. By outlining retrofit options that satisfy potential community-based goals, a specific solution can be chosen to meet those needs.

Table 4.11 present the results from Chapter 4.4 (Possible Retrofit Objectives) showing which retrofit cases achieve each retrofit goal for the 72-year loss (light gray), 475-year loss (gray), and 2475-year loss (dark gray). The shaded boxes indicate the retrofit goal is met by the associated retrofit case, and the white boxes indicate the goal is not met. From Table 4.11 (for the 72-year loss), while retrofitting 90% of the region all to CP or LS, IO retrofit can achieve every retrofit goal by retrofitting at least 60% of the region. Retrofitting to the IO performance level meets the target of every retrofit goal presented in this section, although the percentage of buildings that need to be retrofit varies from 10% to 60% of the region. For the 475-year event, IO retrofit can still achieve every retrofit goal by retrofitting 30% to 60% of the region. Retrofitting the region to CP or LS can only reach the retrofit goals to reduce the number of displaced residents and the number of community fatalities. For the 2475-year loss, retrofitting to IO is again the only retrofit performance level able to meet every retrofit goal with regional retrofit ranges from 30% to 70% of the region, although retrofitting the region to CP or LS can reduce the number of fatalities. While retrofitting the region to CP and LS can reduce regional losses, these options cannot achieve every retrofit goal presented here and the larger 475- and 2475-year losses.

In most cases, the percentage of the region required to be retrofit in order to meet the retrofit goal increases as the year loss increases (i.e. from the 72-year loss to the 475-year loss or the 475-year loss to the 2475-year loss), although in a few cases the percentage of the region does not significantly increase. This implies that as the probability of that level of loss happening decreases (higher year loss), there is more damage accumulation in the region, and therefore a larger percentage of the region needs to be retrofit to achieve the same level of loss reduction. Additionally, IO is assumed to be the most expensive retrofit option (because it requires the most aggressive structural upgrades), therefore other retrofit cases, of varying percentages of IO retrofit, may want to be considered to bring down the cost of retrofitting the region.

Table 4.11 – Regional retrofit cases that meet each retrofit goal for the 72-year loss (light gray), 475-year loss (gray), and 2475-year loss (dark gray). Shaded boxes indicate the retrofit goal is met by the associated retrofit case.

Retrofit Performance Level	*% of Region Retrofit*	*30 % Reduced Displaced Residents*			*30 % Reduced Community Fatalities*			*50 % Reduced Community Fatalities*			*50 % Reduced Repair Time*			*30 % Reduced Unoccupiable Buildings*		
All CP	10%															
	20%															
	25%				░											
	30%				░											
	40%	░			░											
	50%	░			░	▒	▓	░								
	60%	░			░	▒	▓	░						░		
	70%	░			░	▒	▓	░		▓				░		
	75%	░			░	▒	▓	░	▒	▓				░		
	80%	░			░	▒	▓	░	▒	▓				░		
	90%	░	▒		░	▒	▓	░	▒	▓	░			░		
All LS	10%															
	20%															
	25%															
	30%	░			░	▒										
	40%	░			░	▒	▓									
	50%	░			░	▒	▓	░						░		
	60%	░	▒		░	▒	▓	░						░		
	70%	░	▒		░	▒	▓	░		▓				░		
	75%	░	▒		░	▒	▓	░	▒	▓				░		
	80%	░	▒		░	▒	▓	░	▒	▓				░		
	90%	░	▒		░	▒	▓	░	▒	▓	░			░		
All IO	10%				░											
	20%	░			░											
	25%	░			░											
	30%	░	▒	▓	░	▒	▓							░		
	40%	░	▒	▓	░	▒	▓	░						░	▒	▓
	50%	░	▒	▓	░	▒	▓	░						░	▒	▓
	60%	░	▒	▓	░	▒	▓	░	▒	▓	░	▒		░	▒	▓
	70%	░	▒	▓	░	▒	▓	░	▒	▓	░	▒	▓	░	▒	▓
	75%	░	▒	▓	░	▒	▓	░	▒	▓	░	▒	▓	░	▒	▓
	80%	░	▒	▓	░	▒	▓	░	▒	▓	░	▒	▓	░	▒	▓
	90%	░	▒	▓	░	▒	▓	░	▒	▓	░	▒	▓	░	▒	▓
33%CP 33%LS 33%IO	10%															
	20%															
	25%	░			░											
	30%	░			░											
	40%	░	▒		░		▓									
	50%	░	▒		░	▒	▓							░		
	60%	░	▒		░	▒	▓	░						░	▒	
	70%	░	▒		░	▒	▓	░	▒	▓				░	▒	▓
	75%	░	▒		░	▒	▓	░	▒	▓	░			░	▒	▓
	80%	░	▒	▓	░	▒	▓	░	▒	▓	░			░	▒	▓
	90%	░	▒	▓	░	▒	▓	░	▒	▓	░	▒		░	▒	▓
60%CP 30%LS 10%IO	10%															
	20%															
	25%															
	30%				░											
	40%	░			░	▒	▓									
	50%	░			░	▒	▓									
	60%	░			░	▒	▓							░		
	70%	░			░	▒	▓	░		▓				░		
	75%	░	▒		░	▒	▓	░	▒	▓				░		
	80%	░	▒		░	▒	▓	░	▒	▓				░		
	90%	░	▒		░	▒	▓	░	▒	▓	░			░		
All CP - 6-story	10%															
	25%	░			░	▒	▓	░								
All CP - Residential	10%	░														
	25%	░	▒		░	▒	▓	░								
All LS - 6-story	10%															
	25%	░			░	▒	▓	░								
All LS - Residential	10%	░														
	25%	░	▒		░	▒	▓	░								
All IO - 6-story	10%				░			░								
	25%	░	▒	▓	░	▒	▓	░								
All IO - Residential	10%	░	▒	▓	░		▓	░								
	25%	░	▒	▓	░	▒	▓	░	▒	▓						

CHAPTER 5

CONCLUSIONS

This thesis integrates advancements in probabilistic regional loss assessments and in performance-based analysis of retrofit buildings to a regional retrofit study of NDC buildings in Los Angeles, California. The study uses unretrofit archetype buildings which, although developed for the purpose of this study, were designed according to governing codes from the mid-1960s. The study also makes use of a set of 72 retrofit buildings, representing different retrofit alternatives for the existing building stock, which are again consistent retrofit design standards. These buildings are used to represent the NDC building inventory in Los Angeles and are subjected to a probabilistically-robust regional loss analysis that considers over 60,000 future earthquake scenarios that together represent the hazard of this region. This study aims to help stakeholders, including policy-makers, insurance providers, and community advocates, in making resilient decisions regarding seismic hazard mitigation in light of resource limitations. The retrofit cases considered vary in terms of the percentage of buildings retrofit, the selection of those buildings, and the standard used to guide the retrofit design.

The goal of this study is to inform stakeholders with probabilistic community-based results in terms of economic repair costs, repair times, and fatalities for the existing building portfolio of LA, considering a number of possible retrofit alternatives. The *2016 Safer Cities Survey* declares, Southern California should “sustain occupancy, provide shelter, and support economic stability following an earthquake” (SEAOSC, 2016). Retrofit Goal #1, presented above, provides various viable retrofit cases to reduce the number of people displaced from their residence and “sustain occupancy” after a substantial event. Retrofit Goals #3 and #4 propose different retrofit cases to reduce the repair time of buildings damaged and the number of unoccupiable buildings, to be able to “provide shelter” for displaced residents after an earthquake. Finally, Chapter 4.1.5 (Economic Losses) presents the total losses from building damage of the unretrofit and retrofit regions.

The regional retrofit cases considered in this study result in opportunities for community policy-makers to “support economic stability” and protect the safety of the citizens from vulnerable existing buildings. The built community should have further goals than just life safety to sustain stability after a natural disaster. This study reveals retrofitting at least 60% of the region to the IO performance level can achieve every retrofit goal presented, retrofitting at least 90% of the region or CP or LS can reduce the number of displaced residents in the region by 30%, and retrofitting at least 75% of the region to CP or LS can reduce the number of community fatalities by 50%. Preferentially targeting residential buildings for retrofit in more effective in reducing the number of displaced residents, as well as the number of community fatalities. The purpose of targeting specific vulnerable building sets is to identify groups of buildings that will most effectively reduce the risk to human lives. By targeting 6-story NDC buildings (the most vulnerable individual building type) and residential NDC buildings (housing 45,500 people in the city), the city of LA can reduce a significant amount of potential fatalities and number of displaced residents from their home, in comparison to selecting buildings for retrofit at random.

This study does have a few assessment limitations. First, the study only evaluates the regional losses from NDC buildings, and not the rest of the buildings included in the current LA building inventory. Second, all NDC buildings are modeled as frame structures and the associated losses are most likely overestimated for buildings that have walls (likely most of the inventory); infill walls are not also not considered. Third, we do not know the cost of the retrofit strategies, and therefore cannot compute a cost-benefit analysis. There are also limitations to using the median collapse fatality data instead of time- and day- based data, and therefore, there would be full correlations between building occupancy types, which is currently not taken into account. Finally, there are limitations and assumptions in the SP3-generated building loss results. The building components to populate the building, fragility functions, and fatality models were all developed in and follow the FEMA P-58 methodology. The building losses are all evaluated at five hazard levels from the 2009 USGS-defined hazard curve. For community fatalities, we chose to only use the number of fatalities for each building from structural collapse, and not from falling objects or non-structural components. We also chose to use serial repair time as our repair time metric, which is an overestimation for tall buildings, and were unable to quantify recovery time.

REFERENCES

Anagnos, T., Comerio, M. C., Goulet, C., Na, H., Steele, J., & Stewart, J. P. (2008). Los Angeles Inventory of Nonductile Concrete Buildings for Analysis of Seismic Collapse Risk Hazards. Presented at the 14 World Conference on Earthquake Engineering, Beijing, China.

Anagnos, T., Comerio, M. C., & Stewart, J. P. (2016). Earthquake Loss Estimates and Policy Implications for Nonductile Concrete Buildings in Los Angeles. *Earthquake Spectra*, *32*(4), 1951–1973. https://doi.org/10.1193/060415EQS088M

ASCE. (2003). *Seismic Evaluation of Existing Buildings (ASCE/SEI 31-03)* (31st ed.). Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784406700

ASCE. (2006). *Seismic Rehabilitation of Existing Buildings (ASCE/SEI 41-06)* (41st ed.). Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784408841

ASCE. (2013a). Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10). American Society of Civil Engineers.

ASCE. (2013b). Seismic Evaluation and Upgrade of Existing Buildings (ASCE/SEI 41-13). American Society of Civil Engineers.

Bonstrom, H., & Corotis, R. B. (2015). Optimising portfolio loss reduction using a first-order reliability method sensitivity analysis. *Structure and Infrastructure Engineering*, *11*(9), 1190–1198. https://doi.org/10.1080/15732479.2014.945094

Boore, D. M., & Atkinson, G. M. (2008). Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s. *Earthquake Spectra*, *24*(1), 99–138. https://doi.org/10.1193/1.2830434

Chang, S. E., Shinozuka, M., & Moore, J. E. (2000). Probabilistic Earthquake Scenarios: Extending Risk Analysis Methodologies to Spatially Distributed Systems. *Earthquake Spectra*, *16*(3), 557–572. https://doi.org/10.1193/1.1586127

City of Los Angeles. (2015). Ordinance No. 183893, Amending Divisions 93 and 95 of Article I of Chapter IX of the Los Angeles Municipal Code.

City of Los Angeles. (2017). *2017-18 Proposed Budget*. Retrieved from http://cao.lacity.org/budget17-18/2017-18Supp_Info.pdf

City of Los Angeles. (2018). City of Los Angeles 2018 Expense Budget. Retrieved from http://openbudget.lacity.org/#!/year/2018/operating/0/program_priority?vis=barChart

City of West Hollywood. (2017). Ordinance No. 17-1011: An Ordinance of the City of West Hollywood Establishing Seismic Strengthening Requirements for Two Categories of Existing Buildings in the City and Amending Titles 13 and 9 of the West Hollywood Municipal Code.

Comartin, C., Bonowitz, D., Greene, M., McCormick, D., May, P., & Seymour, E. (2011). The Concrete Coalition and the California Inventory Project: An Estimate of the Number of Pre-1980 Concrete Buildings in the State. Earthquake Engineering Research Institute. Retrieved from http://www.concretecoalition.org/wp-content/uploads/2012/05/concrete_coalition_final-revise-0512.pdf

Comerio, M. C. (2006). Estimating Downtime in Loss Modeling. *Earthquake Spectra*, *22*(2), 349–365. https://doi.org/10.1193/1.2191017

Comerio, M. C., & Anagnos, T. (2012). Los Angeles Inventory: Implications for Retrofit Policies for Nonductile Concrete Buildings. Presented at the Proc. of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal.

Concrete Coalition. (2011). *California Inventory Project*. Retrieved from http://www.concretecoalition .org/

Davis, M., & Porter, K. (2016). The Public's Role in Seismic Design Provisions. *Earthquake Spectra*, *32*(3), 1345–1361. https://doi.org/10.1193/081715EQS127M

DeBock, D. J. (2013). *Advancements to performance-based earthquake engineering methods: from building code provisions to regional loss assessment* (Ph.D.). University of Colorado Boulder, Boulder, Colorado.

DeBock, D. J., & Liel, A. B. (2015a). A Comparative Evaluation of Probabilistic Regional Seismic Loss Assessment Methods Using Scenario Case Studies. *Journal of Earthquake Engineering*, *19*(6), 905–937. https://doi.org/10.1080/13632469.2015.1015754

DeBock, D. J., & Liel, A. B. (2015b). A Move toward Improved Portfolio Seismic Risk Assessment Methods for the Practicing Engineer. In *Second ATC & SEI Conference on*

Improving the Seismic Performance of Existing Buildings and Other Structures. San Francisco, California: ASCE. https://doi.org/10.1061/9780784479728.036

Derhake, J. P. (2009). Understanding PMLs and Managing Engineering Providers.

EQE International (EQE), & Geographic Information Systems Group of the Governor's Office of Emergency Services (OES). (1995). The Northridge Earthquake of January 17, 1994: Report of Data Collection and Analysis, Part A: Damage and Inventory Data. EQE International.

FEMA. (1998). FEMA 310 Handbook for the Seismic Evaluation of Buildings. Federal Emergency Management Agency.

FEMA. (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings (FEMA 356). Federal Emergency Management Agency. Retrieved from https://www.fema.gov/media-library-data/20130726-1444-20490-5925/fema_356.pdf

FEMA. (2012). *FEMA P-58: Seismic Performance Assessment of Buildings, Volume 1 - Methodology*. Washington, D.C.: Federal Emergency Management Agency.

Galanis, P. H., & Moehle, J. P. (2014). Development of Collapse Indicators for Risk Assessment of Older-Type Reinforced Concrete Buildings. *Earthquake Spectra*, *31*(4), 1991–2006. https://doi.org/10.1193/080613EQS225M

Goda, K., & Hong, H. P. (2008). Spatial Correlation of Peak Ground Motions and Response SpectraSpatial Correlation of Peak Ground Motions and Response Spectra. *Bulletin of the Seismological Society of America*, *98*(1), 354–365. https://doi.org/10.1785/0120070078

Goda, Katsuichiro, & Hong, H. P. (2008). Estimation of Seismic Loss for Spatially Distributed Buildings. *Earthquake Spectra*, *24*(4), 889–910. https://doi.org/10.1193/1.2983654

Harrington, C. C. (2016). *Advancement of performance-based earthquake engineering for RC frame buildings: application to retrofit design and consideration of vertical ground motions* (Ph.D.). University of Colorado Boulder, Boulder, Colorado.

Haselton Baker Risk Group. (n.d.). Seismic Performance Prediction Program (SP3). Retrieved from www.hbrisk.com

Holmes, W. T. (2009). Progress of Seismic Rehabilitation of Buildings in the U.S. *Improving the Seismic Performance of Existing Buildings and Other Structures*. https://doi.org/10.1061/41084(364)3

ICC. (2015, November). International Existing Building Code.

Jayaram, N., & Baker, J. W. (2009). Correlation model for spatially distributed ground-motion intensities. *Earthquake Engineering & Structural Dynamics*, *38*(15), 1687–1708. https://doi.org/10.1002/eqe.922

Jephcott, D. K. (1986). 50-Year Record of Field Act Seismic Building Standards for California Schools. *Earthquake Spectra*, *2*(3), 621–629. https://doi.org/10.1193/1.1585399

Kim, I., & Hagen, G. (2014). Seismic Assessment and Retrofit of Existing RC Buildings: Case Studies from Degenkolb Engineers, 9.1-9.12.

Liel, A. B., & Deierlein, G. G. (2012). Using Collapse Risk Assessments to Inform Seismic Safety Policy for Older Concrete Buildings. *Earthquake Spectra*, *28*(4), 1495–1521. https://doi.org/10.1193/1.4000090

Liel, A. B., & Deierlein, G. G. (2013). Cost-Benefit Evaluation of Seismic Risk Mitigation Alternatives for Older Concrete Frame Buildings. *Earthquake Spectra*, *29*(4), 1391–1411. https://doi.org/10.1193/030911EQS040M

Loth, C., & Baker, J. W. (2013). A spatial cross-correlation model of spectral accelerations at multiple periods. *Earthquake Engineering & Structural Dynamics*, *42*(3), 397–417. https://doi.org/10.1002/eqe.2212

Lynch, K. P., Rowe, K. L., & Liel, A. B. (2011). Seismic Performance of Reinforced Concrete Frame Buildings in Southern California. *Earthquake Spectra*, *27*(2), 399–418. https://doi.org/10.1193/1.3570684

Manzour, H., Davidson, R. A., Horspool, N., & Nozick, L. K. (2015). Seismic Hazard and Loss Analysis for Spatially Distributed Infrastructure in Christchurch, New Zealand. *Earthquake Spectra*, *32*(2), 697–712. https://doi.org/10.1193/041415EQS054M

Network for Earthquake Engineering Simulation (NEES). (2011). NEES Grand Challenge Inventory of Older Concrete Buildings. National Science Foundation.

Park, J., Bazzurro, P., & Baker, J. W. (2007). Modeling spatial correlation of ground motion intensity measures for regional seismic hazard and portfolio loss estimation. Presented at the ICASP 10, Tokyo, Japan.

Pekelnicky, R., & Poland, C. (2012). ASCE 41-13: Seismic Evaluation and Retrofit of Existing Buildings. Presented at the SEAOC 2012 Convention, Structural Engineers Association of California.

Salgado-Gálvez, M. A., Zuloaga-Romero, D., Bernal, G. A., Mora, M. G., & Cardona, O.-D. (2014). Fully probabilistic seismic risk assessment considering local site effects for the portfolio of buildings in Medellín, Colombia. *Bulletin of Earthquake Engineering*, *12*(2), 671–695. https://doi.org/10.1007/s10518-013-9550-4

Searer, G. R., Paret, T. F., & Freeman, S. A. (2008). ASCE-31 and ASCE-41: What Good Are They? In *ASCE Structures Congress*. https://doi.org/10.1061/41016(314)130

Smyth, A. W., Altay, G., Deodatis, G., Erdik, M., Franco, G., Gu¨lkan, P., … Yu¨zu¨gu¨llu¨, O. (2004). Probabilistic Benefit-Cost Analysis for Earthquake Damage Mitigation: Evaluating Measures for Apartment Houses in Turkey. *Earthquake Spectra*, *20*(1), 171–203. https://doi.org/10.1193/1.1649937

Structural Engineers Association of Southern California (SEAOSC). (2016). Safer Cities Survey. Structural Engineers Association of Southern California; The Dr. Lucy Jones Center for Science and Society. Retrieved from https://www.seaosc.org/resources/Summit/2016SaferCitiesSurvey.pdf

United States Census Bureau. (2016). *2016 Population Estimates*. Retrieved from https://www.census.gov/search-results.html?page=1&stateGeo=&searchtype=web&cssp=SERP&q=los+angeles+city+population&search.x=0&search.y=0&search=submit

United States Geological Survey (USGS). (2015a). Global Vs30 Mosaic. Retrieved from https://earthquake.usgs.gov/data/vs30/

United States Geological Survey (USGS). (2015b). UCERF3: A New Earthquake Forecast for California's Complex Fault System. Retrieved from https://pubs.usgs.gov/fs/2015/3009/pdf/fs2015-3009.pdf

APPENDIX

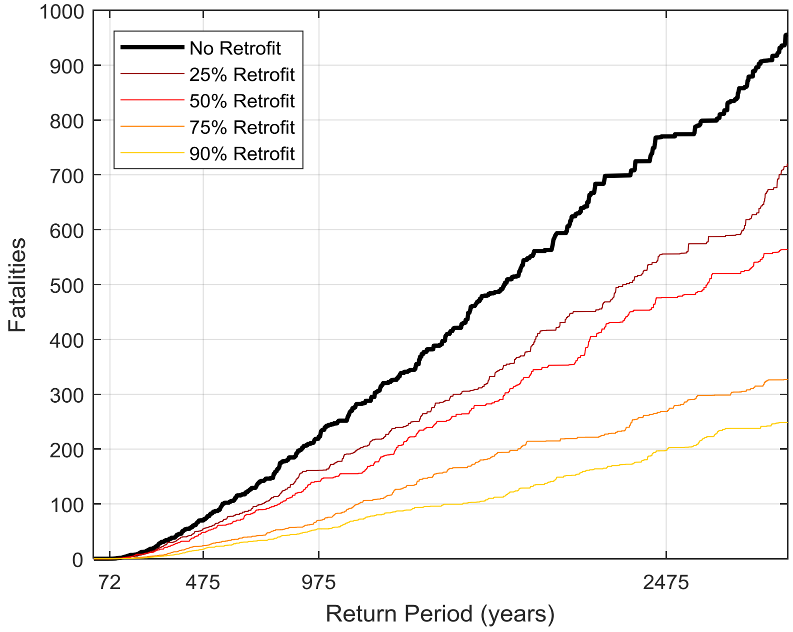


Figure 0.1 – Total regional fatalities presented against return period for 33% of the buildings retrofit to the CP performance level, 33% retrofit to LS, and 33% retrofit to IO (Cases 3.4, 6.4, 9.4, and 11.4).

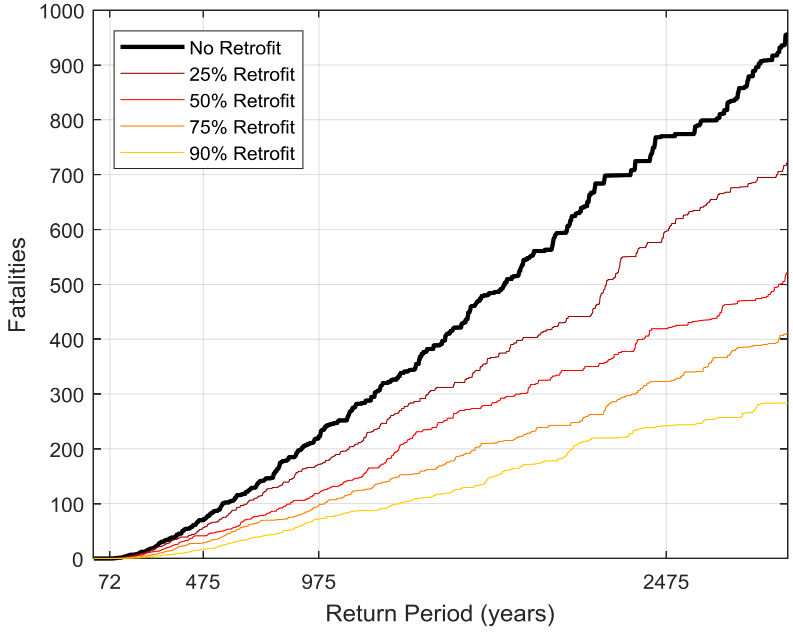


Figure 0.2 – Total regional fatalities presented against return period for 60% of the buildings retrofit to the CP performance level, 30% retrofit to LS, and 10% retrofit to IO (Cases 3.5, 6.5, 9.5, and 11.5).

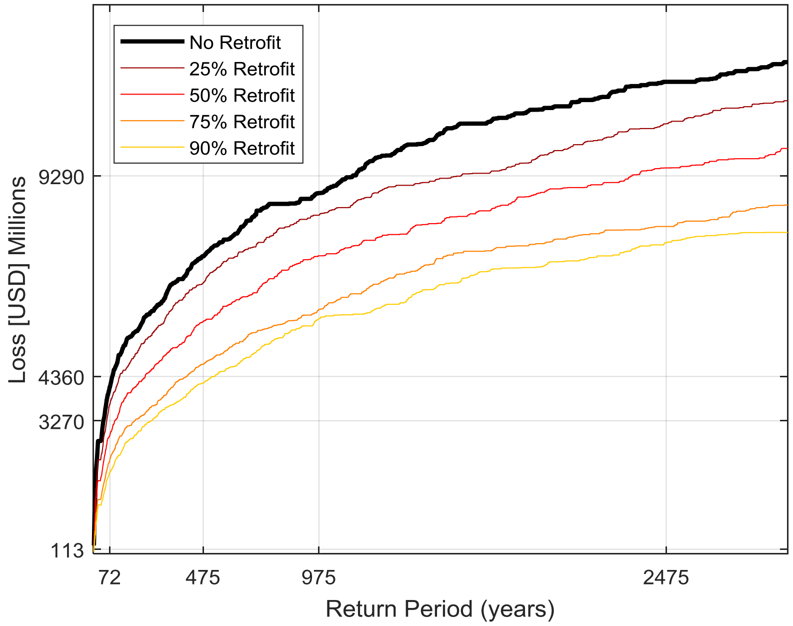


Figure 0.3 – Total regional economic losses presented against return period for buildings retrofit to the LS performance level (Cases 3.2, 6.2, 9.2, and 11.2).

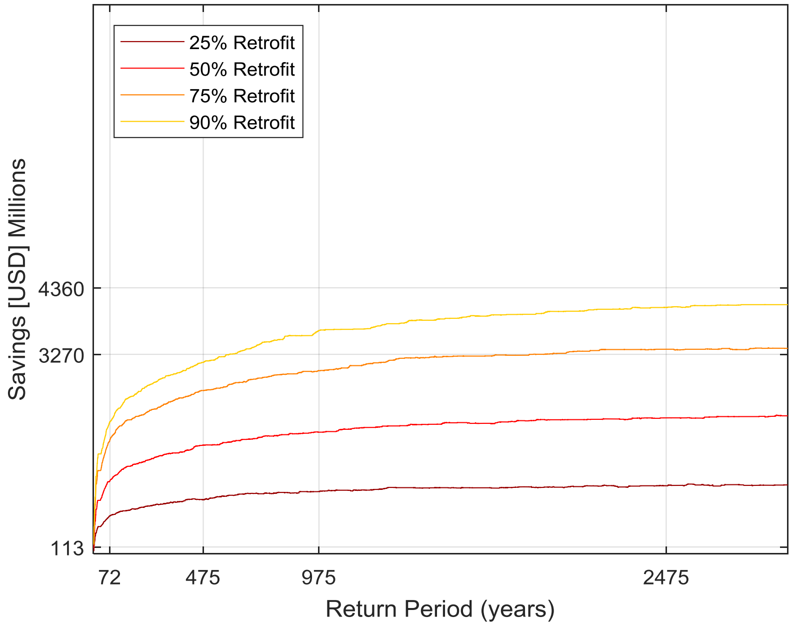


Figure 0.4 – Total regional economic savings presented against return period for buildings retrofit to the LS performance level (Cases 3.2, 6.2, 9.2, and 11.2).

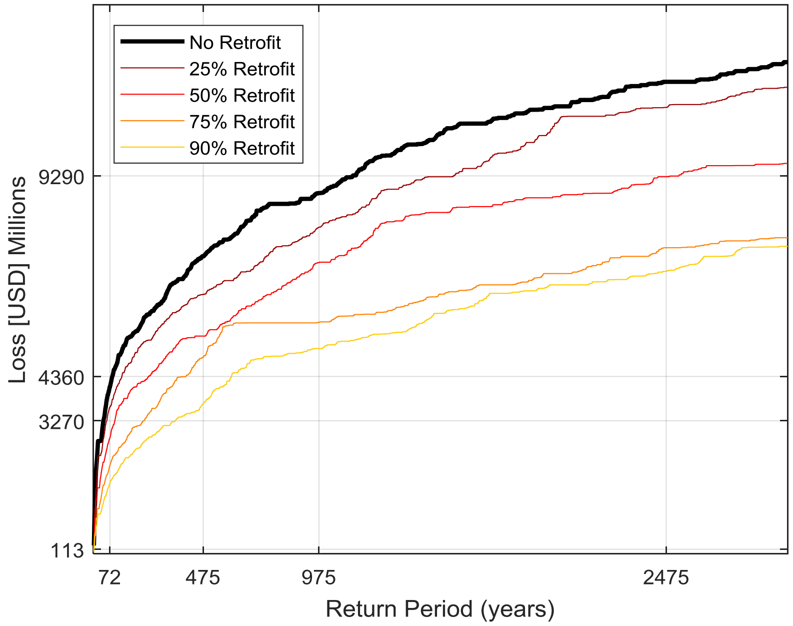


Figure 0.5 – Total regional economic losses presented against return period for 33% of the buildings retrofit to the CP performance level, 33% retrofit to LS, and 33% retrofit to IO (Cases 3.4, 6.4, 9.4, and 11.4).

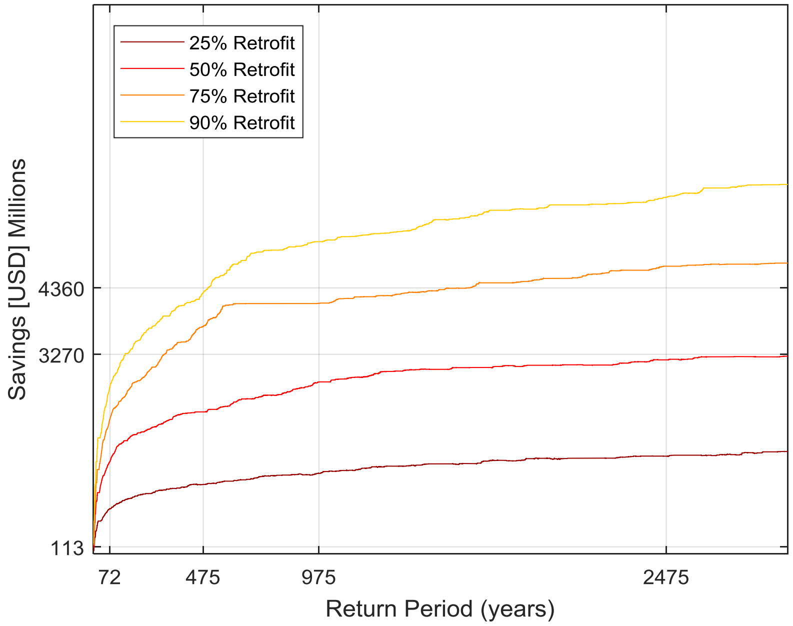


Figure 0.6 – Total regional economic savings presented against return period for 33% of the buildings retrofit to the CP performance level, 33% retrofit to LS, and 33% retrofit to IO (Cases 3.4, 6.4, 9.4, and 11.4).

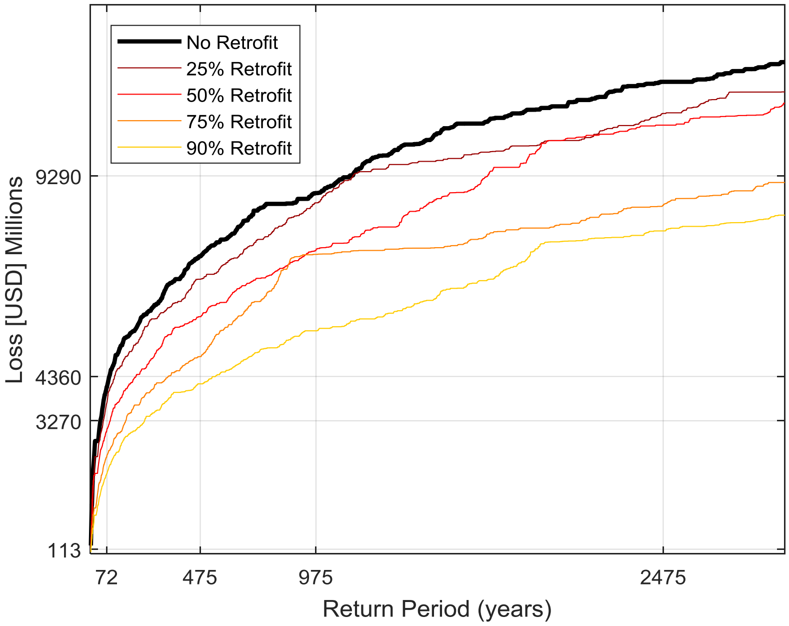


Figure 0.7 – Total regional economic losses presented against return period for 60% of the buildings retrofit to the CP performance level, 30% retrofit to LS, and 10% retrofit to IO (Cases 3.5, 6.5, 9.5, and 11.5).

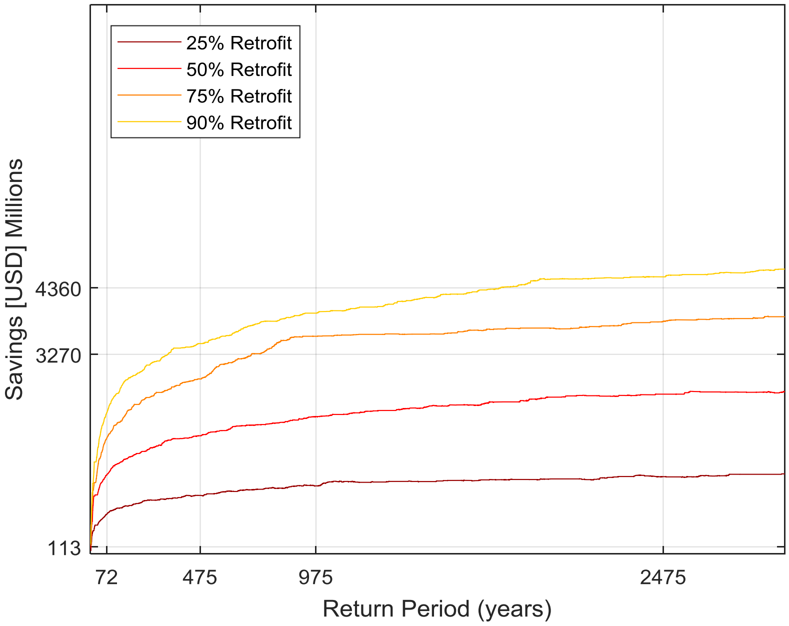


Figure 0.8 – Total regional economic savings presented against return period for 60% of the buildings retrofit to the CP performance level, 30% retrofit to LS, and 10% retrofit to IO (Cases 3.5, 6.5, 9.5, and 11.5).

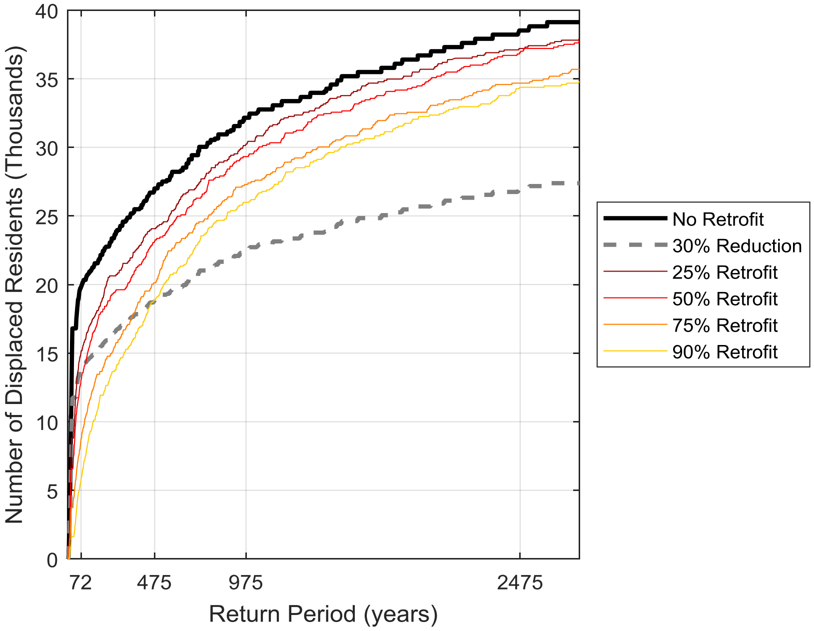


Figure 0.9 – Total displaced residents presented against return period for all buildings retrofit to the CP performance level (Cases 3.1, 6.1, 9.1, and 11.1).

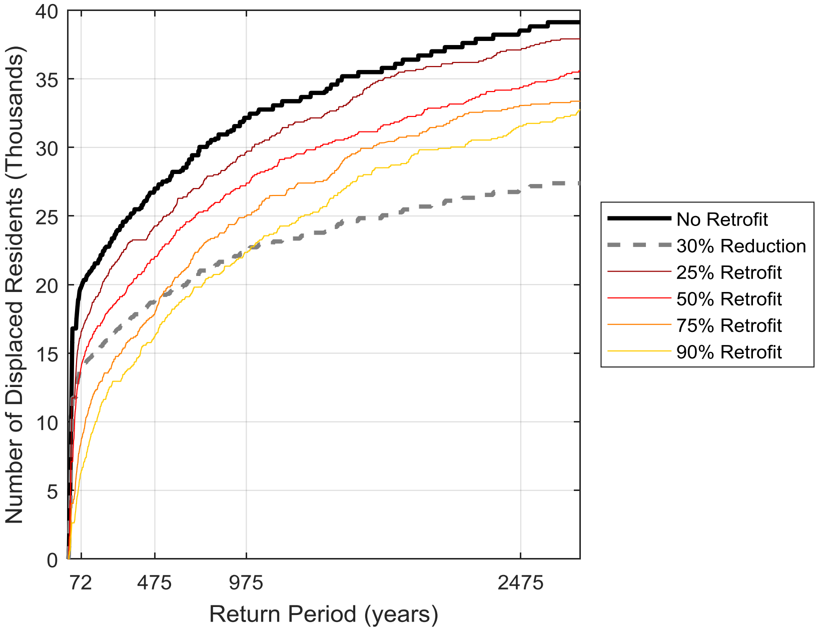


Figure 0.10 – Total displaced residents presented against return period for all buildings retrofit to the LS performance level (Cases 3.2, 6.2, 9.2, and 11.2).

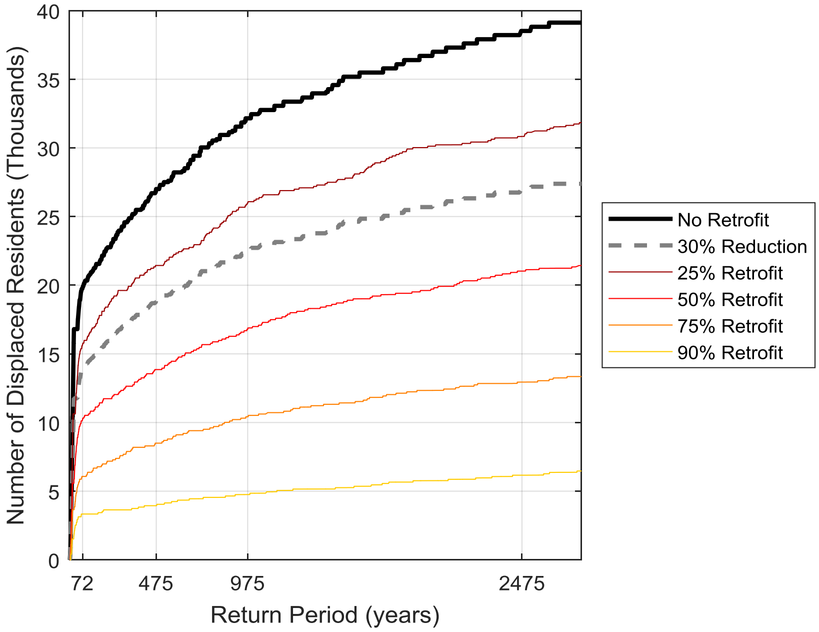


Figure 0.11 – Total displaced residents presented against return period for all buildings retrofit to the IO performance level (Cases 3.3, 6.3, 9.3, and 11.3).

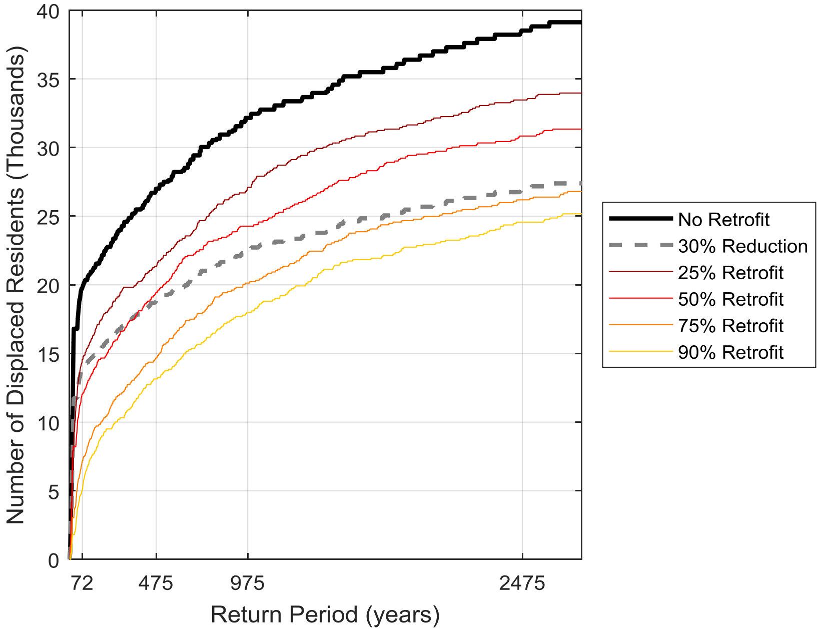


Figure 0.12 – Total displaced residents presented against return period for 33% of the buildings retrofit to the CP performance level, 33% retrofit to LS, and 33% retrofit to IO (Cases 3.4, 6.4, 9.4, and 11.4).

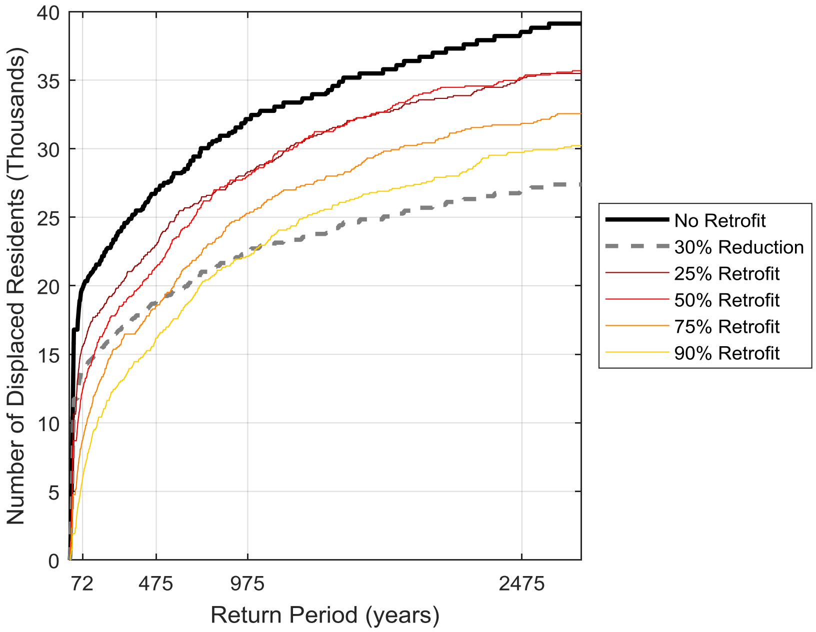


Figure 0.13 – Total displaced residents presented against return period for 60% of the buildings retrofit to the CP performance level, 30% retrofit to LS, and 10% retrofit to IO (Cases 3.5, 6.5, 9.5, and 11.5).