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Earthquake Loss Estimates and Policy Implications for Nonductile Concrete Buildings in Los Angeles

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Collapse potential of nonductile concrete buildings represents a substantial life safety hazard globally that can be mitigated through carefully crafted policy. Mitigation policy should be approached incrementally by (1) understanding problem scale, (2) screening for low and high risk buildings, (3) performing engineering analysis for potentially vulnerable buildings, and (4) retrofit or replacement of high-risk structures. This research addresses initial stages of this sequence for Los Angeles, California. The intent was to investigate approaches for informing mitigation priorities by: characterizing the inventory of approximately 1500 pre-1976 concrete buildings; estimating risk, including identification of building types that contribute most substantially to the risk; and investigating the impact of retrofit policy alternatives. Loss estimates for scenario events are based on the HAZUS^{TM} Advanced Engineering Building Module. Depending on model assumptions, losses range from $1.8 to $28.5 billion and <50 to 8,300 fatalities. We investigate proposals targeting vulnerable buildings for retrofit as compared to retrofitting all buildings in the inventory. Awareness raised by this research contributed to formation of the Los Angeles Mayoral Seismic Safety Task Force, which developed policy proposals.

INTRODUCTION

Mitigation of Collapse Risk in Vulnerable Concrete Buildings was one of the three Grand Challenge projects funded by the United States National Science Foundation (NSF) through the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program. The objective of the project was to study the collapse potential of older nonductile concrete (NDC) buildings, to improve and disseminate effective engineering assessment and retrofit tools, and to inform appropriate incentives or policy measures to mitigate the risk. Numerous papers have described the background and interim findings. The Grand Challenge research project undertaken from 2007 to 2013 included a case study inventory in the City of Los Angeles for loss modeling (Anagnos et al. 2008, 2010, 2012; Comerio and Anagnos 2012), extensive experimental laboratory testing of components (Hassan and Moehle 2012; Henkhaus et al. 2013; Prasad and Hutchinson 2014), and analytical simulations of ground motions, progressive collapse analyses, and building fragility studies (Star et al. 2011; Park and Mosalam 2012; Galanis and Moehle 2015). During this same period, other investigators inventoried these buildings (Comartin et al. 2011), studied their performance (Lynch et al. 2011; Liel et al. 2010; Wu et al. 2009), estimated earthquake losses (Baradaran Shoraka et al. 2013; Jones et al. 2008; Taciroglu and Khalili-Tehrani 2008), and evaluated mitigation strategies (Koutromanos et al.

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2012; Liel and Deierlein 2012, 2013). In addition, a collaborative project of the National Institute of Standards and Technology (NIST), the Federal Emergency Management Agency (FEMA), the Applied Technology Council (ATC), and the Consortium of Universities for Research in Earthquake Engineering (CUREE) aimed to develop nationally accepted collapse assessment and mitigation guidelines for nonductile concrete buildings (NIST 2010, 2013; ATC 2012; Elwood et al. 2012). This paper summarizes the development of the Los Angeles inventory for the NEES Grand Challenge project and focuses on the loss studies and strategies for policy development.

As background, it is important to note that nonductile concrete buildings were a prevalent construction type in highly seismic zones of the U.S. prior to enforcement of codes for ductile concrete in the mid-1970s. In California, NDC buildings were principally constructed between approximately 1890 (when elevators first enabled the construction of relatively tall buildings) and the mid-1970s (when NDC frame collapses and other significant damage in the 1971 San Fernando earthquake motivated improvements in building codes). The Concrete Coalition estimates that in California alone, 20,000 to 23,000 of these buildings exist, including residential, commercial, schools, and critical service facilities (Comartin et. al. 2011; Concrete Coalition 2011). Typically, pre-1976 concrete buildings are assumed to have nonductile detailing; however, it is important to note that there may be well-detailed ductile concrete buildings in this age category. From the early 1960s engineers were experimenting with concepts of confined concrete, flexural ductility, plastic hinge length, and capacity design for shear introduced by Blume et al. (1961), and starting in 1967 the SEAOC Blue Book specified rules for providing ductile behavior in concrete frames and shear walls (McClure 2006; SEAOC 1967). NDC construction is common internationally as well as in the U.S., and remains widespread in many economically underdeveloped countries. The poor seismic performance of NDC buildings has been documented in many earthquakes in both developed and economically underdeveloped countries, including in recent events such as New Zealand (2011) (Smyrou et al. 2011) and Haiti (2010) (O'Brien, et. al. 2011).

Prior experience with losses (Otani, 1999) and of users of the FEMA 356 (FEMA 2000) and ASCE 41 (ASCE 2007) methodologies suggest that these risk assessment tools overstate the seismic risk associated with NDC construction, causing virtually all buildings with this typology in seismically active regions like Los Angeles to be identified as poor performers in need of retrofit. While some structures certainly are at risk for collapse, this overly conservative approach causes the problem to appear so large that, paradoxically, effective public policy to mitigate the risks becomes untenable. Accordingly, the efforts of the Grand Challenge team were specifically directed towards developing strategies to identify the truly dangerous buildings from among the larger vulnerable concrete building population, thereby scaling down an intractable problem to one that could be addressed with an incremental policy (Comerio and Anagnos 2012). Specifically, we advocate a mitigation policy approach with the following incremental stages (1) understanding problem scale, (2) screening for low and high risk buildings, (3) performing engineering analysis for potentially vulnerable buildings, and (4) mitigating high-risk structures. Holmes (2009), in a study of programs for mitigating the seismic risk from existing buildings, found that many programs follow a process similar to this.

In this paper, we describe research addressing initial stages of this sequence for Los Angeles. Specifically, we review a building inventory of pre-1976 concrete buildings and explore insights it provides regarding problem scale and vulnerable building typologies. We conduct example loss estimation exercises targeted at the building inventory as it existed when developed, and how it would be in the future were alternative mitigation policies put into place. This exercise underscores the cost effectiveness of intelligently staged mitigation strategies.

CITY OF LOS ANGELES RESEARCH INVENTORY

We developed an inventory of pre-1976 concrete buildings in the City of Los Angeles to provide a database for investigating the age, size, use, and location of typical buildings and to support loss estimates comparing retrofitted and non-retrofitted scenarios (Anagnos et al. 2008, 2010, 2012; Comerio and Anagnos 2012). The approach was similar to previous work undertaken by Comerio (1992, 2000a, 2000b, 2000c). To develop the inventory, researchers combined information from more than 15 sources. Baseline data on concrete buildings were purchased from the Los Angeles County assessor's office and cross checked using a variety of public sources and sidewalk surveys to verify that the database accurately represented the older concrete building inventory in the City of Los Angeles, without double counting, and that the data were consistent with local zoning patterns. The process for collecting and reviewing data, as well as the challenges posed by the process are discussed in earlier papers (Anagnos et al. 2008, 2010, 2012).

The data were organized in a spatial database using Google Earth Pro™, which has the capability to store photos, drawings, and documents and allows for data retrieval in aggregate or as individual points. The spatial database also enabled overlaying the building locations on planning maps, street maps, and ground motion maps. Equally important, the data were geo-coded and compatible with HAZUS™ risk analysis software.

The study identified approximately 1500 older concrete buildings, comprising about 88 million square feet in the City of Los Angeles. The inventory excludes tilt-ups which largely have been mitigated in compliance with the Los Angeles retrofit ordinance known as Division 91 (City of Los Angeles 1994). For comparison purposes, the Concrete Coalition estimated the number of older concrete buildings in San Francisco to be 3,000 (Comartin et al. 2011). Using default replacement costs per square foot specified in Tables 3.6 and 3.7 of the HAZUS™ Technical Manual (FEMA 2003) and using modifiers to reflect inflation and regional construction costs, the replacement value of the building structures alone was estimated to be $17 billion (with contents replacement estimates were $34 billion).

While the number of older buildings in Los Angeles may initially appear low, given the size of the city—470 square miles with a population close to 4 million—it is important to consider what is not included in the inventory. First, tilts-ups are excluded. Second, the study is confined to the City of Los Angeles and not the greater Los Angeles metropolitan area, so buildings in Beverly Hills, Culver City, Santa Monica and other independent cities in the Los Angeles basin are not included. Third, the City of Los Angeles has had an aggressive retrofit or replacement program for public buildings, with 4.5 million square feet of city-owned buildings structurally upgraded or rebuilt (J. Steele, personal communication, October 27, 2009). Similarly, many federally-owned and state-owned buildings, such as Veterans Administration facilities and universities, also have completed structural retrofits. Fourth, adaptive reuse incentive programs have transformed downtown warehouses into lofts and apartments, with structural improvements completed as part of the change of use. All together, these represent hundreds of buildings that are no longer catalogued on the vulnerable building inventory. Finally, site visits revealed that a number of vulnerable buildings that had been damaged in the 1994 Northridge earthquake had been demolished and the building replaced or the land was vacant.

Reflecting zoning and historical development of the city, older concrete buildings tended to be clustered in certain areas of the city such as downtown and Hollywood, or along major commercial thoroughfares such as Wilshire Boulevard. Many Los Angeles neighborhoods are comprised of large tracts of single-family wood frame houses or small two to three story wood frame apartment complexes. Further, in several areas, building use influenced building configuration, such as high-rise manufacturing and wholesale facilities in the fashion district, movie studios in Hollywood, and the movie palaces along Broadway. The majority of the buildings were built in the 1920s and the 1960s aligning with eras of economic prosperity, and are mainly divided among industrial, commercial, schools, office buildings and residential uses with small numbers of other use-types. Sixty-three percent of the buildings are one to three stories; however, these buildings constitute only 36 percent of the inventory square footage and replacement value. In contrast, 217 high-rise buildings (8+ stories) comprise only 15 percent of the inventory, yet comprise 36 percent of the total building area and 35 percent of the replacement value in the inventory (Comerio and Anagnos 2012).

BREAKDOWN OF BUILDING TYPES

To better understand how the inventoried buildings might be grouped into categories that represent common construction typologies, statistical analyses were performed on sub-categories of data and practicing engineers provided guidance on the evolution of local reinforced concrete design and construction practices. The combination of age, building height, and use is used as a proxy for characterizing common construction typologies and estimating structural performance. For example, the inventory contains many one-story industrial and commercial buildings, which are expected to pose a lower risk because they typically have poured concrete perimeter walls tied to relatively-light wood diaphragm roofs. In another example, the inventory contains fewer than 75 older pre-1930 industrial buildings 4 stories or taller, yet these buildings constitute close to 45 percent of the manufacturing and warehouse square footage. These buildings, with heavy concrete floors, likely pose a higher collapse risk than the one-story buildings because many of them are frame structures or have perforated walls with large windows.

When a similar analysis is completed for each use category, and further reviewed by building age, patterns emerge that reflect the architectural characteristics of a period as well as the common construction methods used. The research team reviewed groupings of buildings sharing common characteristics with a panel of professional structural engineers, whose guidance helped define the twelve groupings shown in Table 1 for use in analysis of losses and policy alternatives. Half of the buildings in the "Other" group are post-1960 low rise, and about 20 percent are office buildings of four or more stories constructed between 1930 and 1959. The remaining 40 buildings in this group are a mix of churches, museums, utilities, warehouses and commercial buildings. It should be emphasized that the building groups are general descriptors for analysis, and not all buildings in any given building group exhibit all of the common characteristics summarized in Table 1. To give a general idea of what these buildings might look like, images from FEMA 154 (2002) and of buildings instrumented by the California Strong Motion Instrumentation Program (SMIP) are referenced in Table 1. These are not necessarily buildings in the Los Angeles database.

Table 1. Inventory groups for loss analysis

Group	Common Characteristics*	Number	Square Footage (millions)	Replacement Value ($ millions)	Contents Value ($ millions)
1: <1960, 1-3 story, various occupancies (except parking garages and education)	Walls dominate structural systems, vertical elements generally not critical elements driving collapse, wood roofs with steel or wood interior columns	14	14.5	3,027	3,404
2: <1930, 4+ story, warehouse, light manufacturing	Frame structures with shear critical columns, frames with infill, or perforated walls with large windows, may have loading docks/warehouse doors and soft first story (e.g SMIP-24236)	72	8.2	1,407	1,792
3: <1930, 4-7 story, , office/commercial	Perimeter perforated shear walls, generally no soft story	63	4.5	1,031	1,064
4: < 1960, 4+ story, apartment, hotel, nursing home	Perimeter perforated walls with interior columns or frame with URM infill, generally no soft story (Figure E-34, FEMA 154)	30	10.8	1,609	805
5: < 1930, 8+ story, commercial/office	Perimeter perforated walls with weak first story, torsion likely due to plan irregularity or continuous walls on some sides (e.g SMIP-24579)	49	6.6	1,534	1,541
6: 1960-1979, 1-3 story, non-office commercial	Shopping centers, banks, studios, etc., perimeter walls, or frame with widely spaced columns, in some cases weak anchorage between roof and walls (e.g. SMIP-58740)	71	6.3	1,207	1,207
7: 1960-1979, 4-7 story, commercial/office	Concrete frame in both directions with soft first story, may or may not have core wall (e.g. SMIP-58462 or 13214)	55	3.7	1,098	1,318
8: 1960-1979, 8+ story, apartment	Frame with shear-critical columns, typically walls in short direction	13	1.7	257	129
9: 1960-1979, 8+ story, hotel	Frame with shear-critical columns, typically walls in short direction which may be discontinuous at first floor creating soft story (e.g SMIP-24464)	17	3.6	480	240
10: 1960-1979, 8+ story, modern office	Moment frames, many with core walls, likely soft first story (e.g SMIP-24571 or 24322)	41	6.3	1,582	1,735
11: All education		13	4.9	1,192	1,309
12: Parking garage	Combined frames and walls, stiffness irregularities	71	8.9	826	457
Other	Churches, museums, utilities, warehouses, office and commercial	43	8.1	1,870	2,192
Total		**1,452**	**88.1**	**17,121**	**17,193**

* Images of similar building types can be found at the California Strong Motion Instrumentation Program (SMIP) at http://www.strongmotioncenter.org/

Each group in Table 1 will in principle contain buildings with multiple construction types (e.g., frames with and without URM infill, combinations of bearing walls and frames). Nonetheless, for a preliminary study the groupings capture certain common architectural and engineering design conventions, which in turn correspond in a general sense to construction type. For example, the low-rise pre-1930 buildings, of any occupancy, commonly use walls for the vertical elements, which generally are not critical elements for collapse. On the other hand, many of the 4+ story, pre-1930 warehouse structures have soft first stories and perimeter walls or frames with URM infill, suggesting the need for engineering analysis to better understand their collapse mechanism and potential. Frames with shear-critical columns typify the 8+ story apartments. Groups with structural characteristics that typify buildings with a high potential for collapse, such as high rise frame buildings, were targeted for more in-depth analysis to better understand performance and the likely collapse mechanism. The research team used the "top ten deficiencies" in older concrete buildings (NIST 2010) in developing representative analytic models. For this study, three characteristic idealized frame buildings were identified and their seismic performance simulated by Galanis and Moehle (2014) to inform adjustments to fragility curves. The building groups were also used for loss estimation purposes, as described in the next section.

LOSS MODELING

SCENARIO EVENTS

The study considered two scenario earthquakes for loss estimation: a **M**7.8 strike-slip earthquake on the southern San Andreas fault and a **M**7.15 reverse-slip earthquake on the Puente Hills fault. The San Andreas scenario has a relatively short recurrence interval of about 150 years. The ShakeOut scenario on the San Andreas fault (Jones et al. 2008) estimated $213 billion in economic losses (including lifeline and fire damage) and 1,800 fatalities in an eight county region. Puente Hills is a rare (once every ~3,000 years) but very damaging earthquake for the Los Angeles. Field et al. (2005) estimated between $82 and $252 billion in building economic losses, and between 3,000 and 18,000 fatalities for the Puente Hills event. The simulations for both earthquakes were modified from those used in earlier, similar simulations (San Andreas - Graves et al. 2011; Puente Hills - Graves and Somerville 2006) as described further below.

The San Andreas fault scenario ruptures (from south to north) the Coachella, San Bernardino, and Mojave segments. The Coachella segment has a slip deficit since its last major event (in 1680; Sieh 1986) of about 6 to 7 m, whereas the San Bernardino and Mojave segments ruptured more recently (1857) and have a lower slip deficit of about 3 to 4 m (Graves et al. 2011). For this reason, the earthquake is considered more likely to originate on the Coachella segment and the rupture has its hypocenter there. This choice is significant because the ground motions in the Los Angeles basin are more severe at long periods for a north-rupturing event on these fault segments than a south-rupturing event (Graves et al. 2008). The rupture model used for these simulations is provided in Graves et al. (2011) and was not modified for this application.

The Puente Hills fault scenario ruptures a thrust fault beneath downtown Los Angeles. The fault dips at 27 degrees downward towards the north. The full length and width of the fault are assumed to rupture up-dip from near the base of the fault plane to within 3 km of the ground surface (hence, the fault rupture is 'blind' because no surface rupture is expected). Figure 1 shows the original slip distribution considered by Graves and Somerville (2006) and the revision used for the present scenario (not previously published). The general patterns of slip distribution are roughly similar for the two models, but they are distinguished by stronger slip heterogeneity in the updated model with tighter concentrations of large slip (asperities) and also the existence of regions of little or no slip. These features are not strongly present in the original model. The total seismic moment is constrained to be the same for both models (**M**7.15). Both models have similar average slip displacements (132 cm versus 139 cm).

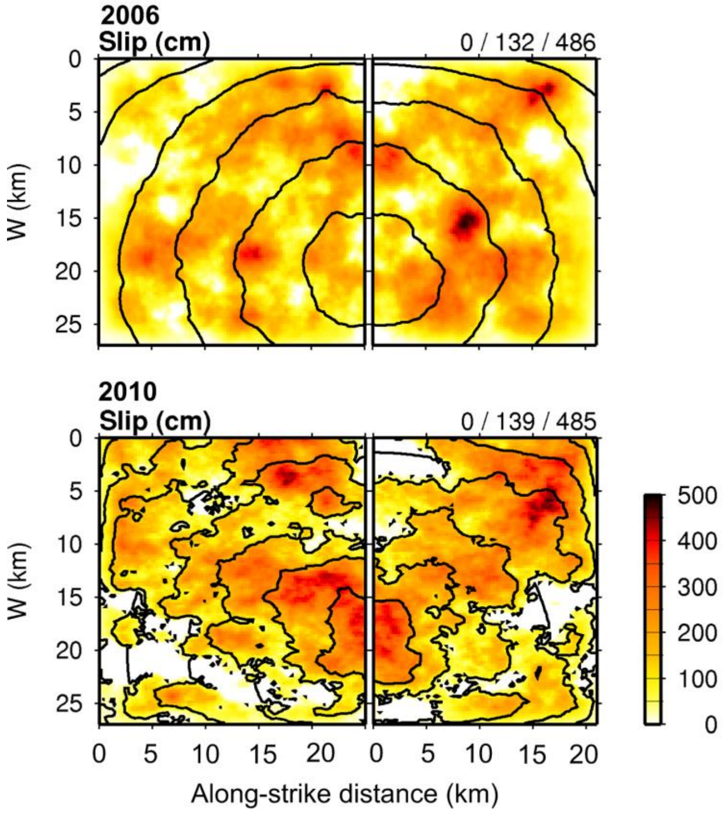

Figure 1. Comparison of slip distribution and rupture propagation contours for original (2006) and updated (2010) Puente Hills rupture models. The two rectangles indicate separate fault segments. Numbers in upper right indicate minimum, average and maximum slip. The updated model exhibits stronger heterogeneity in both slip and rupture propagation, enhancing high frequency energy release. Image provided by R.W. Graves (*personal communication*, 2015).

The broadband (0–10 Hz) simulations were performed by RW Graves (personal communication 2013) using the hybrid methodology described by Graves and Pitarka (2010). In this hybrid approach, long period ground motions ($T \geq 1$ s) are computed from a physics-based deterministic procedure and short period motions ($T < 1$ s) are computed using a semi-stochastic procedure. The deterministic procedure considers both heterogeneous fault rupture and 3-D wave propagation through the crust and in the sedimentary basins within the Los Angeles region. Validation exercises by Star et al. (2011) revealed issues of too-fast distance attenuation and too-low within-event standard deviation at short periods for earlier realizations of these simulations. A subsequent calibration process removed these biases (Seyhan et al. 2013), resulting in decreased crustal damping and increased randomization of ground motion amplitudes.

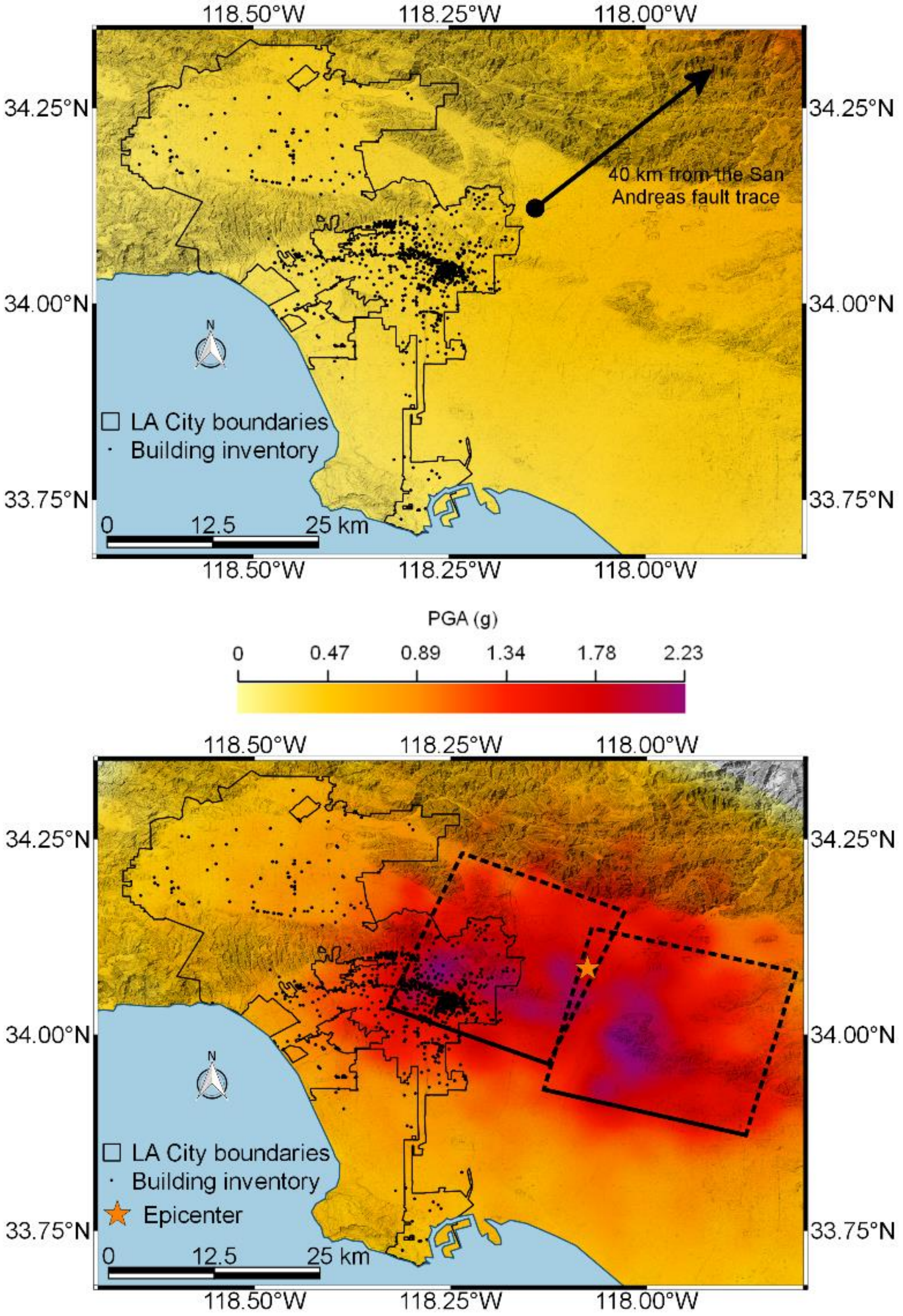

Figure 2. Maps of peak ground acceleration from simulated ground motions for M7.8 San Andreas (top) and M7.15 Puente Hills ruptures (bottom). The surface projections of the fault rupture planes are shown for the Puente Hills scenario, with solid lines indicating the top of the ruptured fault segments. The Puente Hills scenario exposes the concrete building inventory, represented by the black dots, to much higher ground motions.

The grid of points where ground motions are computed has a 2 km spacing (northing and easting) for the San Andreas event and 1 km for Puente Hills. Figure 2 shows the spatial distribution of ground motions in the form of peak ground accelerations (PGA) superimposed on the study region. Downtown Los Angeles is approximately 55-60 km from the closest portion of the San Andreas event, but lies on the hanging wall of the Puente Hills rupture. As a result PGA values are much larger for Puente Hills (approximately 1g or more near downtown Los Angeles) as compared to 0.1-0.3g from San Andreas. For downtown locations, the differences in pseudo spectral accelerations between events are reduced to about a factor of three at 1.0 sec and to null (essentially no difference) at 3.0 sec.

METHODOLOGY

Loss estimates were calculated based on the HAZUS^{TM} Advanced Engineering Building Module (AEBM) (NIBS 2003) with modifications to default damage and loss functions, and default building values, as described in this section. HAZUS^{TM} defines 36 model building types related to construction material and structural system. This study considered only three model building types: C1 – concrete moment frames, C2 – concrete shear walls, and C3 – concrete frames with unreinforced masonry (URM) infill walls. Damage functions for each model building type, which reflect building capacity and response, take into account the structural system as well as building height and seismic design criteria.

Sensitivity analyses were performed to compare losses for modeling assumptions such as assigning model building type C1, C2 or C3, or code design levels. Many frame buildings include interior walls, for example around stairwells and elevators, or masonry infill for fire safety in selected walls. Typically concrete interior walls reduce the probability of collapse, thus modeling buildings as pure frames (model building type C1) may overestimate losses. Masonry interior walls may not reduce collapse risk to the same extent as concrete. Sensitivity analyses showed 5% to 38% reduction in losses and 5% to 49% reduction in deaths depending on the earthquake scenario when C1 structures were modeled as C2 using default HAZUS^{TM} capacity and fragility curves. The model accommodates three building heights: low-rise (1-3 stories), mid-rise (4-7 stories) and high-rise (8+ stories). HAZUS^{TM} defines four design levels based on modern design criteria for seismic zones as defined in codes such as the NEHRP *Provisions for Seismic Regulations for New Buildings* (FEMA 1997): high-code, moderate-code, low-code and pre-code. HAZUS^{TM} Table 5.20 (FEMA 2003) provides guidance on mapping the design levels to older buildings. Damage states (slight, moderate, extensive, complete) are defined separately for structural and nonstructural systems. Detailed discussion of the damage states for each system and the form and parameters of the capacity and fragility curves used in HAZUS^{TM} is found in Chapter 5 of the technical manual (FEMA 2003) and in Kircher et al. (1997). It is important to note that the parameters of the capacity curves and fragility curves represent the average characteristics of the total population of buildings within each class. Some adjustments to these capacity and fragility curves were made to reflect the characteristics of the older buildings in the present inventory, as described further in this section.

We developed protocols for assigning occupancies, model building types, and code levels to individual buildings. These assignments in turn governed building replacement and contents value and losses, estimates of exposed population, choice of fragility curves, damage, casualties, and business interruption losses. Structures with multiple uses were assigned to an occupancy class that reflected the majority use of the building. For example, a building with stores on the first floor and apartments on the upper five floors would be classified as a residential occupancy. Occupancy assignment affects estimates of day and night exposed population, replacement value, and contents value.

The 1933 Field Act mandated earthquake resistant construction for California public schools and required all plans and specifications to be reviewed and approved by the Division of the

State Architect. To reflect the improved building standards and oversight of public schools mandated by the Field Act, only low-code (no pre-code) fragility curves were assigned to school buildings.

Data collected from the assessor's office and other public databases provided preliminary evidence of whether or not the structure could be classified as a frame. Some individual buildings were verified in discussions with local engineers and sidewalk inspections; however, it was difficult to determine if a frame included URM infill, which was commonly used for fire resistance in the early part of the 20th century. Engineers gave conflicting reports about the use of URM infill in Los Angeles after the 1933 Long Beach earthquake. Starting in 1933 the State of California prohibited the construction of URM buildings, yet the Los Angeles Building Code included unreinforced masonry load tables and specifications until the adoption of the Division 88 Ordinance (City of Los Angeles 1981). Some experts indicated that local engineers stopped using URM infill before 1981 even though not yet required by the Los Angeles building code. HAZUS™ does not include a model building type for concrete frames with reinforced masonry infill, and our research produced no clarity with respect to the use of reinforced and unreinforced infill. As a modeling assumption, frames built before 1934 were assigned to the concrete frame with URM infill model building type (HAZUS™ type C3) and those built in 1934 and after were assigned to concrete frame model building type (HAZUS™ type C1).

The structural and nonstructural replacement value of the inventory was estimated by multiplying the square footage of each building, taken from Los Angeles County assessor's data or estimated from a building footprint measured on Google Maps™, by default replacement costs found in Tables 3.6 and 3.7 of the HAZUS™ Technical Manual (FEMA 2003). Default replacement values are based on 2002 construction costs (R. S. Means 2002) so were multiplied by an inflation index of 1.115 as well as a regional multiplier to account for Los Angeles construction costs. The value of contents (e.g. furniture, computers, equipment, and supplies) was estimated as a percentage of structural and nonstructural replacement costs using HAZUS™ Table 3.10 (FEMA 2003). Inventory value and losses were not included in the model, but business interruption was. Building populations during the day (3 PM) and night (3 AM) were estimated using ATC-13 Table 4.12 (Applied Technology Council 1985).

For each earthquake scenario, each building was subjected to three analytic cases 1) baseline, 2) deficient, and 3) mitigated. It should be noted that in each of the cases, HAZUS™ loss modeling parameters were changed to reflect the vulnerability of older buildings in the inventory. The default capacity and fragility curves defined in HAZUS™ for C1, C2 and C3, which are based on a range of construction quality, are expected to be biased toward better performance than the set of older buildings in the inventory.

In the baseline case each building was considered to be nonductile concrete without any additional structural deficiencies such as a soft story or plan irregularity. To reflect the generally poorer performance of this subset of concrete buildings compared to default HAZUS™ model building types, in the baseline case strength was reduced to 60 percent of the HAZUS™ default value for high-rise structures, 75 percent of default for mid-rise, and 90 percent of default for low-rise. The capacity of URM infill structures (C3) was modeled as 80 percent of shear wall structures (C2). Model assumptions were validated by subjecting the baseline inventory to ground motions from the 1994 Northridge earthquake and comparing loss ratios from the model to insured loss trends from the Northridge earthquake (Table 4, Kircher et al. 1997; Wesson et al. 2004). In the deficient case, all buildings were assumed to have one or more significant structural deficiencies, strength was reduced to 50 percent of HAZUS™ default for all building heights, and the collapse probability was doubled. For the deficient case, ductility was also reduced to 67 percent of the HAZUS^{TM} default value. Fragilities in the mitigated case were assigned as if the buildings were designed according to 2013 building codes and practices.

A fourth case, labeled targeted poor performers, combined selected results from the baseline and deficient cases to better understand the contribution of Group 2, 5, 8, and 9 building types from Table 1. These groups were identified by the panel of structural engineers (which helped develop Table 1) as having a high probability of including specific deficiencies, such as shear critical columns, soft stories, and stiffness irregularities causing torsion. Particular concerns for the identified groups were identified as follows:

- Group 2 buildings are likely to have a soft story due to extensive loading docks;
- Buildings in Groups 8 and 9 are characterized by shear critical columns and soft stories;
- Group 5 buildings often have weak or soft stories and solid walls on one side causing torsion.

A random subset of 50% of buildings in the targeted groups was assumed to have one or more deficiencies. All the other buildings were modeled at the baseline level. The targeted poor performers case provides insight into the sensitivity of modeling assumptions and is thought to be a more realistic representation of losses than either the baseline or the deficient case. Of course, the design and construction of some buildings could make them better performers than the baseline case; although this is a possibility, a “targeted good performers” case was not modeled.

RESULTS

The HAZUS^{TM} methodology estimates economic losses as well as a range of social losses such as displaced households, short-term shelter needs, and casualties. We compiled only economic losses, life threatening injuries, and fatalities as potential parameters for informing policy recommendations. It is important to note that building collapse drives the generation of fatalities and life threatening injuries. Therefore, a large number of fatalities and life threatening injuries is an indicator of collapse. Economic losses presented here are limited to structural and nonstructural damage, damage to contents, loss of income due to business interruption, and rental and relocation expenses in cases where damage is so extensive that occupants have to move to a new location. Losses to inventory or losses due to secondary effects such as landslide, liquefaction, ground failure, fire, flooding, or hazardous material release are not included. Interaction effects such as impacts of interruption in delivery of water and electrical power loss or transportation disruption are not included. With more detailed data, a community could explore other parameters in developing policy.

For each building group, losses were calculated for three construction categories: frames (C1), bearing wall buildings (C2), and frames with URM infill (C3). These three categories were summed to arrive at the total losses for each building group. Table 2 summarizes estimated losses for the complete inventory subjected to San Andreas and Puente Hills ground motions for the four cases: baseline, targeted poor performers, deficient, and mitigated. Percent economic loss is defined as economic losses divided by the total building replacement value and contents. The large ranges in fatalities and life threatening injuries reflect the different building populations during day and night. For this case study, since only 204 of the buildings are residential, more casualties occur during the day when people are in the 1248 commercial, industrial, religious, and school buildings.

The San Andreas earthquake generates \$1.8 billion total economic loss to the baseline inventory (\$907 million in structural, nonstructural, and contents losses) in the City of Los Angeles. The ShakeOut scenario (Jones et al. 2008) estimated \$213 billion in economic losses in an eight county region. In contrast, the Puente Hills event, which has a much longer return period and hence is less likely to occur in any given time interval, produces more than 10 times the losses to the baseline inventory (\$19.0 billion total and \$6.9 billion in structural, nonstructural, and contents losses). The increased losses from the Puente Hills scenario relative to San Andreas are due to much larger ground motions, particularly at the short oscillator periods that are typical of low-rise buildings that dominate the inventory (Figure 2). In particular, the San Andreas event produces significantly smaller ground motions in the downtown Los Angeles area where many of the buildings are clustered, triggering fewer collapses. Thus fatalities the Puente Hills event are 5 to 40 times larger than for San Andreas.

Table 2. Estimated losses for full inventory

Case	Economic Losses (\$ billions)[a]	Percent Economic Loss	Fatalities[b]	Life Threatening Injuries[b]
		San Andreas (**M**7.8)		
Baseline	1.8	5%	<50	<20
Targeted Poor Performers	3.0	9%	10 to 270	4 to 130
Deficient	10.2	30%	250 to 2,700	100 to 1,300
Mitigated	0.4	1%	0	0
		Puente Hills (**M**7.15)		
Baseline	19.0	55%	270 to 2,100	100 to 1,000
Targeted Poor Performers	19.5	57%	300 to 2,500	130 to 1,200
Deficient	28.5	83%	1,000 to 8,300	500 to 4,100
Mitigated	5.9	17%	<65	<25

[a] Includes business interruption and relocation expenses

[b] The lower limit reflects night time values and the upper limit reflects day time values

In the targeted poor performers case, only 75 buildings are modeled as having one or more deficiencies and yet economic losses increase by 67 percent and fatalities increase five-fold in the relatively likely San Andreas scenario. The increase in losses reflects the high collapse potential of those buildings with deficiencies. The impact of this modeling assumption is less evident in the relatively infrequent Puente Hills scenario because the large ground motions cause even baseline buildings to collapse. Therefore, the presence of deficiencies does not dramatically increase collapse potential for the Puente Hills earthquake.

The deficient case, in which the performance of all buildings in the inventory are affected by the presence of one or more deficiencies that would make them particularly vulnerable to collapse, produces economic losses that are 1.5 to 6 times higher and casualties that are up to 50 times larger than the baseline case. This is an unlikely case, but it suggests an upper bound on losses.

A comparison of the baseline and mitigated cases shows that mitigating (retrofitting, replacing, or converting to lower risk use) all buildings can reduce the losses by 70 to 80 percent (See Table 2). However, this is not a practical solution as the cost would be prohibitive. Furthermore, some of the better performing buildings do not generate significant economic losses or casualties, therefore they do not represent a high priority for investment of limited mitigation resources.

To inform policy, investigations of the performance of specific groups of buildings were undertaken to reveal which groups contribute the greatest casualties and economic losses. Figures 3 and 4 compare daytime fatalities and economic losses for the thirteen identified groups along with each group's building and contents value and square footage. Breaking the losses into small groups and calculating the percentage of fatalities and losses gives additional insight into the behavior of the inventory. In the San Andreas scenario, two groups stand out as contributing a higher percentage of casualties and losses as compared to their value and area: Group 2, pre-1930 4+ story warehouse and manufacturing buildings, and Group 5, pre-1930 8+ story commercial office buildings. These two groups contribute 69% of the fatalities and 48% of the economic loss while representing only 18% of the value and 17% of the total area. By comparison, in the Puente Hills scenario, Groups 1, 2 and 5 are the major contributors to losses (50%), and Groups 1, 3, 5 and 11 are the major contributors to daytime fatalities (77%). It should be noted that when nighttime fatalities are considered, Groups 4 and 5 become significant in both earthquake scenarios.

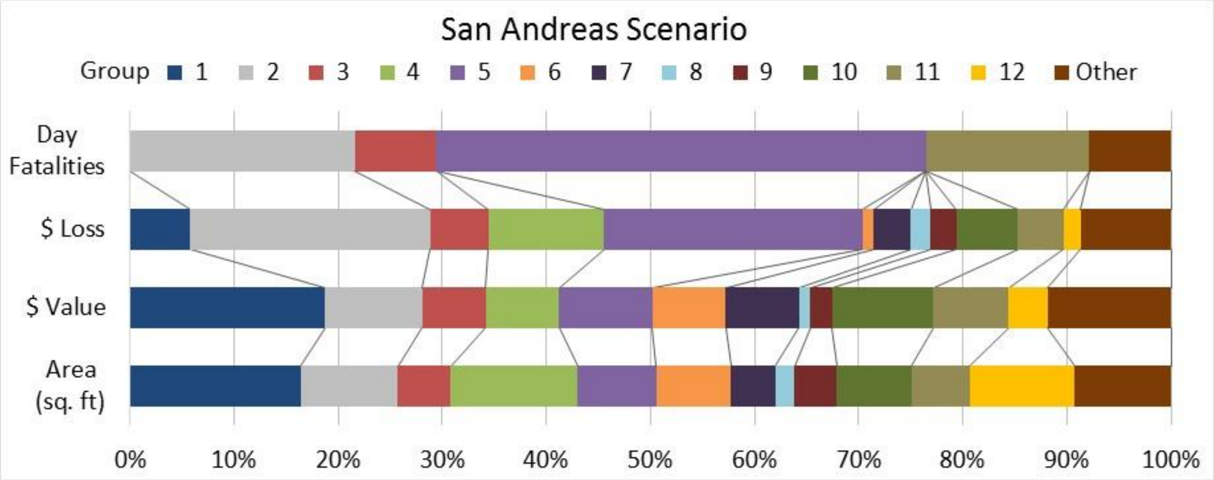

Figure 3. Percentage of building value, square footage, baseline daytime fatalities, and baseline economic losses (including business interruption and relocation expenses) for each of the inventory groups for the San Andreas scenario. Building value includes contents.

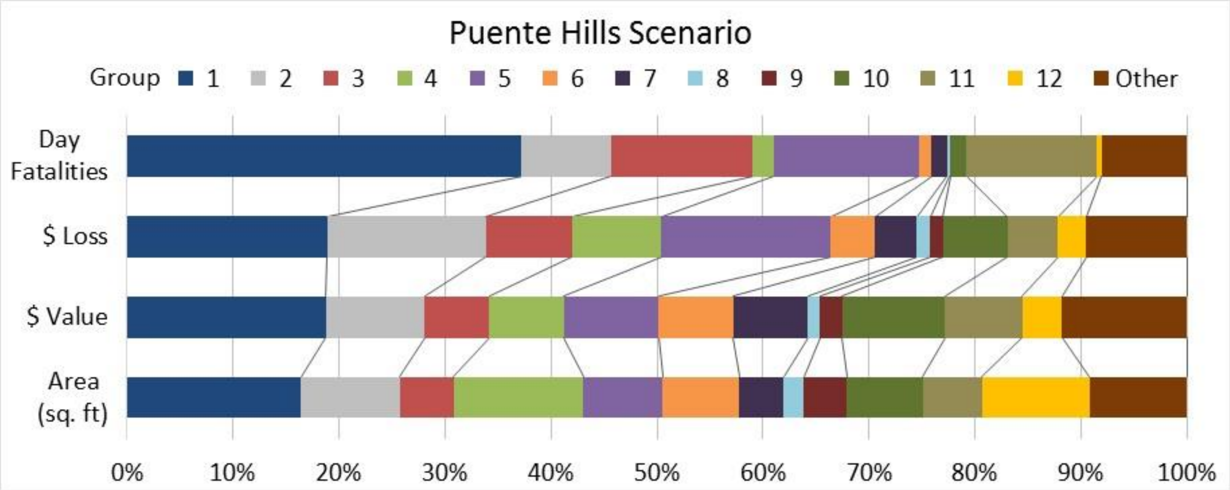

Figure 4. Percentage of building value, square footage, baseline daytime fatalities, and baseline economic losses (including business interruption and relocation expenses) for each of the inventory groups for the Puente Hills scenario. Building value includes contents.

When thinking about policy development and parameters that could be used to trigger mitigation, other inventory subgroups merit investigation, for example building height, construction date, or the presence of URM infill. In the San Andreas scenario, 65 percent of the economic losses and 71 percent of the daytime fatalities occur in high-rise buildings (8+ stories) for the baseline case. Similarly pre-1930 buildings contribute 70 percent of the economic losses and 82 percent of the fatalities for the baseline case. Overall, URM infill buildings produce essentially all fatalities and life threatening injuries in the San Andreas scenario and more than 50% in Puente Hills. For San Andreas, baseline buildings modeled as URM infill in Groups 2, 4 and 5, are responsible for 69 percent of the total estimated daytime fatalities and 100 percent of nighttime fatalities. Similarly, 84 percent of economic losses within these three groups are due to URM infill losses. This study is an example of how this process could be applied to several scenarios, but clearly other scenarios and sub-groups could be investigated. The important point is that certain high-risk subsets of buildings can be the major contributors to the total losses and should be targeted in policy development.

POLICY IMPLICATIONS

The loss estimation methodology from the prior section can be used to illustrate the anticipated impact of alternate policy proposals. Many approaches are possible for creating mitigation policies. While a policy could be broad and aimed at all pre-1976 nonductile concrete buildings (the entire inventory), a policy could also be targeted to specific groups of buildings based on age (e.g., those built pre-1930) or height (e.g., 8+ story high-rises). In addition, a policy could target highly vulnerable sub-groups such Group 2 pre-1930 warehouse and light manufacturing, or frame buildings with URM infill in Groups 2, 4, and 5. Per the sequential process given in the *Introduction* (problem scale, screening, then engineering analysis, and mitigation as needed), the present subject of targeted building groups for policy is a key part of the screening stage.

Loss estimates for the case in which the entire inventory is retrofitted are summarized in Table 2. As described in the previous section, the reduction in total economic losses is shown to be 70 to 80% relative to the baseline case. In Table 3, we present anticipated losses for four additional mitigation proposals (results for the baseline case from Table 2 are also listed for reference). The proposals are as follows

1. Proposal 1: Retrofit all high-rise buildings in the inventory (Groups 5, 8, 9, 10)
2. Proposal 2: Retrofit all pre-1930 buildings (except schools)
3. Proposal 3: Retrofit all pre-1930 4+ story warehouses and light manufacturing buildings (Group 2)
4. Proposal 4: Retrofit frames with URM infill in Groups 2, 4, and 5.

The results in Table 3 demonstrate how the losses from the different cases can be combined to explore the benefits of mitigation policies. As a rough indicator of the cost of each proposal, a cost index has been defined that is equal to the replacement cost of the buildings addressed by the proposal divided by the replacement cost of the total inventory. An effectiveness index defined as the percent reduction in economic losses divided by the cost index is used to roughly compare the benefit/cost ratio of the various proposals.

Table 3. Estimated losses for sample mitigation proposals

	San Andreas (**M**7.8)					Puente Hills (**M**7.15)		
Proposal	No. Buildings Addressed	Cost Index[a]	Economic Losses ($ billions)[b]	Effectiveness Index[c]	Fatalities	Economic Losses ($ billions)[b]	Effectiveness Index[c]	Fatalities[d]
1	217	35%	0.9	1.5	<15	14.0	0.75	160 to 1,680
2	590	40%	0.7	1.5	<10	14.0	0.67	115 to 720
3	72	8%	1.5	2.5	<40	17.0	1.3	260 to 1,930
4	126	16%	1.0	2.7	<20	15.6	1.1	160 to 1,730
Baseline	1452	-	1.8	-	<50	19.0	-	270 to 2,100

[a] Replacement cost of buildings addressed by proposal/ Replacement cost of total inventory

[b] Includes business interruption and relocation expenses

[c] Percent reduction in economic losses/Cost index

[d] The lower limit reflects night time values and the upper limit reflects day time values

Proposal 1 retrofits all 217 high-rise buildings. In this proposal, San Andreas losses are cut in half and fatalities are reduced by about two thirds, whereas Puente Hills losses are reduced by about 35 percent and fatalities are reduced by 20 to 35 percent. Proposal 2 retrofits all pre-1930 buildings in the inventory except schools. Schools were excluded for two reasons. First, our understanding of school buildings was limited because the construction date was difficult to obtain (though a large percentage of the schools were likely built in the 1950s and 1960s when Los Angeles was growing). In addition, public schools are governed by state-level policies and agencies and therefore are outside the direct control of local government policies. Proposal 2 affects close to three times the number of buildings as Proposal 1 and has the highest cost index of the four proposals, yet the loss reduction is not significantly larger than Proposal 1, thus the economic effectiveness indices are nearly the same. Table 4 demonstrates why this is the case. Proposal 1 targets high-rise buildings for mitigation efforts, which comprise 65% of the economic losses, and Proposal 2 attempts to mitigate pre-1930 buildings, which comprise 70% of economic losses. Therefore these two proposals achieve essentially the same economic loss reduction but at different levels of mitigation cost. Clearly life-safety issues also need to be considered.

Table 4. Percent of economic losses for baseline San Andreas scenario

Year Built	**All Heights**	**1 to 3 stories**	**4 to 7 stories**	**8+ stories**
Pre-1930 (except schools)	**70%**	4%	15%	50%
1930 and after, and all schools	30%	6%	9%	15%
All Years		10%	25%	**65%**

Proposal 3 targets the older mid-rise and high-rise warehouses and manufacturing buildings that are typical of the fashion district and toy district in downtown Los Angeles, which affects 72 structures. The downtown area is undergoing significant redevelopment where many buildings are being converted from commercial or industrial to residential occupancies, which in turn triggers requirements to improve seismic performance. This proposal, which carries the lowest cost of the four, reduces San Andreas losses by 17 percent and fatalities by about 20 percent, whereas Puente Hills losses are reduced by about 10 percent and fatalities by 0 to 8 percent. It has the highest effectiveness index for the Puente Hills scenario and the second highest for San Andreas. Proposal 4 targets the three groups with the highest percent loss and the most fatalities: frames with unreinforced masonry infill in Groups 2, 4, and 5. San Andreas losses are cut by about 45 percent and fatalities are reduced by about 60 percent, whereas Puente Hills losses are reduced by about 17 percent and fatalities are reduced by 17 to 40 percent. Proposal 4 has the highest effectiveness index for the San Andreas scenario and the second highest for Puente Hills.

One of the project goals was to provide decision makers with rational strategies for developing retrofit priorities and policy. Because the four proposals do not require retrofit of all NDC buildings, they may be more acceptable to the community. However, other factors influence policy development such as recent seismic activity, public sentiment, legislative processes, the state of the economy, and previous experience with mitigation programs (Liel and Deierlein 2012).

The development of policy is a local political process and requires a tiered approach: (1) understanding problem scale, (2) screening for low and high risk buildings, (3) performing engineering analysis for potentially vulnerable buildings, and (4) retrofit or replacement of high-risk structures. Regarding Step 1, the inventory developed as part of the present work was intended for research applications, whereas a city would need to develop and validate a full and more detailed building inventory[1]. Regarding Step 2, in an ideal situation where resources were unlimited, engineers would investigate all buildings based on site visits, plan reviews, and related activities to distinguish relatively low-risk and high-risk construction types on a structure-specific basis. In the work described previously in this section, groups of buildings were used as a proxy for building performance and to inform priority setting, which represents a lower-cost alternative that may have appeal from a policy perspective. Formal municipal implementation of a screen approach like that described here should consider additional earthquake scenarios involving other major fault systems within Los Angeles in a probabilistic risk analysis. Moreover, if building drawings and other detailed information on construction were available, improved fragility curves could be developed to improve the loss models and target high-risk buildings. The ATC 78 project (ATC 2012) is filling an important need for a screening method that is more accurate than an inventory analysis, but less costly than a detailed building analysis. A city-enacted a mitigation policy would need to specify how to address lower priority structures identified by Step 2 including delaying or exempting them from retrofit, and then Steps 3 and 4 would be undertaken for structures not screened out in Step 2.

IMPACTS ON THE CITY OF LOS ANGELES

Prior to, and during the course of this research, our team grappled with what seemed to be a general “lack of appetite” for retrofit policies aimed at NDC buildings by policy makers, city staff, and building owners. For Los Angeles and for most cities, the risk analysis is complex, the costs are high, and tenants typically are displaced during construction. As such, the team’s motivation was to develop a staged approach (as described earlier) to identify the subsets of older concrete buildings that had the highest potential casualties and economic losses so that these might be given a higher priority for mitigation. We hoped that policy makers and building owners would be persuaded by the data, and would be willing to address the highest-risk

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[1] Fred Turner (2013) of the California Seismic Safety Commission suggested several steps to ensure that an inventory is acceptable to the community. These include holding a public hearing to establish criteria for the inventory, notifying owners before the publication of the inventory, receiving and responding to owner comments, publishing a draft inventory, receiving and responding to public comments, and having a process to modify the final inventory once new information becomes available.

building types. Defining exactly what constitutes the highest risk is complex and potentially controversial.

Preliminary loss modeling results, as well as a targeted policy approach, were presented at the Northridge 20 conference at UCLA in January 2014 at the same time that the inventory was posted in the NEES Project Warehouse and provided to the Department of Building and Safety in the City of Los Angeles. For more than a year prior to that public release of data, the Los Angeles Times followed this research project and wrote more than a dozen articles and editorials on earthquake safety in general and on concrete building safety in particular. This intense focus raised public awareness and contributed to Mayor Eric Garcetti's creation of a Mayoral Seismic Task Force, led by Dr. Lucy Jones of the USGS, to develop a report and a set of policy proposals.

The task force produced a report, *Resilience by Design,* in December 2014, which recommended sweeping seismic safety policies, including not only the mandatory retrofit of pre-1980 nonductile concrete buildings within 25 years, but also the mandatory retrofit of pre-1980 soft first story buildings (largely wood frame construction) within 7 years, and the development of a building rating system. Details of the implementation of the policy are still under development including notification, retrofit priorities, and specifications for evaluation, analysis and design. In addition, the report recommends major improvements to the water system and telecommunications infrastructure. The stated goal of these policy recommendations is to protect lives, improve the city's capacity to respond to and recover from earthquakes, and to protect the economy of the City and all of southern California (Mayoral Seismic Task Force, 2014). The Los Angeles City Council passed, and Mayor Garcetti signed, an ordinance to this effect on October 9, 2015, the implementation of which is currently underway by the Los Angeles Department of Building and Safety.

CONCLUSIONS

The research goal of the inventory component of the NEES Grand Challenge project was to demonstrate a methodology for informing policy development, which included using data and loss models to target the most vulnerable buildings using an incremental approach that included problem scale, screening, followed by engineering analysis, and mitigation as needed. The research inventory focused on pre-1976 concrete buildings, which are assumed to represent buildings that were built with nonductile detailing; however, it is important to note that the formal Los Angeles City-led inventory currently in progress will need to verify the inventory to better understand specific building characteristics that would drive building damage and collapse. Although it is important to recognize that every building is unique, it is also important to find mechanisms by which building performance can be generalized for policy development. While a scenario approach was used for this project, communities should consider a whether a probabilistic risk assessment approach would be more appropriate.

The categorization of buildings in the inventory allows decision makers to estimate the impacts of retrofits (in terms of loss-reduction and public safety) on a range of options such as particular building use-types or on high-rise buildings of all types. It also allows for estimation of a benefit-cost in the form of an effectiveness index for various retrofit approaches. The simplified index in this study included only economic losses, but others have demonstrated how life safety could be included in a more detailed effectiveness index (Liel and Deierlein 2013). Additional social impacts such as displaced households and shelter needs could be considered. Ultimately, inventory data on particular building types in specific settings can help to refine risk mitigation policies and help cities set priorities for retrofit of older vulnerable building stocks. Because there are many assumptions made in loss estimation models, the uncertainty needs to be accounted for in policy development. Soliciting more information from building owners, evaluating multiple scenarios with sensitivity analyses, and developing probabilistic analyses can reduce uncertainty.

Ultimately an inventory guides policy approaches, and targeted retrofits of specific groups of buildings with high loss and fatality risk estimates is cost effective and can influence how cities plan for mitigation. Policy makers need to be cognizant of the complexity of the assumptions used in loss models and take them into account when developing voluntary and/or mandatory programs to mitigate risk. For example, the City of San Francisco began undertaking loss studies in the 1990s with the Community Action Plan for Seismic Safety (CAPSS 2015), but it took 15 years of working with the community to developing a soft story retrofit ordinance and extensive long range resilience planning.

The use of inventories, combined with the development of loss estimates and retrofit options, is critical to an incremental policy approach. The Los Angeles case suggests that all cities can use inventories to develop preliminary evaluations of seismically vulnerable building types and to educate the community before proposing targeted strategies for addressing the risk. Of course, cities need to learn from prior experience with retroactive ordinances such as those for masonry (Olson 1985; Comerio 1992; FEMA 1994) and soft-story buildings (City and County of San Francisco 2015). Cities also need to engage civic groups; professional associations of earth scientists, engineers, and architects; lending institutions; owners and tenants in discussion of policy options, retrofit finance, timelines, and rating systems to communicate risks to the public and to build coalitions of support for community seismic safety. Additionally, creative incentives such as permit fee waivers for seismic retrofit or tax benefits for adaptive re-use help to make seismic policies politically palatable. Finally, efforts such as ATC 78 (ATC 2012) are attempting to fill a strong need for improved guidelines to rapidly assess and screen buildings and develop cost-effective retrofits. Seismic safety requires long range planning and implementation timelines, as the experience in both San Francisco and Los Angeles demonstrates.

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