PROBABILISTIC ESTIMATION OF EARTHQUAKE LOSSES FOR ACUTE CARE HOSPITALS IN CALIFORNIA

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ABSTRACT :

Recent seismic performance evaluations of acute care hospital buildings in the state of California show that a considerable percentage of such hospitals have extremely high potential risk of collapse or significant loss of life in the event of a strong earthquake. One of the major challenges in seismically upgrading these facilities is the highly expensive reconstruction costs of hospitals. One possible financial resource to pay for the high costs of reconstruction is to use the reduction in the hospitals pure premium for earthquake insurance once they are upgraded. In this study the level of reduction in the average annual losses for a group of hospitals located in California is quantified. To estimate losses of the hospital facilities an earthquake model that is recently developed at the Risk Management Solutions, Inc. (RMS) and is released as part of the RMS 2008 release is used. The developed model is based on the latest research publications on performance-based earthquake engineering and in particular the performance of hospital equipment during earthquakes. It is found that upgrading poor performing hospital facilities can lead to major savings in the earthquake pure premium of such hospitals. It is suggested that the savings in the level of expected losses as a result of upgrading hospitals are taken into account when conducting feasibility studies on hospital reconstruction.

KEYWORDS: Hospital Buildings, Seismic Performance, Loss Estimation, Performance-Based Earthquake Engineering

1. INTRODUCTION

The Office of Statewide Health Planning and Development (OSHPD) has recently evaluated the seismic performance of acute care hospital buildings in California and has concluded that 40% of such hospitals are highly vulnerable in the event of a strong earthquake and will not be able to provide acute care services after the occurrence of such an event. In 1973 the Hospital Facilities Seismic Safety Act (HFSSA) was enacted as a response to the poor performance of California hospitals during the February 9th, 1971 San Fernando Valley Earthquake. Two decades after the San Fernando earthquake, the poor seismic performance of California hospitals during the January 17th, 1994 Northridge Earthquake, prompted the enactment of Senate Bill (SB) 1953 (Chapter 740, 1994) which is an expansion to the scope defined in HFSSA and requires all general acute care hospitals to evaluate the seismic performance of each hospital building. SB 1953 mandates that by January 1 2008 any general acute care hospital building that has not been mitigated and poses a potential risk of collapse or significant loss of life shall only be used for non-acute care purposes.

There are major challenges in achieving the goals set by SB 1953 in terms of seismic safety for California hospitals (Meade, and Kulick, 2007). One of these challenges is the highly expensive cost of hospitals which have made them one of the most expensive facilities in the built environment with a roughly cost of $ 1000 per square foot for a finished facility. Recent studies suggest that this expensive cost of rebuilding old hospitals can cause major delays in achieving SB 1953 deadlines. To overcome this problem one possible approach is to find out the cost benefits that hospital owners can achieve by saving on their earthquake insurance premiums in long term and use that saving toward upgrading their old hospital buildings.

In this study the amount of savings on insurance costs is estimated for 26 hospital buildings in the State of California by estimating the average annual losses of these locations during a series of events and losses from two historical events and comparing these losses to the case in which all these locations have been seismically upgraded to meet the latest code requirements for hospitals in California. Losses are estimated using a recently developed RMS earthquake model that provides the functionality of estimating earthquake losses for acute care hospital facilities in the United States. The developed model by the authors allows users to model various hospital buildings located in the U.S. and in particular, for the state of California to model hospital buildings according to the seismic performance ratings defined by the OSHPD of California. The developed model is released as part of RMS's 2008 product release and with the exception of the vulnerability model that has been updated with new hospital vulnerability functions, uses the same standard earthquake model components, namely geocoding, geotechnical, hazard, and financial components that RMS earthquake model for the U.S. uses.

2. SEISMIC PERFORMANCE LEVELS OF ACUTE CARE HOSPITALS

Tables 1 and 2 present the structural and non-structural performance categories (SPC and NPC) as defined by California's office of statewide health planning and development (California's General Acute Care Hospitals, 2001). These categories have been used to rate the acute care hospital facilities in California. As can be seen in the tables, hospital facilities that are rated as SPC-1 or SPC-2 need to be replaced or they have to be removed from the acute care hospital facilities list and only provide non-acute services.

Table 1 Structural Performance Categories (SPC) defined by California's office of statewide health planning and development (California's General Acute Care Hospitals, 2001).

Structural Ratings	Ratings Description
SPC-1	These buildings pose a significant risk of collapse and a danger to the public after a strong earthquake. These buildings must be retrofitted, replaced or removed from acute care service by January 1, 2008.
SPC-2	These are buildings in compliance with the pre-1973 California Building Standards Code or other applicable standards, but are not in compliance with the structural provisions of the Alquist Hospital Facilities Seismic Safety Act. These buildings do not significantly jeopardize life, but may not be repairable or functional following strong ground motion. These buildings must be brought into compliance with the Alquist Act by January 1, 2030 or be removed from acute care service.
SPC-3	These buildings are in compliance with the structural provisions of the Alquist Hospital Facilities Seismic Safety Act. In a strong earthquake, they may experience structural damage that does not significantly jeopardize life, but may not be repairable or functional following strong ground motion. Buildings in this category will have been constructed or reconstructed under a building permit obtained through OSHPD. They can be used to 2030 and beyond.
SPC-4	These are buildings in compliance with the structural provisions of the Alquist Hospital Facilities Seismic Safety Act that may experience structural damage which could inhibit the building's availability following a strong earthquake. Buildings in this category will have been constructed or reconstructed under a building permit obtained through OSHPD. They may be used to 2030 and beyond.
SPC-5	These buildings are in compliance with the structural provisions of the Alquist Hospital Facilities Seismic Safety Act, and are reasonably capable of providing services to the public following strong ground motion. Buildings in this category will have been constructed or reconstructed under a building permit obtained through OSHPD. They may be used without restriction to 2030 and beyond.

3. DEVELOPMENT OF VULNERABILITY FUNCTIONS

In order to estimate earthquake losses for various seismic performance levels of hospitals, we need to develop vulnerability functions. Vulnerability functions provide information on the level of damage in a building as a

Table 2 Non-structural Performance Categories (NPC) defined by California's office of statewide health planning and development (California's General Acute Care Hospitals, 2001).

Non-structural Ratings	Ratings Description
NPC-1	In these buildings, the basic systems essential to life safety and patient care are inadequately anchored to resist earthquake forces. Hospitals must brace the communications, emergency power, build medical gas and fire alarm systems in these buildings by January 1, 2002.
NPC-2	In these buildings, essential systems vital to the safe evacuation of the building are adequately braced. The building is expected to suffer significant nonstructural damage in a strong earthquake.
NPC-3	In these buildings, nonstructural systems are adequately braced in critical areas of the hospital. If the building structure is not badly damaged, the hospital should be able to provide basic emergency medical care following the earthquake.
NPC-4	In these buildings, the contents are braced in accordance with current code. If the building structure is not badly damaged, the hospital building should be able to function, although interruption of the municipal water supply or sewer system may impede operations.
NPC-5	These buildings meet all the above criteria and have water and wastewater holding tanks, sufficient for 72 hours of emergency operations, integrated into the plumbing systems. They also contain an on-site emergency system and are able to provide radiological service and an outside fuel supply for 72 hours of acute care operation.

function of the intensity of the hazard. For earthquake peril, the input to a vulnerability function is the level of seismic hazard intensity in terms of the spectral displacement (S_d) and the output is the mean damage ratio (*MDR*) which is the level of the damage in the property normalized by the replacement value of the property.

According to the information provided in tables 1 and 2, we have developed vulnerability functions for hospital facilities with various seismic performance levels ranging from SPC1 to SPC5. Vulnerability functions are developed for various types of construction, various height ranges and year of constructions for different regions in the United States. To limit total number of vulnerability functions, it is assumed that structural and non-structural performance categories are at the same level. For example, for a hospital building with structural performance category 1 (SPC1), the non-structural performance category is also 1, i.e. NPC1.

A total of 288 sets of vulnerability functions for building, content and business interruption coverages have been developed in this project, using a two-step approach. In the first step base vulnerability functions are developed following a simplified version of the Pacific Earthquake Engineering (PEER) Center methodology (Cornell, Krawinkler, 2000) that integrates probabilistic estimations of the structural response from conducting incremental dynamic analysis together with fragility functions and cost functions developed for structural and non-structural components in a hospital. In this study, probability parameters, namely median and standard deviation, of the peak interstory drift ratio and peak floor acceleration of a structural model of a hospital building developed in OpenSees (PEER, 1997) platform are computed to develop base vulnerability functions for hospital facilities. Figure 1 presents an elevation view of a structural model for braced steel frame structure developed in OpenSees Navigator (Yang et al., 2004). Figure 2 shows the results processed from conducting incremental dynamic analysis using OpenSees for two types of structural responses, peak interstory drift ratio and peak roof acceleration. The dots on the graphs represent results for each of the nonlinear response history analyses conducted on the model using ground motions scaled to certain levels of ground motion intensity. More information on conducting probabilistic response estimation for building loss estimation can be found in Aslani and Miranda (2005).

Estimated structural response parameters are integrated with fragility functions of the structural and non-structural components in a hospital facility using total probability theorem as follows

$$MDR(S_d) = \int_0^{\infty} E[DR \mid EDP] \cdot \left| dP(EDP \mid S_d) \right| \tag{3.1}$$

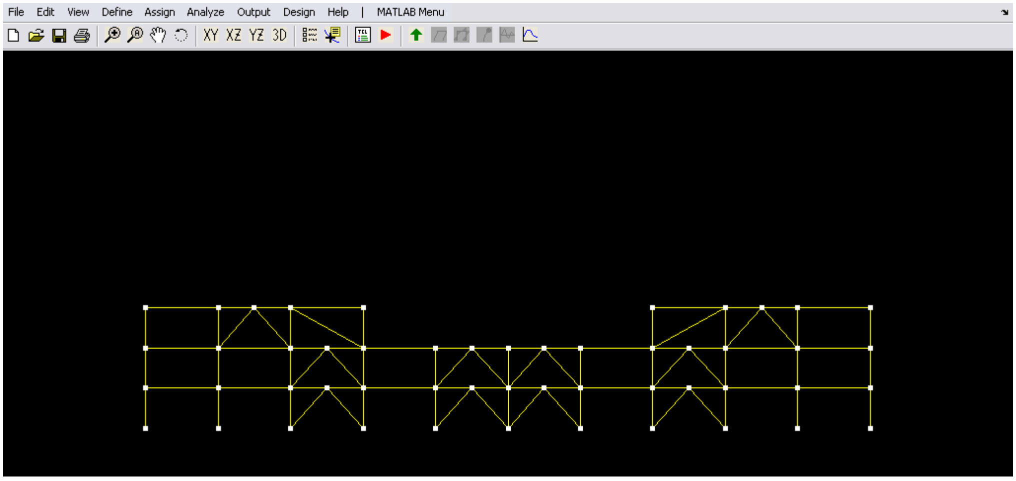

Figure 1 Elevation view of a frame of a hospital building developed in OpenSees Navigator.

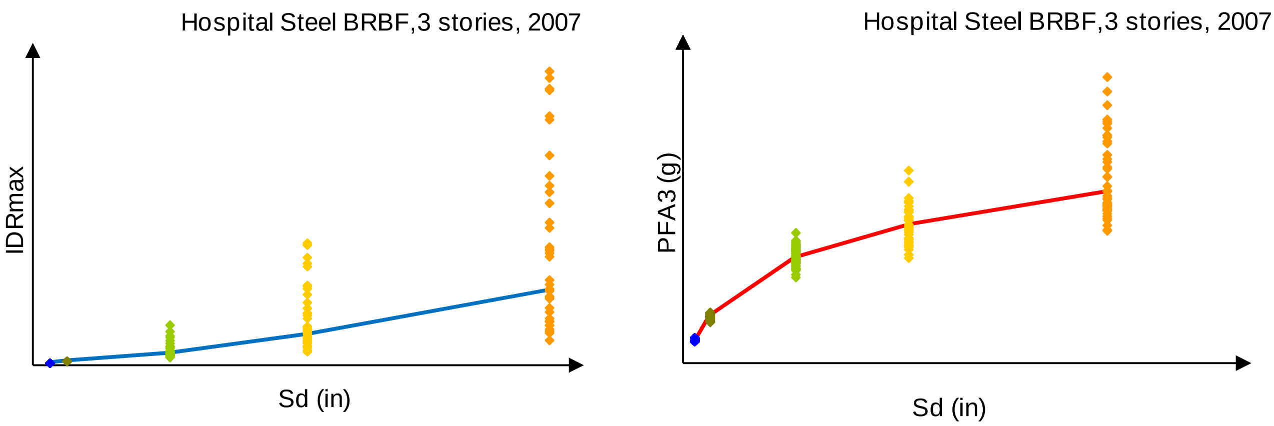

Figure 2 Results of the incremental dynamic analysis using OpenSees.

where $dP(EDP|S_d)$ is the probability density function of the Engineering Demand Parameter (EDP) of the building, in this case peak interstory drift ratio or peak floor acceleration, and $E[DR|EDP]$ is the expected value of the damage ratio given the level of deformation (EDP) in the building and is computed as follows

$$E[DR \mid EDP] = \sum_{i=1}^{m} E[DR \mid DM_i] P(DM_i \mid EDP) \tag{3.2}$$

where $E[DR|DM_i]$ is the expected cost of repair or replacement normalized by the replacement cost, shown here as damage ratio (DR), given that the building is experiencing damage state DM_i, $P(DM_i|EDP)$ is the probability of experiencing damage state DM_i conditioned on the level of EDP which is computed from component-level fragility functions, and m is the number of damage states. In particular, in this study the fragility functions for the seismic performance of steel structures are inferred from the study conducted by Ramirez et al. (2008) on

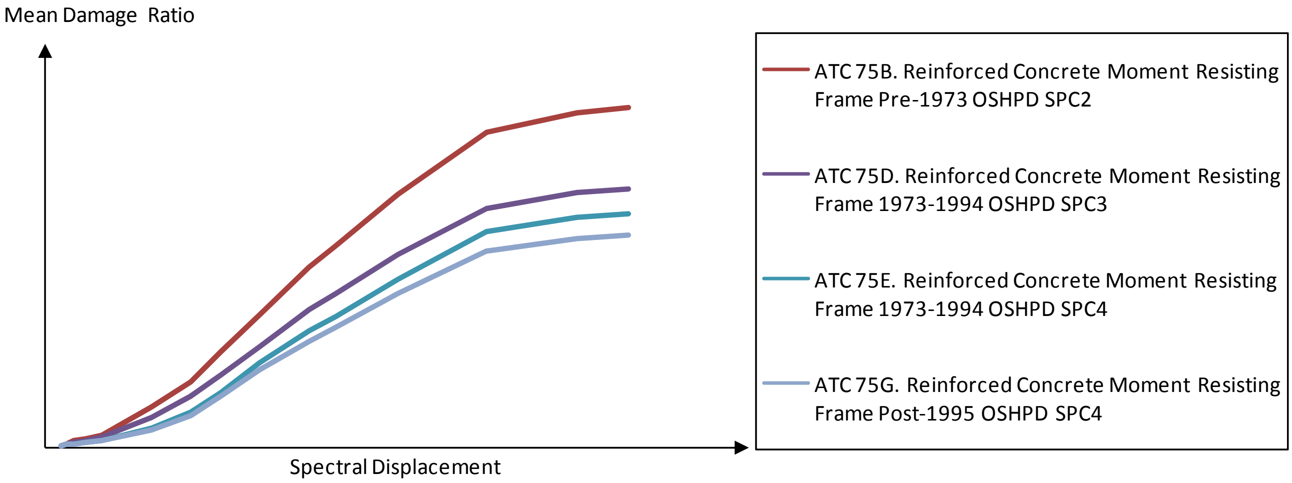

Figure 3 Vulnerability functions developed for acute care hospital facilities.

the fragility of pre-Northridge welded steel moment-resisting beam-column connections. For non-structural drift-sensitive components, fragility functions presented in Aslani and Miranda (2005) are used and for non-structural acceleration-sensitive components used in hospitals, the study conducted by Chaudhuri and Hutchinson (2005) on the seismic performance characterization of the bench- and shelf-mounted hospital equipment is used to assess the seismic fragility of such equipment. It should be noted that more information on developing a probabilistic loss estimation methodology for buildings can be found in Aslani and Miranda (2005).

Once the base vulnerability functions are developed, in the second step relativities are developed among various construction types, height, year and SPC ratings and base vulnerability functions are expanded for various types of hospital facilities. For example, a relativity-based approach is used to develop vulnerability functions for a mid-rise braced steel structure with a seismic performance rating of SPC 4 built after year 2000 using the base vulnerability function developed for a low-rise braced steel structure built in post-2000. Vulnerability functions developed using the two-step approach explained are then validated and calibrated using the loss results estimated from them for various hospital facilities and comparing the losses relative to each other and to historical losses. Figure 3 shows an example of the vulnerability functions developed for reinforced concrete moment resisting frames for various SPC performance categories.

4. BUILDING EXPOSURE USED IN THIS STUDY

In order to investigate the level of losses during future earthquakes on poor performing hospital buildings, an exposure database is created that consists of 26 acute care facilities that are rated as SPC1 and SPC2 facilities. The exposure database contains 89% SPC1 locations and 11% SPC2 locations. Figure 4 presents exposure breakdowns by geographic location, coverage, construction material and height. As can be seen in the figure, 47% of the locations are located in Southern California and the rest of them are in Northern California. The exposure is consisted of 73% reinforced concrete buildings, 26% steel structures and 1% wood. Figure 4 also presents the height breakdown of the exposure considered in this study. Majority of the buildings considered, 53%, are high rises, in the 8-14 stories range while 27% of the buildings are mid-rise and 20% are low-rises. It should be noted that almost all the hospitals considered in the exposure database, are built prior to 1973.

5. ECONOMIC INCENTIVES OF IMPROVING THE SEISMIC PERFORMANCE OF HOSPITAL FACILITIES

One of the main concerns in upgrading hospitals to be in compliance with the OSHPD SPC5 rating is the high

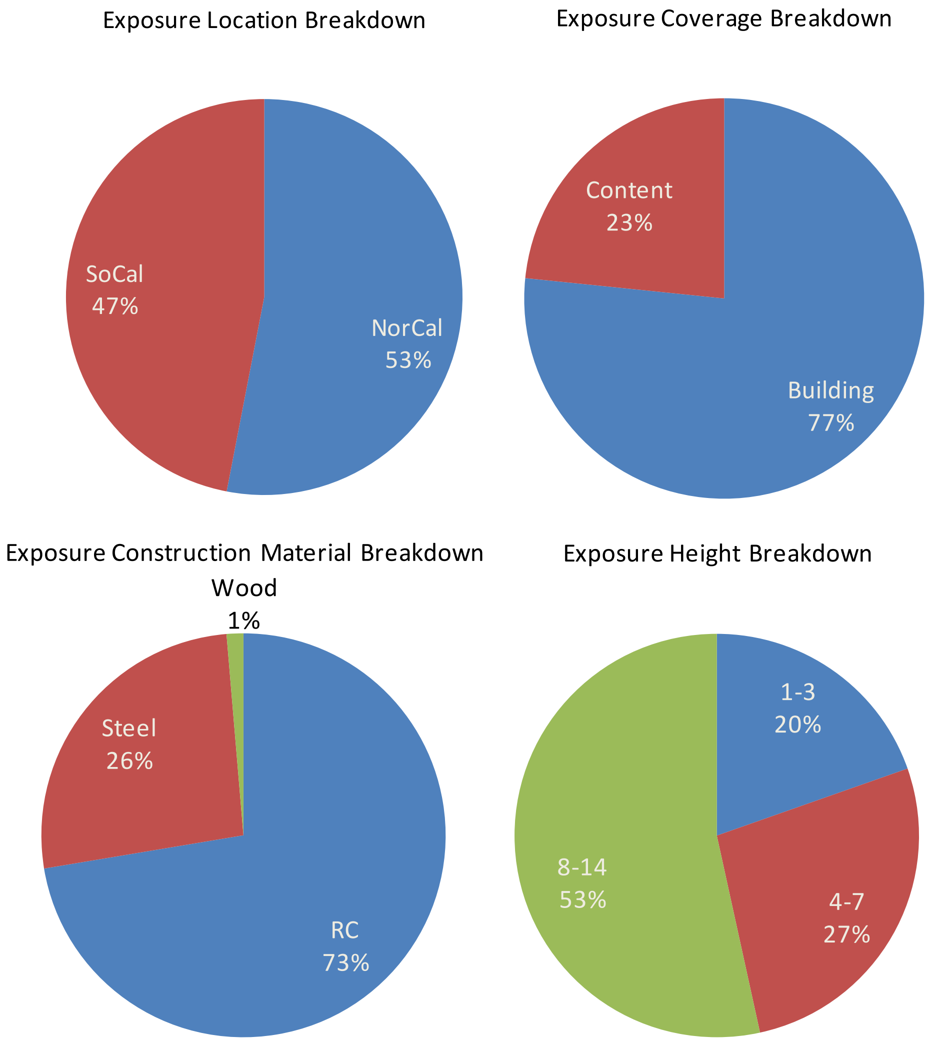

Figure 4 Exposure breakdowns by geographic region, coverage, construction material and height.

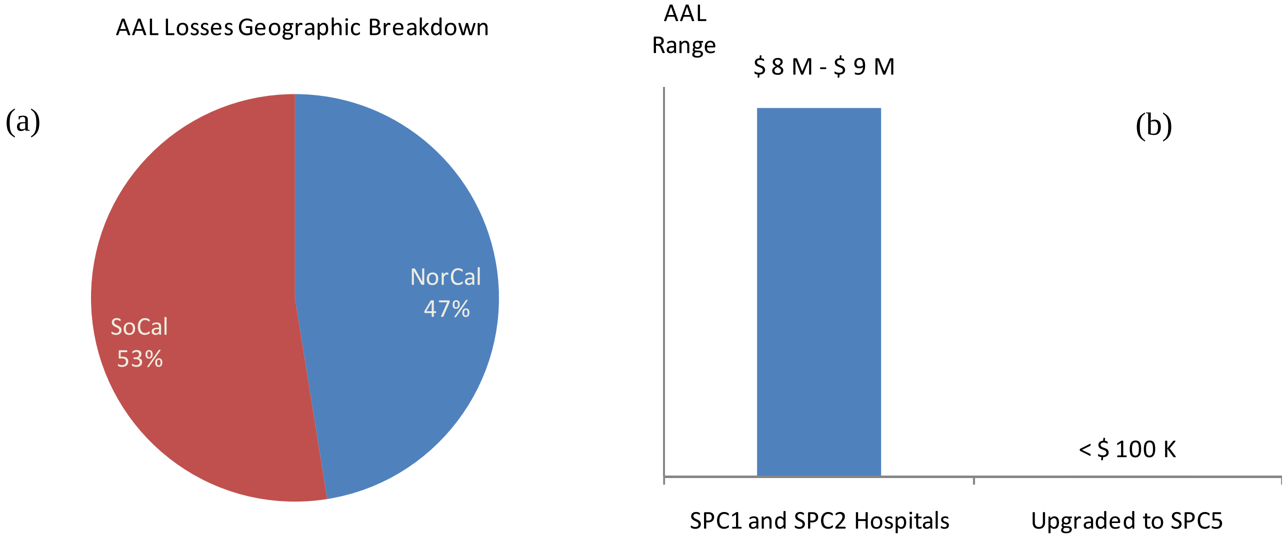

Figure 5 (a) Average annual losses by geographic region, (b) Variations in the average annual losses as a result of seismic performance improvements repair costs associated with their reconstruction. In this section, we investigate the benefits of such an upgrade in decreasing the losses from future earthquakes and as a result lowering the pure premium to purchase the same level of earthquake insurance. Figure 5a presents a breakdown of the average annual losses estimated from the exposure database used in this study. Comparing figure 5a with figure 4 shows that although only 47% of the exposure value is located in southern California this exposure contributes to more than 50% of the losses, suggesting that the exposure located in southern California is probably more vulnerable than the hospital buildings in northern California or the faults in southern California are capable of producing stronger ground motions. Figure 5b provides an estimate of the expected losses from the exposure considered in this study. It can be seen that the average annual losses for all of these SPC1 and SPC2 hospitals are in the range of $ 8 M - $ 9 M. If all of this exposure is upgraded to a SPC5 seismic performance level, the average annual losses decrease to less than $ 100 K. In other words, one could save $ 8 M per year by investing in upgrading these 26 acute care hospital facilities. Presented in figure 6, are the losses from two historical events, the magnitude 6.7 Northridge earthquake occurred in January 17th 1994 and the magnitude 6.9 Loma Prieta earthquake occurred in October 17, 1989. As can be seen from the graphs shown in figure 6, repeat of Northridge earthquake can cause losses in the order of $ 1M in the 26 hospital locations considered in this study and repeat of Loma Prieta earthquake can cause losses in the order of $ 600 K. Once the hospital locations are upgraded, no major losses will be experienced as a result of the repeat of each of these two earthquakes.

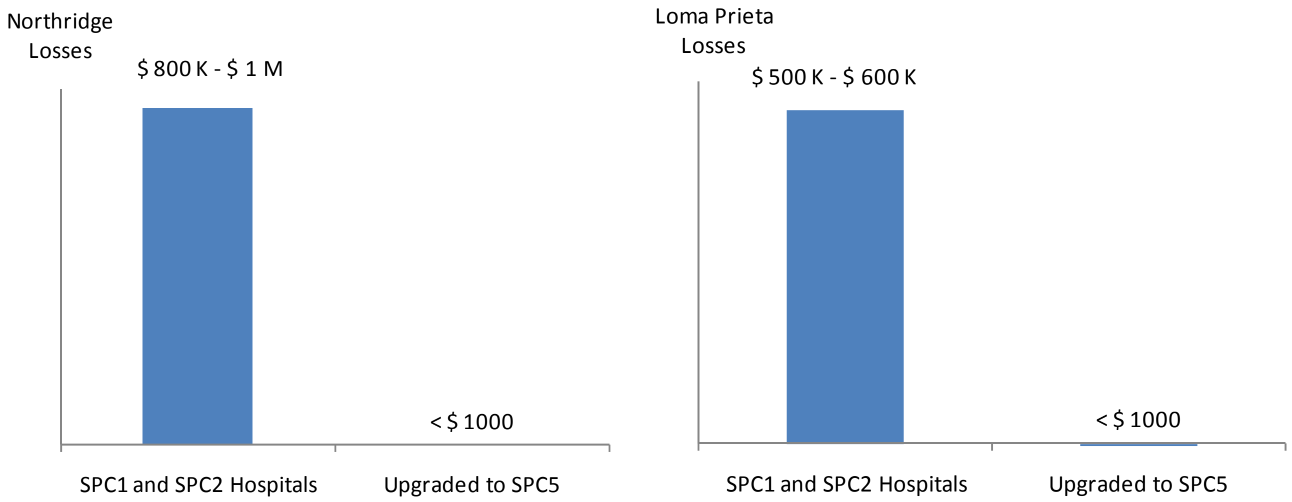

Figure 6 Variations in the historical losses as a result of seismic performance improvements for 1994 Northridge earthquake and 1989 Loma Prieta earthquake

6. CONCLUSIONS

The Office of Statewide Health Planning and Development (OSHPD) in the state of California requires that hospital buildings that are rated as poor performing hospitals, are upgraded to a seismically acceptable performance level such that they can provide acute care services after a major earthquake event. The high cost of construction for hospital buildings has made this task very challenging for hospital owners. One possible way of making the seismic upgrade of poor performing hospitals more financially feasible is to look at the possibility of saving on insurance costs when purchasing earthquake insurance for these seismically upgraded hospital buildings.

In this study, a database of 26 hospital buildings in the state of California that are rated as SPC1 and SPC2 according to the OSHPD guidelines, i.e. their performance during major earthquakes will be poor and they will not be capable of providing acute care services after a major event, is evaluated. It is shown that if these hospital buildings are seismically upgraded the losses will significantly decrease. Average annual losses estimated from the original hospital buildings are in the order of $ 8 M - $ 9 M. Once all these buildings are upgraded to meet with the latest building code requirements in California, the losses decrease to $ 100 K. Therefore, it is concluded that one can save significantly on earthquake insurance once these buildings are upgraded.

The same locations are also used to estimate historical losses from the repeat of the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake. It is shown that the losses from the repeat of these two major events on the portfolio of buildings considered are in the order of $ 500 K to $ 1 M. After upgrading the portfolio of buildings considered to SPC5 buildings, no major losses will be experienced during these two events.

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