# Modeling Nonstructural Damage for Metropolitan Building Stocks

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Summary:
Nonstructural systems typically represent over 70 percent of dollar damages from a seismic event. To understand the value of nonstructural mitigation measures, such as changes to building codes, it is important to estimate how those changes will decrease damage at the metropolitan scale. This paper does three things: (1) describes a method to estimate the current quantity of nonstructural components present in a metropolitan area; (2) demonstrates a method to forecast the amount of nonstructural systems for future time periods at the metropolitan scale; and (3) forecasts nonstructural damage for future time periods based on the growth of the building stock over time. The method can help to assess the benefits of the nonstructural mitigation measures developed through experimental and simulation research on seismic vulnerability. This analysis is demonstrated for three metropolitan regions that face a range of seismic hazards: Los Angeles, California; Salt Lake City, Utah and Memphis, Tennessee.

*Keywords: Nonstructural, Damage, Modeling, Buildings, Inventory*

## 1. INTRODUCTION

Nonstructural systems are those parts of buildings that are critical to its functionality, but are not directly involved in the load bearing function. They include piping, ceilings, partition walls, lighting and HVAC systems. Nonstructural systems are a major contributor to both seismic losses and their failure can also disrupt the building's ability to function. Compared to the load bearing structural system that has been the focus of decades of research, the nonstructural systems can sustain damage at much lower earthquake intensities (Miranda, 2003). Therefore, it is not surprising that recent research reveals that of the total predicted damage, nonstructural systems account for a major proportion, 78.6% (FEMA, 2008). This paper addresses the impact of the nonstructural mitigation measures developed through experimental and simulation research on metropolitan scale vulnerability over time (Burby et al., 1998; May et al., 1998; Mileti, 1999). An overall description of the entire project of which this project is a part is provided in Filiatrault et al., 20011)

This paper describes a method to estimate the amount of existing and future non-structural components and damage for a metropolitan scale building stock. Such estimates are essential to understand how large a decrease in losses can be gained by implementing nonstructural mitigation measures over time at the metropolitan scale. The research reported here focuses on three main nonstructural systems: ceilings, piping and partition walls. This analysis is limited to three occupancy types: offices, schools, and hospitals, but the same method can be applied to other occupancy types.

The research explores how improved nonstructural design and construction techniques will affect the seismic vulnerability at the metropolitan scale over time as new buildings are added incrementally. This analysis is based on existing building inventory data for three metropolitan regions (Los Angeles, CA; Salt Lake City, UT; and Memphis, TN) with a range of seismicity. The core county of the metropolitan area is used: Los Angeles County, CA; Salt Lake County, UT; and Shelby County, TN. This existing building inventory is then translated into quantities of nonstructural systems using normative ratios for each occupancy class. Since we plan to assess the impact of improved nonstructural design and construction techniques over time, we need to project the quantity of nonstructural systems that will be added in the future. Future building square footages are forecast based on population and employment projections provided by regional planning agencies. These future building stocks are then translated into future quantities of nonstructural systems for each case study area. The amount of future nonstructural damage is calculated for scenario earthquakes in each study area using the HAZUS-MH loss estimation software provided by FEMA (2003).

## 2. EXISTING BUILDING INVENTORY

Figure 1 depicts the process used to estimate current and future amounts of nonstructural systems for the three occupancy types: office, hospitals and schools. This estimated future building stocks were used to estimate the amount of new ceilings, piping, and partitions that will be added during each 5-year time period from 2005-2025. Comparing damage estimates with and without mitigation measures provides the basis for calculating the benefits of implementing mitigation measures through changes in building codes and practices. This will provide a quantitative basis upon which public officials can decide to adopt and implement improved building codes.

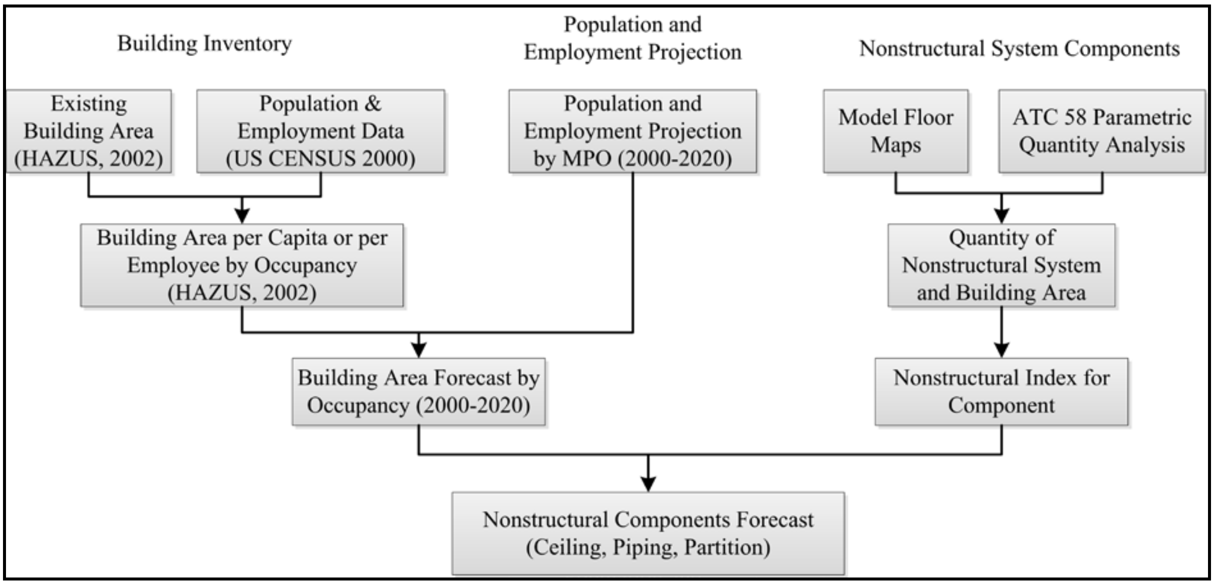


**Figure 2.1**. Flowchart of Estimating Nonstructural Systems by Building Type in Metropolitan Regions

The first step in the analysis is to determine the square footage of the existing building inventory by occupancy type. Gross building square footage by occupancy is calculated for each metropolitan area using HAZUS-MH, a geographic Information system (GIS) software program for estimating potential losses from disasters developed by the Federal Emergency Management Agency (2003). The square footage of existing buildings in each occupancy class are shown in Table 2.1.

**Table 2.1**. Square Footage (in thousands) by Occupancy for Three Metropolitan Regions

| Occupancy | Los Angeles Co. | Salt Lake Co. | Shelby Co. |
|---|---|---|---|
| Total | 5,811,372 | 605,954 | 739,631 |
| Office | 384,013 | 43,229 | 49,919 |
| Hospital | 23,670 | 2,909 | 4,269 |
| School | 42,773 | 4,431 | 7,918 |

It is important to note that, since HAZUS-MH is GIS-based loss estimation tool, the building inventory data is spatially located. The number and square footage of buildings is aggregated to relatively small areas called census tracts. The building square footage of offices in Shelby County (Memphis), Tennessee is shown in Figure 2.2, and the location of schools and hospitals are shown in Figure 2.3. Similar maps are available for the Salt Lake and Los Angeles study areas.

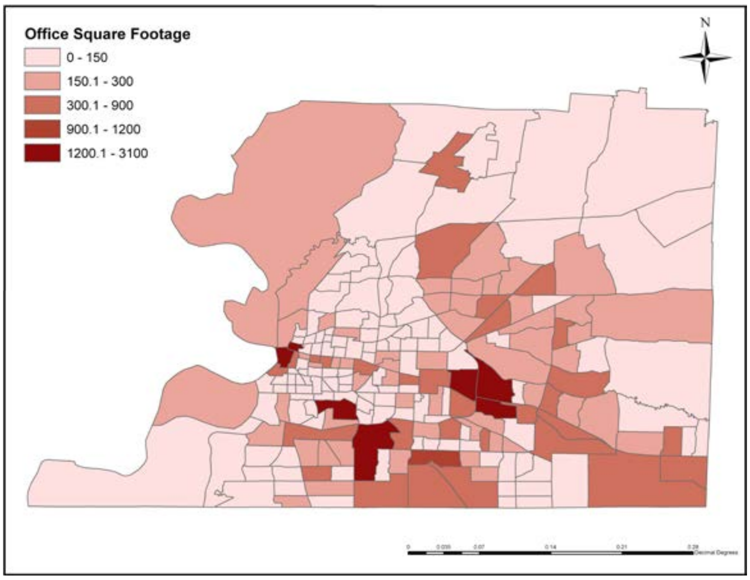


**Figure 2.2**. Office Square footage in Shelby County TN

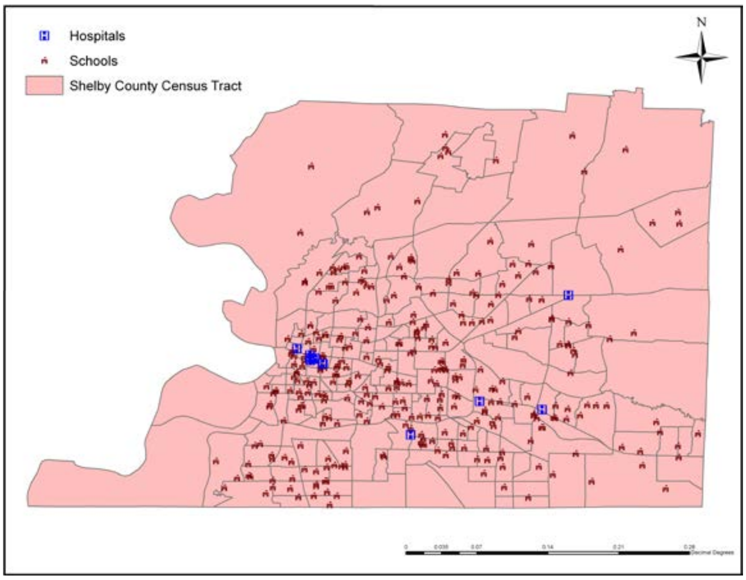


**Figure 2.3**. Hospitals and School in Shelby County, TN

## 3. FORECASTING FUTURE BUILDING INVENTORY BY OCCUPANCY TYPE

To be able to forecast the future quantities of nonstructural systems, we must first forecast the future amounts of office, hospital and school square footage for each of the case study areas. Using widely accepted forecasts of population and employment produced by the Metropolitan Planning Organization in each region, a simple per capita or per employee model will be used to forecast the future square footage of hospitals, schools, and offices that will exist for each 5-year time period from 2010 to 2020. Future office building stock was forecast as a function of the number of employees in the office sector. Future amounts of hospitals and schools were forecast based on future population projections.

Table 3.1 provides the forecasts of population and employment developed by the Metropolitan Planning Organization (MPO) in each region. These forecasts are used to forecast the future square footage of hospitals, schools, and offices that will exist for each 5-year time period from 2000 to 2020.

**Table 3.1**. Population and Employment Forecast (2000-2020) for Three Metropolitan Regions

| | Los Angeles Co. | | Salt Lake Co. | | Shelby Co. | |
|---|---|---|---|---|---|---|
| Year | Population[1] | Employment[1] | Population[2] | Employment[2] | Population[3] | Employment[3] |
| 2000 | 9,519,338 | 3,953,415 | 898,387 | 445,128 | 897,472 | 631,614 |
| 2005 | 10,206,001 | 4,397,025 | 955,541 | 616,395 | 904,000 | 634,729 |
| 2010 | 10,615,730 | 4,552,398 | 1,037,048 | 695,685 | 910,905 | 645,051 |
| 2015 | 10,971,602 | 4,675,875 | 1,127,884 | 767,083 | 922,264 | 680,062 |
| 2020 | 11,329,829 | 4,754,731 | 1,211,775 | 837,366 | 935,318 | 716,120 |

1. Southern California Association of Governments
2. Wasatch Front Regional Council;
3. Memphis Urban Area Metropolitan Planning Organization

The amount of future office building area was forecast using office space per employee and employment forecasts from Table 3.1. Nelson (2004) defines three main types of office jobs, FIRE (Finance, Insurance and Real Estates), Service (professional, scientific, and management, and administrative services) and Government. Using this definition of office employment, the office employment proportion of total employment is .22 in Los Angeles County, .25 in Salt Lake County and .21 in Shelby County. Using those proportions and Nelson's estimate of 350 square feet per office worker, we forecast the future amount of office space shown in Table 3.2.

**Table 3.2**. Office Building Area Forecasts for Three Metropolitan Regions

| Year | Los Angeles Co. | Salt Lake Co. | Shelby Co. |
|---|---|---|---|
| 2000 | 304,422,665 | 39,554,261 | 46,504,819 |
| 2005 | 338,581,725 | 54,773,119 | 46,734,172 |
| 2010 | 350,545,828 | 61,818,862 | 47,494,166 |
| 2015 | 360,053,860 | 68,163,318 | 50,071,975 |
| 2020 | 366,125,966 | 74,408,695 | 52,726,873 |

The amount of hospital and school square footage was forecast using simple per capita multipliers. This analysis shows the square footage of hospitals in Los Angeles County growing from 23.67 million square feet in 2000 to 28.17 million in 2020. Hospital space in Salt Lake County grows from 2.91 million in 2000 to 3.92 million in 2020. Hospitals in Shelby County grow from 4.27 million to 4.45 million in 2020. Schools building area is also driven by population growth and, therefore, follows a similar pattern from 2000 to 2020: Los Angeles 42.77 million to 50.91 million; Salt Lake County 4.43 million to 5.98 million; and Shelby County 7.92 million to 8.25 million.

Since the population and employment forecasts were all done at the census tract level, the forecasts of office, hospital and school grown are also spatially distributed to the census tract level. All there occupancy classes show significant growth in all three case study areas. Implementing better nonstructural construction techniques represents a significant opportunity to mitigate nonstructural damage.

## 4. ESTIMATING QUANTITIES OF NONSTRUCTURAL SYSTEMS

The next step in the process was to develop a model to estimate the quantity of nonstructural systems, ceilings, piping and partition walls, as a function of the building square footage for each occupancy type. The relationship of the quantity of these nonstructural systems per thousand square feet of building was determined by analyzing the blueprints from example buildings of each occupancy type. This analysis produced indices that show the square footage of ceilings per square foot of floor space and the linear feet of partition walls per square foot of floor space. We were not able to calculate a piping index using this method.

As a part of its Seismic Performance Assessment of Buildings Methodology Applied Technology Council has developed a similar set of indices, which they refer to as Normative Quantities for nonstructural building elements (ATC, 2001, Appendix F). As shown in Table 4.1 their indices are quite close to those developed from our example buildings. To account for the uncertainty inherent in both approaches, we will use the highest and lowest index from the two methods to estimate the quantity of square footage of ceilings and the linear feet of piping and partitions in our analysis. The estimate of the nonstructural systems is produced by multiplying the estimated building square footage for each occupancy type by the corresponding nonstructural index in Table 4.1.

**Table 4.1**. Nonstructural Indices from ATC-58 and Example Buildings

| | ATC 58 Normative Quantity Analysis | | | Example Building Plans | | |
|---|---|---|---|---|---|---|
| | Ceiling Index | Piping Index | Partition Index | Ceiling Index | Piping Index | Partition Index |
| Office | 1.00 | 0.17-0.22 | 0.07-0.12 | 0.90-1.00 | --- | 0.10-0.13 |
| Hospital | 1.00 | 0.20-0.25 | 0.08-0.14 | 0.90-1.00 | --- | 0.06-0.09 |
| School | 1.00 | 0.15-0.20 | 0.03-0.10 | 0.90-1.00 | --- | 0.06-0.08 |

The detailed forecast of nonstructural systems for offices in three metropolitan areas is shown in Table 4.2. Based on our estimates, the nonstructural components in offices will increase at different rates in the different cases from 2000 to 2020, reflecting the differential rates of employment growth. In Los Angeles, Salt Lake County and Shelby County, nonstructural elements in offices in are expected to increase by 20.3%, 88.1% and 13.4%, respectively.

**Table 4.2**. Nonstructural System Forecast for Offices in Three Metropolitan Regions

| County | Year | Ceiling (1,000 sq. ft.) | | Piping (1,000 linear ft.) | | Partition (1,000 linear ft.) | |
|---|---|---|---|---|---|---|---|
| | | Minimum | Maximum | Minimum | Maximum | Minimum | Maximum |
| Los Angeles | 2000 | 273,980 | 304,423 | 51,752 | 66,973 | 21,310 | 39,575 |
| | 2005 | 304,724 | 338,582 | 57,559 | 74,488 | 23,701 | 44,016 |
| | 2010 | 315,491 | 350,546 | 59,593 | 77,120 | 24,538 | 45,571 |
| | 2015 | 324,048 | 360,054 | 61,209 | 79,212 | 25,204 | 46,807 |
| | 2020 | 329,513 | 366,126 | 62,241 | 80,548 | 25,629 | 47,596 |
| Salt Lake | 2000 | 35,599 | 39,554 | 6,724 | 8,702 | 2,769 | 5,142 |
| | 2005 | 49,296 | 54,773 | 9,311 | 12,050 | 3,834 | 7,121 |
| | 2010 | 55,637 | 61,819 | 10,509 | 13,600 | 4,327 | 8,036 |
| | 2015 | 61,347 | 68,163 | 11,588 | 14,996 | 4,771 | 8,861 |
| | 2020 | 66,968 | 74,409 | 12,649 | 16,370 | 5,209 | 9,673 |
| Shelby | 2000 | 41,854 | 46,505 | 7,906 | 10,231 | 3,255 | 6,046 |
| | 2005 | 42,061 | 46,734 | 7,945 | 10,282 | 3,271 | 6,075 |
| | 2010 | 42,745 | 47,494 | 8,074 | 10,449 | 3,325 | 6,174 |
| | 2015 | 45,065 | 50,072 | 8,512 | 11,016 | 3,505 | 6,509 |
| | 2020 | 47,454 | 52,727 | 8,964 | 11,600 | 3,691 | 6,854 |

The quantity of nonstructural systems in hospitals and schools follow a similar pattern since they are both driven by population growth. Figure 4.1 depicts the growth of nonstructural systems in Hospital in Los Angeles County over time. The nonstructural systems in hospitals increase by 19%, from 2000-2020. Across all occupancies, Los Angeles has the largest amount of nonstructural components, and Salt Lake County is the fastest growing of the three cases.

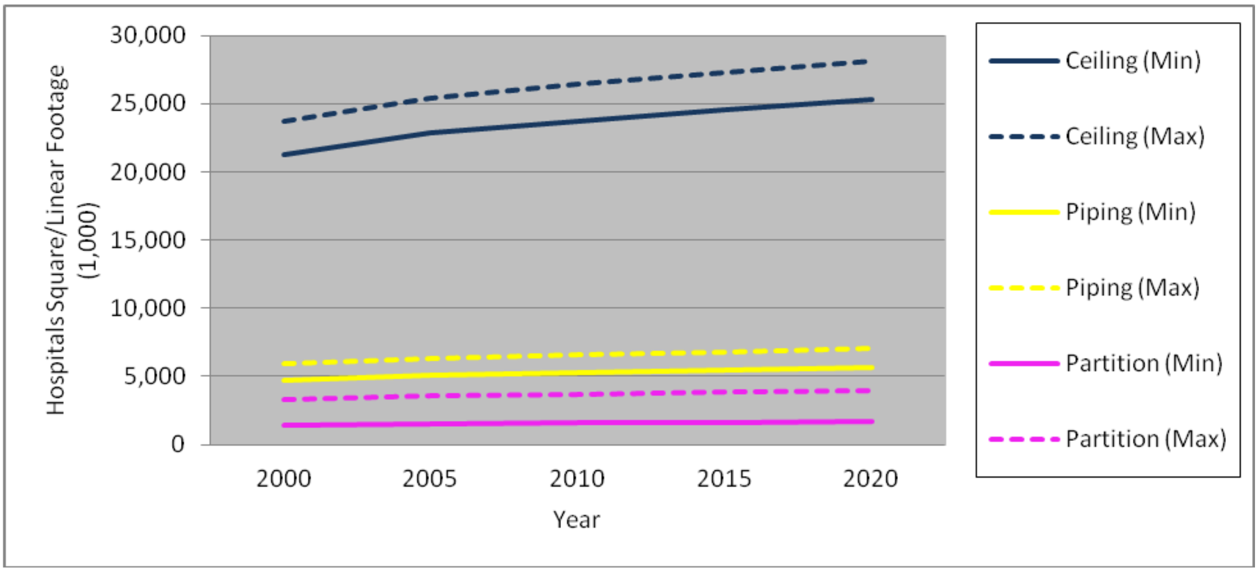


**Figure 4.1**. Nonstructural System Quantities in Hospital Buildings in Los Angeles County

## 5. ESTIMATING NONSTRUCTURAL DAMAGE

In a later part of this study we will be developing specific fragility curves for each of these non structural systems. In the interim we will use HAZUS-MH to estimate nonstructural damage for each case study area. HAZUS-MH is a comprehensive risk assessment system developed by Federal Emergency Management Agency (FEMA) for analyzing potential losses from natural hazards including floods, hurricane winds and earthquakes. HAZUS-MH combines advanced scientific and engineering knowledge with geographic information systems (GIS) to estimate the damage from earthquakes and other natural hazards (FEMA, 2003).

For this research, two earthquake scenarios were modeled for each of the three metropolitan case studies. The selection of the scenarios was based on the historical events or recent scientific analysis by the U.S. Geological Survey (USGS). Detailed information for each scenario is listed in Table 5.1.

**Table 5.1**. Size and Location of Scenario Earthquakes

| County | Scenario Name | Detailed Information Regarding the Scenario | | |
|---|---|---|---|---|
| | | Magnitude | Location | Depth |
| Los Angeles | San Andreas Fault | 7.4 | N 34.1, W 117.1 | 10 Km |
| | Newport-Inglewood Fault | 6.9 | N 33.78, W 118.14 | 0 Km |
| Salt Lake | Wasatch Fault | 7.3 | N 40.67, W 111.91 | 0 Km |
| | West Valley Fault | 6 | N 40.7, W 111.88 | 8 Km |
| Shelby | Marked Tree | 6.2 | N 35.53, W 90.42 | 10 Km |
| | New Madrid | 7.7 | N 36.59, W 89.53 | 10 Km |

Table 5.2 shows the total building damage for each scenario, including structural damage, nonstructural damage, content damage, and inventory damage that estimated using the direct physical damage module of HAZUS-MH. The building damage estimates are a weighted average of the

probabilities of being in each damage state (None, Slight, Moderate, Extensive, Complete). The Newport-Inglewood and Wasatch Fault 7events produced the most structural and nonstructural damage. The ratio of nonstructural damage to structural damage ratio varies among the scenario events from just over 50 percent for the 6.2 magnitude Marked Tree event near Memphis to over 80 percent for the Newport-Inglewood event in Los Angeles. The Newport-Inglewood event had more severe damage than the larger San Andreas event due to its location near downtown Los Angeles.

Since we have not yet developed fragility cures for individual systems, we have developed a sensitivity testing model that allows us to test the effect over time of different levels of nonstructural design and construction techniques. For this analysis these techniques are applied only to the new increment of development each year between 2000 and 2020 and not to the existing building stock. As an example, using the mitigation impact tool to understand the Newport -Inglewood event, we find that nonstructural mitigation techniques that reduce nonstructural damage for new Office construction by 10 percent will reduce the nonstructural damage from the Newport-Inglewood event in 2020 from \$3.13 billion to \$3.07 billion. If, however, those mitigation techniques were able reduce the damage by 25 percent, they would further lower the total nonstructural damage in 2020 to \$2.99 billion. Figure 5.1 illustrates how this mitigation sensitivity testing tools works. I is important to realize that since the mitigation techniques are only applied to new construction, the large existing base of buildings is not impacted by the new measures. This is a useful tool to understand the relative benefits of alternative mitigation nonstructural mitigation strategies.

**Table 5.2**. Damage Values for Scenario Earthquakes

| Scenario | Occupancy | Total Building Damage (\$1,000) | Structural Damage (\$1,000) | Nonstructural Damage (\$1,000) | Nonstructural Damage Ratio |
|---|---|---|---|---|---|
| San Andreas Fault (magnitude 7.4) | Office | 227,449 | 27,922 | 132,077 | 58.10% |
| | Hospital | 20,982 | 1,669 | 11,845 | 56.50% |
| | School | 23,006 | 2,679 | 13,865 | 60.30% |
| Newport-Inglewood Fault (magnitude 6.9) | Office | 3,348,129 | 704,326 | 2,576,354 | 76.90% |
| | Hospital | 263,215 | 41,745 | 214,001 | 81.30% |
| | School | 268,909 | 52,157 | 210,291 | 78.20% |
| Wasatch Fault Zone Salt Lake City Segment (magnitude 7.3) | Office | 1,945,323 | 384,330 | 1,370,527 | 70.50% |
| | Hospital | 222,435 | 25,997 | 123,542 | 55.50% |
| | School | 183,211 | 29,599 | 109,136 | 59.60% |
| West Valley Fault (magnitude 6.0) | Office | 561,858 | 93,895 | 315,935 | 56.20% |
| | Hospital | 48,973 | 5,631 | 26,067 | 53.20% |
| | School | 40,521 | 7,161 | 23,076 | 56.90% |
| New Madrid (magnitude 7.7) | Office | 116,226 | 26,218 | 63,087 | 54.30% |
| | Hospital | 17,811 | 2,927 | 9,498 | 53.30% |
| | School | 16,962 | 3,606 | 9,666 | 57.00% |
| Marked Tree (magnitude 6.2) | Office | 51,574 | 8,549 | 27,889 | 54.10% |
| | Hospital | 6,889 | 840 | 3,612 | 52.40% |
| | School | 7,942 | 1,420 | 4,307 | 54.20% |

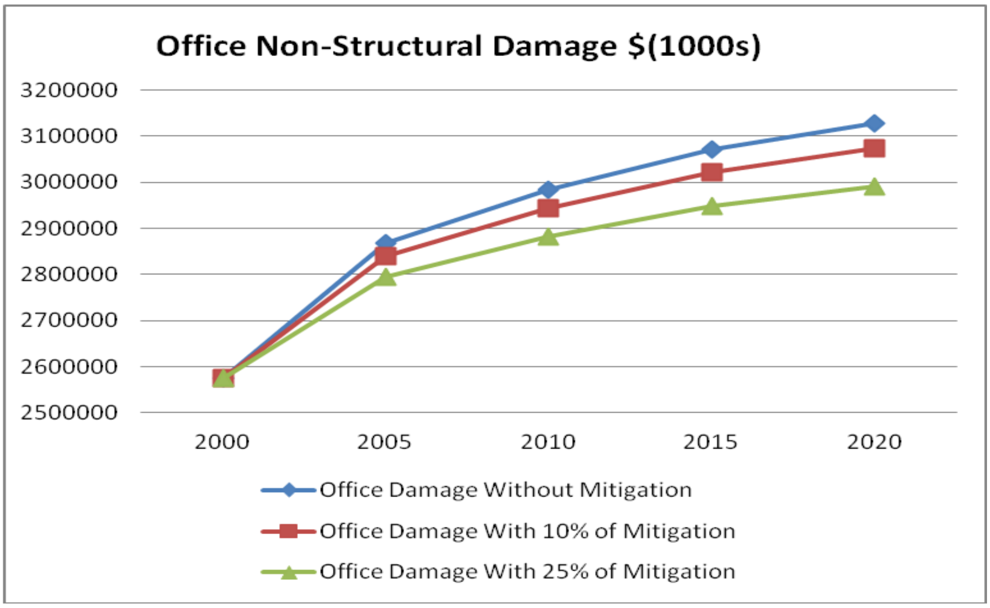


**Figure 5.1**. Impact of Mitigation Measures over Time, Newport-Inglewood Case

## 6.0 CONCLUSIONS AND FURTHER RESEARCH

This research has laid the groundwork for a rigorous vulnerability analysis of nonstructural mitigation measures at a metropolitan scale. It is designed to estimate the benefits in terms of decreased damage, if nonstructural mitigation measures are utilized for new construction of three occupancy types (offices, hospitals and schools). This research requires estimating the current building inventory of these three occupancies and forecasting the future amount of each occupancy type that will be constructed through 2020. These projections of future building stock are based on forecasts of population and employment for each of our three case study regions (Los Angeles, Salt Lake City and Memphis). Current and projected population and employment data have been collected from the Metropolitan Planning Organizations for each of the case study regions. A method to estimate and forecast nonstructural systems by occupancy was developed and implemented. The nonstructural quantity estimates for each metropolitan region seem reasonable based on limited calibration. However, there remain some significant uncertainties in the estimates. The main sources of those uncertainties are building area per capita and per employee and differences within occupancy types.

HAZUS-MH provided a useful platform to estimate the nonstructural damage for two scenario earthquakes in each metropolitan region. Two earthquake scenarios for each case study region were modeled using HAZUS-MH and the estimated nonstructural damage provided the baseline for the mitigation analysis. It produced damage estimates for the metropolitan regions based on new construction with current nonstructural system construction technology. To better understand the improved performance of nonstructural systems with mitigation measures applied, we have developed a mitigation sensitivity testing tool. The changes in damage due to the improvements of the nonstructural systems in the metropolitan regions can be estimated using this approach. Hopefully, this research provides policy makers with a way to analyze and forecast the results of improved nonstructural design and construction practices for the ceiling-piping-partition systems.

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