Inventory of Non-ductile Concrete Buildings in High Seismic Risk Areas of California

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ABSTRACT

The purpose of this research is to develop and refine methods in order to get an accurate estimate of the number of non-ductile concrete buildings in California. The construction of non-ductile concrete buildings in high seismic risk areas of California was very common prior to the enforcement of modern seismic codes for ductile concrete in the mid-1970's. The construction of non-ductile concrete buildings most likely continued until about 1980 as it almost certainly took a few years for the new seismic code standards to take full effect. These buildings have proven to have poor seismic performance through the catastrophic failures seen in earthquakes over the last 15 years. It was initially estimated that there are 40,000 non-ductile concrete buildings in California alone, serving as residential dwellings, commercial buildings and critical service facilities. The extreme risk these buildings present and the potential scale of the problem has motivated the compilation of an inventory of non-ductile concrete buildings in California. Estimates have been prepared by professional engineers for almost 30 cities and extensive census data has been collected for approximately 350 cities in California. The data for these cities has been examined closely for possible trends and characteristics. It is simply too difficult and time consuming to collect estimates for each city individually; therefore, regression models and statistical predictive models have been explored in an attempt to estimates the number of non-ductile concrete buildings for a city. Consequently, a better total estimate for the number of non-ductile concrete buildings can be determined as well as the location of some of these buildings by county and city. Combined with research related to the failure type of these buildings and risk mapping, it will be possible to pinpoint which non-ductile concrete buildings are dangerous.

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1 INTRODUCTION

The greatest earthquake risk in the United States is from damage and collapse of older buildings designed with insufficient consideration of earthquake effects. Concrete buildings built prior to the implementation of modern seismic code standards for ductile detailing in the mid-1970's have proven to perform very poorly in recent earthquakes. Catastrophic damage and failure of these buildings have been seen in earthquakes including Northridge (1994); Kobe, Japan (1995); Chi Chi, Taiwan (1999); Kocaeli, Duzce and Bingol, Turkey (1999, 1999, 2003); Sumatra (2005); and Pakistan (2005). Jack Moehle, a Civil Engineering professor at the University of California at Berkeley, has asserted, "Existing vulnerable buildings are the number one seismic safety problem in the world, and non-ductile reinforced concrete buildings are a noteworthy percentage of these." It has been estimated that there are 40,000 non-ductile concrete buildings in California alone, serving as one story family dwellings to multi-story critical service facilities. Identifying and retrofitting all of these buildings would be nearly impossible due to the high cost of retrofitting buildings as well as the potential number of non-ductile concrete buildings that may be in California. Although non-ductile concrete buildings are at risk of substantial damage and collapse under seismic forces, not all non-ductile concrete buildings are dangerous. In fact, in Charles Kircher's recent findings on estimated losses due to a repeat of the 1906 San Francisco Earthquake he states, "50% of the casualties are coming from 5% of the buildings." Knowing this, it is essential to find a way to pinpoint the most dangerous concrete buildings that could cause the majority of damage and loss of lives in the next large earthquake. This has motivated a compilation of an inventory of non-ductile concrete buildings in California in order to provide a better total estimate of the number of these buildings as well as their location by county and city in California.

1.1 Defining Non-ductile Concrete Buildings

Ductile materials experience extensive plastic deformation and high energy absorption before failure, whereas brittle materials do not. A building with a lateral force resisting system that is considered ductile will experience a large amount yielding during an earthquake, which would allow people to vacate the building before it fails. In recent earthquakes non-ductile concrete buildings have proven to do the opposite. These buildings have the potential to fail without warning causing catastrophic damage and loss of lives. Post-earthquake studies have shown that many older reinforced concrete buildings were detailed with too much spacing between stirrups and inadequate flexural reinforcement, causing them to experience a non-ductile behavior. The poor performance of older reinforced concrete buildings in these large earthquakes triggered the enforcement of a modern seismic code for ductile detailing in 1976. The construction of non-ductile concrete buildings probably continued until about 1980, as it almost certainly took a few years for the new code to take full effect. For the purposes of the building inventory of California, non-ductile concrete buildings are defined as concrete buildings built before 1980.

1.2 Concrete Coalition

In order to address the high earthquake risk posed by older, non-ductile concrete buildings in California and the rest of the western United States, the Earthquake Engineering Research Institute (EERI) has recently partnered with structural engineers, building officials, public policy interests, building owners and managers to form the Concrete Coalition. The Concrete Coalition is uniting professionals to collaboratively and effectively develop and implement mitigation strategies for non-ductile concrete buildings. This building inventory research was done in association with the Concrete Coalition.

1.3 Objectives

This inventory of non-ductile concrete buildings is being done to obtain an accurate estimate of the number of these buildings in California as well as their location. Once a complete inventory is done, the total number of non-ductile concrete buildings can be compared to the initial estimated of 40,000 and further efforts can be pursued to identify the most dangerous buildings. Additional research is being done to identify and analyze the failure types of these buildings along with the creation and improvement of a web-based seismic risk map tool. Collectively, all the research on the non-ductile concrete Grand Challenge Project will help to pinpoint the most dangerous buildings that are at risk of collapse and failure during the next earthquake. From there, actions can be taken to properly retrofit those buildings and effective retrofit policy can be developed.

2 VOLUNTEER REPORTS AND ESTIMATES

Practicing engineers have volunteered to provide estimates for the number of non-ductile concrete buildings for numerous northern and southern California cities. To date, around 30 reports have been submitted with more expected soon. Various professionals have used different approaches and techniques to collect data and provide estimates. For smaller cities it is possible to simply identify areas where older concrete buildings might be present and do some quick field work for verification, but for larger cities more precise methods must be used. Some of the sources that have been used by professionals include Sanborn maps (fire insurance maps), zoning and land use maps, Google Earth, talking with building officials, field work and more. All of the reports that have been submitted were closely reviewed and questions were generated for the volunteers to get a better idea of where their estimates were coming from. Although it is impossible to get an exact number of non-ductile concrete buildings for each city because of mixed-use construction and other ambiguities, most professionals were pretty confident in their estimates. Some volunteer reports were extremely through and precise.

2.1 Use of Google Earth

The majority of the volunteers used Google Earth as a source to help obtain the number of non-ductile concrete buildings in a given city. Most volunteers used it as a starting point by identifying city limits and possible areas of interest. Although it is difficult and inaccurate to identify a buildings structural type using Google Earth, it is relatively easy to distinguish residential neighborhoods from industrial or commercial areas. This allows for residential areas to be eliminated and industrial or commercial areas to be further examined by field work, since it is very unlikely a non-ductile concrete building will be found as a single family dwelling. After identifying areas of interest, most volunteers proceeded to field work and street surveying of those areas.

The city of Burlingame is an example of how some volunteers used Google Earth. Figure 2.1 shows how they used Google Earth to map the city limits of Burlingame and then isolate areas of interest.

Figure 2.1: Burlingame's use of Google Earth

2.2 Use of Sanborn Maps

Another source commonly used by volunteers to provide estimates were Sanborn maps. Sanborn maps were created and used for fire insurance purposes and updated until the 1980's. For the non-ductile concrete building inventory, buildings constructed before 1980 are being included; therefore, some of these maps were extremely helpful but not all of the maps were updated as late as the 1980's. These maps contain information including the outline of each building, size, shape, construction materials, heights, building use and function, city boundaries, street name, addresses, and more. The maps are color coordinated by construction type: blue is for concrete and concrete block, pink is for brick and tile, yellow is for wood, grey is for iron and brown is for fire proof construction. Although the maps are color coordinated, it was also useful to read the notes on each building because many of the buildings were mixed use construction. The method used with the Sanborn maps was to go through the pages and identify and count the buildings that were blue and concrete but not concrete block. It is possible that some of the buildings found on the Sanborn maps could have been demolished or retrofitted; therefore, the majority of volunteers did field work to verify the concrete buildings found in the Sanborn maps. Figure 2.2 show an example of a page from the Sanborn map of Redwood City.

Figure 2.2: Sanborn map of Redwood City

2.3 Field Work and Street Surveying

Google Earth, Sanborn maps and other sources are good methods of identifying areas of a city where older concrete buildings are likely to be located, but doing actual field work is the key to verifying these buildings actually exist. Almost all of the professional volunteers did some sort of street surveying by foot or car. For smaller cities, it was possible to do field work for all the areas of interest and actually locate the concrete buildings found in the Sanborn maps. Bigger cities tended to have more and larger areas of interest which made it difficult to do field work of all the areas. Consequently, field work was usually done for parts of the areas of interest and then a factor was applied to the whole area based on how many pre-1980 concrete buildings were found and verified. Frequently professional judgment was used during field work because it can be difficult to distinguish a building's structural systems with all the architectural finishes covering them. Volunteers of cities that had done extensive field work often were more confident in their estimates and reports.

2.4 Review of the Volunteer Reports

To better understand how the estimates for each city were generated, a full review of all the volunteer reports was done and questions were produced for the volunteers to answer. Both the review and questions helped gauge the thoroughness and accuracy of each city’s approach and report. Some of the questions asked to the volunteers included:

- How were the years between the last update of the Sanborn map and 1980 accounted for?
- How confident (0-100%) are you in the reported estimate of pre-1980 concrete buildings?

- If you had to provide a range rather than a number for the estimate of pre-1980 concrete buildings, what would it be?

From the responses, it appeared that overall most of the volunteers were pretty confident in their reports and estimates. Almost all volunteers said they were upwards of 70% confident in their estimate of pre-1980 concrete buildings, with some saying they were 90%-95% confident. It would be very difficult and time consuming to do an extremely precise non-ductile concrete building inventory of California, which is why volunteers were asked to provide good estimates. So far, the volunteers have exceeded expectations and provided more thorough reports and estimates than anticipated.

3 COLLECTING CENSUS DATA

Extensive census data has been collected for about 350 coastal California, particularly for the cities in which volunteer reports have been submitted. The goal of gathering all the detailed census data is to identify trends and characteristics that help classify each city as a residential or industrial city. However, in most cases it was not that simple because the majority of cities fall somewhere in the middle. Some of the census data that has been collected includes: population, land area, number of households, percent of single housing units, percent of multiple housing units, number of employees, number of establishments, population growth data, and more. Classifying a city as residential, industrial or somewhere in between helps to get an initial idea of how many pre-1980 concrete buildings could be found in that city. If the census data shows that a city is predominately residential it is also important to know if the housing units are mostly single family or multi-family units. The expected number of pre-1980 concrete buildings in a single family residential city would most likely be low because most homes are wood and not concrete. More pre-1980 concrete buildings would be expected in a multi-family residential city because it is more likely for apartment complexes to be concrete construction. The most pre-1980 concrete buildings would be expected in cities classified as industrial or commercial. For the industrial and commercial cities a lot of census data had to be considered to get an idea of how many older concrete buildings could be expected such as population, population density, historical population and construction data, number of employees, number of establishments, and more. Even though the census data was very helpful in classifying some cities by type and providing a rough approximation of the number of concrete buildings that could be expected, in no way did it provide an accurate estimate of the number of pre-1980 concrete buildings.

4 STATISTICAL PREDICTIVE MODELS

Using both the census data and volunteer reports, statistical models have been developed with the objective of confidently predicting the number of pre-1980 concrete buildings in a city. It would be entirely too time consuming and difficult to collect volunteer reports and estimates for every city in California; therefore, the statistical predictive models aim to estimate the number of pre-1980 concrete buildings using various indicators from the census data without having professional engineers submit volunteer reports. Peter May, a Political Science professor from the University of Washington, has handled all of the statistical modeling for the project. The models are generated using a sample of cities for which there are volunteer reports. The volunteer estimates and census data for those cities are used to produce models which estimate the number of pre-1980 concrete buildings for the cities not used to create the models. From a modeling perspective, not all of the indicators from the census data work well to provide a precise model. Also, some of the cities used to create the models have characteristics unlike any of the other cities such as Los Angeles and San Francisco. The statistical models generate equations that predict the number of pre-1980 concrete buildings as well as a 95% confidence interval. The confidence interval gives an estimated range of values in which there is 95% confidence the number of pre-1980 concrete buildings for a given city falls in that range. When new reports are submitted the volunteer estimates are compared with the model's estimates and the predictive models are checked for accuracy. Once enough new reports are submitted the predictive models can be refined by adding the new volunteer estimates to the sample used to generate the models. Currently, a statistical predictive model has not been found that is accurate enough to use to estimate the number of pre-1980 concrete buildings. Although, as more volunteer estimates are added to the sample, the refined models seem to be getting more accurate.

5 RESULTS AND CONCLUSION

The volunteer reports from about 30 cities have yielded a total estimate of approximately 7,600 pre-1980 concrete buildings. Los Angeles, San Francisco and Oakland account for about 6,000 of the total estimate. None of the other cities' estimates exceed a few hundred, while most are less than 60. There are a couple cities whose estimates and approaches need to be further evaluated because their estimates seem very low given the size, population and other characteristics of the cities. Table 5.1 below shows the volunteer estimates for the number of pre-1980 concrete buildings for each city.

CITY	POPULATION	ESTIMATED PRE-80 CONCRETE BUILDINGS
Emeryville	6,882	44
Fairfax	7,319	18
Piedmont	10,952	8
Solana Beach	12,979	3
Mill Valley	13,600	13
Albany	16,444	36
Millbrae	20,718	52
El Cerrito	23,171	22
Calabasas	23,652	2

Eureka	25,579	10
Burlingame	27,380	240
Novato	50,335	18
San Rafael	55,716	53
Alameda	70,576	150
Napa	74,782	14
San Leandro	78,178	43
Santa Monica	91,124	70
Daly City	100,339	30
Berkeley	100,744	275
Fullerton	132,787	60
Santa Rosa	154,212	55
San Bernardino	205,010	5
Glendale	207,157	160
Riverside	290,086	6
Oakland	395,274	1300
Long Beach	492,912	400
San Francisco	739,426	3000
Los Angeles	4,018,080	1500

Table 5.1: Volunteer estimates for the number of pre-1980 concrete buildings

At this point it is difficult to tell how the total estimate for the number of non-ductile concrete buildings in California would compare to the initially estimated 40,000. Proportionally with around 30 cities accounting for approximately 7,600 concrete buildings, the total estimate for around 350 cities could easily be well above 40,000. On the other hand, most of the largest cities in the state are already accounted for; therefore, the total estimate could also potentially be around or below 40,000. An accurate total estimate can be determined once a statistical model is developed and refined that closely predicts the number of pre-1980 concrete buildings for each city. Once additional volunteer reports are submitted the older models can be examined for accuracy and then refined by adding the new cities and their estimates to the sample of cities with volunteer reports. This process can be iterated until an accurate model is found.

After an accurate total estimate for the number of non-ductile concrete buildings in California is determined, proper steps can be taken to pinpoint the most dangerous and hazardous buildings in the inventory. Additional research is being done related to the failure type of an exterior concrete beam-column connection and the development of a web based risk mapping tool. This non-ductile concrete building inventory combined with the related research will allow for older concrete buildings at the most risk for damage and collapse in the next earthquake to be identified. Once these buildings are identified, appropriate action can be taken to either retrofit or completely demolish the building. Furthermore, effective retrofit policy can be developed and implemented to make sure the retrofit of dangerous non-ductile concrete buildings meets modern seismic code standards. Pinpointing the most hazardous non-ductile concrete buildings and correctly retrofitting them could prevent the next large earthquake in California form being catastrophic.

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