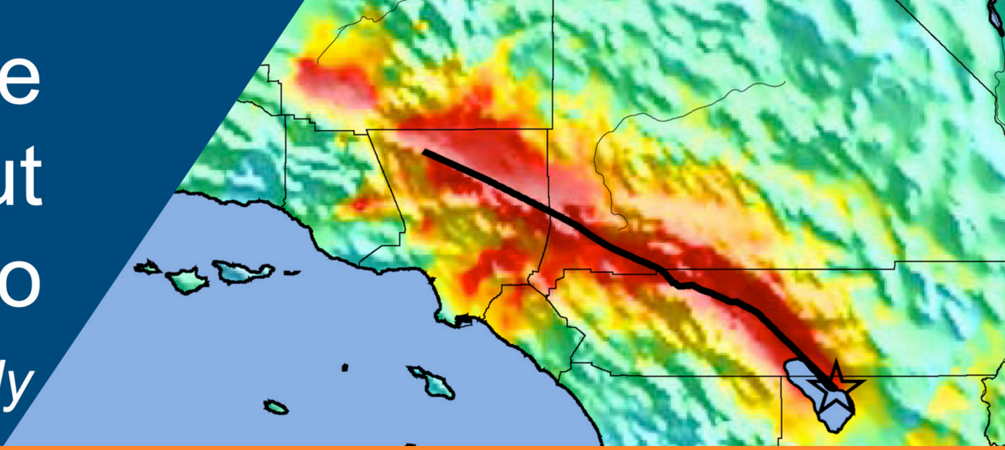
The ShakeOut Scenario

Supplemental Study



Older Reinforced Concrete Buildings

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Note: over the course of the ShakeOut Scenario, the project name evolved. Where a study mentions *the SoSAFE Scenario* or *San Andreas Fault Scenario,* it refers to what is now named the ShakeOut Scenario.

M7.8 Southern San Andreas Fault Earthquake Scenario: Non-ductile Reinforced Concrete Building Stock

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This document summarizes the estimated performance of Non-Ductile Reinforced Concrete Buildings (NDRCB's) in Riverside County, subjected to a probable M7.8 earthquake due to a rupture on the Southern San Andreas Fault. The estimations presented herein are admittedly *crude*, and are primarily based on observations from past earthquakes, the available building inventory data from *Los Angeles County*, and the personal judgments of the authors. The actual numbers, constitution, distribution, and uses of NDRCB's in relevant areas of the *Riverside County* are *unknown* to the authors at the present time, preventing a detailed assessment. This situation unfortunately confines the utility of the data presented herein. Nevertheless, it also clarifies that a systematic research on cataloguing the NDRCB stock in Riverside County, and assessing their collapse risk is an urgent need.

INTRODUCTION

Existing stocks of vulnerable structures arguably constitute the most critical hazard risk seismic regions of the United States. A considerable portion of this stock consists of Non-ductile Reinforced Concrete Buildings (NDRCB's)—a term used to signify a reinforced concrete structural system that has very limited capacity to absorb and dissipate the destructive energy of strong ground shaking beyond its limited elastic range, and hence, one that is extremely vulnerable to collapse.

Reinforced concrete construction has begun in the U.S. at the turn of twentieth century. Seismic design of reinforced concrete structures was at its infancy in 1950's, and lacked critical improvements to detailing requirements until 1970's. The watershed event that is typically cited to delineate the commencement of ductile reinforced concrete design is the 1971 San Fernando Earthquake. Observations of the performance of reinforced concrete buildings in this event and subsequent studies led to improved provisions that appeared in the 1976 Uniform Building Code. These design provisions and requirements have been further improved ever since.

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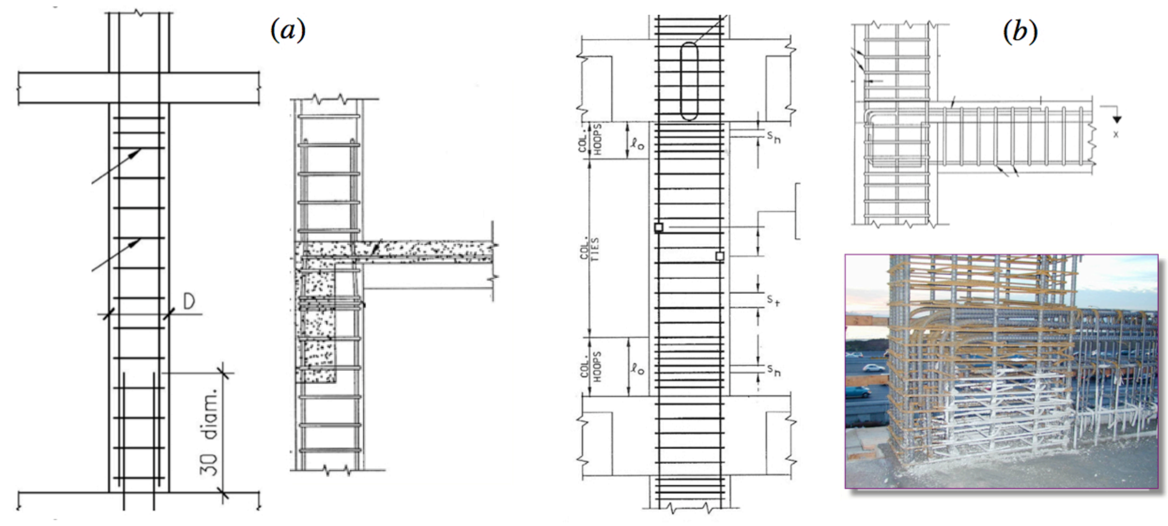

Figure 1. Typical reinforcement details of beams and beam-column joints in (*a*) older and (*b*) modern construction (Figures reprinted from Moehle *et al.*, 2007).

There are three basic types of structural deficiency encountered in reinforced concrete construction. These are design, detailing, and construction deficiencies. Design deficiencies include:

- Inadequate provisioning of lateral-load resisting members (e.g., lack of shear walls or special moment-resisting frames);
- Lack of redundancy (alternative load paths) in the structural system (i.e., the beams and columns are sparse, or improperly located, such that a total structural collapse is triggered in the event of damage to only a few members);
- Irregularities in plan or elevation (e.g., L or T-shaped plan, or vertical setbacks);
- Presence of soft or weak stories, especially at the ground floor, as in the case of tall first stories with large openings for doors and windows;
- Presence of short columns, which usual fail in a specific pattern that is catastrophic;
- Presence of overhangs;
- Strong-beam weak-column joints, that is, cases where the beams are stronger than the columns they connect to. The problem is that damage at such connections tends to occur in the columns rather than the beams, and since the floors above the column rely on the column more than on the beam; and, column damage can be more catastrophic than beam damage.

Key detailing deficiencies include:

- Inadequate transverse reinforcing bars: These are the smaller steel reinforcing bars running perpendicular to the axis of the beams and columns in Figure 1. Transverse reinforcement provides resistance against shear forces and imparts confinement to concrete within. This confinement increases the ultimate strength of concrete, and enables a beam or column to accommodate more damage without failing catastrophically. It is especially important to avoid wide spacing of transverse bars (see, Figure 1a) near beam-column joints. Modern design codes provide specific provisions for narrower transverse reinforcement spacing (see, Figure 1b).
- Short overlap lengths at spliced joints: These are locations where one of the

reinforcing bars that runs longitudinally along, say, a column ends and overlaps with another that continues farther along the column, as in the bottom portion of the column shown in Figure 1a. If the overlap is too short, the force in one bar cannot be adequately transferred to the next one, which produces a generally unanticipated weak point in the column. Figure 1b shows mechanical connectors in place of the splice (the two small white boxes in the middle of the column).

Adverse conditions such as those listed above may be further aggravated by construction deficiencies, such as low-quality workmanship, use of inferior materials, and deviations from structural drawings and specifications during the construction phase.

INCIDENCE, TYPE, AND USE OF NDRCB'S IN CALIFORNIA

The risk posed by NDRCB's in California is generally accepted as being significant. An important conclusion of a recent study by Kircher *et al.* (2006) suggest that 50% of the expected casualties in a repeat of the 1906 San Francisco Earthquake will be due to 5% of all the building stock. This small percentage comprises NDRCB's as well as soft-story wood and unreinforced masonry structures. The same study estimates that a M7.9 rupture of the San Andreas Fault will kill more than 1,800 and seriously injure 8,000 people if it occurs during the night. During the daytime these figures climb to 3,400 and 12,500, respectively. Nevertheless, it is stated in the same study that little data on the actual number and square footage of NDRCB's were available. It was assumed that all pre-1974 concrete buildings were collapse hazards. Furthermore, a validation study performed with data from the 1989 Loma Prieta Earthquake indicated that the loss estimates could be as high as twice of what may actually occur, somewhat quantifying the uncertainty in these predictions.

An ongoing investigation on NDRCB's through a NEES project titled "*NEES-GC: Mitigation of Collapse Risk in Vulnerable Concrete Buildings*" also provides relevant statistics. This project's inventory studies suggest that could be as many as 1000 NDRCB's in Los Angeles County under risk of collapse due to strong ground shaking where, again, this assessment is largely based on building vintage [Stewart *et al.*, 2007]. Over 90% of this building stock is composed of commercial/industrial structures. Almost 20% of the commercial structures have 6 to 13 floors, while nearly all of the rest (i.e., ~80%) are one story high. Approximately one-half of the smaller group of approximately 100 residential NDRCB's is 1 to 4 stories high, while the rest have 5 stories or more. The mean square-footage value for all these buildings is slightly above 50,000 sq-ft.

OBSERVED PERFORMANCE OF NDRCB'S FROM PAST EARTHQUAKES

Figures 2 through 7 exemplify the strikingly poor performance of NDRCB's observed during recent earthquakes in the U.S. and around the world. They bear a significant risk of complete or partial collapse under strong ground motions. While there might be a marked difference between the casualty figures between a partial and a complete collapse, the building in question would be a complete economic loss in either case.

Figure 2. Joint failures observed in non-ductile reinforced concrete buildings due to strong ground shaking (Figure reprinted from Moehle *et al.*, 2xxx).

Figure 3. Damage to non-ductile reinforced concrete buildings due to 1994 Northridge Earthquake (Photos procured from USGS archives).

Figure 4. Olive View Hospital, Psychiatric Unit. This unit was a 2-story reinforced concrete building. The structural system was a moment resisting frame. Earthquake: San Fernando, California earthquake, Feb. 9, 1971 Magnitude: 6.6 (Figure and caption procured from USGS archives).

Figure 5. Overall view of Kaiser Permanente office building looking toward the northeast. The brick facades at either end of the structure have separated from the concrete frame, and the second floor of the structure has completely collapsed. The bays at the north and south ends of the building are also partially collapsed from the second to the fifth floor. Earthquake: Northridge, California earthquake, Jan. 17, 1994 Magnitude: 6.69 (Figure and caption procured from USGS archives).

Figure 6. South elevation (front view) of an irregular, U-shaped reinforced concrete building in Nishinomiya with 3rd floor collapse. (Kobe, Japan). Earthquake: Kobe, Japan earthquake, Jan. 17, 1995 Magnitude: 6.69 (Figure and caption procured from USGS archives).

Figure 7. View of partially collapsed apartment buildings in Kobe, Japan. Earthquake: Kobe, Japan earthquake, Jan. 17, 1995 Magnitude: 6.69 (Figure and caption procured from USGS archives).

As the California Seismic Safety Commission proclaimed, “the types that will fail are well known, but identifying individual structures that are likely to collapse is a monumental task that will take decades of effort” (CSSC, 1995). Anything short of detailed simulations for a given earthquake scenario with full knowledge of specific locations of NDRCB’s, will yield only crude estimates of the actual risk they pose.

The assertion that all NDRCB’s exposed to strong ground motions will collapse may be very conservative. There are studies that provide less dire predictions on their expected performance. Moehle *et al.* (2004), based on a study by Otani (1999), state that the collapse risk of "lightly reinforced concrete buildings" assessed with current predictive tools may be overestimated. Their study relies on post-earthquake reconnaissance data from several events, as illustrated in Figure 8 below. Most relevant among these statistics is perhaps those from the 1995 Kobe Earthquake, because they are restricted to buildings constructed before the enforcement of "1981 Building Standard Law" in Japan—A situation reminiscent of the seismic code improvements that occurred in mid-1970s in the United States.

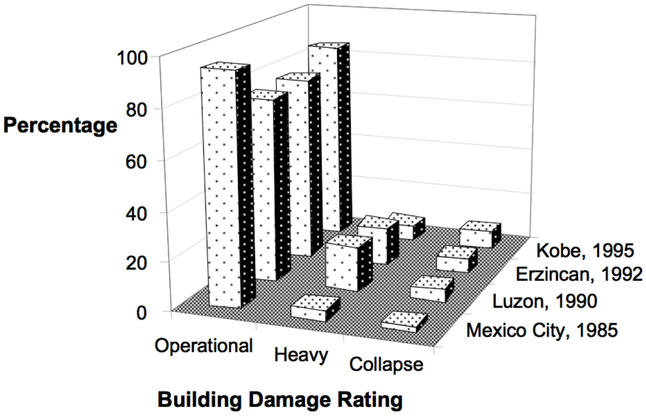

Figure 8. Damage statistics for lightly reinforced concrete buildings from four earthquakes. (Figure reprinted from Moehle *et al.*, 2004.)

DAMAGE SCENARIO

At the present time, statistics of the NDRCB's in Riverside and San Bernardino Counties (i.e., the most vulnerable populated areas to a probable Southern San Andreas earthquake) are *unknown* to the authors. As such, subsequent predictions are based on preliminary data presently available for Los Angeles County as mentioned above, and are obtained without the aid of detailed predictive computational tools (e.g., HAZUS). Therefore, it is possible to provide the only coarsest estimates of damage.

The typical method to evaluate the expected seismic performance of a model structure is to use the *nonlinear static pushover analysis* under different levels of shaking that depend on the location and distance of the structure from the earthquake event. This method yields structure's capacity and the demand on it posed by the earthquake. For evaluating the capacity, we built a computer model of a 5-story reinforced concrete frame (Figure X) that exhibits typical deficiencies of NDRCB's. Following the methods described in seismic evaluation codes FEMA356 and ATC, we have evaluated the performance level of the model NDRCB on several locations along/around the San-Andreas fault.

Given the engineering analyses just mentioned and the historical damage reflected in Figure 8, we suggest a realistic range of possible outcomes is that on the order of 10 to 100 NDRCBs in Riverside, San Bernardino, and Los Angeles Counties will collapse, a somewhat larger fraction will be heavily damaged (to the extent of being red-tagged and therefore both unsafe to enter and also potentially a total economic loss), and the rest might be operational, even if damaged and requiring repair. Given the level of shaking in Palm Springs, it seems realistic to assume that most NDRCBs in that city would be at least heavily damaged by the earthquake, and that a significant fraction, perhaps on the order of 10%, would partially or completely collapse.

That means that in an earthquake occurring at 10am on a typical Thursday morning, throughout the study region perhaps 5,000 to 10,000 people would be in collapsed buildings, with roughly 90% of them in partially collapsed buildings (such as shown in Figures 2 through 7) and the remainder in complete collapses. Perhaps 10,000 to 20,000 people would be in heavily damaged ones. Deaths and injuries resulting from this damage are described elsewhere. We emphasize that these figures are offered as merely realistic professional judgments for use in emergency planning. We consider them accurate to within no less than perhaps 1/2 an order of magnitude. A thorough engineering analysis is called for to produce a strongly defensible estimate of what would actually happen to these buildings and their occupants in the scenario earthquake.

REPAIR AND DAMAGE MITIGATION THROUGH RETROFIT

Seismic repair and/or strengthening approaches to NDRCB's generally consist of system behavior improvement and/or component repair/strengthening. Figure 9 illustrates some of the common techniques. One such technique is the formation of new shear walls by infilling some of the bays of the existing frames with cast-in-place reinforced concrete infill walls, or precast panel walls. Use of cast-in-place infill walls as a method of system rehabilitation is presently a common application in other earthquake-prone regions of the world such as Turkey, where a significant number of NDRCB's exist (Sucuoglu, 2006). Such walls, when adequately anchored into the surrounding frame using various types of connections (e.g., shear keys, dowels, chemical anchors) not only increase the lateral stiffness of the building significantly, but also relieve the existing non-ductile frames from being subjected to large lateral force demands. The critical issue in prediction of the seismic performance of a building strengthened with shear walls is the distribution of lateral earthquake forces to the walls and the frame. Therefore, determination of the internal force distribution in the building structure needs to be investigated through system-level studies.

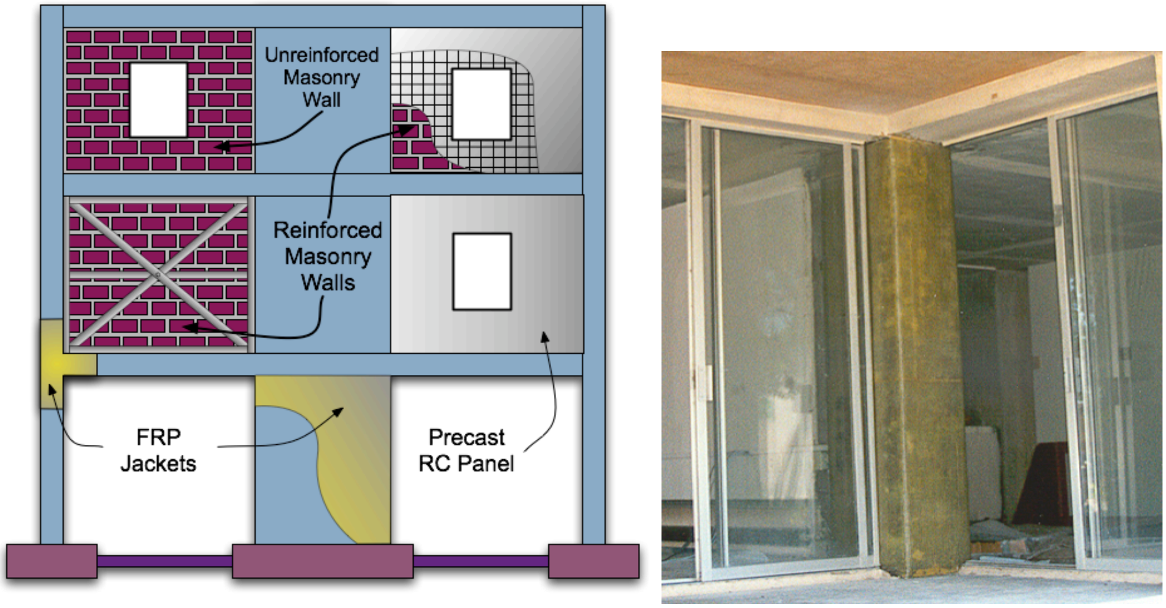

Figure 9. Typical seismic retrofit techniques for NDRCB's (left); a column wrapped in Fiber-Reinforced Polymer (photo reprinted from Moehle *et al.*, 2007.)

Another category of retrofit is the strengthening of individual components, whereby structural members and their connections can be repaired and/or strengthened by epoxy injection in the cracks, by reinforced concrete or steel jacketing, or by fiber reinforced plastic (FRP) or carbon fiber wrapping (Beres *et al.*, 1992). In general, columns are regarded as the most critical structural members to be rehabilitated, since the failure of columns may lead to collapse (Moehle, 2000). In all these solutions, the critical issue is the bond and shear connection between new and existing layers. Insertion of steel bracings or beams is another commonly used repair/strengthening application.

The need to retrofit a structure—that is deemed to be non-ductile—is somewhat controversial, because the type, extent, and hence the cost of retrofit crucially depends on the outcome of a collapse risk assessment investigation. It is often argued that the current assessment methodologies for NDRCB's may be overly conservative (Moehle, 2004). This argument is supported by comparison of measured capacity of older non-ductile beam-column joints from tests and capacity bracketed in code provisions such as FEMA 356 (2006). Current research on NDRCB's is directed towards better assessment of their collapse risk, which in turn will yield a clearer picture of feasible retrofit strategies for NDRCB's in California.

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