Seismic Design - Evaluation and Retrofit of Existing Buildings

An Online Continuing Education Course for Engineers

Course Number: BD-3011

Credit: 3 Hours / 3 PDH / 3 CPD

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INTRODUCTION

It is widely recognized that the most significant seismic risk in the U.S. resides in our existing older building stock. Much of the country has enforced seismic design for new buildings only recently; even on the West Coast, seismic codes enforced in the 1960s and even into the 1970s are now considered suspect. Although there are sometimes difficulties in coordinating seismic design requirements with other demands in new construction, the economical, social, and technical issues related to evaluation and retrofit of existing buildings are far more complex.

This course describes the many issues associated with the risk from existing buildings, including common building code provisions covering older buildings, evaluation of the risks from any one given building and what levels of risk are deemed acceptable, and methods of mitigation of these risks through retrofit. A FEMA program to provide methods to mitigate the risk from existing buildings has been significant in advancing the state of the art, and this program is described in some detail, particularly the model building types used in most, if not all, of the FEMA documents.

The basic concepts used for seismic design or estimation of seismic performance are the same for any building. The development of seismic systems as seen through examples of buildings in the San Francisco Bay Area is particularly relevant to the issues covered in this course, because systems typically evolved due to poor performance of predecessors.

Nonstructural systems in buildings create the majority of dollar loss from buildings in earthquakes, although the quality of structural performance affects the level of that damage.

BACKGROUND

In every older building, a host of new "deficiencies" are identified as the state of the art of building design and building codes evolve and advance. Code requirements change because the risk or the expected performance resulting from the existing provisions is deemed unacceptable. Deficiencies are commonly identified due to increased understanding of fire and life safety, disabled access, hazardous materials, and design for natural hazards. Thus, it is not surprising that many of the older buildings in this country are seismically deficient, and many present the risk of life-threatening damage. It is not economically feasible to seismically retrofit every building built to codes with no or inadequate seismic provisions, nor is it culturally acceptable to replace them all. These realities create a significant dilemma: How are the buildings that present a significant risk to life safety identified? How is the expected performance predicted for older buildings of high importance to businesses or for those needed in emergency response? How can we efficiently retrofit those buildings identified as high risk?

The term seismic deficiency as used in this course is a building characteristic that will lead to unacceptable seismic damage. Almost all buildings, even those designed to the latest seismic codes, will suffer earthquake damage given strong enough shaking; however, damage normally considered acceptable should not be expected in small events with frequent occurrence in a given region, and should not be life threatening. Damage may be judged unacceptable due to resulting high economic cost to the owner or due to resulting casualties. Therefore, conditions that create seismic deficiencies can vary from owner to owner, from building to building, and for different zones of seismicity. For example, unbraced, unreinforced brick masonry residential chimneys are extremely vulnerable to earthquake shaking and should be considered a deficiency anywhere that shaking is postulated. On the other hand, unreinforced brick masonry walls, infilled between steel frame structural members, are expected to be damaged only in moderate to strong shaking and may not be considered a deficiency in lower seismic zones. Seismic deficiencies identified in this course generally will cause premature or unexpected damage, often leading to threats to life safety, in moderate to strong shaking. Buildings in regions of lower seismicity that expect Modified Mercalli Intensity (MMI) levels of not more than VII, or peak ground accelerations (PGA) of less than 0.10g (g = acceleration of gravity), may need special consideration.

Of course, every building with completed construction is "existing." However, the term existing building has been taken to mean those buildings in the inventory that are not of current seismic design. These groups of buildings, some of which may not be very old, include buildings with a range of probable performance from collapse to minimal damage. In this course, the term "existing building" is used in this context.

Changes in Building Practice and Seismic Design Requirements Resulting in Buildings that are Currently Considered Seismically Inadequate

The evolution of building systems in the San Francisco Bay Area was probably driven more by fire, economic, and construction issues than by a concern for seismic performance, at least in the first several decades of the twentieth century, but many changes took place. In the time frame of the twentieth century, due to the rapid increase in understanding of the seismic response of buildings and parallel changes in code requirements, it should be expected that many older buildings will now be considered seismically deficient.

Seismic codes in this country did not develop at all until the 1920s, and at that time they were used voluntarily. A mandatory code was not enforced in California until 1933. Unreinforced masonry (URM) buildings, for example, a popular building type early in the twentieth century and now recognized as perhaps the worst seismic performer as a class, were not outlawed in the zones of high seismicity until the 1933 code, and continued to be built in much of the country with no significant seismic design provisions until quite recently. Figure 1 shows an example of typical URM damage. The first modern seismic codes were not consistently applied until the 1950s and 1960s, and then only in the known regions of high seismicity. Of course, not all buildings built before seismic codes are hazardous, but most are expected to suffer far more damage than more modern buildings.

Even buildings designed to "modern" seismic codes may be susceptible to high damage levels and even collapse. Our understanding of seismic response has grown immensely since the early codes, and many building characteristics that lead to poor performance were allowed over the years. For example, concrete buildings of all types were economical and popular on the West Coast in the 1950s and 1960s. Unfortunately, seismic provisions for these buildings were inadequate at the time, and many of these buildings require retrofit.

Figure 1: Example of buildings with no code design. Damage shows classic URM deficiencies.

- Changes in Expected Shaking Intensity and Changes in Zoning

  Similar to advancements in structural analysis and the understanding of building performance, enormous advancements have been made in the understanding of ground motion, particularly since the 1950s and 1960s. The seismicity (that is, the probability of the occurrence of various-sized earthquakes from each source) of the country, the likely shaking intensity from those events depending on the distance from the source and the local soil conditions, and the exact dynamic nature of the shaking (the pattern of accelerations, velocities, or displacements) are all far better understood. These advancements have caused increases in seismic design forces from a factor of 1.5 in regions very near active faults (on the West Coast) to a factor of 2 to 3 in a few other areas of the country (e.g. Utah; Memphis, Tennessee). The damage to the first Olive View Hospital (Figure 2), in addition to other issues, was a result of inadequate zoning.

- Changes in Required Strength or Ductility

  The required lateral strength of a seismic system is generally traded off with the ductility (the ability to deform in-elastically-normally controlled by the type of detailing of the components and connections) of the system. Higher strength requires lower ductility and vice versa. The most significant changes in codes-reflecting better understanding of minimum requirements for life safety-are general increases in both strength and ductility. Many building types designed under previous seismic provisions, particularly in the 1950s, 1960s, and 1970s, are now considered deficient, including most concrete-moment frames and certain concrete shear walls, steel-braced frames, and concrete tilt-ups. Other buildings designed with systems assumed to possess certain ductility have been proven inadequate. Figure 3 shows typical steel moment-frame damage in the Northridge earthquake caused by brittle behavior in a structural system previously thought to be of high ductility.

- Recognition of the Importance of Nonlinear Response

  Historically, a limited amount of damage that absorbed energy and softened the building, thus attracting less force, was thought to reduce seismic response. Although this is still true, it is now recognized that the extent and pattern of damage must be controlled. Early codes required the design of buildings for forces three to six times less than the elastic demand (the forces that the building would see if there was no damage), assuming that the beneficial characteristics of damage would make up the difference. Unfortunately, buildings are not uniformly damaged, and the change in structural properties after damage (nonlinear response) often will concentrate seismic displacement in one location. For example, if the lower story of a building is much more flexible or weaker than the stories above, damage will concentrate at this level and act as a fuse, never allowing significant energy absorption from damage to the structure above. This concentrated damage can easily compromise the gravity load-carrying capacity of the structure at that level, causing collapse. Similarly, concrete shear walls were often "discontinued" at lower floors and supported on columns or beams. Although the supporting structure was adequately designed for code forces, the wall above is often much stronger than that and remains undamaged, causing concentrated and unacceptable damage in the supporting structure.

  A final example of this issue can be seen by considering torsion. Torsion in a building is a twisting in plane caused by an imbalance in the location of the mass and resisting elements.

  Older buildings were often designed with a concentration of lateral strength and stiffness on one end-an elevator/stair tower, for example-and a small wall or frame at the other end to prevent torsion. However, when the small element is initially damaged, its strength and stiffness changes, and the building as a whole may respond with severe torsion.

  Current codes contain many rules to minimize configurations that could cause dangerous nonlinear response, as well as special design rules for elements potentially affected (e.g., columns supporting discontinuous shear walls). Olive View Hospital featured a weak first story in the main building, causing a permanent offset of more than one foot and near collapse; discontinuous shear walls in the towers caused a failure in the supporting beam and column frame, resulting in complete overturning of three of the four towers. Figure 4 shows a typical "tuck-under" apartment building in which the parking creates a weak story.

Philosophy Developed for Treatment of Existing Buildings

Building codes have long contained provisions to update life-safety features of buildings if the occupancy is significantly increased in number or level of hazard (transformation of a warehouse to office space, for example). As early as the mid-1960s, this concept started to be applied to seismic systems. Many older buildings contained entire structural systems no longer permitted in the code (e.g., URM, poorly reinforced concrete walls), and it quickly became obvious that 1) these components could not be removed, and 2) it was impractical and uneconomical to replace all older buildings. The "new" code could therefore not be applied directly to older buildings, and special criteria were needed to enable adaptive reuse while meeting the need to protect life safety of the occupants. In some cases, an entirely new and code-complying lateral system was installed, while leaving existing, now prohibited, construction in place. This procedure proved very costly and disruptive to the building and was thought to discourage both improved seismic safety and general redevelopment.

Figure 2: Olive View Hospital. A brand new facility that was damaged beyond repair in the 1971 San Fernando earthquake due to a shaking intensity that exceeded what was expected at the site and a design that, although technically complying with code at the time, contained several structural characteristics now considered major deficiencies. The lateral system contained nonductile concrete frames, discontinuous shear walls, and a significant weak story.

Figure 3: An example of a recently designed building with seismic deficiencies not understood at the time of design. In this case, the deficiency was "pre-Northridge" moment-frame connections, which proved to be extremely brittle and unsatisfactory. Hundreds, if not thousands, of these buildings were designed and built in the two decades before the Northridge earthquake (1994).

Figure 4: A 1970s building type with a deficiency not prohibited by the code at the time—a tuck-under apartment with parking at the ground level, creating a weak story. Many of these buildings collapsed in the Northridge earthquake. Sixteen deaths occurred in the Northridge Meadows apartments, or 42% of those directly killed by the earthquake.

Figure 5: A tuck-under similar to Figure 8-4, but much more modern and designed at a time when the weakness of the parking level was more understood. In this case, the detailing of the small wood shear walls at that level was poor. This practice created another set of deficient "existing" buildings.

Figure 6: A tilt-up damaged in 1994. Despite suspicions that the code-required roof-to-wall ties were inadequate, it t...
code cycles and in...
increases in require...
obtain adequate co...
Thousands of tilt-ups...
inadequate connecti...
in the West, althoug...
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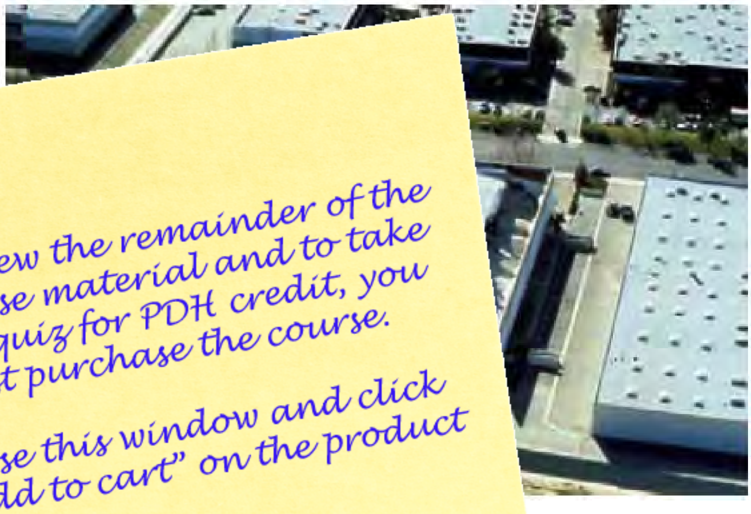

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A philosophy quickly d... ed differently from
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The smaller force levels ... minimum life safety, but not the
damage control of new b... echnically controversial and unproven concept, but
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