Journal of Consumer Attorneys Associations for Southern California
ADVOCATE
February 2010 Issue

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Earthquake Damage

Who is to blame?

Introduction

When is the "big one" going to hit? That is the first question I am asked when people realize I am a Structural/Earthquake Engineer. Although I can't answer their question, I am routinely impressed by the depth of earthquake-related knowledge possessed by Southern Californians and their willingness and interest to initiate conversations on the topic. Most of these conversations ultimately lead to a single question: Are our buildings strong enough to handle the next earthquake?

In order to find the answer to this rather complex question, one should know how earthquakes occur, how buildings behave under earthquake loads, and eventually what the contributing factors are to earthquake damage in buildings. Through discussing these items, the current article answers common questions about the seismic behavior of structures and gives an in-depth description of the causes of building damage during earthquakes.

In the author's opinion, knowing more about earthquakes and the way our buildings behave under earthquake loads will help us improve the way we prepare for and react to these natural events and as a result could diminish their catastrophic consequences in our society.

How do earthquakes occur?

Earthquakes occur as a result of a sudden release of energy in the earth's crust. The waves created by this release of energy radiate in all directions, arrive at a building site, and cause the ground at the base of the building to suddenly move. This movement is transferred up the building and generates forces in the building itself that are proportional to the acceleration of the base motion and the weight (mass) of the building. These sudden forces are typically the main cause of earthquake damage to our buildings.

Under non-earthquake conditions, most of the forces on a building's skeleton (structure) are caused by gravity. These gravity forces, which include the weight of the building, its contents, and its occupants, are essentially constant and not subject to sudden changes in size and direction. These gravity forces are called static forces by earthquake engineers. During an earthquake, however, there are additional forces in a building's structure and these earthquake-related forces change rapidly with time (and are thus called dynamic forces). In other words, the size and direction of the earthquake-related forces in a building continuously change during the course of an earthquake. This dynamic property of earthquake forces makes it a challenge to adequately design and construct buildings to tolerate them.

Building types

Buildings are usually categorized based on the material used in their construction. Common types of structures are steel, concrete, wood, and masonry. Structural elements responsible for supporting the gravity loads are usually well known to building occupants. Most people are familiar with the beams, columns, walls, slabs, and footings that comprise the gravity load resisting system. They provide a continuous and proper load path to keep the building stable under static weight loads.

However, many people are not aware of a second system that supports the lateral loads (seismic and wind loads) imposed on a structure during its lifetime. In engineering terms, this system is referred to as Lateral Force Resisting System, or LFRS. In steel structures, the LFRS can consist of rigid frames, braced frames, steel plate shear walls, or a combination of these systems. In concrete buildings, however, the common LFRSs are concrete shear walls and rigid frames. Wood buildings commonly use wood shear walls, and masonry structures are supported laterally by masonry shear walls. It is also customary to combine these systems to create a more efficient hybrid system depending on the location and function of the building. This combined condition is widely seen in the LFRS of tall and special buildings.

The big one!

Most residents of Southern California naturally want to know when the big one is going to hit. Earth scientists and seismologists working on earthquake prediction constantly study the likelihood of future earthquakes and try to estimate the probabilities of earthquakes occurring in a specific area during a certain period of time. This is typically done by studying the pattern of past earthquakes in order to determine the likelihood of similar earthquakes in the future. The other method often used for predicting earthquakes is to monitor the rate of strain accumulation in a fault. Although the purpose of both methods is to increase the reliability of predicting earthquakes, these predictions can only be expressed in terms of probability rather than a certainty. The main goal of these prediction studies is to make the public aware of the potential for large earthquakes in certain geographic areas and allow them to adequately prepare for a possible event. Engineers, on the other hand, are responsible for creating structures that can withstand certain earthquakes using the limited resources available. Unlike the scientists whose job is to predict earthquakes, structural engineers try to increase public safety by designing the best possible structure given the financial and technical limitations. In other words, the role of a structural engineer is to make the community sleep better at night by creating earthquake resistant structures that deliver an acceptable degree of safety.

Who is to blame?

After an earthquake, one question that comes to mind is “Who is to blame for the damage?” Earthquake damage is often the direct result of construction defects that don’t materialize until the building experiences the earthquake forces it was originally designed to withstand. These defects include deficiencies in the design, construction, or material used at the time the building was constructed.

Design deficiencies may exist as the result of a building not being properly designed according to applicable building codes or design standards. This may be due to the designer not having the knowledge or expertise needed for a particular type of construction, or it could be caused by errors during the design process. A clear example of the latter is when junior engineers in a structural design firm take over the design process, and the designed product is not fully overseen by the responsible professional engineer (i.e., the Structural Engineer of Record). This can happen when a design firm has too many projects or needs to reduce the engineering cost of a building by using a cheaper work force.

Construction deficiencies usually arise when the structure is not built as designed. This could be caused by the construction team not adhering to the design documents or the contractors making substitutions or changes without the knowledge and approval of the architect or structural engineer of record. The latter situation occurs when the contractor is either unaware of the consequences of deviating from the design or deliberately chooses to ignore the design to cut costs. Proper construction is often expensive and it is not uncommon for some contractors to reduce labor and material costs by using substandard construction methods or materials. Proper and timely inspections by the design team can significantly reduce these types of defects.

The other type of construction defect is associated with material deficiencies. The structural engineer assumes certain properties and characteristics for the materials used in the design. Naturally, any deviation from these properties or any defect in the materials used in construction may result in a structure that is significantly different from the designer’s intent. In some cases, material suppliers provide products that have different properties than those specified by the designer. Proper material testing and inspection programs are essential during construction to minimize this type of deficiency.

Another kind of defect that may be caused by either improper design or construction is the lack of serviceability considerations in a building. A good example is the existence of inadequate seismic separations or expansion joints between adjacent buildings. Although each individual building may be properly designed to the applicable building code, the lack of sufficient separation between the two buildings may result in pounding effects and unexpected impact forces at the interface between the buildings. The impacts may not only cause local damage to the exterior of the building, but can also affect the dynamic characteristics of the structures and produce unexpected structural damage. Another example of this condition is when the building skin is not properly designed or detailed to accommodate the predicted lateral movement (drift) of a building during an earthquake. For instance, if the maximum building drift during an earthquake is 1/2" between floors while the glass glazing attached to adjacent floors can only accommodate 1/4" of relative displacement, the additional displacement may compromise the integrity of the building's skin. This may manifest as structural or waterproofing problems following an earthquake.

Although the construction defects described above appear to be the major causes of damage observed in typical buildings following an earthquake, there are other aspects that can also play a significant role in contributing to the damage. These elements are mainly associated with the fact that our building codes and standards of practice are far from perfect, partly due to the limitation of our knowledge about the nature of earthquakes.

As described above, our knowledge of earthquakes is primarily based on past experience. Each new earthquake teaches new lessons to the engineering community and helps it improve its design practices. This doesn't mean our current designs are unsafe. On the contrary, the knowledge obtained from previous earthquakes has enabled us to design and build structures that possess an acceptable degree of life safety, even during severe earthquakes. The expertise gleaned from examining previous earthquakes is reflected in today's building codes and state-of-the-art design guidelines; however, the fact that no two earthquakes are the same indicates that the level of our understanding of earthquakes, and consequently the current design standards, are constantly works in progress.

In addition to the items described above, aging and deterioration of structural elements can significantly contribute to the earthquake damage in buildings. *Figures 1* through *8* depict some examples of structural damage during historic earthquakes.

Most people believe that the severity of an earthquake is solely reflected by its magnitude measured on the Richter scale. Although magnitude is a measure of the energy released by an earthquake, it is only one of many parameters that define earthquake severity for a building. Other parameters like earthquake duration, displacement, velocity, acceleration, frequency content, depth, site distance to epicenter, soil conditions, and soil-foundation-structure interaction may also play a critical role in the kinds of structures affected by a particular earthquake and the type of damage caused by that earthquake.

For instance, earthquakes with large, slow movements (long period) tend to create more damage in taller and more flexible buildings such as skyscrapers and towers. On the other hand, earthquakes with small, fast movements (short period) usually target shorter, less flexible structures. That is why the generalizations that tall buildings are more likely to collapse and short buildings are safer during an earthquake, without considering the characteristics of the ground motion, are invalid. For the same reason, a smaller magnitude earthquake may cause more damage to a certain building than a larger earthquake with different properties. The other item to note is that our knowledge about the behavior of structural systems and building materials is limited. After each major earthquake, we realize that some buildings do not behave the way our theoretical methods predicted. This was clearly observed in steel structures after the Northridge Earthquake in California and the Kobe Earthquake in Japan.

Northridge Earthquake shakes Southern California

On the morning of January 17th, 1994, a magnitude 6.7 earthquake shook Southern California. Most of the damage was observed in San Fernando Valley, Simi Valley, and other areas north and west of the City of Los Angeles. The earthquake was reported to be the most costly earthquake in US history, with an estimated loss of twenty billion dollars. As reported by the United States Geological Survey (USGS), sixty people were killed, more than 7,000 injured, and about another 20,000 displaced. In Los Angeles, Ventura, Orange, and San Bernardino Counties, damage to more than 40,000 buildings was reported.

Following the earthquake, there was widespread damage to the beam-to-column connections used in many steel buildings. These connections, now known as Pre-Northridge connections, are part of the LFRS of steel buildings, and their failure raised major questions regarding the behavior of this commonly used connection. *Figure 9* illustrates the typical damage observed in the beam-to-column connections of steel buildings following the Northridge Earthquake. Before the Northridge earthquake, steel buildings were believed to have good seismic performance because their ductility and flexibility allowed them to survive large ground motions. After the Northridge Earthquake and the Kobe, Japan earthquake in 1995, the observed damage in numerous steel structures surprised many owners and building experts.

In California, many insurance claims and lawsuits were filed due to losses following the Northridge Earthquake. As experts examined these cases, a variety of possible causes were considered. The severity of the problem and extent of damage were so high that Federal Emergency Management Agency (FEMA) initiated a joint venture between Structural Engineers Association of California (SEAOC), Applied Technology Council (ATC), and Consortium of Universities for Research in Earthquake engineering (CUREe) termed the SAC project to study the observed damage in the beam-to-column connections of steel buildings.

The study found that local connection defects, including the flaws associated with field welding of beam-to-column joints using backing bars, were the major contributors to the observed damage. Based on these findings, the use of traditional Pre-Northridge connections became prohibited in new construction, and modified methods of rigid beam-to-column connection were born. Through testing, these connections demonstrated improved seismic behavior compared to Pre-Northridge connections. Dogbone or Reduced Beam Section (RBS), SitePlate, and SlottedWeb are a few examples of this group of enhanced beam-to-column connections, also referred to as Post-Northridge connections.

The role of structural and earthquake engineering experts in evaluating the observed damage in steel buildings was crucial to supporting the lawsuits and insurance claims filed after the earthquake. Most of these cases were more complicated than a typical construction defect case. The fact that many of the damaged steel buildings were designed and built according to codes and practices common at the time of construction created a lot of confusion and contributed to the complexity of the litigation. The Northridge Earthquake proved to the engineering community that steel buildings were susceptible to earthquake damage and that the previous assumptions about the behavior of these structures needed to be revised to avoid similar problems in the future.

What do we need to know?

There are earthquakes occurring somewhere on the planet every hour. Most of them are either too small to be felt by people or they occur in remote locations far from buildings. In California we experience a large number of these natural events. The good news is that our building codes and construction standards are among the best in existence, and our structures are designed and constructed to a higher standard than most other places in the world.

However, each major earthquake challenges our existing theories and assumptions. There is no doubt that Southern California is due for a sizeable earthquake. It is not clear exactly when it is going to happen or how powerful it is going to be. What we do know is that by increasing our knowledge of earthquakes and improving our construction practices, we can diminish the potentially devastating effects of large earthquakes.

Surprisingly, some people think that if all building codes and standards are followed in the design and construction of a building, the product is going to be "Earthquake Proof". In earthquake engineering, the term "Earthquake Proof" is unrealistic. Our knowledge of the behavior of structural systems during earthquakes is limited, and new seismic events teach us new lessons. The provisions of building codes are written to achieve a certain level of safety under code-defined design earthquakes. The established level of safety is different among building standards and is determined by the code writers and lawmakers. In other words, our structures are not typically designed to withstand the most extreme scenario and as a result are expected to suffer some degree of damage during a severe earthquake. The main goal of the building code is to achieve a high level of life safety while spending an acceptable amount of money and resources. This is a complicated optimization problem that is periodically reviewed and modified in building codes and standards. The reason our structures are not designed for the largest theoretically possible earthquake is the extremely high cost of such a design. This implies that even properly designed buildings may suffer some degree of damage during some seismic events. After an earthquake, structural and earthquake engineering experts will perform investigations and assess the earthquake damage. Qualified experts with extensive training and knowledge of building codes and standards of practice and care can help the court to understand the role of each party involved in the construction process and help determine which party is responsible for the observed damage and loss.

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Figure 1. Damage due to soil liquefaction in apartment buildings in Niigata, Japan, Niigata Earthquake (magnitude 7.5), June 16, 1964. Liquefaction is a phenomenon that happens when the strength of saturated soil is reduced by the earthquake's sudden movements and as a result the soil behaves like a heavy liquid. Photo courtesy of NGDC (www.ngdc.noaa.gov).

Figure 2. Damage due to ground deformation in a school in Anchorage, Alaska Earthquake (magnitude 9.2), March 28, 1964. Photo courtesy of NGDC (www.ngdc.noaa.gov).

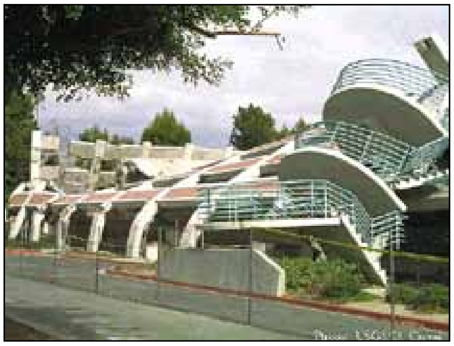

Figure 3. Severe damage in a concrete parking structure, California State University, Northridge, Northridge Earthquake (magnitude 6.7), January 17, 1994. Photo courtesy of USGS (www.usgs.gov).

Figure 4. Soft story damage in a building during Northridge Earthquake (magnitude 6.7), January 17, 1994. Soft story is typically the result of one the stories being laterally softer than the others due to large window and door openings or parking garages. Photo courtesy of USGS (www.usgs.gov).

Figure 5. Soft story damage in a building during Loma Prieta Earthquake (magnitude 6.9), October 17, 1989. Photo courtesy of USGS (www.usgs.gov).

Figure 6. San Francisco Bay Bridge 2nd level collapse, Loma Prieta Earthquake (magnitude 6.9), October 17, 1989. Photo courtesy of USGS (www.usgs.gov).

Figure 7. Massive earthquake and fire damage in San Francisco, San Francisco Earthquake (magnitude 7.8), April 18, 1906. The fire resulting from the earthquake was a major contributor to the losses. Photo courtesy of USGS (www.usgs.gov).

Figure 8. The Agassiz statue, Stanford University, San Francisco Earthquake (magnitude 7.8), April 18, 1906. Photo courtesy of USGS (www.usgs.gov).

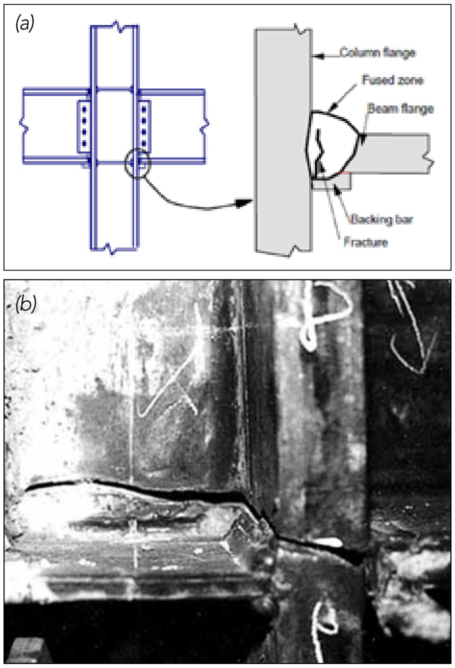

Figure 9: (a) Typical fracture initiation in Pre-Northridge beam-to-column connections in steel buildings; (b) Propagation of crack into the column flange and web. Photos courtesy of FEMA (FEMA-267: SAC Interim Guidelines and FEMA-350: Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings, June 2000).

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