# OBSERVATION AND ASSESSMENT OF FAILURE REASONS OF EARTHQUAKE DAMAGE TO BUILDINGS

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Abstract: Because many people are killed by the collapse of buildings in great earthquakes such as the Chi-Chi earthquake in Taiwan, a very important issue in reducing the total death toll in earthquakes is building safety. The period of these collected earthquakes is from 1906 to 1999 and the areas cover all over the world such as the United States, Turkey, Japan, Taiwan, China, etc. The failure reasons of earthquakes damage to buildings have been broadly classified according to five characteristics: 1) Failure on zoning; 2) Failure on design (building code conformance); 3) Failure on design (building code non-conformance); 4) Failure on superior; and 5) Other reasons. By way of this observation and the further statistical analysis, the failure reasons of buildings from the past earthquakes can be assessed and applied to reduce casualties and damage in future events.

Keywords: Earthquake, Collapse of buildings

## 1. INTRODUCTION

Recently, there has been a serious of major earthquakes. These great earthquakes hit our world and caused significant terrible losses. Many of the victims, who died from two of these biggest earthquakes in that period, the Chi-Chi earthquake in Taiwan and Kocaeli earthquake in Turkey, still lie buried amid the collapsed homes. In fact, the death toll of the Turkey earthquakes expects more than 40,000 and the total death toll from the Taiwan earthquakes is about 2,350. Furthermore, the death toll from earthquakes in the last 100 years is close to 3 million and it probably makes earthquakes the most terrible natural disaster in the world [22].

Each time a damaging earthquake occurs; various groups such as scientists, engineers, and others collect new information and fresh data. These data are useful in designing the buildings, planning where to build and not to build, and knowing how to prepare for an earthquake so personal safety can be improved. However, even though a great deal of time and effort has put into the development of better safety of buildings, collapsed buildings can still be counted by the thousands. For instance, 600,000 buildings collapsed in the 1976 Tangshan (China) earthquake, 400 structures were destroyed in the 1985 Mexico City, 28,000 buildings were destroyed in the 1989 Loma Prieta (California) earthquake, and 17,000 buildings totally collapsed in the 1999 Chi-Chi (Taiwan) earthquake [1,2,14,22].

In fact, many people are killed by the collapse of buildings in earthquakes and a very important element in the reducing the loss of lives in earthquakes is building safety. It relies heavily on the knowledge and skills of the engineer and lessons learned from past earthquakes. For this reason, the purpose of this study is to focus on assessment of the failure reasons of buildings from the past earthquakes because a study of the large and damaging earthquakes of the past can be applied to reduce casualties and damage in future events.

## 2. METHOD OF OBSERVATIONS AND ASSESSMENT

To obtain useful engineering information from the observation of building damage, the historic data and information of certain high intensity earthquakes are collected. The period of these earthquakes is from 1906 to 1999 and the areas cover all over the world such as the United States, Turkey, Japan, Taiwan, China, etc. Moreover, the failure reasons of earthquakes damage to buildings have been broadly classified according to five characteristics: 1) Failure on zoning; 2) Failure on design (building code conformance); 3) Failure on design (building code non-conformance); 4) Failure on superior; and 5) Other reasons

### *2.1 Failure on zoning*

Arguably one of the most important reasons to cause building failure is zone selection. Without a good zone conditions a building or other structure is certain to fail in an earthquake. In fact, zone conditions generally differ from each other with regard to the likelihood of earthquakes and with regard to their probable frequency and intensity [8]. Primarily the historical records of earthquakes and faults in the region can determine the zone situation. For instance, the great activity zones in the United States locate in the western states, Alaska, and some island areas because of the high frequency and intensity of past earthquakes in their local historic records [13].

On the other hand, the soil condition could be very important to influence the damage. A good soil, such as bedrock, is the best site to build because the foundation of buildings can be firmly attached to solid rock. For this reason, the structure moves with ground as a unit when it moves. However, a loose-soil is much less desirable because the soil will respond by moving in different directions and amounts at the same time [2].

### *2.2 Failure on design (building code non-conformance)*

The observation of earthquake damage has been a very important factor in the development of methods for the design of earthquake resistant buildings. In fact, the basic seismic requirements of building codes are largely based on observations by competent professionals. The useful information of earthquakes will be referred to as having had a major influence on the development of seismic code. This is because many residents, including consulting engineers and municipal officials, who are directly concerned with building codes and damage to buildings, have observed their effects [8].

While the building code plays an important role in the development of building designs, its conformance will likewise influence its earthquake resistance. However, some researchers stated that building code of structural designs is inadequate to prevent damages from earthquakes. Bolt [1] argued that the building code is still unsophisticated, especially if the architectural form is unusual or the materials are untried. Fisette [7] concluded that building codes only established minimum standards. In fact, building code requirements have to be increased because building technologies have improved as time goes on. Nevertheless, even after a great earthquake – 1906 San Francisco – buildings were still designed without consideration of the earthquake force in California building code until 1933, and the influence of building height on seismic forces was not considered until 1943 [8].

### *2.3 Failure on design (building code conformance)*

The current design philosophy is to keep seismic stresses within the elastic range for earthquakes that can be expected to occur once or twice moderate level during a building's life span, and to prevent collapse for larger, less frequent earthquake (EQE 1995). It means the 100% earthquake resistant structure dose not exist in any modern city. However, a carefully designed building is the best survival insurance available in earthquake disaster. The role of a knowledgeable architect is invaluable because major structural damage may result in grave risk to human life if a building has not been designed and constructed to absorb the swaying ground motions.

One of the most common failure reasons on design is the neglect of building shape. Several researchers have already concluded the importance of this configuration such as Bolt [1], King and Jackson [12], and Brumbaugh [2]. From the evidence of the past earthquakes, buildings have irregular shapes suffer great damage than buildings have regular shape. Buildings with irregular shape, such as L, T, U, and H are more vulnerable than regular one, such as a box-like shape. Buildings with wings or differ levels in different parts of a structure are more dangerous. In addition, buildings with varying height may cause problems because the various levels will cause the building to vibrate at two different frequencies, rather than moving as unit [8]. Moreover, probably, the most general problem created by inappropriate design practices now a day is the soft-story approach. It means a weak level or story within a building susceptible to collapse during ground shaking [2]. It exists commonly in two recent earthquakes, Chi-Chi earthquake in Taiwan and Kocaeli earthquake in Turkey [14,16].

### *2.4 Failure on supervision*

Another failure reason comes from the poor quality of construction. An earthquake strengthening building requires not only structural plans and specification but also plans and specifications for architectural work and for mechanical and electrical work. For the purpose of coordination of these parties, qualified supervision may be the most essential factor to construct the work. Without qualified construction system and supervision, buildings cannot resist the sudden movement from an unexpected earthquake.

### *2.5 Other reasons*

Finally, any other possible reason that may cause building failure is classified into this group. It includes the type of structural system and materials. For instance, one report from Manshield University summarized that mobile home units statistically tend to be subject to great damage from equivalent intensities of shaking than do wood-frame dwellings (King and Jackson 1998).

## 3. OBSERVATIONS AND ASSESSMENT OF EARTHQUAKE DAMAGE TO BUILDINGS

In order to analyze damage to buildings, fourteen earthquakes are collected from 1906 to 1999 all over the world. These earthquakes are listed in date order, not in magnitude order (see table 1).

Table 1 Earthquakes in past times (location, date, country and magnitude)

| Location | Date | Country | Magnitude |
|---|---|---|---|
| San Francisco | 1906/04/18 | U.S. | 6.9 |
| Leeward Islands | 1974/10/08 | U.S. | 7.5 |
| Tangshan | 1976/07/28 | China | 7.8 |
| Carlisle | 1979/12/25 | England | 5.0 |
| Cadoux | 1979/06/02 | Australia | 6.25 |
| Campania-Basilicata | 1980/11/23 | Italy | 6.9 |
| Loma Prieta | 1989/10/17 | U.S. | 7.0 |
| Hokkaido Nansei-oki | 1993/07/12 | Japan | 7.8 |
| Northridge | 1994/01/17 | U.S. | 6.4 |
| Kobe | 1995/01/17 | Japan | 7.2 |
| Asana-Ceyan | 1998/06/27 | Turkey | 6.2 |
| Kocaeli | 1999/08/17 | Turkey | 7.4 |
| Athens | 1999/09/07 | Greece | 5.9 |
| Chi-Chi | 1999/09/21 | R.O.C. | 7.6 |

Source: [3,4,5,6,7,9,13,14,15,16,17,19,20,21,22]

Every year there are many people killed by earthquakes. Reports of dreadful loss of life from earthquakes around the world continue. In 1976 of July 28 shock (local time) near Tangshan, China, probably kill over 600,000 people; and over 40,000 were killed in an earthquake near Kocaeli in Turkey on August 17 in 1999 (see table 2). In addition, hundreds of thousands were injured, and the earthquakes produced enormous economic losses. Most casualties were directly caused by the collapse of weak houses and buildings.

Table 2 Casualties and damage from earthquakes (1906-1999)

| Location | Death | Homeless | Buildings Destroyed |
|---|---|---|---|
| San Francisco | Over 3,000 | 225,000 | 28,188 |
| Leeward Islands | N.A. | N.A. | Over 20 |
| Tangshan | 600,000 | 700,000 | 650,000 |
| Carlisle | N.A. | N.A. | N.A. |
| Cadoux | N.A. | N.A. | Over 100 |
| Campania-Basilicata | 4,689 | 170,000 | Over 200 |
| Loma Prieta | 63 | N.A. | 28,322 |
| Hokkaido Nansei-oki | 196 | N.A. | 2,520 |
| Northridge | 57 | Over 1,000 | 15,305 |
| Kobe | 5,500 | 300,000 | 180,000 |
| Asana-Ceyan | 150 | N.A. | N.A. |
| Kocaeli | 40,000 | 400,000 | 180,000 |
| Athens | 143 | N.A. | 40 |
| Chi-Chi | 2,350 | N.A. | 17,000 |

Source: [3,4,5,6,7,9,13,14,15,16,17,19,20,21,22]

Five characteristics of the failure reasons of earthquakes damage to buildings are shown in table 3. They include: 1) Failure on zoning; 2) Failure on design (building code conformance); 3) Failure on design (building code non-conformance); 4) Failure on superior; and 5) Other reasons. Since data is too hard to be collected completely, many items are still label to N.A. in this study.

In general, if a building is new, it may be constructed by reinforced concrete or steel frame. According to table 3, we can find out a tendency of failure on design (building code non-conformance) is much more severe than failure on design (building code conformance) if earthquake time before 1980, but after 1980 is not.

Comparing to Kobe and Northridge earthquake, the vast majority of deaths in Kobe occurred in the collapse of housing built by using traditional Japanese methods. The Traditional Japanese housing construction is based on a post-and-beam method with little lateral resistance. Exacerbating the problem is the practice of using thick mud and heavy tile for roofing, resulting in a structure with a very heavy roof and little resistance to the horizontal forces of earthquakes. On the other hand, U.S.-style frame housing with lightweight roofs is now coming into use in Japan and newer housing constructed using these methods had little or no damage from the earthquake.

While there are more similarities than differences in structural performance in the Kobe and Northridge earthquakes, there are important differences that explain why the Kobe Earthquake was so much more damaging. Some of the lessons from these differences apply only to Japan; others apply to all areas of the world at risk from earthquakes.

Another significant difference between the Kobe area and the Northridge area is the quality of the soils. Because of a severe shortage of available land, much of modern urban in Japan, including Tokyo is built on the worst soil possible for earthquakes. Much of the newer construction in Kobe, particularly larger buildings, is built on very soft, recent alluvial soil and on recently constructed near-shore islands. Most of the serious damage to larger commercial and industrial buildings and infrastructure occurred in areas of soft soils and reclaimed land. The worst industrial damage occurred at or near the waterfront due to ground failures-liquefaction, lateral spreading, and settlement.

## 4. DISCUSSION

By far the shaking of the ground is one of the most important hazards for our human beings. The shakes cause objects to fall and structures to collapse partially or totally. A great deal can be learned about building safer structures by studying these effects and assessing the failure reasons from the past as soon as possible on the spot, and many valuable studies of this kind have been published.

Unfortunately, structural damage in historical earthquakes is usually not easy to evaluate. For some major historical earthquakes, the effects have been recorded in other ways. For example, the damage resulting from one that struck Basel, Switzerland, on October 18, 1356 is represented for posterity in a woodcut done 2 centuries later. Nevertheless, the five criteria we discuss the reasons of buildings collapse or damage in this study were discussed in the following sections.

Table 3 Five characteristics of the failure reasons of earthquakes damage to buildings

| Location | Failure on zoning | Failure on design (Building code non-conformance) | Failure on design (Building code conformance) | Failure on supervision | Other reasons |
|---|---|---|---|---|---|
| San Francisco | N.A. | 27,839 | N.A. | N.A. | N.A. |
| Leeward Islands | N.A. | N.A. | Over 10 | N.A. | N.A. |
| Tangshan | Over 100 | Over 420,000 | Over 100,000 | N.A. | N.A. |
| Carlisle | N.A. | N.A. | N.A. | N.A. | N.A. |
| Cadoux | N.A. | Over 80 | N.A. | N.A. | N.A. |
| Campania-Basilicata | N.A. | Over 150 | Over 10 | N.A. | N.A. |
| Loma Prieta | Over 800 | Over 800 | Over 6400[a]<br>Over 8000[b] | N.A. | N.A. |
| Hokkaido Nansei-oki | Over 100 | Over 500 | Over 500 | Over 10 | Over 400 |
| Northridge | Over 200 | 250 | 14,600 | Over 50 | N.A. |
| Kobe | Over 50 | Over 36 | Over 394[a]<br>Over 3535[b] | Few | Over 500 |
| Asana-Ceyan | N.A. | N.A. | N.A. | N.A. | Over 100 |
| Kocaeli | Over 1,000 | Over 50,000 | Over 50,000 | Few | Over 100 |
| Athens | N.A. | N.A. | N.A. | N.A. | Over 100 |
| Chi-Chi | Over 500 | Over 2000 | Over 3000[a]<br>Over 5000[b] | Over 250 | Over 20 |

a: weak first-story system b: normal buildings

Source : [3,4,5,6,7,9,13,14,15,16,17,19,20,21,22]

*4.1 Failure on zoning*

The ground shaking damages the soils and foundation materials under structures, and much of the destruction in earthquakes is a consequence of this ground failure. This type of hazard can be minimized by taking care to construct buildings off the fault traces, as specified by geological information. In fact, a few structures were damaged in our collected data because special geological maps have now been drawn for various areas throughout the world. For example, a map of California published by the Division of Mines and Geology shows all known active faults (historical rupture, Quaternary displacement, and so on) in the state. Such broad maps are, of course, not foolproof because some active faults may not have been detected at the time of publication (such as the 1971 San Fernando faulting, the 1975 faulting south of Oroville and the 1983 Coalinga faulting), and some faults marked as active may not again be the source of large earthquakes.

The 1971 San Fernando earthquake north of Los Angeles provided firsthand observations of the effect of surface rupture on various types of structures. Flat-lying San Fernando is almost entirely built up with single-story wood-frame houses. The fault offset (up to 1 meter vertically and 1 meter laterally) produced on structure collapses, no deaths, and few serious injuries. Damage to houses along the fault scarp ranged from minor to that requiring expensive repairs, and a few homes were completely demolished. Water and gas pipes crossing the fault rupture were often compressed and ruptured, and concrete roadbeds were crushed and over thrust.

*4.2 Failure on building code non-conformance design*

More people are killed by the collapse of structures in earthquakes than by any other cause. This was clear in the 1989 Loma Prieta earthquake when 41 people perished in the collapse of the Interstate-880 freeway in Oakland, or in Northridge where the largest fatality count came from the collapse of an apartment building. Thus, a very important element in the reduction of the loss of lives in earthquakes is structural safety.

In 1933, the first earthquake provisions were incorporated in the building code of the City of Los Angeles. The first building code provisions for earthquake resistant building design specified a single seismic coefficient for determining the design forces. However, problem in structural safety is deciding how safe a building should be. This is in part an economic question and to ride them out without significant damage. The cost of such structures may be more than its economically feasible in some situations. The question then becomes: How strong should a building be? The question has been formulated as follows: How safe should a building be? According to the Uniform Building Code (UBC), a structure should, in general, be able to:

(1) Suffer no damage from a minor level of earthquake ground motion
(2) Respond to a moderate level of earthquake ground motion without structural damage
(3) Respond to a major level of earthquake ground motion having an intensity equal to the strongest experienced or forecast for that location, without collapse

This approach protects occupants first and then builds in an economically reasonable amount of survivability of the structure to minimize economic loss.

*4.3 Failure on building code conformance design*

The single- and two-story wood-frame houses typical of the United States, and the light wooden buildings of Japan are examples of places that are among the safest to be in an earthquake. These buildings can suffer damage, but it is minor in comparison with the total collapse that can and does occur elsewhere. But even in these countries the trend is to experiment with new materials and change the design of ordinary buildings, so that the increase in seismic risk may not be recognized until an earthquake occurs. For example, the 1971 San Fernando earthquake in California demonstrated that well-constructed concrete-block structures, unlike older weak masonry, have a high seismic resistance. However, some newly completed wood-frame houses of split-level design, presumably built to code, collapsed. Unlike the older houses with quite small windows and a separate garage, there was insufficient shear bracing in the narrow garage walls at ground level. Shaking collapsed the garage, causing the rooms above to drop into the garage, many on the family cars.

Numerous total and partial collapses of buildings were recorded. Collapses were observed in both first story and mid-height stories. Weak (insufficient strength) and soft (insufficient stiffness) story failures were widespread in Loma Prieta, Northridge, Kobe, and Chi-Chi. Such failures were often a result of geometric changes in the seismic framing system to accommodate changes in building occupancy, with examples of the latter including (a) retail occupancy to residential occupancy, and (b) parking to residential occupancy. Other failures have been attributed to (a) mid-height changes in the type of framing system, typically a transition from steel reinforced concrete to reinforced concrete, and (b) the use of now outdated design lateral force profiles.

Otherwise, vertical and plan irregularity in stiffness and/or strength has been cited as the main cause for collapse of many buildings in past earthquakes. Buildings located on street corners are prime candidates for plan (torsional) irregularity. Often these buildings are composed of moment frames (and windows) on the street frontages, and stiff infill masonry or concrete walls supported by moment frames on the remaining faces – often resulting in a large eccentricity of the centers of mass and stiffness, and significant torsional response in the event of an earthquake.

Aesthetic requirements and architectural constraints can often result in vertical irregularity, namely, a large change in strength and stiffness in a seismic framing system between two adjacent stories. An apparent example of vertical irregularity in a building can often be seen a modern reinforced concrete building incorporating structural walls, and the degree of structural damage immediately below the regular framing.

To prevent damages from earthquakes, the first requirement is to determine whether a building should be strengthened. It is safe to say that building must be strengthened if it was designed and built before the applicable building code contained earthquake resistant design requirements. This situation often exists, because the inclusion of earthquake requirement in building codes is relatively recent, for example, 1933 in the City of Los Angeles. Even if a building was designed under a seismic code, it may have deficiencies, and this can only be determined by a review of the structural design and an inspection of the building.

If strengthening is necessary, the strengthened building structure should meet the same requirements as prescribed for a new building, relative to vertical bracing elements, diaphragms, and foundations.

### *4.4 Failure on supervision*

Observations of earthquake performance demonstrate clearly and repeatedly the need for punctilious attention to design, detail, and construction. In particular, structures that rely on ductile response and that do not provide multiple load paths to the foundation require dedicated, professional inspection to ensure that required ductile details are properly implemented. The designer must ensure that construction drawings and documents are clear and unambiguous, and that actual conditions of construction do not interfere with the behavior intended in design.

As examples of the importance of construction, inadequate details at the base of columns are believed to have been contributory to the column failure. Improper anchorage of transverse reinforcement has resulted in failure of confinement in columns and improperly executed construction joints in shear walls have resulted in movement and damage along the joints. Numerous other examples where poor construction and material quality contributed to building failures can be found.

### *4.5 Other reasons*

Finally, mobile home is discussed in this section. A mobile home is a factory-built dwelling built entirely of lightweight metal construction or a combination of a wood and steel frame structure. In this case, the exterior is typically protected with siding of wood, aluminum or fiberglass.

Mobile home units statistically tend to be subject to greater damage from equivalent intensities of shaking than do wood-frame dwellings. In an earthquake, the typical jacks on whom the coach is placed will tip, and the coach will fall off some or all of its supports. It is not uncommon for the jacks to punch holes through the floors of he coach in this process. The mobile home unit usually remains relatively undamaged. The major problem is that even at these relatively low damage amounts, the mobile home becomes uninhabitable; it must be returned to a foundation, re-leveled and reconnected to utilities. A corner foundation would typically prevent the coach from falling off its base and the damage would be less severe.

## 5. CONCLUSION

As suggested: "Earthquakes don't kill people; buildings kill people." This is a bit too shortsighted, but certainly the failure of structures is a major cause of loss of life. Building safety relies heavily on the knowledge and skills of the engineer and lessons learned from past earthquakes. If we understand why lives are lost and buildings fail, this knowledge may be used in the future to eliminate the causes, or at least to reduce the magnitude of loss.

In this study, the causes of damage were attributed to one or a combination of the following: 1) Failure on zoning; 2) Failure on design (building code conformance); 3) Failure on design (building code non-conformance); 4) Failure on superior; and 5) Other reasons. Based on the historical data analysis by using these causes, we can find out that most of the buildings were damaged by failure on design (either building code non-conformance or conformance). Moreover, the causes of failure on design (building code non-conformance) seems to be much more severe than failure on design (building code conformance) before 1980, but after 1980.

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