The 2008 Sichuan Earthquake

Assessment of Damage and Lessons Learned

By H. Kit Miyamoto, M.S., S.E., Amir S.J. Gilani, Ph.D., S.E., and Tom Chan, M.S., S.E.

The 2008 Sichuan Earthquake was a large-magnitude event that caused unprecedented casualties and damage. Close to 90,000 people were classified either as fatalities or as unaccounted for. More than 4 million people were displaced, and the number of collapsed or seriously damaged structures exceeded 25 million. The reconstruction cost alone (not including financial losses) is estimated at over US$150 billion. As astounding as these numbers seem, they were not unexpected, given the region's seismicity, its population growth, and the local design and construction practices.

This area of China was classified as a moderate zone (similar to Zones 2 to 3 in the corresponding U.S. codes). However, close examination of past events shows that this site and its surroundings have historically been susceptible to large earthquakes. China's rapid economic growth over the past three decades has resulted in major industrial development, population growth, and increased building construction in the affected area. Unfortunately, not all the commercial and residential buildings were designed, detailed, or constructed to provide adequate life-safety and property protection. The schools and hospitals were especially hard-hit in this earthquake. For collapsed buildings, the lack of ductility, the absence of a well-defined load path, the building design irregularity, and the construction practice and quality control were the primary contributing factors. Many schools constructed with unreinforced masonry (URM) walls collapsed. Nonductile reinforced-concrete (RC) buildings performed slightly better: Many of them sustained significant damage. Light industrial buildings also fared better; however, many of these structures had equipment and nonstructural damage, resulting in extended business interruptions.

While some of the surveyed damage is unique to China, many observations also apply to other locations, including many parts of the United States. For example, in past earthquakes in California, URM and nonductile RC buildings have performed poorly; nonstructural and equipment damage has been widespread even from moderate earthquakes, leading to financial losses; and lifeline damage and interruptions have occurred. Fortunately, robust assessment techniques and both conventional and innovative retrofit strategies are available to address such vulnerabilities.

Figure 1: URM wall and RC floor plank collapse, Juyuan Middle School.

The Seismic Event

The May 12, 2008, magnitude 7.9 Sichuan (Wenchuan) Earthquake struck along one of the faults at the base of the Longmenshan Mountains, approximately 1,550 kilometers (1,000 miles) southwest of Beijing, China. This shallow earthquake occurred on relatively stiff soil, and, as such, large seismic waves reached the surface and propagated rapidly without losing much energy. This resulted in a rupture length of more than 200 kilometers (130 miles). This event is classified as an X on the Modified Mercalli Intensity (MMI) scale, indicating violent shaking and heavy damage. The main shock was followed by a number of aftershocks, including a magnitude 6.0 aftershock on May 25th, 13 days after the main shock, which caused additional casualties and damage.

This area of China was assigned a moderate seismicity in seismic design maps. However, several large earthquakes had previously occurred in the vicinity. The 1933 Diexi Earthquake occurred nearly 80 kilometers (50 miles) from the epicenter of the 2008 earthquake, destroying many towns and villages and causing more than 9,000 fatalities. The strong-motion instrumentation program in China is administered by the China Earthquake Networks Center. In the Sichuan Province, an instrumentation program comprising more than 200 stations, including an array of 60 sensors along the Longmenshan Fault, was in place at the time of the 2008 earthquake. Very high horizontal and vertical ground accelerations (on the order of 0.6g) were recorded. Such high values point out the need to revise the design maps for this area.

The most severe damage was primarily concentrated along a band close to the rupture zone. Due to the directionality of the fault rupture, damage was most extensive perpendicular to the rupture direction. For many structures, if the lateral-load resisting members were stronger perpendicular to the fault, they fared better; whereas, if the lateral-load-resisting members were weak in that direction, severe damage or collapse followed. As shown in *Table 1*, the human and financial costs associated with this earthquake are astounding and tragic.

Our team was one of the first to visit the site. This article presents the results from the reconnaissance survey, attempts to describe the causes for the disproportional failures observed in certain construction, presents cost-effective retrofit options available, and briefly discusses a risk management program under way to mitigate similar types of damage in Turkey.

Table 1: Estimated Damage from 2008 Sichuan Earthquake.

Human Loss	**Fatalities**	**Missing**	**Casualties**	**Evacuated**	**Displaced**
	69,000	19,000	375,000	15 million	4.5 million
Infrastructure Damage	**Buildings**	**Dams**	**Roads**	**Bridges**	**Water Pipelines**
	26 million*	2,400	53,000 km	3,000	47,000 km

* Includes 5 million collapsed.

STRUCTURAL PERFORMANCE

discussion of performance issues relative to extreme events

Figure 2: Soft-story collapse, Hanwang Hospital.

Figure 3: Captive column failure, Hanwang High School.

Summary of Observed Damage

Unreinforced masonry (URM) bearing walls, hybrid URM column-concrete beam, and cast-in-place reinforced concrete (CIP-RC) moment frames were the most common construction for residential and commercial buildings, including schools and hospitals.

The URM buildings were the most vulnerable, and such structures have fared poorly in other earthquakes throughout the world. In the United States, many building collapses in past earthquakes in California and elsewhere were attributed to such construction because of its lack of ductility. In China, the problem was compounded when a unique system using URM walls and columns with reinforced-concrete (RC) beams, intended to confine the precast RC slabs, was used in design. In most cases, these slabs were not anchored to the beams and therefore did not provide any diaphragm action to distribute loading to the columns and walls, and they simply collapsed.

Multistory residential and commercial buildings using nonductile RC framing also fared poorly. The main causes of damage were a soft story at the ground, a lack of confinement for the concrete columns and joints, and a captive column failure. In many buildings, infill URM or partition walls were used between RC columns. These walls typically terminated above the first story to allow for a parking garage at the ground level and introduced a weak or soft story at the base of the building, resulting in single-story side-sway collapse at ground level. Additionally, many infills did not extend the full height of a story because of windows or other openings. This configuration reduced the clear height of columns and prevented the formation of ductile flexural hinging, as well as caused brittle shear or compression failure of columns, compromising their vertical-load-carrying capacity.

Many schools and hospitals collapsed in this earthquake. The death toll in these structures exceeded 10,000, and more than 7,000 classrooms were damaged. In typical practice, essential facilities such as schools and hospitals are designed with a higher seismic force (importance factor) to account for a larger mandated factor of safety. In the Sichuan Earthquake, these buildings were disproportionately damaged. The main culprits were the poor detailing, lack of a well-defined load path, and inadequate ductility of the design and construction. Surprisingly, such damage was observed even in newer-vintage (constructed in the 1980s and 1990s) buildings.

The three-story Juyuan Middle School, approximately 20 kilometers from the fault rupture, was hit hard. The school, constructed in 1996, housed 1,000 students, and more than 700 died when the building collapsed. Construction consisted of nonductile RC beams supported by URM walls, with precast concrete floor planks. *Figure 1* shows the collapsed floor precast planks. As shown, the planks pulled away from the walls on one side, and were hanging from the walls on the opposite side. This type of damage was quite common. A lab building adjacent to the collapsed school with similar construction, built in 1996, did not collapse. This better performance was likely due to the orientation of its URM walls.

The five-story Hanwang Hospital was built in 1999. Construction consisted of nonductile RC framing and URM walls. The ground floor was designed as a parking garage; therefore, the URM bearing walls terminated at the first floor, creating a bottom story with much lower lateral stiffness. This soft story completely collapsed during the earthquake (*Figure 2*), and the upper floors dropped down one floor.

The four-story Hanwang High School is within 10 kilometers of the ruptured fault, and sustained significant damage but no collapse. Construction consisted of CIP-RC framing and URM walls. The walls had extensive damage, and concrete columns failed because the URM walls created captive columns (*Figure 3*).

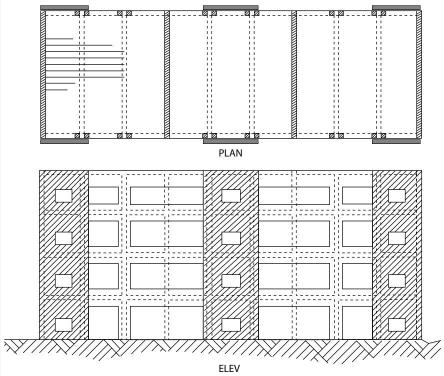
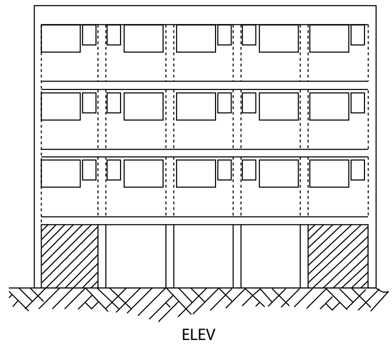
The Mianzhu Experimental School is located about 20 kilometers from the fault rupture. Framing was comprised of nonductile CIP-RC columns and beams, as well as URM infill walls, and there was significant structural damage. In particular, a large flexural demand and a lack of adequate confining transverse reinforcement resulted in severe column damage (*Figure 4*).

Application to the United States

Knowledge and experience from past earthquakes provide a warning for similar vulnerable environments around the world, including in the United States. In the United States alone, many parts of the Midwest, Northwest, West and East Coast are at risk for damage from earthquakes, and a concerted effort is needed to address such vulnerabilities. For this effort to be successful, it is important to objectively examine

Figure 4: Column flexural damage, Mianzhu Experimental School.

Table 2: Sample Building Retrofit Options.

Deficiency	URM bearing wall with lack of capacity and ductility	Soft story at ground floor
Retrofit options	• Add full-height, ductile, RC shear walls on the exterior of the building • Place the structure atop seismic isolators	• Add single-story, ductile, RC shear walls on the exterior of the building • Add viscous or Visco-elastic dampers to the ground floor
Schematic		

building performance, including detailed hazard and risk management studies. Fortunately, many tools are now available and more are under development.

Seismic Retrofit Options

Cost-effective and robust seismic retrofit techniques are available for every deficiency identified in the Sichuan Earthquake. Both conventional and innovative schemes are available to address vulnerable URM and nonductile RC frame buildings; to mitigate soft-story response; and, to ensure that structures have adequate strength, stiffness, and ductility. *Table 2* presents sample cost-effective retrofit options to strengthen URM wall buildings and structures with soft stories.

Risk Management Methodology for Structural Engineers

Performance-based engineering has been used to upgrade many suspect buildings in California and elsewhere. This approach has enabled engineers to predict more realistically, and with more confidence, the response of structures during earthquakes of various return periods.

By incorporating research tools and state-of-the-art concepts developed by the Federal Emergency Management Agency (FEMA), structural engineers can now communicate more easily with building owners using the language of risk management. By performing a probabalistic analysis, engineers can readily quantitatively communicate to owners the expected casualties, repair costs, and business interruption (BI) for a given earthquake scenario for the existing and retrofitted building conditions. This ability, combined with the confidence levels for a given retrofit, has allowed owners to see more clearly the advantages of seismic retrofit for specific cases.

A World Bank program is currently under way in Istanbul using this methodology to address vulnerable schools and hospitals. These buildings use the same suspect details as those observed in China. Many buildings in Turkey have now been retrofitted or are in design to ensure the safety of occupants.

Discussion

One issue that was immediately obvious from a survey of damage in the Sichuan region was that, as far as the building structures were concerned, there were no new technical lessons to be learned for structural purposes and the earthquake did not produce any unexpected results. The type of damage observed has been seen repeatedly in many parts of the world. Nonetheless, it is the responsibility of the structural engineering profession to educate the public and officials about potential future events and, in particular, address the seismic vulnerability associated with URM and nonductile RC buildings.

- Nearly all the collapsed buildings in the Sichuan Earthquake were constructed with very little seismic resistance, ductility, or redundancy. URM bearing walls, nonductile RC moment frames, questionable load paths, lack of diaphragms, poor detailing, and undesirable structural configurations all contributed to the observed damage.
- Past experience has shown that the United States is also vulnerable to danger from earthquakes. The same type of structures that collapsed in China also exists in many regions of the United States, and could result in unnecessary loss of life and large financial losses.
- Cost-effective retrofit options are available to address such vulnerabilities. Such retrofits have been successfully applied in California, Japan, and elsewhere.
- International communities and structural engineers must share their knowledge, developing and building on lessons learned from past experiences, and help increase awareness of earthquake risks. A comprehensive approach is needed, incorporating input from all stakeholders, including structural engineers, government officials, owners, and risk management specialists.

The authors hope that the material presented in this article, and in particular observations from the earthquake zone, refocuses the profession into a more rigorous approach that addresses vulnerable structures. They would especially like to see this material serve as an impetus in developing evaluation programs that lead to the seismic retrofit of many of the suspect buildings in the United States and elsewhere. Such efforts, and the many lives that will be saved, will serve as the legacy of the many people who experienced the Sichuan Earthquake and its tragic consequences.▪

H Kit Miyamoto, M.S., S.E. is the president and CEO of Miyamoto International. He is a registered structural engineer, and has visited and surveyed earthquake damage around the world. Kit can be reached at ***kit@miyamotointernational.com****. (Miyamoto, 2008; Sichuan, China M8 Earthquake Field Investigation Report)*

Amir SJ Gilani, Ph.D., S.E. is a structural specialist at Miyamoto International. He is a registered structural engineer and specializes in performance based engineering and innovative retrofit technologies. Amir can be reached at ***agilani@miyamotointernational.com****.*

Tom Chan, Vice President of Miyamoto International, has 30 years of structural and earthquake engineering experience. Tom has investigated many earthquakes worldwide since 1979. He can be reached at ***tchan@miyamotointernational.com****.*

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