Earthquake Reconnaissance of the 2008 Sichuan Earthquake and Retrofit Options

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Abstract

On 12 May 2008, a magnitude 7.9/8.0 earthquake struck China, approximately 80 km west of Chengdu in the Sichuan (Wenchuan) province and 1550 km southwest of Beijing. This event occurred on one of the faults that run along the base of the Longmenshan Mountains marking the boundary of the Tibetan plateau. The rupture of the fault extended over 200 km and exceeded 6 m on the surface. The fatalities exceeded 69000 and millions were injured or left homeless. This area had previously been considered a moderate earthquake zone by the Chinese Building Code, and hence, the level of damage was not anticipated. Many buildings and bridges collapsed or sustained severe damage. Schools and hospitals were especially vulnerable and many collapsed. Several factors contributed to the unprecedented level of devastation. For the collapsed buildings, the lack of ductility, the absence of a well-defined load path, and the building irregularity were primary contributors. Many schools used a non-ductile masonry-concrete framing with hollow precast decks. Residential unreinforced masonry bearing wall buildings also fared poorly and many of them collapsed. Non-ductile reinforced concrete framed buildings performed slightly better but sustained significant damage. For concrete framed buildings, the infill walls were terminated at the first floor introducing weak story at the ground level. Captive column failure was also common resulting from attachment of partial height infill walls to concrete columns. The observed types of damage have previously been witnessed in many parts of the world in past earthquakes. Fortunately, robust, simply implemental, and cost-effective retrofit methodologies have been developed to alleviate such failures. Both conventional and innovative retrofits options are available. The authors were some of the first foreign structural engineers to reach the area and survey the damage. Their observations and recommendations for future mitigations are presented here.

Introduction

The Sichuan province is a large region in China encompassing 450000 km^2, with a population of 120 million. This area has seen rapid population growth, development, and quick-paced industrialization in the past thirty years. Additionally, the province is home to many of China's rivers, bridges, and dams and boosts as being the home of the beloved Panda.

On 12 May 2008, a shallow-depth magnitude 8.0 earthquake struck Sichuan Province in China. It resulted in over 69000 fatalities, injured more than 370000, and left millions homeless. Table 1 lists the human, financial, and infrastructure damage from this earthquake. As the incredulous numbers in this table indicate, this major natural disaster caused astonishing and unprecedented losses.

Table 1. Earthquake Losses (USGS, MCEER)

Human loss	Fatalities + missing	69000 + 18500
	casualties	375000
	Evacuated	15 million
	Homeless	4.5 million
Infrastructure damage	Collapsed buildings	5 million
	Damaged structures	21 million
	Dams damaged	2400
	Road damaged	53000 km
	Bridges damaged	3000
	Water pipelines	47000 km
Financial impact	Provinces effected	10
	Cost	> $100 billion

As of 26 June 2008, 18000 people were still missing. Thousands were trapped beneath the rubble of damaged or collapsed buildings. Thousands of structures were damaged, including numerous schools and hospitals, and commercial, industrial, and residential buildings. The total monetary loss to date, as reported by Chinese officials, is more than 1 trillion yuan (US$146 billion), or 4% of China's 2007 gross domestic product.

Because seismic waves associated with shallow quakes can reach the surface with very little energy loss, they produce stronger shaking and usually more damage. Additionally, because of the stiff soil and rocks surrounding the fault, the waves traveled far without losing their strength. The energy level of this event was estimated at 30 times that of the 1995 Kobe Earthquake (Yuji Yagi, Tsukuba University).

This area of China was classified as having moderate seismicity and as such, the extent of damage was to some extent unexpected. However, the disproportionate damage to non-ductile structures, such as unreinforced masonry (URM) buildings, was predictable given the poor performance of such construction in other parts of the world in past earthquakes. This highlights the need for seismic strengthening of vulnerable structures.

In addition to casualties and collapsed buildings, this strong earthquake particularly affected businesses and industry in the area, and it presents lessons not only in China, but worldwide. The earthquake damaged many unreinforced masonry buildings and nonductile concrete buildings. These vulnerable building types are found not only in China, but also in many regions, including the Midwestern United States, Eastern Europe, South America, Japan, and the U.S. pacific Northwest. Nevertheless, tragedies such as the one witnessed in China can be avoided in the next big event since the profession is equipped with seismic retrofit and risk management tools—in particular, identifying and rehabilitating dangerous buildings and protecting equipment systems in manufacturing facilities.

The first author of this paper was among the first foreign engineers to visit the site days after the event and was able to survey the damage and document his observations. This paper presents the results from a reconnaissance survey conducted by the author, attempts to describe the causes for disproportional failures observed in certain construction, and presents cost effective retrofit options. It is hoped that the findings presented in this paper will assist in preventing future disasters.

Seismicity of the Area

The earthquake epicenter was located at latitude 30.99 degrees and longitude 103.36 degrees, 80 kilometers west of Chengdu, the Sichuan Province capital, and 1500 kilometers southwest of Beijing. The earthquake had an epicentral depth of 19 kilometers. The earthquake occurred as the result of movement on the Longmenshan Fault. This thrust fault (Figure 1) runs along the base of the Longmenshan Mountains in Sichuan Province in southwestern China. It marks the boundary of the Tibetan plateau. The strike of the fault plane is approximately northeast. The fault rupture started in the mountains and then, over the next 50 seconds, traveled at least 200 kilometers toward the northeast, tearing apart the land along the front of the mountain range. Ground rupture exceeded 6 meters.

On a continental scale, the seismicity of central and eastern Asia is a result of the collision of the Indian and Eurasian Plates. The Indian Plate moves northward toward the Eurasian Plate with a velocity of about 50 millimeters per year (Figure 2). The white arrows in Figure 2 are the GPS stations indicating the direction of the land movement. The collision of the plates results in uplifting of the Asian highlands—the Himalayas and the uplifted Tibetan Plateau are testament to this process. The earthquake occurred on one of the faults along the plate boundaries in the Sichuan area.

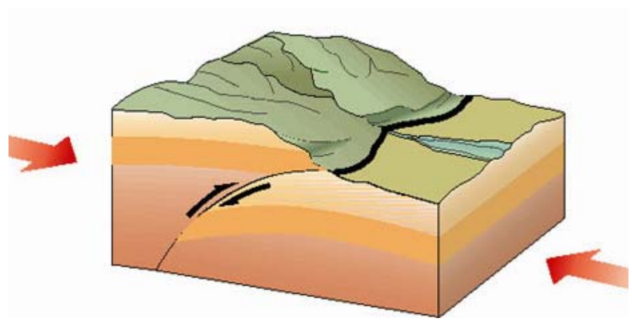


Figure 1. Trust Fault (from Caltech)

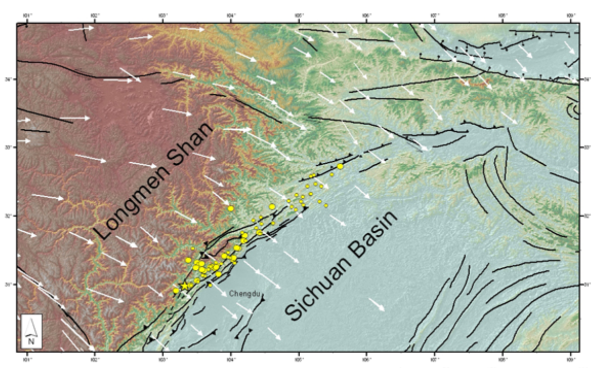


Figure 2. Movement of Tectonic Plates (from USGS)

Figure 3 depicts the major earthquakes influencing the region and a close-up of the earthquake epicenters and local faults. The Sichuan province of China has seen many earthquakes the most recent of which occurred in 2008.

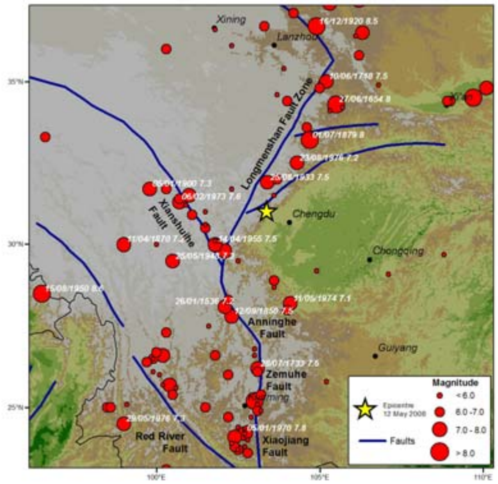


Figure 3. Local Faults and Earthquakes (from BGS)

Table 2 lists the major earthquakes that have affected this area. The Diexi earthquake (nearly 80 km from the epicenter of the 2008 earthquake) occurred on August 25, 1933. It destroyed the town of Diexi and many villages, and caused many landslides. Fatalities were recorded as far away as Chengdu.

Table 2. Past Major Earthquakes in the Wenchuan Province

Date	Mw	Comments
1786	7.8	Garzê Earthquake
1816	7.5	Luhuo Earthquake
1850	7.5	Xichang Earthquake
1933	7.4	Diexi Earthquake, Over 9000 fatalities.
1948	7.3	Sichuan Earthquake, 800 fatalities.
1955	7.5	Dardo Zheduo Earthquake,
1955	7.5	Kangding Earthquake, Dardo
1973	7.4	Luhuo Earthquake
1976	7.2	Songpan-Pingwu Earthquake. 41 fatalities.
1981	6.9	Dawu Earthquake
1982	6.7	Batang Earthquake
2001	6.0	Yajiang Earthquake
2008	8.0	Sichuan Earthquake. Over 69000 fatalities.

2008 Wenchuan (Sichuan) Earthquake

Figure 4 presents the intensity for the magnitude 8.0 event as felt according to the Modified Mercalli Intensity (MMI) scale. This quake is classified as an X event on the MMI scale. This MMI corresponds to violent shaking and heavy damage.

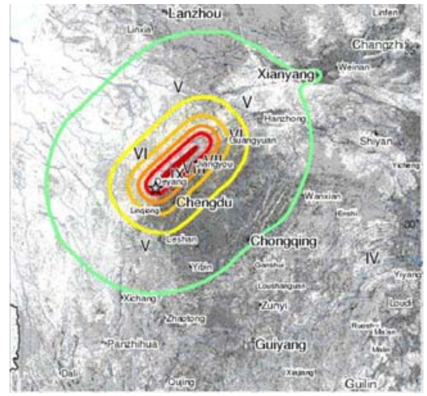


Figure 4. Trust Fault (from USGS)

The event caused tremendous damage in the Sichuan province as seen in Figure 5. Table 3 lists the estimated population exposures for a given intensity.

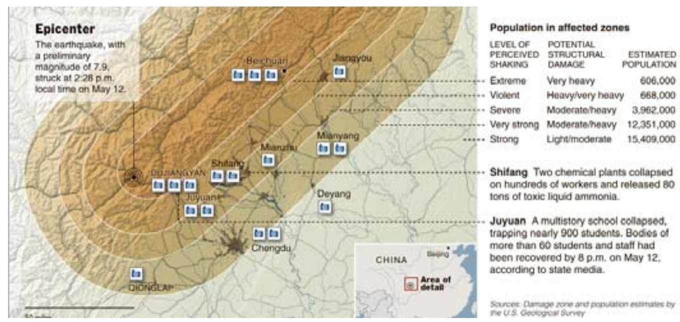


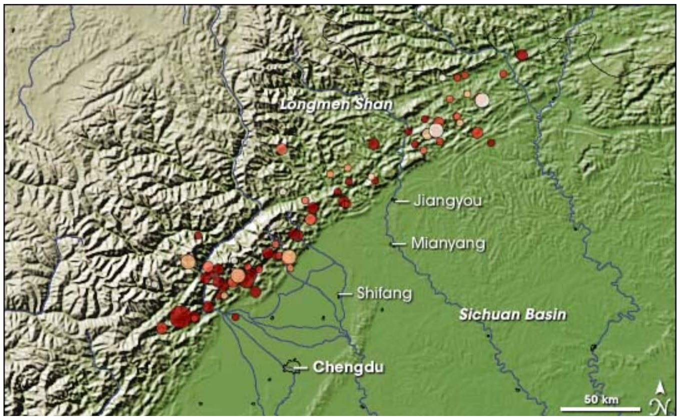
Figure 5. Movement of the Tectonic Plates (NY Times)

Table 3. Estimated Population Exposure (Millions of People) for Various MMI Intensities (Geology.cm)

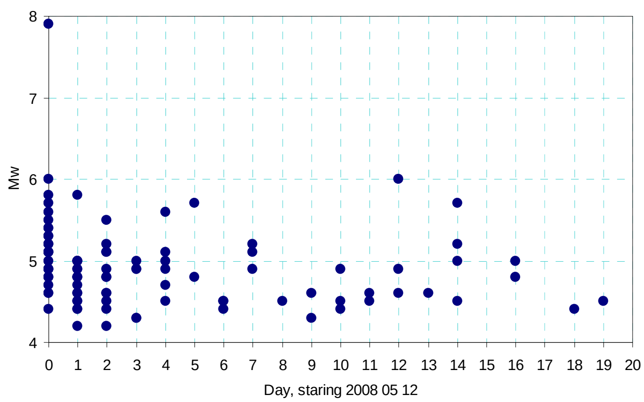
Intensity	IV	V	VI	VII	VIII	IX	X
Population exposure	190	90	15	13	4	0.7	0.6

As Figure 5 and Table 3 show, over 5 million citizens were subjected to severe shaking and 100000's of building would have potentially experienced heavy to very heavy damage. Before the May event, there was a low level of seismic activity for some time around the epicenter.

The main 8.0 shock was followed by a number of aftershocks. Figure 6a shows the location of these aftershocks, which occurred northeast of the epicenter and followed the edge of the Longmenshan mountain range. Figure 6b presents the magnitude and date of aftershocks that had magnitudes of 4.0 and above. The magnitude 6.0 event on 25 May, 13 days after the main shock, caused additional casualties and damage.

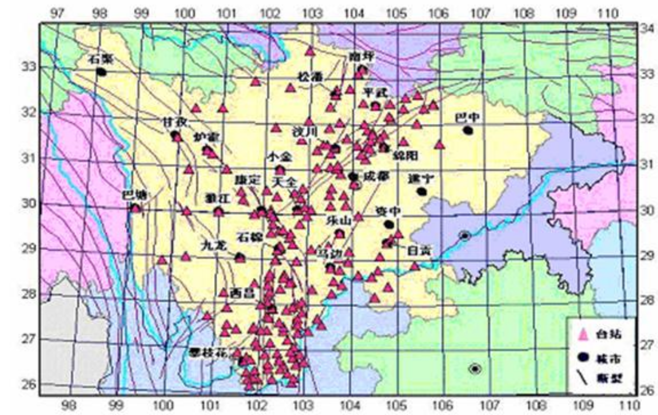


a. Location (from NASA Earth Observatory)

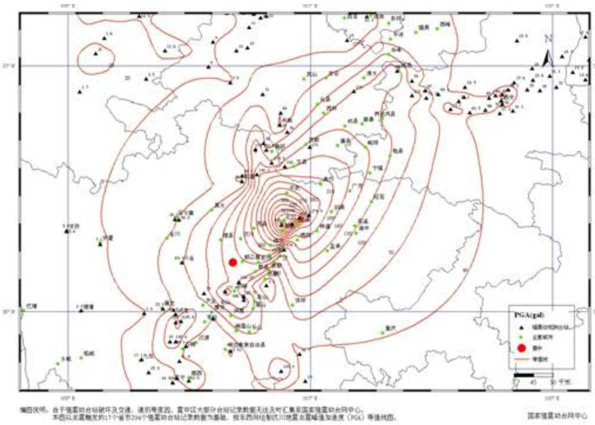


b. Distribution and Magnitude

Figure 6. Aftershocks to the 2008 Sichuan Earthquake



a. Array of Strong Motion Sensors



b. Contour of Recorded Ground Accelerations

Figure 7. Seismicity of the Impacted Region (CENC)

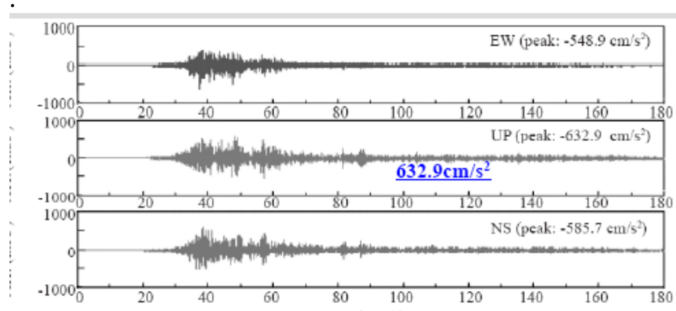


Figure 8. Sample Recorded Acceleration Data (MCEER)

Many modern large buildings in China are instrumented with strong-motion sensors to monitor earthquake accelerations. This instrumentation program is administered by the China Earthquake Networks Center (CENC). In addition to sensors in the Sichuan Province, 260 digital stations in 17 other provinces have recorded ground motions (Figure 7a). CENC is processing the recorded data and strong-motion records of the 2008 earthquake, and this information will be available shortly. In the Sichuan Province, an instrumentation program comprising 211 stations was completed in 2007. The instrumentation array includes 60 stations along the Longmenshan Fault. As a result, a number of strong motion records were obtained from stations in Sichuan. Figure 7b presents the isocontour of peak ground acceleration (PGA). As depicted in Figure 8, very high vertical accelerations were recorded.

Surveyed Damage

The reconnaissance spent one week at the site, surveying damage. Figure 9 presents a map of the Sichuan province. The surveyed areas are marked on the map.

Figure 9. Map of Surveyed Area in the Province

Most commercial, retail, and residential buildings at the earthquake site consisted of three types of structures: unreinforced masonry (URM) bearing walls for low-rise residential buildings, Hybrid URM column-concrete beam and reinforced concrete moment frames for low-rise to mid-rise buildings including schools and hospitals. The URM buildings use an unconventional floor system. It consists of concrete ring beams at the perimeter with interior hollow precast slab strips. There is minimal reinforcement continuity between the concrete floor slabs and the URM walls.

Before the 2008 Sichuan Earthquake, this area of China was considered a moderate seismic zone. However, the weak seismic systems and poor detailing, combined with increased ground motions, resulted in catastrophic failures. Dangerous buildings of URM, nonductile concrete, and poor seismic configuration are not China's issue alone. These dangerous building types are found worldwide, including South America, the United States, Canada, Japan, Southeast Asia, and Eastern Europe. URM and nonductile concrete construction is especially prevalent in regions not recognized as high seismic areas. It is critical to upgrade these structures to protect lives in future events.

A suspect floor detail included precast concrete slab system with perimeter (ring beam). The hollow precast slabs were not mechanically attached together and were connected to the perimeter URM bearing walls with wire mesh reinforcement. The ring beams were intended to "confine" the slab segments. This type of detail performed very poorly and collapsed in many buildings leading to many casualties. There was no diaphragm action in the floor and the precast panel anchorage to the perimeter walls was inadequate.

Overall, these structural systems have a very questionable load path for seismic loading, little redundancy, and low ductility or energy dissipation. Many of these buildings had interior partition (party) URM walls. For many of these buildings, structural performance depended on the orientation of URM party walls. If the predominant seismic excitation occurred in the direction of party walls, the structure generally survived because the number and length of the walls in this direction was adequate to resist the seismic loading without exceeding the wall capacity. If the predominant seismic excitation occurred parallel to window lines with narrow URM walls, major damage or collapse resulted because there was insufficient wall strength in that direction.

Two other prominent failure modes included soft (weak) story collapse and captive column failure. The former was due to termination of the URM walls above grade. The latter was the result of attachment of partial height URM walls to concrete columns, reducing the clear length of the column and precluding ductile flexural yielding. For reinforced concrete moment frame building, non-ductile detailing of reinforcement such as at the joints or for column plastic hinge zones also resulted in many failures.

Schools and Hospitals

Many schools and hospitals collapsed in this Earthquake. The death toll is expected to exceed 10000, and more than 7000 classrooms were damaged. Many of the collapsed buildings were of recent vintage, having been built in the 1990's. Most of the school buildings and hospital structures investigated consisted of URM construction or nonductile cast-in-place reinforced concrete (CIP-RC) construction. Several examples of damaged schools and hospitals are summarized below.

Juyuan Middle School

This three-story school is in Juyuan, a town in the county-level city of Dujiangyan. Juyuan has a population greater than 50000 and is approximately 50 kilometers from Chengdu and 20 kilometers from the fault rupture. The school housed 1000 students. It is a relatively modern building, constructed in 1986, but used non-ductile detailing. More than 700 died when the building collapsed. Construction consisted of nonductile CIP-RC beams supported by URM walls, with precast concrete floor planks. There were no or minimal mechanical ties connecting the floor planks to the URM walls. Figure 10a shows the collapsed floor precast planks. Note that the planks pulled away from the walls and have rotated downward. They are attached to the remaining walls hanging by the wire steel reinforcement. The collapsed URM walls and nonductile concrete beam is shown in Figure 10b. A lab building adjacent to the collapsed school and with similar construction did not collapse. This better performance was likely due to the orientation of its URM walls or better construction quality. Figure 11 shows the cracked walls.

a. Collapsed Floor Planks

b. Collapse URM Wall and Concrete Beam

Figure 10. Collapsed Juyuan Middle School

Figure 11. Shear Cracks in Masonry Walls

Juyuan Primary School

This complex consists of a four-story and a three-story building located a few km away from the collapsed Juyuan Middle School. It was constructed in 2007 and framing comprised of CIP-RC beams and columns, and URM walls. It only sustained minor shear (diagonal) cracks in the walls and minor pounding damage between buildings. Its good performance (Figure 12) could likely be attributed to its vintage and good construction practice.

Figure 12. Undamaged School Building

Xingfu Primary School

This four-story school is in the town of Xingfu, in the county-level city of Dujiangyan. It has a population of more than 300000 and is located 15 kilometers from the fault rupture. The building collapsed and killed more than 300 of the 600 occupants. Building framing consisted of nonductile CIP-RC columns and beams, URM walls, and precast concrete floor planks. The stairway (Figure 13) survived the event. This was a typical observation. The stairwells added stiffness and resistance to this portion of the buildings and survived even when the main building had collapsed. In many instances, the students and teachers who stayed in the classrooms perished, whereas those who had left the rooms and were in the stairway area survived.

Figure 13. Collapsed Xingfu Primary School

Hanwang High School

This four-story school is located in the Hanwang township of Mianzhu with a population of more than 60000. Hanwang is at the foot of the Dragon Gate Mountains, within 10 km of the fault. The building sustained significant damage but no collapse. Construction consisted of CIP-RC framing and URM walls. The walls had extensive damage and concrete columns failed. The column failed in shear (Figure 14) because the infill URM walls butted up against the concrete columns creating captive columns and preventing flexural yielding.

Figure 14. Captive Column Failure

Hanwang Primary School

The main school building collapsed, but the adjacent dormitory building survived although its walls were cracked (Figure 15). Both structures were built in 1994 and were of similar construction using URM walls and precast concrete floor planks. The better performance of the dormitory is attributed to the redundancy provided by the many interior URM walls and shorter spans for precast floor planks.

Figure 15. Cracked URM Walls

Mianzhu Experimental School

This school is located in the city of Mianzhu, with a population well over 500000, about 20 km from the fault rupture. Framing comprised of nonductile CIP-RC columns and beams, and URM bearing walls. There was significant structural damage. In particular, large flexural strains and lack of adequate confining transverse reinforcement resulted in severe column damage and loss of core concrete at the plastic hinge zones (Figure 16) comprising the lateral and vertical load capacities of these columns.

Figure 16. Column Flexural Failure

Xingfu Hospital

A wing at the Xingfu Hospital collapsed (Figure 17), resulting in 200 fatalities. This wing, constructed in 1996, had typical nonductile CIP-RC framing with URM walls and precast concrete floor planks. An adjacent wing, constructed in 2000, performed better and sustained moderate structural damage, shear-wall cracks, and nonstructural damage, dropped ceiling panels (Figure 18).

Figure 17. Collapsed Hospital Wing

Figure 18. Nonstructural Damage

Hanwang Hospital

This five-story hospital was constructed in 1999. Construction consisted of nonductile CIP-RC framing and URM walls. The ground floor was designed as a parking garage. Hence, the URM bearing walls were terminated at the first floor, creating a bottom story with much smaller lateral stiffness. This soft story completely collapsed during the earthquake (Figure 19) and the upper floors dropped down one floor.

Figure 19. Soft Story Collapse of Hospital Building

Industrial Facilities

Structural, nonstructural, and equipment damage was extensive and widespread. The extent of damage was attributed to the lack of redundancy and ductility of nonductile CIP-RC and URM construction and to the lack of adequate tie-down and anchorage for equipment. Industrial damage depended on the magnitude of ground accelerations. In sites with large acceleration, the building damage was significant, whereas, in sites with moderate ground shaking, buildings performed well but equipment damage was extensive. The equipment damage observed in this event is a common occurrence seen in many other events. Such loss is preventable with cost-effective tie down retrofits. Earthquake damage caused shutdowns, and being surrounded by other collapsed buildings and devastation, including loss of workers, increased business interruption (BI) further. Observations from a number of industrial facilities are presented here.

Glass Manufacturer

This 300-employee glass manufacturer, built in 1996, is located near the city of Mianzhu. The plant has several production and storage buildings, and many of the one-story buildings used lightweight steel construction. Two URM stacks measuring 50 m high and 5.8 m wide failed. The top 5 meters of the stacks collapsed (Figure 20) due to large accelerations. A mezzanine structure above the bottle production machine failed because it was not properly braced. Equipment at this plant was generally well anchored and performed well. Approximately 10% of the glass bottle inventory was destroyed when it fell from the 5 m tall product shelves (Figure 21).

Figure 20. Damaged URM Stack

Figure 21. Loss of Inventory

The loss of the stacks is critical since the plant cannot operate without them. It is estimated that repairs could take up to six months. Such extended BI could lead to up to 50% revenue loss and could compromise the factories market share including its sole-source agreement with a Chinese wine label.

Steel Fabricating Plant

This lightweight steel fabricating plant, built in 2003, is southwest of the city of Mianyang, 40 kilometers from the fault rupture. No major damage was observed to either structural or nonstructural components (Figure 22), except for some broken window glass, which was caused by excessive building displacement. However, this facility sustained one week of BI because after the earthquake, workers were reluctant to return to work until structural inspection was completed. Such problems can be avoided by proper preparatory training.

Figure 22. Undamaged Building

Packaging Plant

This packaging plant is located in the Hanwang township of Mianzhu. The plant was constructed of precast roof panels over steel trusses supported by steel columns, and URM infill walls. These walls did not have adequate out-of-plane anchorage and many sections, including part of the roof (Figure 23) collapsed because of out-of-plane seismic excitations. BI for this plant is expected to exceed six months. BI was exacerbated when the plant grounds were used by emergency medical units (Figure 23). This usage precluded accessing the site and beginning structural repairs.

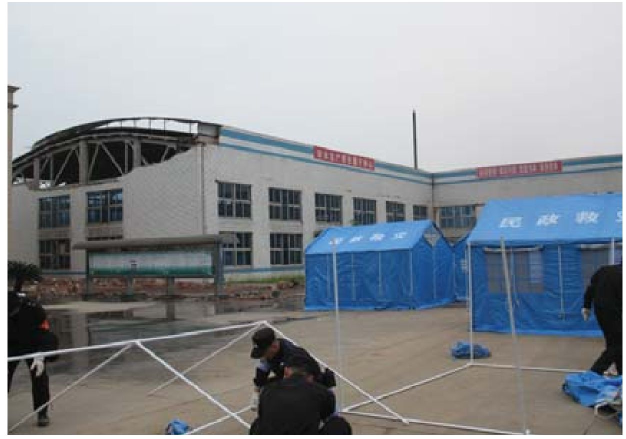


Figure 23. Damaged URM Wall and Emergency Tents

Light Industrial Plant

This light industrial plant is located in the Hanwang township. The plant was constructed of precast roof panels over steel trusses supported by concrete columns. This structure performed well, except for the collapsed entrance canopy. Unanchored heavy pieces of equipment slid at least 150 mm off their base (Figure 24). BI is expected to be several months because of direct damage to the building and unanchored equipment.

Figure 24. Sliding of Non-Anchored Equipment

Steel Fabricating Plant

This steel fabricating plant is located in the Hanwang township. The plant was constructed with a lightweight steel roof, steel trusses, and steel braces. The structure performed well and had little damage. However, unanchored heavy pieces of equipment slid off their bases (Figure 25) causing BI of several months.

Figure 25. Sliding of Non-Anchored Equipment

Commercial Buildings

Many commercial structures performed adequately, particularly those built after the late 1990's. Typical commercial structures usually consisted of retail stores on the ground level with three to seven stories of mid-rise residential or office occupancy above. These buildings use CIP-RC moment frames at the storefront and URM walls. The concrete columns were closely spaced and provided adequate strength and redundancy. Nonstructural damage often included damage to unbraced ceilings and equipment.

Office Building 1

The two-story and four-story office complex, still under construction, is located in the town of Juyuan, Dujiangyan City, very near the collapsed middle school building. The structural damage was minor and consisted of cracking of URM walls. Nonstructural damage was mainly the panel loss and grid collapse of suspended ceilings (Figure 26). The ceilings did not have lateral bracing.

Figure 26. Damaged Suspended Ceiling

Retail with Mid-Rise Residential

This five-story building is located in Xingfu. Construction consisted of nonductile CIP-RC columns and beams, URM walls, and precast concrete floor planks. The corner of the structure collapsed into the street. It appears that the termination of walls above the ground floor resulted in a soft story response at that floor, leading to collapse (Figure 27). Incidentally, an almost identical building next door, only sustained minor damage, leading to the conclusion that the construction quality and detailing are the likely differences.

Figure 27. Collapsed Corner of the Building

Office Building 2

This three-story office building is located in the Hanwang township of Mianzhu. It sustained minor damage, although many close by buildings collapsed. The only visible damage was to the wood roof (Figure 28). This concrete structure has many walls, and appears to be well designed and constructed.

Figure 28. Damaged Roof of the Building

Bank of China Building

This five-story office building is located in the business district of Dujiangyan City, almost 25 km from the epicenter. Construction consisted of nonductile CIP-RC frames, URM walls, and precast floor planks. This structure collapsed (Figure 29). Bank branches experienced significant damage and collapse in hard hit areas, including those of China Construction Bank Corp. and Agricultural Bank of China. Within three weeks of the earthquake, financial institutions began providing financial services in tent banks and mobile banking stations, complete with security cameras, in much of the disaster zone.

Figure 29. Collapsed Bank of China Branch

Residential (Houses and Apartment) Buildings

Hundreds of thousands of houses collapsed because of the Earthquake. Most of the collapses were in older, traditional URM bearing wall construction or in modern buildings that had soft stories at the ground floor. Typical traditional houses are composed of URM walls and wood roof systems with clay tiles for waterproofing. The URM walls are composed of either red brick or mud brick, and without reinforcement.

This type of system has very little lateral capacity and no ductility. These roof tiles are lighter and thinner than the similar Japanese version, and are not interlocked. Therefore, under seismic acceleration, they dislodged and saved the structure itself by reducing the inertial mass. However, if ground shaking intensity is high enough, the URM walls will fail due to lack of capacity, ductility, and out-of-plane anchorage.

Some URM mid-rise structures performed adequately and did not collapse, with the exception of units with configuration irregularities. Typical mid-rise apartment buildings were constructed of URM bearing walls and concrete floors. Often, the perimeter RC ring beams served as the collector/chord elements. Typical concrete members had nonductile details. Since a typical apartment is very small, many interior partition walls were used in construction. This configuration provided additional shear strength and redundancy and improved the performance of the building.

Residential Village North of Mianzhu

This small village of residential structures sustained severe damage and over 80% of the buildings collapsed (Figure 30). The structures were built of brick walls and wood-frame roofs with lightweight black roofing tiles.

Figure 30. Collapsed Residential Units

Apartment Building Complex

Several eight-story apartment buildings, constructed of URM bearing walls and concrete slabs, constitute a complex in the center of Hanwang. Many diagonal shear cracks occurred in the walls between windows (Figure 31), but the buildings did not collapse due to the redundancy and lateral capacity provided by the network of interior walls.

Figure 31. Cracked URM Walls

Residential Complex

In this complex, a construction detail was used that called for connecting the adjacent residential units via a narrow corridor with a large number of windows. Hence, this portion of the complex, had little lateral stiffness or strength. The corridor URM walls for this complex failed, resulting in a portion of the building tilting and dropping by 3 m, and causing a vertical split in the corridor (Figure 32).

Figure 32. Vertical Split and Displaced Apartment Complex

Transportation Infrastructure

Transportation systems serving the earthquake-affected area are a combination of road and rail. Movement of personnel, heavy equipment, and hardware to support repair efforts was seriously impeded by closures of both highways and rail lines. Serious damage or collapse of bridges, overpasses, and tunnels was another factor closing major traffic arteries. Because the routes for transporting equipment and construction material were limited, clearance of landslides or repair of bridges and roads was hampered. More than 90 tunnels were damaged.

Bridges

Over 3000 bridges were damaged. The damage was caused by both the large ground accelerations and ground rupture. The fault rupture crossed some bridges and in these instances, significant damage was observed. The damage was especially severe when the longitudinal axis of the bridge was normal to the direction of main shaking. The Chinese bridge code differs from the US AASHTO LRFD code and typically results in less seismic demand on columns (MCEER). The bridge damage was comprehensive and varied. Some of the observed damage included:

- Complete and partial bridges collapse. Figure 33 shows the collapsed 4-span reinforced concrete arch Hsiaoyudong bridge
- Un-seating of one or more spans. Figure 34 shows the lost approach span of the Miatzuping bridge. This 19-span bridge is 1440 m long. The construction was completed but it was not open to traffic at the time of the earthquake.
- End diaphragm large longitudinal movement and unseating from abutments
- Damaged abutment backwalls, shear keys, and wingwalls
- Hinging at the base of columns
- Failure of transverse coupling beams at the piers
- Damaged shear keys at the bents
- Damged deck and railing
- Transverse and torsional movement of superstructure spans for skew bridges

Figure 33. Collapsed Bridge (NCREE)

Figure 34. Bridge with Un-Seated Span (NCREE)

Roadways

Over 16000 km of highway was damaged. Roadway damage (Figure 35) was the result of ground shaking (acceleration), surface rupture, and earthquake related geotechnical issues such as landslide, and slop instability. Furthermore, in the mountain regions, landslides or slipping road or rail foundations blocked many traffic arteries. Heavy rains and aftershocks in the weeks following the earthquake exacerbated sliding initiated by the first shock. Routes into most of the heavily damaged area were reported as open two weeks after the earthquake

Figure 35. Damaged Roadway

Railways

Railways were damaged because of shifting ground (Figure 36), slipping, or settlement. Rail lines are especially susceptible to earthquake damage because they must remain in alignment and therefore have less tolerance for ground shaking and movement. Rail-line restoration trailed behind roads. Many rail routes are electric powered and therefore require restoration of the power grid.

Figure 36. Damaged Roadway

Lifelines

Lifelines serving the earthquake area in Sichuan Province include electric power, telecommunications, road and rail lines, and local potable water supplies. All these systems suffered serious damage and prolonged service outage. Power and telecommunications were the first lifelines to be restored, with most of the disrupted service area back in operation within a week of the earthquake. Water systems normally take longer for full restoration, with many communities in the most heavily shaken areas still isolated from adequate transportation or water service a month after the earthquake.

Electricity Generation and Distribution

Electric power is critical for operating communications, water supply, and rail lines. The Sichuan Province power grid lost about 40% of its load following the earthquake, even though only a small portion of the service area lies within the region of severe shaking. Power throughout the 54-county area that suffered the worst effects is supplied by a combination of local power grids and the national system, the State Grid Corporation of China (SGCC).

During the period of approximately one week when much of the area lacked power, mobile generators mounted on trucks or trailers were brought into the damaged region to supply critical facilities. Mobile power was also critical to repair and restart substations and generating plants. Within two weeks of the earthquake, power had been restored to all but isolated pockets where serious damage in local distribution substations prevented reenergizing.

Substations

As in past earthquakes, damage to the power system was concentrated in the most critical, high-voltage substations. Fifteen 220-kV substations and a critical 500-kV substation were out of service primarily because of the collapse of tall ceramic switchyard equipment. Additional effects to the power system included sporadic damage to high-voltage transmission lines, most often due to landslide beneath transmission towers in mountainous regions.

Repair crews and technicians from the SGCC and from local power systems outside the province began round-the-clock work to restore the system, beginning immediately after the earthquake. The main elements of the high-voltage grid operated by SGCC were restored by 18 May, six days after the earthquake. Fifteen of the 54 counties damaged by the earthquake still had areas lacking power by that time.

Figure 37 shows the damage to a substation located near Mianzhu, approximately 20 kilometers from the fault rupture.

This substation was shut down for five days because porcelain components of high voltage elements dislodged from their steel pole base. URM walls, subjected to out-of-plane seismic excitation and lacking bracing, also failed. In addition, water pipes into the substation's supply tank failed, elongating the downtime for this substation.

Figure 37. Collapsed URM Wall at a Substation

Telecommunications

Damage to communications systems was concentrated in about 12 counties in the most heavily shaken area. A total of 616 landline switching stations (central offices), 16500 wireless stations, and 11000 km of fiber-optic line were reported as damaged.

Damage to this infrastructure included partial collapse of building enclosures of switching stations; collapse of interior switch racks, power supply, and other equipment; and damage or misalignment in towers supporting microwave antennae. Fiber-optic cable, while generally resistant to earthquake damage, was lost due to building collapse; toppling of pole-mounted cable; or soil displacement, landslide, or liquefaction damage to buried cable.

Prolonged outage of communications systems is often driven by power outage. Telecom systems operate on DC power provided by large battery racks at switching stations. However, normal AC power from the regional electric grid must be available to maintain charge in the batteries. Therefore, telecommunications usually cannot be restored until power is restored.

Temporary telecommunications equipment was deployed throughout the damaged area to allow coordination of repair and rescue efforts. Temporary equipment included mobile microwave transmitters, radio sets, satellite cell phones, and portable power generators.

Restoration of telecommunications trailed restoration of the power system, with much of the heavily damaged area restored to some level of communication after 18 May, about a week following the earthquake.

Water

Potable water is critical for life support and sanitation for the population in the earthquake-affected region. Water is also critical for restoring large industrial and commercial operations, and utilities. Cooling systems for large buildings, including telecommunications and data-processing centers, normally depend on evaporative cooling towers. Therefore, much of the high-tech infrastructure of the region could not resume operation until water service was restored.

Within two weeks, water was restored to more than half of the area that initially lost water service after the earthquake. However, large pockets remained without water, primarily due to breaks in water pipelines. China Urban Water Association (CUWA) reported that 7800 km of water pipes and 839 tanks were damaged. Figure 38 shows the broken water mainline and spillage in Chengdu city after the earthquake. Pipeline damage was attributed to the ruptures in the rigid buried pipes subjected to seismic waves, ground shaking, and differential displacement. Additionally, settlement, liquefaction, and landslides in the mountains and riverbed areas contributed to pipeline damage. Other impediments to restoring water were ruptures in storage tanks, reservoirs, and water towers. Sources of raw water were disrupted in certain areas when earthquake- or rain-triggered landslides created inadvertent dams in rivers, cutting off flow to some water systems and flooding or contaminating others.

Figure 38. Broken Water Mainline (MCEER)

Survey of Water Towers

A water tower, constructed of URM, is located in the town of Juyuan, adjacent to the Juyuan Middle School collapse. The tower has leaned extensively and it threatens the adjacent, and undamaged, commercial building; thus making the building inaccessible. There is also a large shear crack in the tower wall (Figure 39). It is unlikely that this structure would be repaired.

Figure 39. Large Shear Crack in URM Water Tower

A concrete water tower located in the township of Hanwang constructed of CIP-RC, and was undamaged (Figure 40). Nearby buildings were damaged extensively and collapsed. The good performance of this tower is attributed to its structural system and dynamic properties.

Figure 40. Undamaged Water Tower

Dams

This area of China, is the basin of many rivers flowing from the nearby mountains. There are thousands of dams in this region and many were subjected to severe ground shaking (Figure 41). Over 2400 large and small dams were damaged. The Three Gorges River Dam was not damaged. However, hundreds of important dams sustained either collapse or serious damage. Figure 42 shows the damaged Deyang City dam.

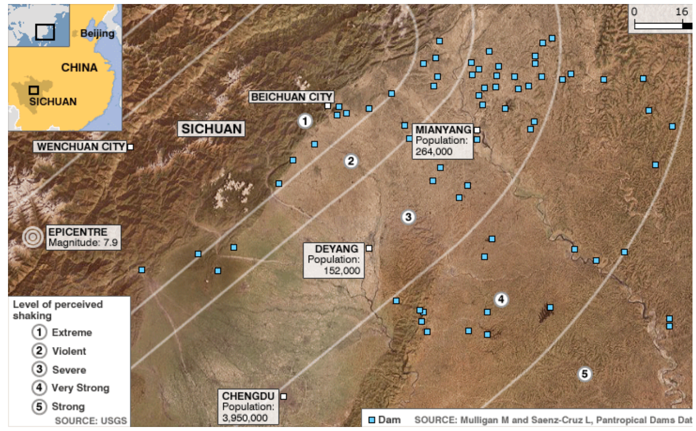


Figure 41. Important Dams in Regions of Strong Shaking (BBC)

Figure 42. Damaged Dam (MCEER)

Emergency Response

The severity of the earthquake and the exceptional damage were unexpected. The human and infrastructure loss was unprecedented. Nonetheless, shortly after the earthquake, the Chinese government mobilized the emergency response team and dispatched rescue and recovery teams. The national disaster plan was initiated and the plan was executed exceptionally well following the earthquake. Within 24 hour of the earthquake, national emergency response had began, over 150000 local and army core rescues and 30000 medical staff had arrived at the hardest hit areas. Thousands of emergency tents (Figure 43) had been setup. Personnel disinfected (Figure 44) the area and survivors to prevent spread of infectious diseases. The only noticeable omission was a system of tagging the surviving buildings (green for safe, yellow for damaged, and red for dangerous) to provide valuable information to public.

Figure 43. Post Earthquake Emergency Response Tents

Figure 44. Post Earthquake Emergency Response Disinfection

Seismic Retrofit

The Sichuan, China, Earthquake did not produce results that were unexpected. In fact, the collapsed of URM and nonductile RC framed buildings have been observed previously in other earthquakes. Nearly all the collapsed buildings had low strength, or stiffness, and ductility; little redundancy; questionable load path, and some undesirable seismic configuration (soft story, short columns, or irregularity). Cost-effective retrofit options are available to mitigate such deficiencies. Typical options are presented in this section.

Since schools, hospitals, and apartments can be classified as important buildings and high-density population areas, the discussion presented hereafter emphasizes these buildings.

While the basic ideas discussed here do not address substandard construction, retrofitting might have prevented the sudden and total collapse of many buildings and the subsequent loss of life.

The retrofit options discussed in the following paragraphs are intended to provide the basis life safety goal, that is to prevent collapse. Higher retrofit goals such as minimizing structural damage or immediate occupancy are also possible, albeit at a greater monetary cost.

URM Bearing Walls, RC Frames, and Precast Floors

Table 4 lists the seismic deficiencies, retrofit objectives, and robust means of achieving these goals for URM buildings with precast panel floors. As discussed in the earlier sections indicated, this type of construction is especially vulnerable to earthquake damage. The existing building condition is shown in Figure 45, whereas; Figure 46 depicts the rehabilitated condition.

Table 4. Seismic Retrofit of URM Bearing Walls

Building Type	URM bearing wall
Deficiencies	Lack of lateral capacity and ductility
Retrofit goal	Retrofit design
Confine floor panels to work as a diaphragm	Check strength and ductility of the RC ring beams. Reinforce and confine them as needed. Add ring beams at each floor if they are not present.
Eliminate lateral loading demand on URM walls	Add full-height ductile, RC shear walls on the exterior of the building to carry the entire lateral load demand.
Enhance capacity of URM walls	Apply engineered cementations concrete (ECC) to the exterior of the walls. ECC will add strength and ductility to the walls and allows them to resist seismic forces without collapse.
Reduce seismic demand	Placing the structure atop of seismic isolator bearings to get a low frequency and highly damped building that would protect the non-ductile components.

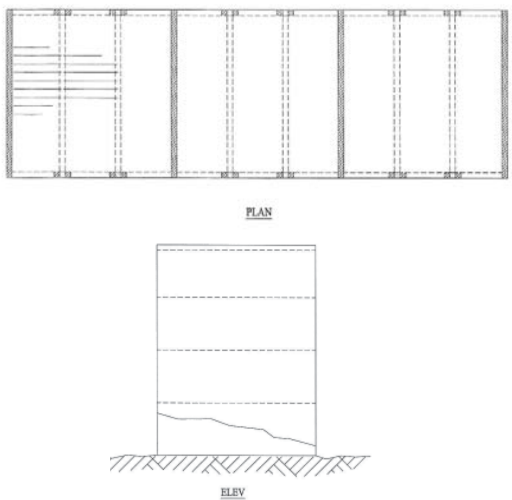


Figure 45. Existing Condition URM Building

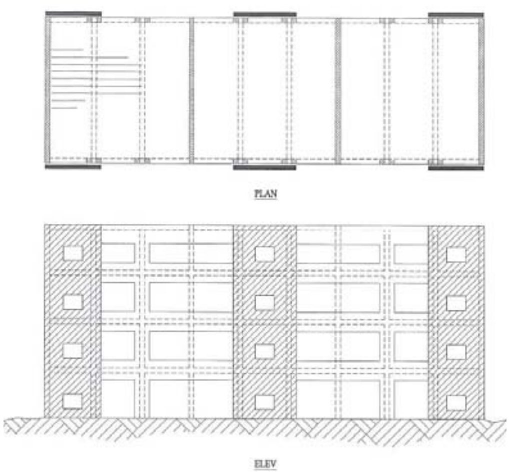


Figure 46. Retrofitted Condition URM Building

Nonductile RC Moment Frames

Table 5 lists the seismic deficiencies, retrofit objectives, and robust means of achieving these goals for buildings that use RC framing and precast panel floors. The existing building condition is shown in Figure 47, whereas, Figure 48 depicts the rehabilitated condition

Table 5. Seismic Retrofit of Nonductile RC Frames

Building Type	Nonductile RC moment frame with URM infill
Deficiencies	Inadequate joint capacity, lack of column confinement, captive columns
Retrofit goal	Retrofit design
Confine floor panels to work as a diaphragm	Check strength and ductility of the RC ring beams. Reinforce and confine them as needed. Add ring beams at each floor if they are not present.
Eliminate lateral loading demand on existing frame	Add full height ductile RC shear walls on the exterior of the building to carry the entire lateral load. Discount any contribution from existing frames.
Enhance capacity and ductility of existing frames	Cut the connection between the partial height infill URM walls and concrete columns to mitigate short column failure; Wrap columns using FRP to increase confinement and ductility; Add prestressing or confinement to joints to increase shear capacity; Add shotcrete to the existing members to increase capacity
Reduce seismic demand	Placing the structure atop of seismic isolator bearings to get a low frequency and highly damped building that would protect the non-ductile components.

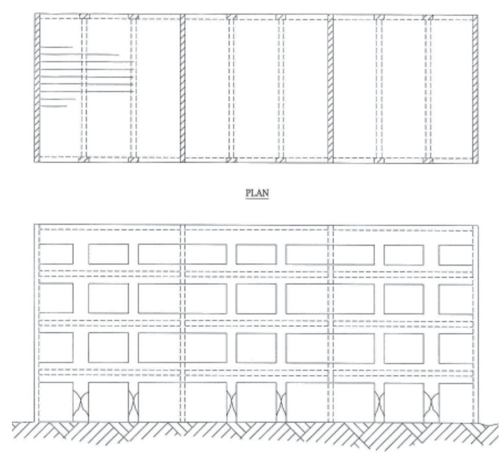


Figure 47. Existing Condition RC Frame Building

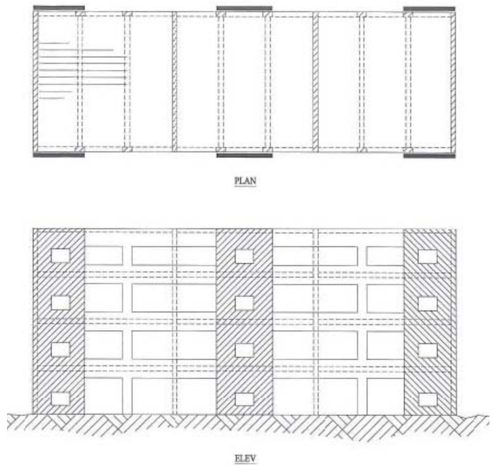


Figure 48. Retrofitted Condition RC Frame Building

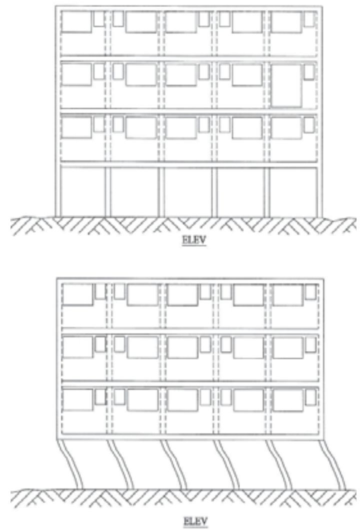


Figure 49. Existing Condition RC Frame Building

Buildings with Soft Story at the Ground Floor

Table 6 lists the seismic deficiencies, retrofit objectives, and robust means of achieving these goals for buildings that exhibit soft story response at the ground floor. Many such buildings collapsed in the 2008 earthquake as the result of low lateral stiffness at the first floor. The existing soft story condition is shown in Figure 49, whereas, Figure 50 depicts the rehabilitated condition.

Table 6. Seismic Retrofit of Nonductile RC Frames

Building Type	Soft story at ground floor
Deficiencies	Termination of walls above the ground floor reduces lateral stiffness of that floor and results in sideway collapse of that floor
Retrofit goal	Retrofit design
Confine floor panels to work as a diaphragm	Check strength and ductility of the RC ring beams. Reinforce and confine them as needed. Add ring beams at each floor if they are not present.
Eliminate the soft story by adding walls	Add single-story ductile reinforced concrete shear walls on the exterior of the building to carry the entire lateral load.
Eliminate the soft story by adding bracing	Add single story steel braces on the exterior of the building to increase the lateral stiffness of the ground floor.
Reduce seismic demand on the first floor	Add viscous or Visco-elastic dampers to the ground floor to reduce seismic demand in the first floor and eliminate the soft story.

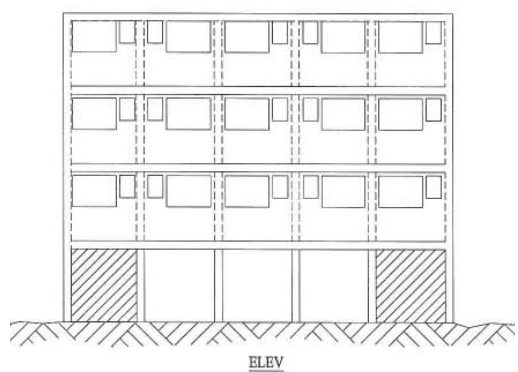


Figure 50. Retrofitted Condition RC Frame Building

Summary, Conclusions, and Recommendations

The Sichuan, China, Earthquake did not produce results that were unexpected. The reconnaissance data and literature surveyed showed the following:

- Nearly all the buildings that collapsed in and around the Sichuan Province were constructed with very little seismic resistance, ductility of redundancy. URM bearing wall, nonductile concrete moment frames, questionable load path, lack of diaphragm, poor detailing, and non-desirable structural configurations all contributed to the observed damage.
- China is not an exceptional case when considering vulnerable structures. The recent earthquakes in Turkey, Indonesia, Peru, Pakistan, Iran, and elsewhere have all shown strikingly similar findings when it comes to collapse of susceptible nonductile buildings. Nonductile

and vulnerable construction is found everywhere and they predictable perform poorly in earthquakes.

- It is vital to identify seismic hazards and to develop retrofit programs for hazardous structures. The immense damage seen in Sichuan could have been avoided through seismic risk management—particularly in identifying and rehabilitating dangerous buildings and in protecting nonstructural components.
- International communities and structural engineers must share their knowledge, developing and building on lessons learned from past mistakes, and increase awareness of earthquake risks. Such action should be taken to ensure the safety of citizens and especially our children.

References

Banking - http://www.grgbanking.com/english/

Briefing by Xi Guohua, 19 May 2008 17th CPC, Central Committee, Central Commission for Discipline Inspection

Briefing by Gu Junyuan, 19 May 2008 Chief Engineer of the State Electricity Regulatory Commission (SERC)

BBC, British Broadcasting Company

British Geological Survey (BGS) http://www.bgs.ac.uk/

California Institute of Technology http://www.tectonics.caltech.edu/

China Earthquake Networks Center (CENC) - http://www.csi.ac.cn/

Geology.com

MCCER, earthquake engineering to extreme event, University at Buffalo

NASA Earth Observatory - http://earthobservatory.nasa.gov/

NCREE, National Center for Research on Earthquake Engineering, Taiwan

New York Time

United State Geological Survey (USGS)