RECONNAISSANCE REPORT OF THE 2008 SICHUAN EARTHQUAKE, DAMAGE SURVEY OF BUILDINGS AND RETROFIT OPTIONS

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ABSTRACT :

On 12 May 2008, a magnitude 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 tectonically related 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 approached 70,000 and millions were injured or left homeless. Damage was estimated at billions of US $. This area had previously been considered a moderate earthquake zone by the Chinese Building Code, and hence, the level of damage was not anticipated. Thousands of buildings and many bridges collapsed or sustained severe damage. Schools and hospitals were especially vulnerable and many such buildings collapsed. Many 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 hybrid structural system comprised of masonry columns, concrete beams, and hollow precast decks. This system was responsible for a disproportionate number of collapsed buildings. Residential unreinforced masonry buildings also fared poorly and many of them collapsed. By comparison, non-ductile reinforced concrete framed buildings performed slightly better. Many of these buildings sustained significant damage, but did not collapse. For concrete framed buildings, the presence of masonry infills introduced additional failure modes. For many 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. Analytical tools, experimental data, and available knowledge provide the basis of the suggested retrofits with the objective of strengthening and adding ductility to the structure to protect vulnerable non-ductile components. 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 in this paper.

KEYWORDS: Magnitude 8 earthquake, collapsed building, URM building, non-ductile concrete, incomplete load path, seismic retrofit

1. INTRODUCTION

The 12 May 2008, magnitude 8.0 Sichuan (China) earthquake resulted in over 69,000 fatalities, injured more than 370,000, and left millions homeless. As of 26 June 2008, 18,000 people were still missing. Millions 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). This quake is classified as an X event on the Modified Mercalli Intensity (MMI) scale (Figure 1) indicating violent shaking and heavy damage. The event caused tremendous damage as indicated in Figure 2. The main shock was followed by a number of aftershocks. Figure 3 shows the location of these aftershocks including a magnitude 6.0 event on 25 May, 13 days after the main shock, caused additional casualties and damage.

The authors (Miyamoto and Wada) were two of the first engineers to visit the site. This paper presents the results from a reconnaissance survey conducted by the authors, 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 mitigating such disasters in the future.

2. SITE SEISMICITY

The earthquake epicenter was located 80 kilometers west of Chengdu, the Sichuan Province capital, and 1500 kilometers southwest of Beijing. The earthquake had an epicentral depth of 19 kilometers and occurred as the result of movement on the Longmenshan Fault. This thrust fault runs along the base of the Longmenshan Mountains in Sichuan Province in southwestern China. The fault rupture started in the mountains and traveled at least 200 kilometers toward the northeast. Ground rupture exceeded 6 meters. Figure 4 depicts the major earthquakes impacting the region and a close-up of the earthquake epicenters and local faults. The Sichuan province of China has seen many earthquakes. The 1933 Diexi earthquake occurred in Diexi, (nearly 80 km from the epicenter of the 2008 earthquake and destroyed the town of Diexi and many villages, and caused many landslides.

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 China Earthquake Networks Center (CENC) has instrumented many buildings in China. 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. Very high vertical accelerations, order of 0.64g were recorded.

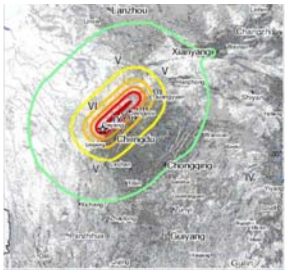

Figure 1. Intensity map (USGS)

Figure 2. Damage map (NY Times)

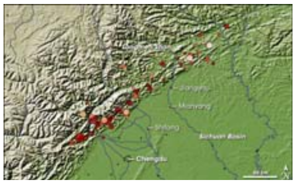

Figure 3. Aftershocks (NASA)

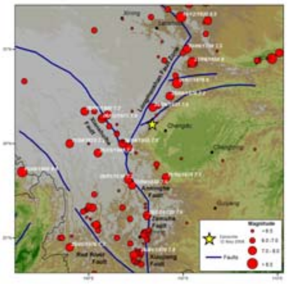

Figure 4. Local faults and earthquakes (BGS)

3. BUILDING STRUCTURES

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 cast-in-place reinforced concrete (CIP-RC) moment frames for low-rise to mid-rise buildings including schools and hospitals. The buildings use an unconventional floor system. It consists of concrete ring beams at the perimeter with interior hollow precast slab planks. There is minimal reinforcement continuity between the concrete floor slabs and the URM walls.

3.1.1 *Schools and Hospitals*

Many schools and hospitals collapsed in this Earthquake. The death toll is expected to exceed 10,000, and more than 7,000 classrooms were damaged. Many of the collapsed buildings were newer structures and consisted of URM construction or nonductile CIP-RC construction. Several examples of damaged schools and hospitals are summarized below.

3.1.2 *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 50,000 and is approximately 20 kilometers from the fault rupture. The school, constructed in 1986, housed 1000 students. More than 700 died when the building collapsed. Construction consisted of nonductile CIP-RC beams supported by URM walls, with precast concrete floor planks. Figure 5 shows the collapsed floor precast planks. Note that the planks pulled away from the walls, were hanging, and attached to the opposite walls. The collapsed URM walls and nonductile concrete beam is shown in Figure 6. A lab building adjacent to the collapsed school with similar construction did not collapse. This better performance was likely due to the orientation of its URM walls or better construction quality. Figure 7 shows the cracked walls.

3.1.3 *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 300,000 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 8) survived the event. The stairwells added stiffness and resistance to this portion of the buildings and survived even when the main building had collapsed.

3.1.4 *Hanwang High School*

This four-story school is located in the Hanwang township of Mianzhu with a population of more than 60,000 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 (Figure 9) because the URM walls created captive columns and prevented flexural yielding.

3.1.5 *Mianzhu Experimental School*

This school is located in the city of Mianzhu, with a population well over 500,000, 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 demand and lack of adequate confining transverse reinforcement resulted in severe column damage (Figure 10).

3.1.6 *Hanwang Primary School*

The main school building collapsed, but the adjacent dormitory building survived although its walls were cracked (Figure 11). 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 5. Collapsed floor planks

Figure 6. Collapse URM wall and concrete beam

Figure 7. Shear cracks in masonry walls

Figure 8. Collapsed primary school

Figure 9. Captive column failure

Figure 10. Column flexural failure

Figure 11. Cracked URM wall

3.1.7 *Xingfu Hospital*

A wing at the Xingfu Hospital collapsed (Figure 12), 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 2,000, performed better and sustained moderate structural damage, shear-wall cracks, and nonstructural damage, dropped ceiling panels (Figure 13).

3.1.8 *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 14) and the upper floors dropped down one floor.

Figure 12. Collapsed wing

Figure 13. Nonstructural damage

Figure 14. Soft story collapse

3.1.9 *Industrial Facilities*

Structural, nonstructural, and equipment damage was widespread and 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 similar to observations from past earthquakes. Such loss is preventable with cost-effective tie downs which can reduce business interruption (BI). Observations from a number of industrial facilities are presented here.

3.1.10 *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 15) 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. The loss of the stacks is critical since the plant cannot operate without them. The estimated BI is up to six months.

3.1.11 *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 16), except for some broken window glass, which was caused by excessive building displacement. However, this facility sustained a BI of one week of BI after the earthquake.

3.1.12 *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 17) collapsed because of out-of-plane seismic excitations. BI for this plant is expected to exceed six months.

3.1.13 *Light Industrial Plant*

This light industrial plant is located in the Hanwang. 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. BI is expected to be several months because of direct damage to the building and unanchored equipment.

3.1.14 *Steel Fabricating Plant*

This steel fabricating plant is located in the Hanwang. 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 18) causing BI of several months


Figure 15. Damaged URM stack


Figure 16. Undamaged building


Figure 17. damaged URM and emergency tents


Figure 18. Sliding of un-anchored equipment

3.1.15 *Commercial Buildings*

Many commercial structures performed adequately, particularly those built after the late 1990’s. Typical commercial structures usually consisted of a 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.

3.1.16 *Office Building 1*

The 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 19). The ceilings did not have lateral bracing.

3.1.17 *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 20). 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.

3.1.18 *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 had collapsed. The only visible damage was to the wood roof (Figure 21). This concrete structure has many walls, and appears to be well designed and constructed.

3.1.19 *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 22). 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.

Figure 19. Damaged suspended ceiling

Figure 20. Collapsed corner of the building

Figure 21. Damaged roof of the building

Figure 22. Collapsed Bank of China branch

3.1.20 *Residential (Houses and Apartments) Buildings*

Many 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. This type of system has little lateral capacity and ductility. The roof tiles are lighter and thinner than the similar Japanese version and are not interlocked. Thus, in earthquake, they dislodged and saved the structure by reducing the inertial mass. Some URM mid-rise structures, with the exception of units with configuration irregularities, performed adequately. 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.

3.1.21 *Residential Village North of Mianzhu*

This small village of residential structures sustained severe damage and over 80% of the buildings collapsed (Figure 23). The structures were built of brick walls and wood-frame roofs with lightweight black roofing tiles.

3.1.22 *Apartment Building Complex*

Several eight-story apartment buildings, constructed of URM bearing walls and concrete slabs, constitute a complex in the center of Hanwang township. Many diagonal shear cracks occurred in the walls between windows (Figure 24), but the buildings did not collapse due to the redundancy and lateral capacity provided by the network of interior walls.

3.1.23 *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 25).

Figure 23. Collapsed residential units

Figure 24. Cracked URM walls

Figure 25. Vertical split and displaced apartment complex

4. LIFELINES

Lifelines serving the earthquake area in Sichuan Province include transportation infrastructure, electric power, telecommunications, road and rail lines, and local potable water supplies. All these systems suffered serious damage and prolonged service outage. 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 highway and rail lines. 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.

4.1. Bridges and Roadways

Over 3000 bridges and 16000 km of highway were damaged. The fault rupture crossed some bridges and in these instances, significant damage was observed. Roadway damage (Figure 26) was the result of ground shaking (acceleration), surface rupture, and earthquake related geotechnical issues such as landslide, and slop instability.

4.2. Railways

Railways were damaged because of shifting ground (Figure 27), 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.

4.3. Electricity Generation and Distribution

The Sichuan Province power grid lost about 40% of its load following the earthquake. 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. Figure 28 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.

4.3.1 *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.

4.3.2 *Water*

China Urban Water Association (CUWA) reported that 7800 km of water pipes and 839 tanks were damaged. Pipeline damage was attributed to the ruptures in the rigid buried pipes subjected to seismic waves, ground shaking, and differential displacement. 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 threatens the adjacent, and undamaged, commercial building; thus makes the building inaccessible. There is also a large shear crack in the tower wall (Figure 29). It is unlikely that this structure would be repaired.

4.3.3 *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 The Three Gorges River Dam was not damaged. However, many other dams were damaged.

Figure 26. Damaged roadway

Figure 27. Damaged roadway

Figure 28. Collapsed URM wall at a substation

Figure 29. Shear crack in URM water tower

5. 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 hours of the earthquake, national emergency response had began, over 150,000 local and army core rescues and 30,000 medical staff had arrived at the hardest hit areas. Thousands of emergency tents had been setup. Personnel disinfected 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.

6. SEISMIC RETROFIT

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 listed in Table 1 and schematically shown in Figure 30. Since schools, hospitals, and apartments can be classified as important buildings and high-density population areas, the presented options emphasize 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 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.

Table 1. Proposed building retrofit options

Building Type	Deficiencies	Retrofit design
All	Lack of diaphragm action	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.
URM bearing wall	Lack of lateral capacity and ductility	Add full-height ductile, RC shear walls on the exterior of the building
		Apply engineered cementations concrete (ECC) to the exterior of the walls
		Place the structure atop of seismic isolators
Nonductile RC moment frame with URM infill	Inadequate joint capacity, lack of column confinement, captive columns	Add full height ductile RC shear walls on the exterior of the building
		Cut the connection between the partial height infill URM walls and concrete columns; Wrap columns using FRP; Add prestressing or confinement to joints to; Add shotcrete to the existing members
		Place the structure atop of seismic isolators
Soft story at ground floor	Lack of lateral stiffness and capacity at a floor	Add single-story ductile RC shear walls on the exterior of the building
		Add single story steel braces on the exterior of the
		Add viscous or Visco-elastic dampers to the ground floor

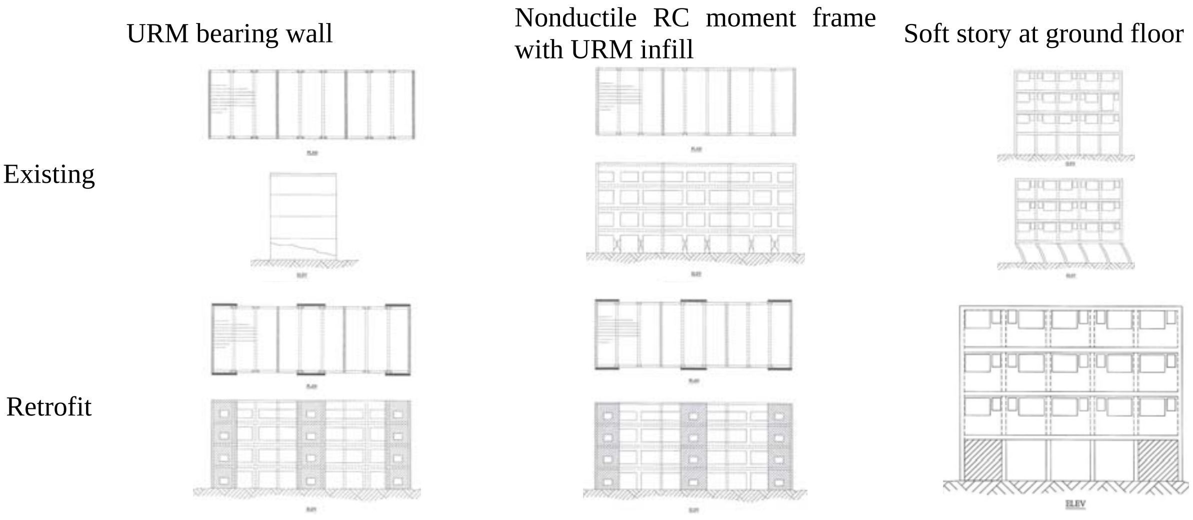

Figure 30. Proposed retrofit schematics

7. 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 collapsed 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 all shown strikingly similar findings when it comes to collapse of susceptible nonductile buildings. Nonductile and vulnerable constructions perform poorly in earthquakes.
- It is vital to identify seismic hazards and to develop retrofit programs for hazardous structures.
- International communities and structural engineers must share their knowledge, developing and building on lessons learned from past mistakes, and increase awareness of earthquake risks.

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