SURVEY OF DAMAGED SCHOOL AND HOSPITAL BUILDINGS IN THE 2008 WENCHUAN EARTHQUAKES, RETROFIT OPTIONS, AND APPLICATION TO TURKEY

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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. The fatalities exceeded 70,000 and millions were injured or left homeless. Damage was estimated at over US $150 Billion. Thousands of unreinforced masonry and reinforced concrete buildings collapsed or sustained severe damage. Schools and hospitals were especially hit hard and many 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 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. 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. Many school and hospital buildings in Istanbul, Turkey also use the same type of construction and are hence vulnerable to collapse. To mitigate this, the government of Istanbul with under the auspices of the World Bank, has developed a program to retrofit thousands of such buildings. In this endeavor, local engineers, and international experts work together to identify suspect buildings (using available plans and site visits), assess the conditions, device a retrofit strategy, and inspect construction sites to ensure that the design, construction and quality control and assurance meet the current knowledge for adequate strengthening to ensure that the retrofitted buildings provide life safety. 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: Sichuan Magnitude 8 earthquake, collapsed school and hospital buildings, URM, non-ductile concrete, seismic retrofit, Istanbul seismic retrofit program

1. INTRODUCTION

The 12 May 2008, magnitude 8.0 earthquake struck Sichuan (Wenchuan), China. The earthquake epicenter was located 80 kilometers west of Chengdu, the Sichuan Province capital, and 1500 kilometers southwest of Beijing.

Miyamoto and Wada were two of the first engineers to visit the site (Miyamoto 2008). This paper presents the results from a reconnaissance survey conducted by the authors, with particular attention to the school and hospital buildings that sustained disproportional failures. This is followed by a description of cost-effective retrofits. Finally, a discussion of similar construction in Istanbul and efforts underway to mitigate future seismic damage in Istanbul are summarized.

2. THE SICHUAN EARTHQUAKE

The earthquake had an epicentral depth of 19 kilometers and occurred as the result of movement on the Longmenshan thrust Fault that runs along the base of the Longmenshan Mountains in Sichuan Province.

The China Earthquake Networks Center 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 (CENC) were recorded.

Because seismic waves associated with shallow quakes can reach the surface with very little energy loss, they produce stronger shaking and more damage. The fault rupture started in the mountains and traveled at least 200 kilometers toward the northeast. Ground rupture exceeded 6 meters.

The severest damage was concentrated along a band close to the rupture zone. Due to the directionality of fault rupture, the damage was the most severe perpendicular to the rupture direction. For many structures, if the lateral 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. This was a massive earthquake. As listed in Table 1, the human and financial cost associate with this earthquake is truly astounding and tragic.

Table 1. Proposed building retrofit options

Human loss	Fatalities	69000
	Missing	19000
	casualties	375000
	Evacuated	15 million
	Displaced	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
	Reconstruction cost	$150 billion
	BI	Months and $B

This quake is classified as an X event on the Modified Mercalli Intensity (MMI) scale (Figure 1) indicating violent shaking and heavy damage. The main shock was followed by a number of aftershocks including a magnitude 6.0 event on 25 May, 13 days after the main shock, that caused additional casualties and damage.

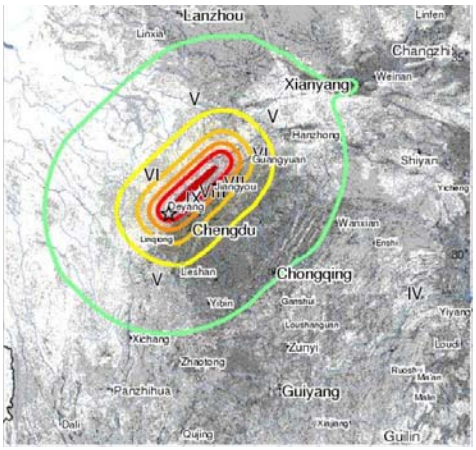


Figure 1. Intensity map (USGS)

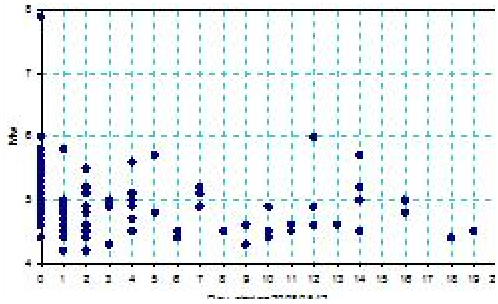


Figure 2. Aftershocks

This part of China was assigned a moderate seismicity in the seismic design maps (see Figure 3). However, several large earthquakes have previously occurred in this area. 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, and resulting in over 9000 fatalities.

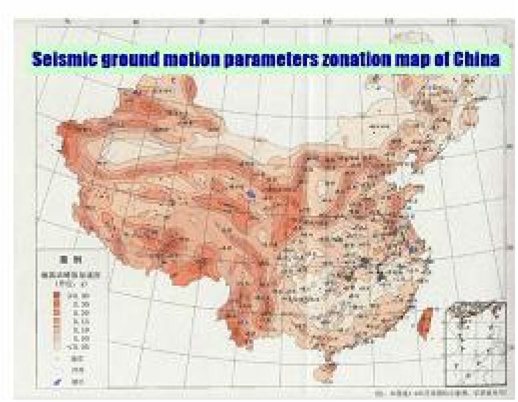


Figure 3. Seismicity map (IWHR 2004)

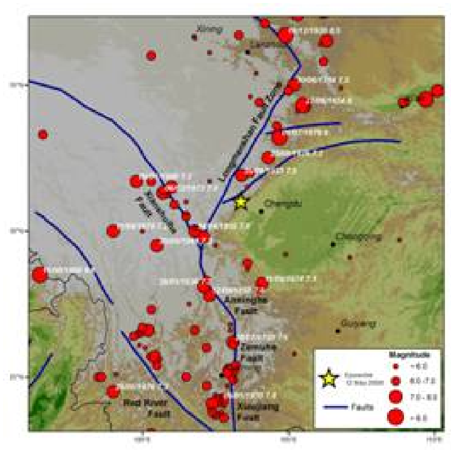


Figure 4. Local faults and earthquakes (BGS)

3. DAMAGE TO SCHOOLS AND HOSPITALS

3.1. Overview

Most buildings at the earthquake site consisted of three types of structures.

- Unreinforced masonry (URM) bearing walls for low-rise buildings
- Hybrid URM column-concrete beam
- Cast-in-place reinforced concrete (CIP-RC) 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 planks. There is minimal reinforcement continuity between the concrete floor slabs and the URM walls.

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.

3.2. Surveyed school damage

3.2.1 *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 5a 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 5b. Figure 5c shows the collapse of a nonductile bond (perimeter) beams. A lab building adjacent to the collapsed school with similar construction, constructed in 1996, did not collapse (see Figure 5d). This better performance was likely due to the orientation of its URM walls or better construction quality.

a. Collapsed floor planks

b. Collapse URM wall and concrete beam

c. Non-ductile CIP-RC beam

d. Cracked URM

Figure 5. Juyuan Middle school damage

3.2.2 *Juyuan Primary School*

The school was built in 2007. This four-story building is a few miles away from the collapsed Juyuan Middle School. Construction consisted of CIP-RC frames (beams, columns) and infill URM walls. There were a few shear (diagonal) cracks in the shear walls and minor pounding damage between buildings (Figure 6a). Overall the damage was minor (Figure 6b). This is likely an indication that the new construction practices could perform well in major earthquakes.

a. Minor pounding damage b. Frontal view of school

Figure 6. Juyuan Primary school

3.2.3 *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 6a) survived the event. The stairwells added stiffness and resistance to this portion of the buildings and survived even when the main building had collapsed. The collapsed first floor is shown in Figure 6b.

a. Collapsed building; note the standing stairway b. Collapsed first floor

Figure 7. Xingfu primary school

3.2.4 *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 7a) because the URM walls created captive columns and prevented flexural yielding. As shown in Figure 7b, the URM walls sustained out-of-plain failure because they were not adequately anchored.

a. Captive column b. Collapsed first floor

Figure 8. Hanwang High School

3.2.5 *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 8a). The URM walls sustained shear cracking (see Figure 8b)

a. Column flexural failure b. Cracked wall

Figure 9. Mianzhu Experimental School

3.2.6 *Hanwang Primary School*

The main school building collapsed (see Figure 9a), but the adjacent dormitory building survived although its walls were cracked (Figure 9b). 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.

a. Column flexural failure b. Cracked wall

Figure 10. Hanwang Primary School

3.3. Surveyed Hospitals

3.3.1 *Xingfu Hospital*

A wing at the Xingfu Hospital collapsed (Figure 11a), 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 11b). Such nonstructural damage, although minor, could be potentially problematic as it can be a falling hazard, block exit, and interfere with the operation of the hospital.

a. Collapsed wing b. Nonstructural damage

Figure 11. Collapsed wing

3.3.2 *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 12a) and the upper floors dropped down one floor (see Figure 12b).

a. Soft story collapse b. Close-up of the first floor

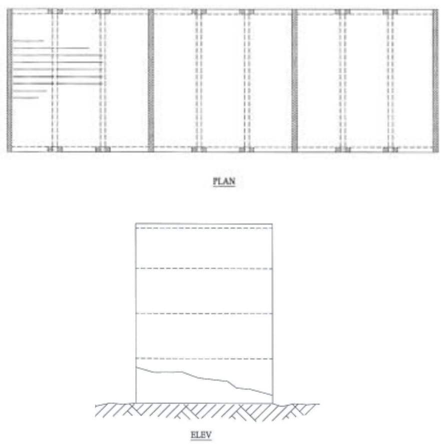
Figure 12. Hanwang Hospital

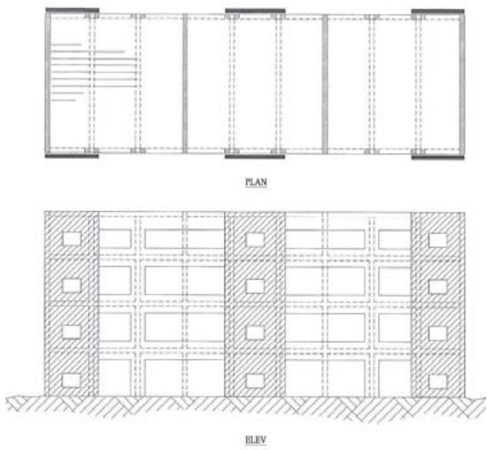
4. SEISMIC RETROFIT OPTIONS

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 2 and schematically shown in Figure 13. Since schools and hospitals 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 2. Proposed building retrofit options

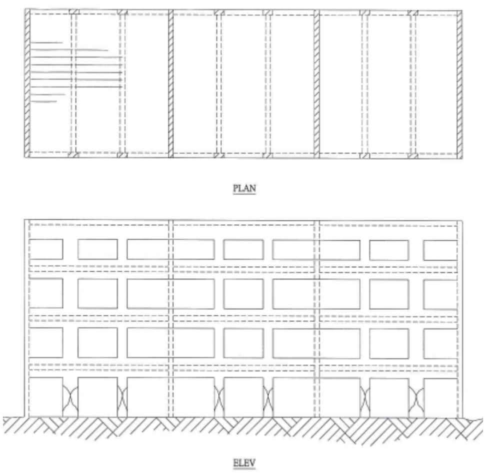
Building Type	Deficiencies	Retrofit design
All	Lack of diaphragm action (load path)	Check strength and ductility of the RC ring beams.
		Reinforce and confine them as needed.
		Add ring beams at each floor if not present.
URM bearing wall	Lack of lateral capacity and ductility	Add full-height ductile, 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	Lack of strength, stiffness, and ductility	Add full height ductile RC shear walls on the exterior of the building
		Add shotcrete to the existing members
		Place the structure atop of seismic isolators
	lack of column confinement	Wrap columns using FRP
	captive columns	Cut the connection between the partial height infill URM walls and concrete columns
	Inadequate joint shear capacity	Add prestressing or confinement to joints to;
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

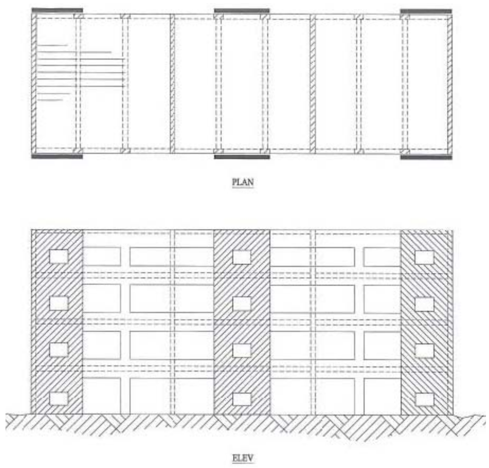




a. Existing b. Retrofitted

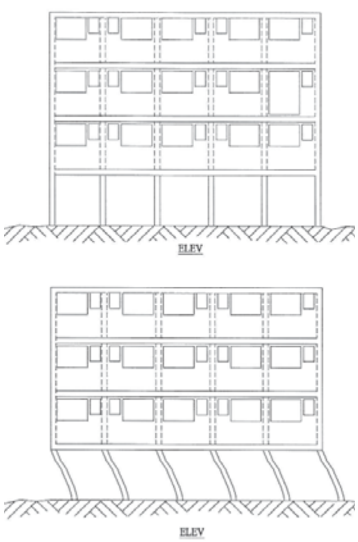
URM bearing wall

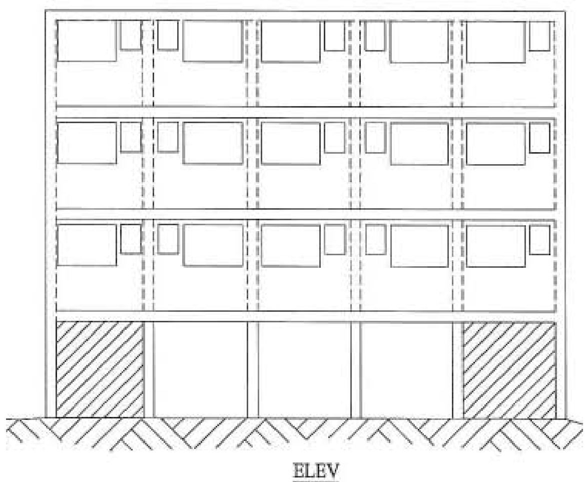




a. Existing b. Retrofitted

Nonductile RC moment frame with URM infill





a. Existing b. Retrofitted

Soft story at ground floor

Figure 13. Proposed retrofit schematics

5. APPLICATION TO TURKEY AND ISTANBUL

Dangerous URM, nonductile RC buildings, and poor seismic detailing and 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. It is imperative to upgrade these structures to protect lives in future events.

In 2006, Istanbul, Turkey, through funding and cooperation from the World Bank, initiated a major earthquake-strengthening program for hundreds of vulnerable school and hospital buildings under the Istanbul Seismic Risk Mitigation and Emergency Preparedness Project (ISMEP). This work entails identifying vulnerable structures and designing optimal retrofits. The work is performed by local engineers with oversight from world experts.

Figure 14 shows a photograph of a vulnerable building taken by the main author (Miyamoto) during a site visit and condition assessment survey. For this building, the walls terminate above first floor to allow for parking. However, this introduces soft-story mechanism at this level and can lead to collapse in a future earthquake. This structure configuration is not much different from many observed in China. Once such dangerous buildings are identified, retrofit measures are proposed and implemented.

Figure 14. A vulnerable structure

Many Istanbul school buildings are seismically strengthened by new CIP-RC shear walls. These walls are designed to carry the entire seismic loading and use ductile detailing and regular configuration. This cost-effective and relatively simple technique would have saved many schools and hospitals during the Sichuan Earthquake. An example of such retrofit is shown in Figure 15

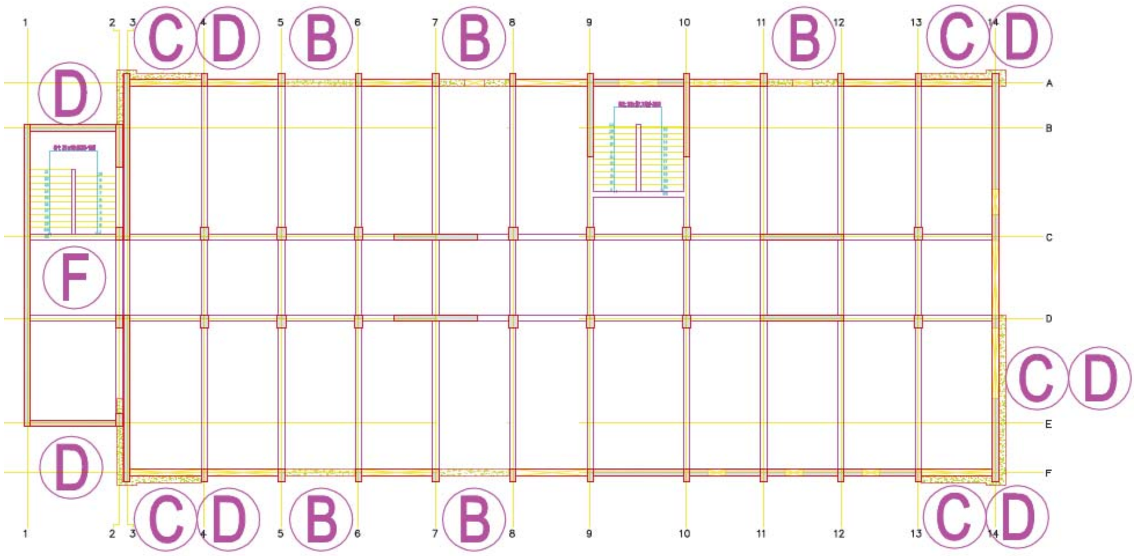


Figure 15. Example of retrofit with new CIP-RC walls

When the new CIP-RC wall retrofit is chosen, care must be taken to address several issues to ensure acceptable seismic performance. These factors include the following.

- The new RC walls should be designed to carry the entire seismic load.
- The walls must be placed symmetrically to ensure that torsion is not introduced.
- Ductile detailing should be used. This entails adequate splice of flexural reinforcement, adequate transverse confinement, ductile boundary members, seismic (135 degree hooks), no splice in the regions of plastic zone, and staggering of lap splices.
- Design of drag (collector) elements to transfer seismic forces in the slabs between the RC walls
- Ensuring deformation compatibility for the existing columns.

6. 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.
- It is vital to identify seismic hazards and to develop retrofit programs for hazardous structures.
- Cost-effective retrofit options are available for vulnerable 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.

- Istanbul provides an excellent example of cooperation between government agencies, local engineers, and world experts in mitigating seismic hazard for essential buildings and for vulnerable structures.

7. REFERENCES

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CENC	China Earthquake Networks Center
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