Damage to Critical Facilities Following the 921 Chi-Chi, Taiwan Earthquake

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Research Objectives

As part of research collaboration between MCEER and the National Center for Research in Earthquake Engineering (NCREE) in Taiwan, a team of MCEER/NCREE researchers undertook a reconnaissance mission shortly after the 921 Chi-Chi earthquake occurred in Taiwan at 1:47 a.m. on September 21, 1999. A major objective of this mission was to assess earthquake-induced damage, to document lessons learned, and to identify short-term strategies for post-earthquake restorations. This paper, a portion of the MCEER/NCREE Reconnaissance Report (MCEER/NCREE, 2000), summarizes preliminary findings on the damaging effects of the earthquake on critical facilities.

Critical facilities include hospitals and health care facilities; schools; police, fire and emergency response stations; key government facilities; and key industries. They provide lifesaving functions and render emergency assistance to communities when a disaster strikes. It is thus particularly important that every effort be made to insure their safety and functionality during and after a disaster. In this paper, damages to some of these facilities due to the 921 Chi-Chi earthquake are assessed, together with their probable causes and impact. Possible corrective actions and research needs in mitigating the effect of a similar future disaster event on these critical facilities are addressed.

It is noted that damage information on many of these facilities is still being collected and processed at the time of this writing. Therefore, they should be considered incomplete and preliminary as reported in this section.

Hospitals

According to available information, there are 4,375 health care facilities within the six-county seismic affected zone, of which 165 are hospitals. Damage to hospitals can be grouped into the following three categories: (1) minor structural damage and minor nonstructural damage, (2) partial

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MCEER Program 1: Seismic Evaluation and Retrofit of Lifeline Systems
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structural damage but serious nonstructural damage, and (3) serious structural damage. In the first category, evacuation of patients and staff was not required and the hospitals were capable of performing emergency care to earthquake victims. In the second, hospitals were rendered non-serviceable and time was required for restoration. This type of damage was prevalent in the areas close to the epicenter. For example, within the critical 48-hour period after the earthquake, close to 1,000 beds were lost for patient care in Nantou county alone. Serious structural damage, or the third category, was also evident in regions close to the epicenter, where major hospitals were closed, requiring either demolition or major repair.

While structural damage was widespread in the six-county affected area, nonstructural damage was found to be a major factor adversely affecting functionality of major hospitals. Common occurrences included fallen interior walls and ceilings, toppling, sliding or collision of medical and non-medical equipment, overturning of water and oxygen tanks, interruption of emergency power, and flooding due to pipe breakage. For a closer scrutiny, several hospitals were chosen for more in-depth site visits. In what follows, damage investigations made on October 5, 1999 at three major hospitals are summarized. The observations described below are based on interior as well as exterior damage inspections and on interviews with hospital officials.

Christian Hospital, Puli

A major facility in Puli and surrounding communities, the Christian Hospital is a 400-bed facility of reinforced concrete (RC) construction consisting of a new (about a year old) section and an old (about 20 years old) section (see Figure 1).

Damage Summary

- New section sustained considerable damage from the main event on 9/21/99. Out of safety concerns primarily due to nonstructural damage (water damage, equipment failure, etc.), the building was evacuated with patients housed in tents on the hospital grounds. The building was immediately inspected and considered safe. Upon interior cleaning, patients were returned to the building.
- The building suffered significant nonstructural damage again from the 9/27/99 M6.8 aftershock. Patients were again evacuated and housed in temporary trailers with considerably reduced capacity (about 50 beds), with overflow transferred to other area hospitals.

This research focused broadly on the damage to numerous critical facilities caused by the 921 Chi-Chi, Taiwan earthquake. It is anticipated that numerous groups including the earthquake research community; seismic code committees; regulatory officials; and administration and technical staff of critical facilities dealing with seismic vulnerability and rehabilitation will have an interest in the issues discussed.

Photographs by T.T. Soong

■ Figure 1. The Christian Hospital sustained considerable damage. Photos show (left) part of the exterior damage to the hospital; and (right) interior damage to partitions and ceilings.

- The first floor of the building remained open and was being used for emergency care, patient registration and processing, command post, and other necessary functions (see Figure 2).

Consequences and Impact

- A major part of the hospital was non-serviceable primarily due to nonstructural damage.
- Drastically reduced capacity (10% of original) at a time when demand was the highest.
- Trauma to patients through two relocations.
- Drastically reduced services due to equipment damage.
- The lack of an earthquake emergency management plan probably made the situation worse.

Restoration

Restoration was underway. It was estimated that the interior would be restored and serviceable within two weeks.

Veterans Hospital, Puli

The Veteran's Hospital is another major hospital located in Puli. It is a 450-bed facility with two main reinforced concrete (RC) buildings

Photograph by T.T. Soong

■ Figure 2. The first floor of the Christian Hospital remained open though the hospital suffered extensive interior damage.

Web Sites

Multidisciplinary Center for Earthquake Engineering Research
http://mceer.buffalo.edu/research/taiwaneq9_99/default.html

Photograph by M. Bruneau

■ Figure 3. An overview model of the Veterans Hospital in Puli. The two white buildings are the newest and both sustained considerable damage.

(the Medical Center and the Administration Center), built about three years ago and several older (about 25 years old) and smaller buildings (see Figures 3 and 4).

Damage Summary

- New buildings sustained considerable damage from the main event. The Medical Building (Bldg. 1) was closed and the patients in the Administration Building (Bldg. 2), along with those in Bldg. 1, were either moved to the older buildings or transferred to other VA hospitals. About 220 patients remained at the hospital.
- Considerable nonstructural damage in Bldgs. 1 and 2, including power failure[1], water damage, and equipment damage. Bldg. 1 also sustained considerable structural damage, probably due to a lack of ductile detailing.

Consequences and Impact

- A major part of the hospital was non-serviceable due to both structural and nonstructural damage.
- Drastically reduced capacity (50% of original) at a time when demand was the highest.
- Trauma to patients due to evacuation.
- Drastically reduced services due to equipment damage.
- As in the case of the Christian Hospital, no earthquake emergency management plan appeared to be in place at the time of the earthquake.

Restoration

Whether Bldg. 1 was to be demolished or repaired remained to be determined. Bldg. 2 was expected to be repaired within two weeks.

Photographs by M. Bruneau

■ Figure 4. The Veterans Hospital sustained both exterior damage (left) and interior damage (right) to the newest buildings of the Medical Center.

Photographs by G.C. Yao

■ Figure 5. Interior damage in the Shiu-Tuan Hospital. Shown are (left) fallen brick inside the hospital and (right) a damaged interior glass brick wall.

Shiu-Tuan Hospital, Tsushan

The Shiu-Tuan Hospital is a 9-story, two year old reinforced concrete (RC) building that has a 400-bed capacity. It is privately owned and is the largest in Nantou county. The structure is situated about 120 m from the Che-Lung-Pu Fault with an uplift of approximately one meter at the site.

Damage Summary

- Structurally intact, it suffered considerable nonstructural damage as in the case of the other two hospitals (see Figures 5 and 6). Interior damage was most severe at the second- and third-floor levels where, unfortunately, some of the major facilities, such as operating and recovery rooms, were located. Patients were moved to open hospital ground and subsequently transferred to other hospitals.
- Hospital closed.

Consequences and Impact

- Trauma to patients due to evacuation and reallocation.
- Hospital closed, making the largest hospital in this vicinity unavailable to patients and earthquake victims.
- Seven patients died due to stoppage of life-support system.

Restoration

Repair was underway and the process was expected to take one to two months. Funds for the repair remained to be found.

Photograph by G.C. Yao

■ Figure 6. Damage to an exterior wall of the Shiu-Tuan Hospital in Nantou county

■ Table 1. Nonstructural Damage in Three Surveyed Hospitals

Cause of Disruption and Evacuation	Christian	Veterans	Shiu-Tuan
Backup Power Outage	X		X
Water Supply Outage	X	X	X
Gas Service Outage		X	X
Elevator Damage		X	X
Communications Failure	X	X	X
Falling Debris	X	X	X
Broken Piping, Water Leakage	X	X	X
HVAC Anchorage Failures	X	X	X
Mechanical Equipment Damage	X	X	X
Toppling of Gas, Liquid Storage Tanks	X	X	X
Medical Equipment Damage	X	X	X
Emergency Evacuation Plan Not in Place	X	X	X

Summary

The damage to the three hospitals and its impact underscores the importance of securing medical equipment and protecting patients and staff from falling debris and overturning objects. As demonstrated in the case studies above, hospitals can be rendered non-serviceable and lives of patients can be lost due to failure of life support equipment in critical care areas. Table 1 is a compilation of nonstructural damage in the three hospitals highlighted in this paper which, incidentally, could have been reduced or even avoided with inexpensive and easily implementable protective measures.

■ Table 2. Extent of Damage to Schools

Type of Institution	Total	Damaged	Damage Ratio (%)
Universities and Colleges	36	33	91.7
Technical Institutions	98	38	38.8
Normal Universities	13	8	61.5
High Schools	242	63	26.0
Middle Schools	715	168	23.5
Elementary Schools	2,557	488	19.1
Schools for the Disadvantaged	20	4	20.0
Total	3,681	802	21.8

Ministry of Education, 1999b

Schools

School buildings sustained severe damage, reaching as far as the city of Taipei, 150 km from the epicenter. As in the 1998 Chia-Yi/Ruei-Li earthquake, the severity of damage to school buildings, as demonstrated in Table 2, again exceeded that of other structures due primarily to the commonality of their weaknesses in construction. The common problems associated with school buildings appeared to be, on the one hand, short-column effects which led to shear failure in columns and, on the other, eccentricity of most school buildings associated with cantilevered corridors at upper floors (see Figure 7). It is estimated that restoration, repair and reconstruction costs associated with school buildings can reach US$ 1.3 billion (Ministry of Education, 1999a).

According to a recent accounting made available by the Ministry of Education, a total of 786 schools were damaged by the earthquake and its aftershocks as listed in Table 3, of which 51 suffered complete collapse. Damage was heavily

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■ Figure 7. Typical damage to schools due to short-column effect and eccentricity

■ Table 3. Damage to Schools

City/County[1]	Universities and Colleges	Technical Institutes and High Schools	Middle Schools	Elementary Schools	Total
Taipei City	8	8	8	43	67
Taipei County	2	1	21	52	76
Yi-Lan County	0	3	1	4	8
Tou-Yuan County	2	1	1	7	11
Hsinchu City	2	0	5	9	16
Hsinchu County	0	1	2	10	13
Miu-Li County	2	4	20	59	85
Taichung City	11	9	19	37	76
Taichung County	3	15	14	39	71
Nantou County	6	11	10	42	69
Chang-Hwa County	3	10	26	46	85
Yu-Lin County	1	6	10	32	49
Chia-Yi City	0	9	7	16	32
Chia-Yi County	2	2	7	35	46
Tainan City	1	0	10	18	29
Tainan County	1	2	0	0	3
Others	3	1	6	39	49
Total	47[2]	83[2]	168	488	786[2]

[1] *Numbers for counties do not include those in cities within the counties.*
[2] *Inconsistencies between Tables 4-2 and 4-3 are probably due to different information sources.*

Ministry of Education, 1999a

■ Table 4. Severity of Elementary and Middle School Damage

County	Total Collapse	Partial Collapse and Nonstructural Damage	Total
Nantou	30	109	139
Taichung	11	32	43
Neighboring Counties	10	41	51

Ministry of Education, 1999a

concentrated in Nantou and Taichung counties as illustrated in Table 4. In Nantou county, for example, 139 out of 186 elementary and middle schools, or approximately 75%, suffered damage serious enough that they had to be closed. This situation not only affected the education of students, but also made them unusable as evacuation and emergency response centers.

Police and Fire Stations

As in the case of schools and other public buildings, police stations and emergency response centers also sustained severe damage in the affected region (for example, see Figures 8 and 9). Damage report forms were sent to these units by the National Center for Research in Earthquake Engineering (NCREE) investigators and those returned to date are summarized in Table 5.

Key Industrial Facilities

Of particular interest to the international business community was impact of the Chi-Chi earthquake on the output at the Hsinchu's Science Based Industrial Park, where about 30 firms produce a significant percentage of the world's semiconductors and silicon wafers. Damage to this facility and its global impact are the focus of this section.

Hsinchu's Industrial Park, situated about 110 km from the epicenter, houses approximately 239 high technology firms that have important links to the world's computer

Photograph by T.T. Soong

■ Figure 9. Heavily damaged Puli Police Station

■ Table 5 Interim Damage Summary Pertaining to Police and Fire Stations

City/County	Severity of Damage				
	Total or Partial Collapse or Overturning	Serious Damage (Requiring Demolition or Retrofit)	Moderate Damage (Requiring Retrofit or Repairable)	Light Damage (Repairable)	No Damage
Nantou County	5	1	1	1	0
Taichung County	--	--	--	--	--
Taichung City	0	0	0	14	0
Miu-Li County	1	0	2	1	4
Chang-Hwa County	0	2	3	0	0
Yu-Lin County	--	--	--	--	--

NCREE, 1999a

and communications industry. Based on the types of products they produce, they can be grouped into the following: Integrated Circuit: 95, Computers and Peripherals: 44, Telecommunications: 36, Electro-optical: 35, Automation: 16, and Biotechnology: 13.

Power to the entire island was interrupted due to damage to the electrical transmission network and switching stations close to the epicenter, due to high-priority user status at the Hsinchu's Industrial Park. Power to the Park was restored to full capacity at 500,000 KV on September 25, 1999, four days after the earthquake. Even so, production loss at the facility was estimated to be around US$ 400 million, most of which incurred at the semiconductor and silicon wafer production facilities.

Overall damage at the facility has been light in comparison with those closer to the epicenter. Again, nonstructural and equipment damage stood out, including fallen ceilings, cracked walls and partitions, shear failure of columns, piping

Photograph by T.T. Soong

■ Figure 8. Total collapse of Puli Town Hall

■ Table 6 Damage Survey at Hsinchu Industrial Park

Forms Returned: 171			
No Damage: 101 **Percent of Total: 59%**	**Damage Reported: 70** **Percent of Total: 41%**		
Damage	Light	Moderate	Serious
Cracks in Walls	55	11	0
Deformed Floors	8	3	0
Shear in Columns	5	0	0

NCREE, 1999b

breakage, and equipment damage. Most of this damage was repaired rapidly and the entire industrial complex has been restored to its pre-earthquake production level. Table 6 lists damage survey results based on the returned survey forms to date.

General Observations and Lessons Learned

Seismicity

Heavy damage to critical facilities in areas close to the epicenter was certainly in large part attributable to the unanticipated high level of ground shaking in the region. For example, Nantou and Taichung counties, where most of the damage occurred, are located in seismic zone 2 with a design peak ground acceleration (PGA) specified at 0.23 g. On the other hand, the actual recorded PGAs in the region were in general higher than 0.35 g, and were as high as 0.92 g. Even accounting for an importance factor of 1.25 for public buildings, the design PGA values were considerably below those actually experienced, causing widespread damage to constructed facilities.

Structural Damage

Beyond high seismicity, several important factors contributing to observed structural damage to buildings, including critical facilities, have been identified and include:

- Short-column effects leading to column shear failure.
- Eccentricity due to cantilevered corridors.
- Lack of ductile detailing.
- Column failures due to inadequately spaced stirrups, reinforcements, and splices.
- Soft-story induced failures.
- Unstable foundations and ground uplift.

However, in spite of these common ills, structural damage to critical facilities appeared to be heavier than those in other sectors. It has been speculated that this may be due to the nature of the bidding process associated with the construction of public and government owned buildings, where fixed-price design/built contracts are practiced. As reported in local news broadcasts, this practice invites abuse and encourages contractors to utilize substandard construction materials and circumvent accepted engineering practices in order to complete their projects under budget.

Nonstructural Damage

As highlighted in several parts of this paper, the impact of nonstructural damage on the loss of functionality of critical facilities has been significant, leading to their inability to perform emergency and lifesaving services and, tragically, loss of lives. While seismic codes exist in Taiwan for buildings and bridges, there appears to be an absence of rational seismic provisions for nonstructural components. Ironically, seismic performance of nonstructural components can be substantially improved using rather simple and inexpensive means.

Research Needs and Recommendations

The outstanding issue identified by other team members from MCEER and NCREE related to construction practices associated with public buildings needs to be critically reviewed. Revisions and modifications appear to be necessary in order to insure quality engineering and quality construction in the future.

Also of critical importance is the nonstructural issue. Stringent seismic design and installation guidelines need to be in place to insure not only structural integrity, but also functionality of critical facilities, which require protecting nonstructural components, as well as structures, from seismic damage under strong ground shaking as experienced in the Chi-Chi earthquake. A systematic development of these guidelines involves the following:

- Review and improve current design and installation practices in nonstructural components.
- Develop effective retrofit strategies for nonstructural components in existing critical facilities.
- Develop effective implementational procedures for existing facilities and new constructions.

Endnotes

[1] The emergency generators also failed. They were located on the second floor of a separate building and, due to amplified acceleration on that floor, major components broke loose and rendered them inoperable.

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