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Near-Fault Seismic Vulnerability of Nonstructural Components and Retrofit Strategies

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ABSTRACT

Seismic design of buildings has been well developed and is being continually updated and improved. Yet nonstructural components housed in buildings are rarely designed with the same care or under the same degree of scrutiny as buildings. As a result, buildings that remain structurally sound after a strong earthquake often are rendered unserviceable due to damage to their nonstructural components, such as piping systems, communication equipment and others. The 1999 Taiwan 921 earthquake further demonstrates the importance of controlling damage to nonstructural components in order to ensure their functionality during and after a major earthquake. This is particularly important in the case of critical facilities since nonstructural components provide life saving functions and render vital emergency assistance to communities when disasters strike.

In this paper, damages to some of the critical facilities due to the 921 earthquake are assessed. This is followed by addressing two important issues associated with seismic performance of nonstructural components: seismic vulnerability and rehabilitation strategies.

INTRODUCTION

Nonstructural components of a building are those systems, parts, elements, or components that are not part of the structural load-bearing system but are subjected to the building dynamic environment caused by, for example, an earthquake. Typical examples of nonstructural components include architectural partitions, piping systems, ceilings, building contents, mechanical and electrical equipment, and exterior cladding. The importance of nonstructural component issues in seismic design and performance evaluation is now well recognized by researchers as well as practicing engineers. The subject received special attention after the San Fernando earthquake in 1971 when it became clear that damage to nonstructural components not only can result in major economic loss, but also can pose real threat to life safety. For example, an evaluation of various veteran hospitals following the San Fernando earthquake revealed that many facilities still structurally intact were no longer functional because of loss of essential equipment and supplies. These damage patterns were, unfortunately, repeated in most recent earthquakes such as the 1989 Loma Prieta earthquake, the 1994 Northridge earthquake, the 1995 Kobe earthquake, and the 1999 Taiwan 921 earthquake. Clearly, seismic vulnerability of nonstructural components has become a critical issue which must be addressed. Ironically, seismic performance of nonstructural components can be substantially improved using rather simple and inexpensive means.

In this paper, damage assessment to some of the critical facilities following the 921 earthquake is presented, followed by a discussions of the development of a systematic seismic vulnerability evaluation procedure and the development of improved design and installation guidelines for nonstructural components.

Damage to 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 life saving 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 section, damages to some of these facilities due to the 921 earthquake are assessed, together with their probable causes and impact.

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: (a) minor structural damage and minor nonstructural damage, (b) partial structural damage but serious nonstructural damage, and (c) serious structural and nonstructural 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. Serious structural and nonstructural 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.

A recent government report on conditions of damage to healthcare facilities in four counties (Taichung, Nantou, Chang-Hwa and Yu-Lin) and Taichung City is summarized in Table 1.

While structural damage was widespread in the six-county affected area, nonstructural damage was found to be a major factor affecting adversely functionality of major hospitals. Common occurrences included fallen interior walls and ceilings, toppling,

Table 1 Damage to healthcare facilities

Damage Condition	Number of Healthcare Facilities
Complete Collapse	86
Partial Collapse	104
Cracks in Beams and Columns	67
Others	124
Total	381

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, six hospitals in the disaster-affected counties, Taichung and Nantou, were chosen for more in-depth site visits. Among the six hospitals visited, two suffered little damage and were able to perform normal medical services. The other four hospitals suffered minor structural damage but extensive nonstructural failures, and were forced to evacuate all patients from the buildings [1]. These four hospitals (Fig. 1) experienced several aftershocks with magnitudes of up to M_L 6.8 without further structural deterioration. In hospitals A and B, patients and staff were able to reoccupy the buildings after restoration work had been completed within one month. The other two hospitals were still undergoing restoration work two months after the main shock and had to send their patients to other hospitals for treatment. As a result of the loss of the four evacuated hospitals, the disaster regions lost more than 1,000 beds in the first week after the 921 earthquake.

These four hospitals were in the strongest shaking area. Interpolation of the strong ground motion contour map [2] gives the approximate PGA values at the hospital, as shown in Table 2, indicating that the estimated roof accelerations were over 1.0g in most hospitals except hospital A, which registered 0.85g at the roof.

The damages to critical nonstructural components in these hospitals were a serious issue. It can be summarized into four groups: falling objects, flooding, loss of electricity, and damaged medical equipment. Another item affected the operation of a hospital greatly is the elevator. Elevators are prone to failure when the PGA reaches 200 gal [3] according to an investigation of the damage analysis of the 1998 Chia-Yi/Ruei-Li earthquake. Infor-

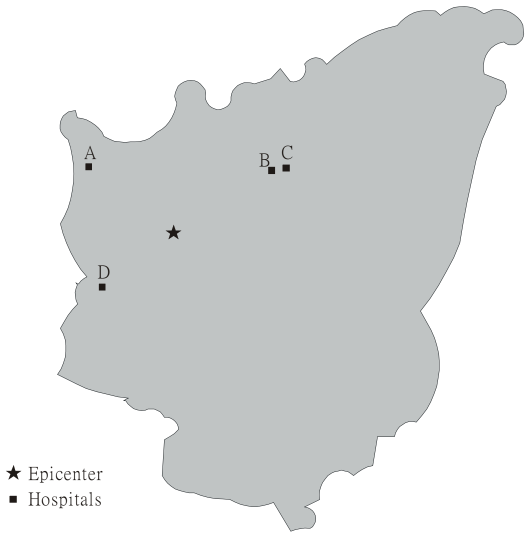

Fig. 1 Locations of the investigated hospitals in Nantou County

Table 2 Acceleration at the four investigated hospitals

Hospitals	EW PGA (gal)	NS PGA (gal)	Estimated Maximum Roof Acceleration (gal)
A	300	200	861
B	560	360	1607
C	580	360	1664
D	480	370	1378

mation on the damage statistics in elevators in the 921 earthquake indicated counterweight derailment could happen when the PGA was only at 80 gal [4]. The importance of elevators in a modern building is obvious, but the seismic capacity of elevators is largely unknown to the building industry at the present.

Schools

School buildings sustained severe structural and nonstructural damage, reaching as far as the city of Taipei, 150km from the epicenter. As in 1998 Chia-Yi/Ruei-Li earthquake, the severity of damage to school buildings, as demonstrated in Table 3, again exceeded that of other structures due primarily to the commonality of their weaknesses in construction. The common structural 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. It is estimated that restoration, repair and reconstruction costs associated with school buildings can reach US$1.3 billion [5].

Table 3 Extent of damage to schools (source: Ministry of Education [6])

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 Disadvantaged	20	4	20.0
Total	3,681	802	21.8

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 4, of which 51 suffered complete collapse. Damage was heavily concentrated in Nantou and Taichung Counties as illustrated in Table 5. 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, affecting not only education of students but also 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 structural and nonstructural damage in the affected region. Damage report forms were sent to these units by NCREE investigators and those returned to date are summarized in Table 6.

Key Industrial Facilities

Of particular interest to the international business community was impact of the 921 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 will be the focus here.

Hsinchu's Industrial Park, situated about 110km from the epicenter, houses approximately 239 hi-tech firms having important links to the world's computer and communications industry. Based on the types of products they produce, they can be grouped into the following: Integrated Circuit: 95, Computers and

Table 4 Damage to schools in Taiwan (source: Ministry of Education [5])

City/County**	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*	83*	168	488	786*

* Numbers not consistent with those shown in Table 3, probably due to different information sources.
** Numbers for counties do not include those in cities within the counties.

Table 5 Severity of elementary and middle school damage (source: Ministry of Education [5])

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

Table 6 Interim damage summary pertaining to police and fire stations (source: NCREE [7,8])

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	–	–	–	–	–

Peripherals: 44, Telecommunications: 36, Electro-optical: 35, Automation: 16, and Biotechnology: 13.

While 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 500,000KV 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, non-structural and equipment damage stood out, which included fallen ceilings, cracked walls and partitions, shear failure of columns, piping breakage, and equipment damage. Most of which were repaired rapidly and the entire industrial complex has been restored to its pre-earthquake production level. Table 7 lists damage survey results based on the returned survey forms to date.

Summary

Heavy damage to critical facilities in areas close to the epicenter was certainly in large part attributable to unanticipated high level of ground shaking in the region and to structural damage. However, as highlighted in several parts of this section, the impact of nonstructural damage on the loss of functionality of critical facilities has been significant, leading to their inability to perform emergency and life saving services and, tragically, loss of lives.

Seismic Vulnerability

In order to improve seismic performance of nonstructural components and to develop effective retrofit strategies, seismic vulnerability of these components must be first established. While many approaches can be followed, the development of fragility information for these components can be very useful. Fragility information not only quantify seismic risk for these components under specified site conditions, but also provide information on the effects of key parameters on the fragility results, leading to the development of effective retrofit strategies.

One approach in developing fragility information for nonstructural components in a systematic way is to first group nonstructural components into the following three main categories:

- Unrestrained nonstructural components
- Restrained nonstructural components
- Nonstructural systems which consist of systems of nonstructural components

Fragility information for the first two groups can be developed analytically and experimentally under a variety of failure modes (e.g., [9,10]). For example, sliding fragility of unrestrained equipment is studied in Chong and Soong [10]. Using floor response spectra to characterize excitation inputs, fragility curves such as those shown in Fig. 2 can be determined to allow a quantitative assessment of seismic risks for this class of components under sliding. Specifically, fragility curves in Fig. 2 are obtained when the coefficient of dynamic friction (μ_d) is 0.4, the

Table 7 Damage survey at Hsinchu Industrial Park (source: NCREE [7,8])

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

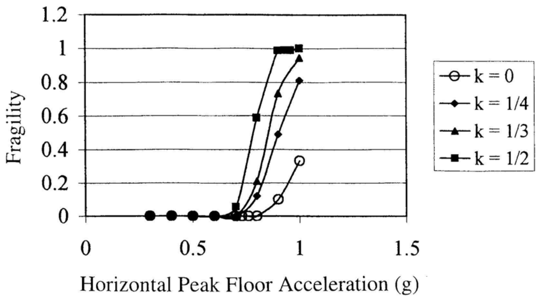

Fig. 2 Fragility curves for μ_d = 0.4 and x_0 = 2in

threshold displacement (x_0) is 2in, and when k varies from 0 to 1/2, where k is the ratio of the vertical to horizontal component of the peak floor acceleration. Figure 2 shows that a key parameter of interest in this case is k. As k increases, the sliding-related risks increase significantly, which is consistent with damage patterns of nonstructural components that have been observed in recent earthquakes. It underscores the need to consider vertical base motion in seismic vulnerability assessment of unrestrained equipment.

Another significant finding in this study is that the absolution acceleration, thus the inertia force, induced by base excitation at a threshold displacement of the component is relatively insensitive to the base motion but only sensitive to μ_d. Surface properties of the component and the base thus become important when impact with neighboring objects become an issue in seismic design.

For the third category in which a nonstructural system consists of many connected individual components, fragility information can be obtained from those of individual components through the construction of a logic tree as illustrated by Fig. 3 for a medical gas supply system [11]. Depending on the way in which the components are connected, fragility equations can be established which relate system fragility to the component fragilities. The logic tree approach can also be used for sensitivity analysis to identify critical components of the system, and to determine confidence intervals for the system fragility.

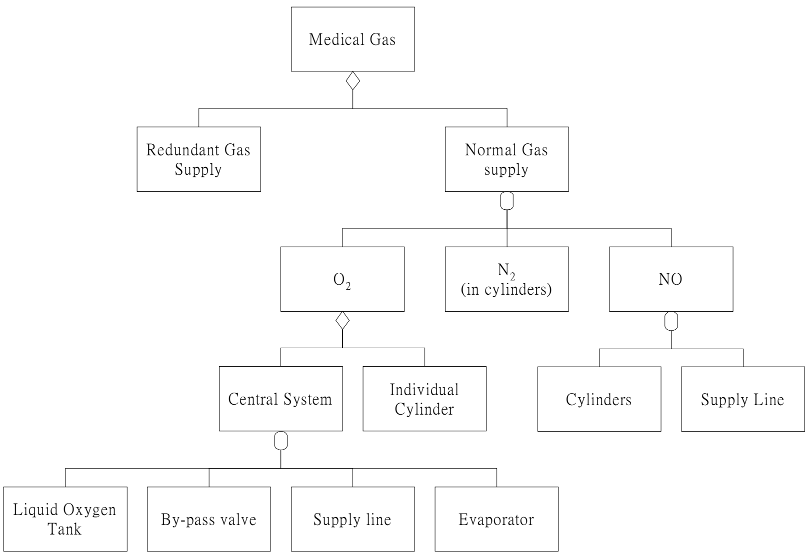

Fig. 3 Logic-tree diagram for a medical gas supply equipment

Retrofit Strategies

Results on seismic vulnerability can guide the development of improved design and installation guidelines for nonstructural components in critical facilities. In a majority of cases, easy and inexpensive solutions can be found which can significantly reduce the risk of seismic damage to nonstructural components [12]. For example, restraint design for computers and data processing equipment at a data center was recently carried out [13]. In this work, an attempt was made to provide a sound basis for designing tethers or cables using site-specific response spectra. The important design parameters were initial angle of cable orientation, initial tension in the cable, and stiffness coefficients of the cables. A preliminary design guide was developed and, in general, the following were noted as important considerations:

- The relative displacement is dramatically increased by steep cable angles, by increases in pre-tension, by reducing the stiffness, and by increasing the equipment weight.
- The optimum angle between the floor slab and the cable can be determined. Increasing the angle causes the equipment acceleration and cable tension to increase significantly compared to decreasing the angle. Accordingly, flattening the cable angle to avoid an obstacle is preferable to steepening the angle.
- Increasing initial tension results in a near equal increase in peak cable tension.
- Doubling friction at the equipment-floor interface causes a 60% increase in acceleration, but has minor effect on displacement and cable tension. Low friction is advantageous for protection of the equipment. This implies that unlocked casters are sometimes helpful.
- Reducing cable stiffness significantly increases displacements, but not accelerations or cable tension.
- Increasing the tributary weight to a cable significantly increases displacements. Accelerations decrease slightly, and cable tension increases modestly.

More complicated nonstructural components may require more advanced retrofit techniques. For example, in the case of rotating machines, it presents a dual isolation problem consisting of isolation of housing structures from the machine vibrations and protection of machines during an earthquake to maintain their functionality. The desirable characteristics of machine mounts for the above two purposes can differ significantly due to the difference in the nature of the excitation and in the performance criteria in the two situations. In Rana and Soong [14], for example, a semi-active mount design is proposed which can accommodate different seismic and operational requirements. A functional diagram with a variable damping element for this scheme is shown in Fig. 4. This scheme includes a sensor which can detect the start of a seismic event and send ON/OFF signal to a switch in a variable

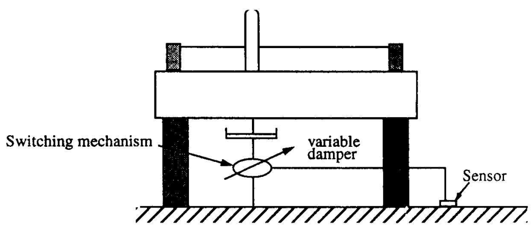

Fig. 4 A semi-active mount design

damper and/or spring element which can change the property of the element.

Concluding Remarks

Nonstructural damage to critical facilities caused by the 921 earthquake and its profound impact underscores the importance of addressing the nonstructural issue in seismic design and installation. While seismic codes exist in Taiwan for buildings and bridges, there appears to be an absence of rational seismic provisions for nonstructural components. There is thus an urgent need to develop stringent seismic design and installation guidelines 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 921 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 construction.

For nonstructural components in critical facilities, higher performance levels demand a more rigorous approach to assessing their seismic vulnerability and to developing appropriate retrofit strategies. This paper has also outlined some of these approaches that can be followed in a systematic development of seismic vulnerability methodologies and retrofit strategies for nonstructural components. In addition, it is shown that, in some cases, simple measures can be taken in order to enhance significantly their seismic performance.

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REFERENCES

1. Lin, C.C. *et al.* (1999). "Medical and industrial facility damage," Complete Reconnaissance Report of the Ji-Ji Earthquake, NCREE, Taipei, Taiwan.
2. Loh, C.H. and Sheu, M.S. (1999). "Preliminary reconnaissance report (2) on the 1999/9/21 Ji-Ji earthquake," NCREE-99-031, Taipei, Taiwan.
3. Yao, G.C. (1999). "Elevator damage in the Ruei-Li earthquake of 1998.7.17," Technical Report in the Department of Architecture, NCKU, Taiwan.
4. Yao, G.C. (2000). "Seismic capacity analysis of passenger elevators in Taiwan," submitted to *Earthquake Engineering and Engineering Seismology* for review.
5. Ministry of Education (1999), "Interim damage report," Taipei, Taiwan (in Chinese).
6. Ministry of Education (1999), Private Communications.
7. National Center for Research in Earthquake Engineering (NCREE), (1999), "Interim damage report," Taipei, Taiwan (in Chinese).

8. National Center for Research in Earthquake Engineering (NCREE), (1999), “Damage report on 921 Ji-Ji earthquake (draft),” Report No. NCREE-99-033, Taipei, Taiwan (in Chinese).
9. Zhu, Z.Y. and Soong, T.T. (1998). “Toppling fragility of unrestrained equipment,” *Earthquake Spectra*, Vol. 14, No. 4, pp. 695–711.
10. Chong, W.H. and Soong, T.T. (2000). “Sliding fragility of unrestrained equipment,” Technical Report MCEER-00-0005, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY.
11. Yao, G.C. (1999). “A study on the earthquake code for building equipment — hospital building,” ABRI Report MIOS 881010-1, Taiwan.
12. FEMA (1994), *Reducing the Risks of Nonstructural Earthquake Damage*, FEMA, Washington, DC.
13. Meyer, J.D., Soong, T.T. and Hill, R.H. (1998). “Retrofit mitigation of mainframe computers and associated equipment — a case study,” *Proc. ATC 29-1 on Seismic Design, Retrofit and Performance of Nonstructural Components*, San Francisco, CA.
14. Rana, R. and Soong, T.T. (1998). “Control of seismic and operational vibrations of rotating machines using semi-active mounts,” *Proc. 2nd International Conference on Structural Control*, Kyoto, Japan.