# Experimental Evaluation of the Seismic Performance of Hospital Sprinkler Systems

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**SUMMARY:**
Immediate operation of a hospital after an earthquake relies heavily on the functional integrity of critical nonstructural components. From the literature review of earthquake damage, it can be observed that the seismic performance of hospital sprinkler systems was unsatisfactory. This paper presents findings from shake table tests on a hospital sprinkler system damaged in an earthquake. The test results identified the dynamic characteristics and the seismic performance of the hospital sprinkler system. Various damage patterns were observed. Before the leakage of water occurred due to rupture of threads, slippage of hanger, crushing of ceiling and partition boards were observed, while cracking or visible bending deformation of the pipes was not observed. Due to the constraint of partition, deformation of hanger was limited while response acceleration of pipe increased.

*Keywords: Sprinkler, piping system, hospital, non-structural components*

## 1. INTRODUCTION

Immediate operation of a hospital after an earthquake relies heavily on the functional integrity of critical nonstructural components. In two major earthquakes which struck Taiwan in 2009 and 2010, reduction of medical functionality caused by serious flooding due to broken sprinkler head and piping joint of sprinkler system was reported. From the literature review of earthquake damage, it can be observed that the seismic performance of hospital sprinkler systems was unsatisfactory (Ayer, J. and Phillips, R., 1998).

Toward performance-based earthquake engineering (PBEE), the issue of non-structural components is known as one of the most critical elements of the PBEE methodology. In recent years, the seismic performance of piping system was studied at various levels, from piping joint (Ju, B. et al., 2011), piping subassembly (Hwang, C. and Yao, G., 2003) to equipment-pipe subassembly (Goodwin, E. et al., 2006). However, due to the complexity of hospital piping systems, the understanding of the behaviour of the system was still quite limited. Therefore, this study takes a hospital sprinkler system damaged in 2010 as testing model. The purpose is to investigate the seismic performance of hospital sprinkler systems and provide test data for characterizing the dynamic behaviour.

## 2. SHAKE TABLE TESTS ON A SUBASSEMBLY OF SPRINKLER SYSTEM OF HOSPITAL

The experimental subassembly was modeled after a hospital sprinkler system that suffered damage in the March 4, 2010 (Jia-sen) earthquake, Taiwan. The recorded PGA at the nearest observation station was around 170gal. A branch pipe in the patient room on the top floor ($7^{th}$ floor) broke and led to sever leakage of water. Figure 2.1 is the plan of the sprinkler piping system in the patient room. Figure 2.2 shows the pictures of the investigation results.

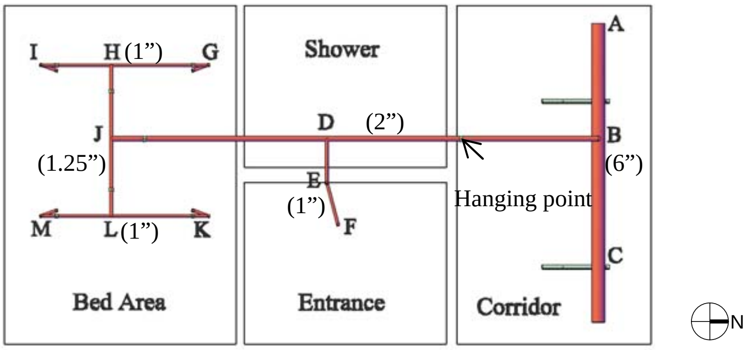



**Figure 2.1.** Plan of the sprinkler system

(a) (b) (c) (d)

**Figure 2.2.** Investigation results of the sprinkler system damaged in 2010 Jia-sen earthquake: (a) bed area (b) from shower room to bed area, (c) entrance, and (d) corridor

### 2.1. Experimental Setup

Based on the investigation results, a sprinkler piping subassembly, as shown in Figure 2.3, was erected. Figure 2.4 shows the elevation. The subassembly was installed to a rigid steel frame of a distribution area of 8×3.5m. Figure 2.5 shows the experimental setup at National Center for Research on Earthquake Engineering (NCREE), Taiwan. The subassembly was supported by unbraced hangers anchored to concrete blocks fastened to the frame top. The investigation results indicated that although no braces were observed, the branches to the patient rooms on the both sides of the corridor limited the movement of the main pipe along the corridor. Thus, in the specimen, braces were installed between the trapezes for the main pipe to provide proper rigidity in the corridor direction. The material of the piping system was hot dip galvanized iron. For the specimen, all the pipe connections were threaded joints. Pipes of four diameters: 6”, 2”, 1.25” and 1”are adopted. The number in the parenthesis in Figure 2.1 indicated the diameter.

Partition walls existed around the shower room. Based on the survey results, the partition next to the corridor had a large opening and did not constraint the pipe. Thus, only the partition walls against the entrance and the bed area were installed in the tests. The drywall partition was light-gage steel-stud framing sheathed by gypsum boards on both sides. Mineral fiber acoustic ceiling boards were placed on a braced steel frame (see Figure 2.6). An opening was drilled on the ceiling board for sprinkler heads. In the tests, water was filled into the subassembly to attain the same water pressure of 6kgf/cm$^2$ as that of the system in the hospital. The instrumentation plan of accelerometer and displacement transducer is shown in Figure 2.7.

### 2.2. Loading Protocols

The subassembly that damaged in the Jia-sen earthquake was located on the top floor of the hospital. Therefore, the input excitations adopted the top floor response of the hospital subjected to the ground motions of seismic intensity scales 4, 5- and 5+ (PGA=25, 80 and 140, respectively). The response was calculated using a single-degree-of-freedom model, which was constructed based on the results of the ambient vibration measurement to the hospital. Eight time histories of acceleration recorded at the nearest seismic station to the hospital during the major earthquakes between 2005 and 2010 were adopted and input to the model. An average acceleration spectrum for equipment mounted on the top floor was generated. The input time history of acceleration was compatible to the spectrum and scaled to three levels of peak value. Following that, the subassembly was subjected to the top floor response of the hospital during the Jia-sen (0304) earthquake. The recorded PGA at the nearest station was 168gal.

Table 2.1 indicates the input excitations, and Figure 2.8 shows the acceleration response spectrum for the two types of input using the achieved excitation data of shake table. PFA represents the peak floor acceleration of the top floor response of the building subjected to the aforementioned ground motions. The calculated floor response was input to the specimen through the rigid frame fastened to the shake table. Two horizontal excitations were input simultaneously.

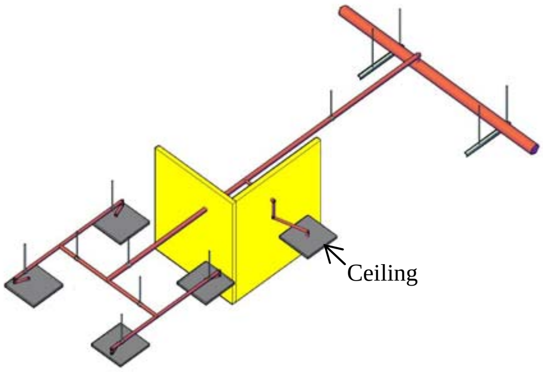



**Figure 2.3.** 3D scheme of the sprinkler piping subassembly

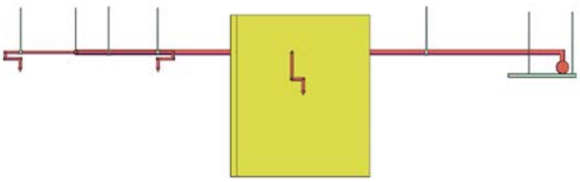


**Figure 2.4.** Elevation of the sprinkler piping subassembly

**Figure 2.5.** Experimental setup

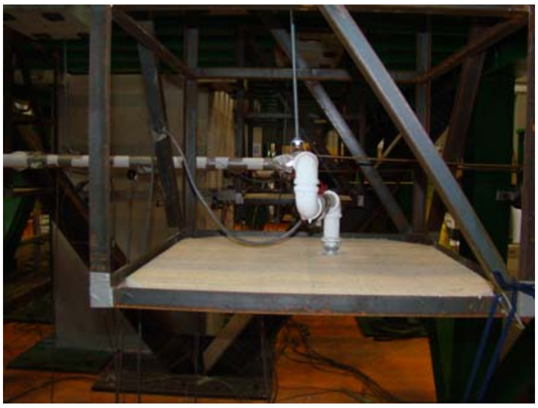


**Figure 2.6.** Installation of ceiling board

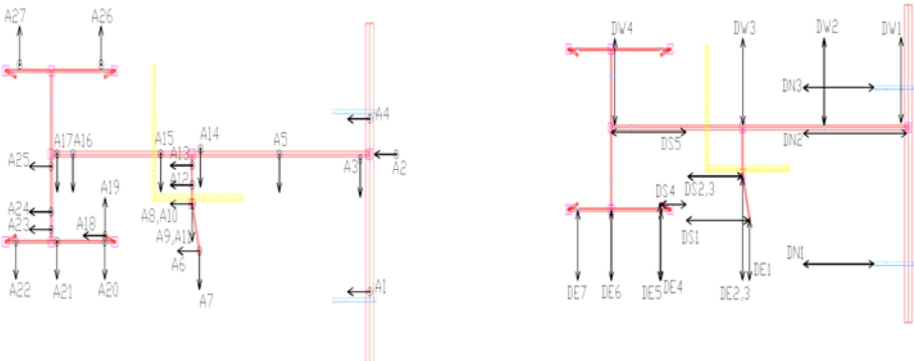
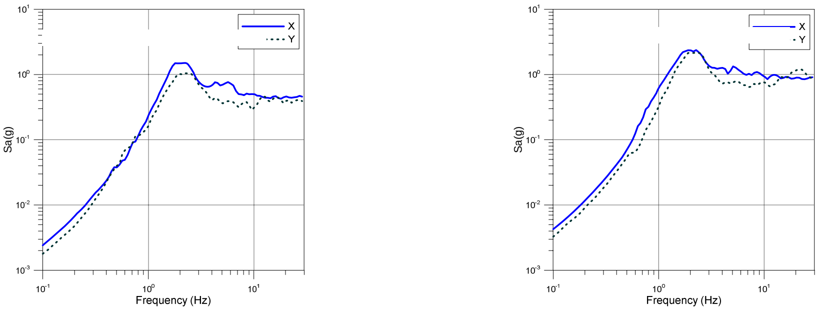



**Figure 2.7.** Instrumentation plan: (a) accelerometer, and (b) displacement transducer

**Table 2.1.** Input motions (Unit: gal)

| Type | PGA | PFA (x, y) | Achieved PFA (x,y) |
|---|---|---|---|
| Spectrum-compatible | 25 | 63, 44 | 68, 48 |
| | 80 | 203, 140 | 213, 168 |
| | 140 | 355, 246 | 408, 286 |
| 0304EQ | 168 | 602, 526 | 836, 591 |




(a) (b)

**Figure 2.8.** Acceleration response spectrum for equipment on the top floor of the hospital subjected to: (a) average of eight records (PGA scaled to 140gal), and (b) Jia-sen (0304) earthquake

## 3. RESULTS AND DISCUSSION

### 3.1. Dynamic Characteristics

White noise excitation was input to investigate the dynamic characteristic of the subassembly. Using the acceleration on the frame top as input, Figures 3.1 and 3.2 show the frequency response functions at the selected locations of the subassembly. Considering the frequency range of the response of building structure, only the result for frequency less than 15Hz was shown. Figures 3.3 and 3.4 show the corresponding mode shapes. Note that the unit distance of deformation is not the same for each mode.

In X-direction, the predominant frequency is 0.8Hz. From the mode shapes shown in Figure 3.3, it can be seen that at the frequency of 0.8Hz the whole specimen translated along X-direction. For sensors Nos. 6, 8 and 10, a peak was observed at 8.3 Hz. It is caused by the lateral vibration of branch DEF. Figure 3.3(b) shows the corresponding mode shape. For sensors Nos. 23 and 24, a peak was observed at 13.5 Hz. It is due to the lateral deformation of branch HJL of the bed area (Figure 2.1).

In Y-direction, the major frequencies of the branch were identified as 7.1, 9.8 and 13.7Hz. From Figure 3.4, it can be seen that the mode shapes are greatly influenced by the lateral deformation of branch BDJ. For sensors Nos. 7, 9and 11, a peak was observed at 11.1 Hz. It is caused by the vibration of branch DEF from the shower room.

Before the partitions were erected, white noise excitation was input as well. As the frequency response functions in Figures 3.1 and 3.2 show, the identified major frequencies were the same as those obtained for the specimen with partitions. The frequencies did not change because a clear spacing existed between the branch and the partition (Figure 3.5), and the identification process used the results under low-intensity input (white noise). However, under the input of earthquake motions, larger deformation of the piping is considered to be constrained by the partitions and the identified mode shape is to be influenced. More details are discussed in section 3.3.

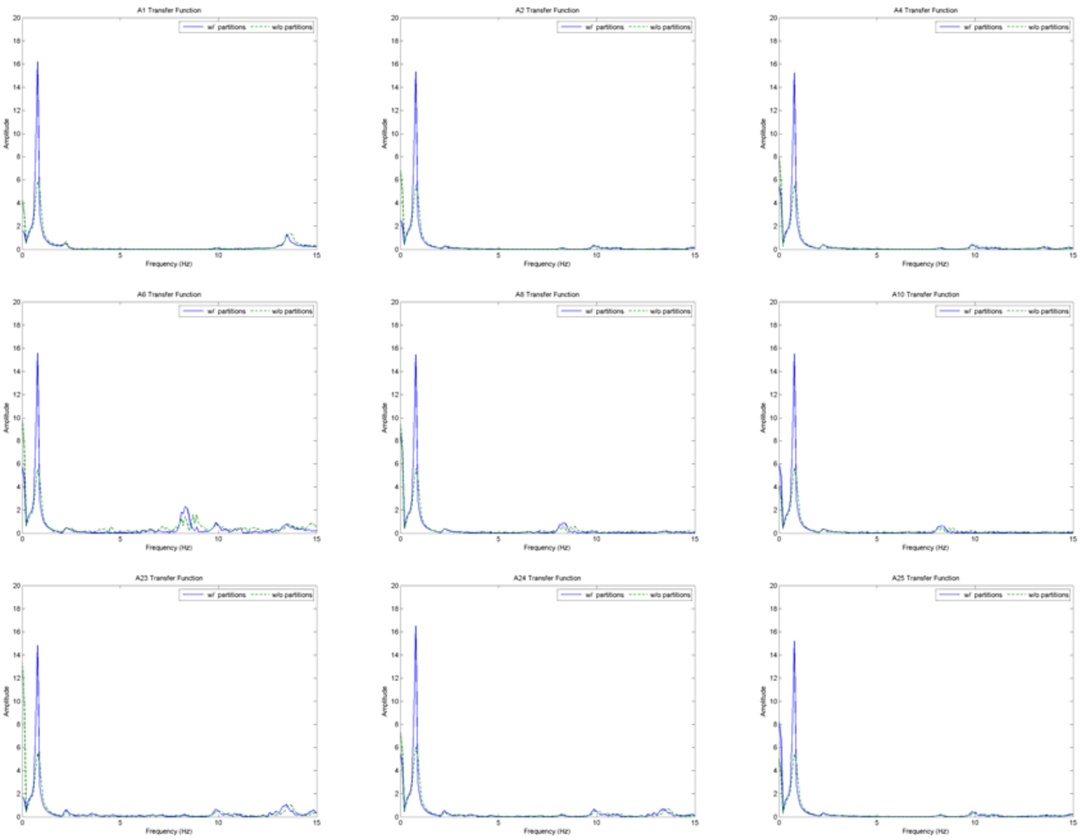



**Figure 3.1.** Frequency response function in X-direction

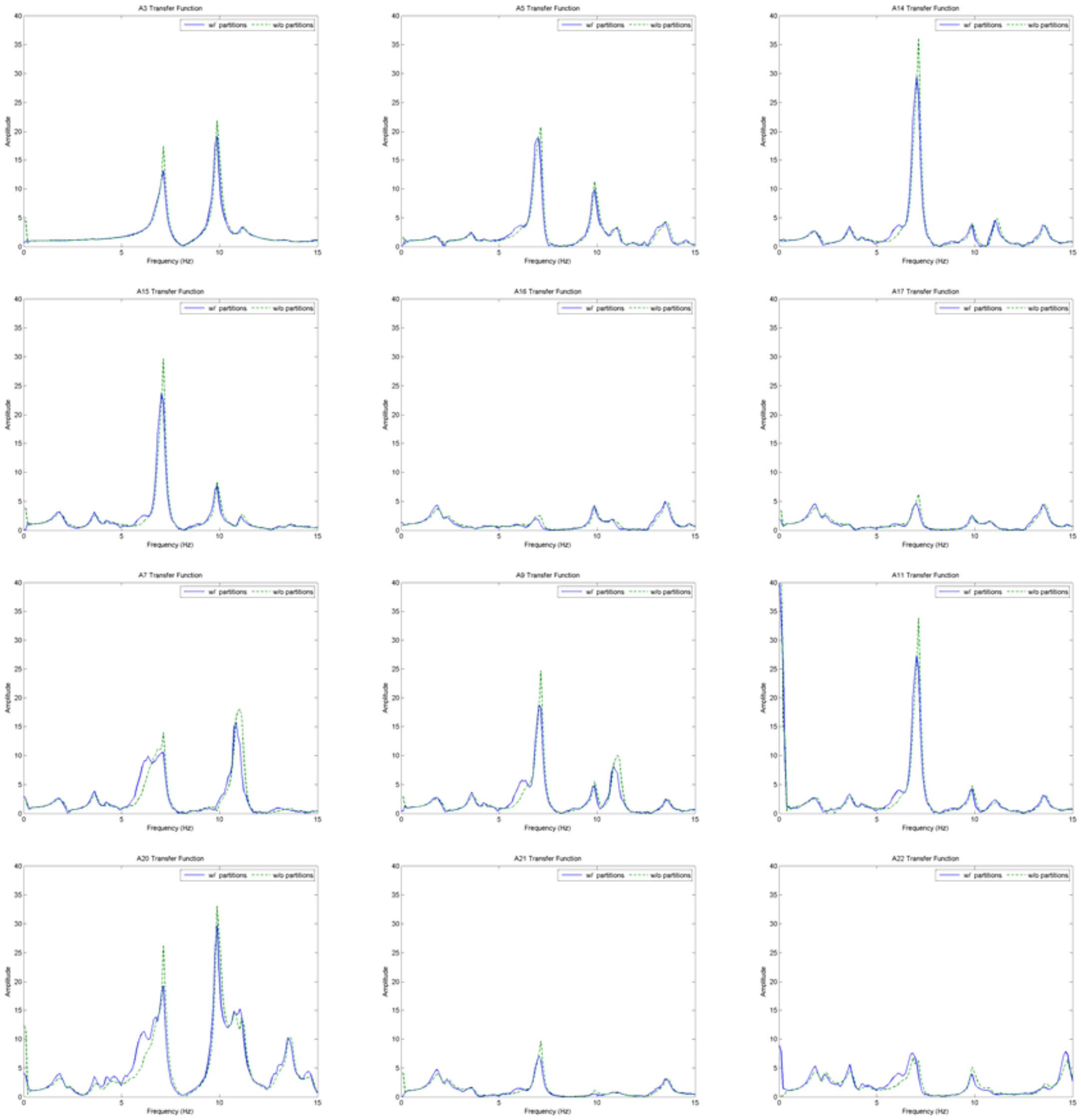
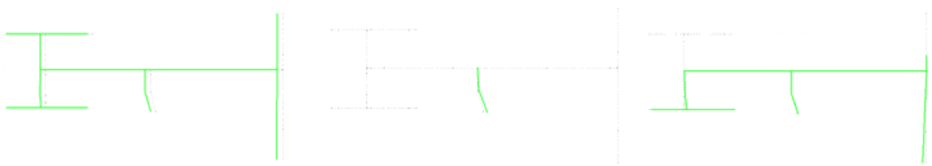
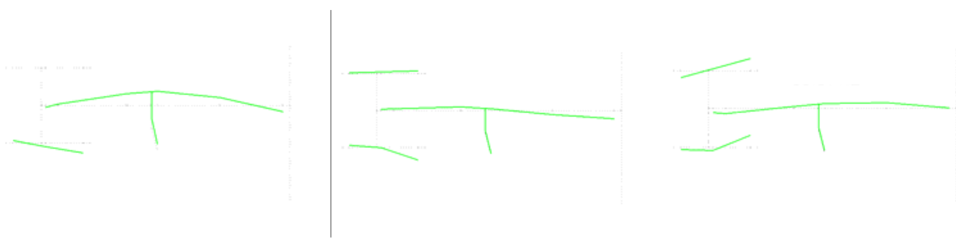



**Figure 3.2.** Frequency response function in Y-direction



(a) 0.8Hz (b) 8.3Hz (c) 13.5Hz

**Figure 3.3.** Mode shapes in X-direction



(a) 7.1Hz (b) 9.8Hz (c) 13.7Hz

**Figure 3.4.** Mode shapes in Y-direction

**Figure 3.5.** Clear spacing between the partition board and the branch

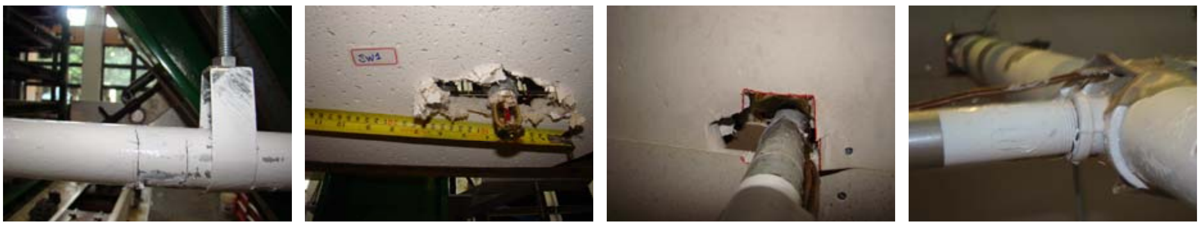
### 3.2. Observations of Damage and the Relationship with Input Acceleration

This section presents the damage of the specimen observed by eyeball inspection. The damage of the sprinkler subassembly is the main concern of the test. The observed damage patterns include slippage of hanger, scrapping off on piping surface (whitewash), and rupture of pipe threads (leading to leakage of water). In addition, for ceilings and partitions, the damage patterns include cracking or crushing of ceiling/partition boards, and out-of-plane deformation of partition boards. Figure 3.6 shows the pictures of various damage patterns of the specimen.

Table 3.1 displays the damage observed after each run. In the table, PFA adopts the recorded testing data in X-direction; the number in parentheses designates the largest range in cm for the corresponding damage. Before leakage of water occurred under the input of 0304 earthquake, cracking or visible bending deformation of the pipes was not observed. In previous research (Taghavi, S. and Miranda, E. 2003), three damage states were defined for sprinkler system: breaking the hangers, damage to pipe, and damage to sprinkler heads. In this test, hangers did not break as their lateral deformation was limited by the partitions. As for sprinkler head, the collision between sprinkler head and ceiling was observed. However, the mineral-fiber ceiling board was comparatively soft and did not break the sprinkler head. Subjected to 0304 earthquake, the crushing range of the ceiling board was as large as 7.0cm (see Figure 3.6(b)).

**Table 3.1.** Relationship of input acceleration and damage

| Item | Location | Spectrum-Compatible | | | 0304EQ. |
|---|---|---|---|---|---|
| | | PFA=68gal | PFA=213gal | PFA=408gal | PFA=836gal |
| T-joint | Shower | 0.3% | 2.2% | 3.2% | Rupture of threads<br>Leakage of water |
| Ceiling | Entrance | No damage | No damage | No damage | Crushing(3.0) |
| | Bed area | No damage | Crushing(0.5) | Crushing(1.0) | Crushing(7.0) |
| Partition | Entrance (N-S) | No damage | Crushing(0.5)<br>Out-of-plane(8.0) | Crushing(2.0)<br>Out-of-plane(8.0) | Crushing(5.0)<br>Out-of-plane(8.0) |
| | Bed area (E-W) | No damage | Crushing(0.5) | Crushing(0.5)<br>Out-of-plane(6.6) | Crushing(1.0)<br>Out-of-plane(6.6) |



(a) (b) (c) (d)

**Figure 3.6.** Damage patterns: (a) slippage of hanger, (b) crushing of ceiling, (c) crushing and out-of-plane deformation of partitions board, and (d) rupture of threads

### 3.3. Response analysis

The rotation at the T-joint where the rupture of threads occurred is of concern. The time history of rotation at the T-joint was calculated using the data recorded by the displacement transducers. For each run, the experienced maximum rotation of the T-joint was indicated in Table 3.1. During the input of 0304 earthquake, the testing was interrupted when water bursting from the ruptured T-joint was observed. Subjected to the spectrum-compatible time history of acceleration with PFA of 408gal, the maximum rotation was 0.032radian (Figure 3.7) and no rupture of threads occurred.

Acceleration response is critical for calculating the inertia force applied to the sprinkler system. In X-direction, the predominant frequency was 0.8Hz. However, as Figure 3.8 shows, the peak values of the recorded acceleration for sensor A2 was much larger than that obtained at 0.8Hz by the spectrum shown in Figure 2.7(a). It is due to the collision between the pipe and partition board. Figure 3.9 shows the relative displacement of branch DE along X-direction. The clear spacing between the branch and partition was around 1.0cm (see Figure 3.5 left). It can be found that the first acceleration spike occurred when the relative displacement became greater than 1.0cm and the collision occurred. Figure 3.10 shows the response recorded at two accelerometers, A5 and A15, in Y-direction. Spikes were observed in the accelerograms of the pipe constrained by the partitions and hangers. Figure 3.11 shows the deformation shape in Y-direction of branch BDJ at the moment the displacement of DW2(A5) attained maximum. It can be seen that due to the partition, the deformation shape under earthquake motions was quite different from that obtained in Figure 3.4.

In section 3.2, the damage pattern of broken hanger was not observed due to the constraint of partition. In contrast, response acceleration of the pipe increased due to the existence of partition. Making use of acceleration spectrum to estimate the inertia force applied to the pipe, the collision with partition should be properly taken into consideration.

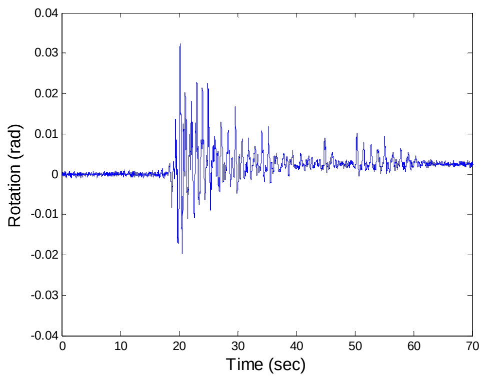



**Figure 3.7.** Time history of rotation of the T-joint subjected to the spectrum-compatible time history of acceleration with PFA of 408gal

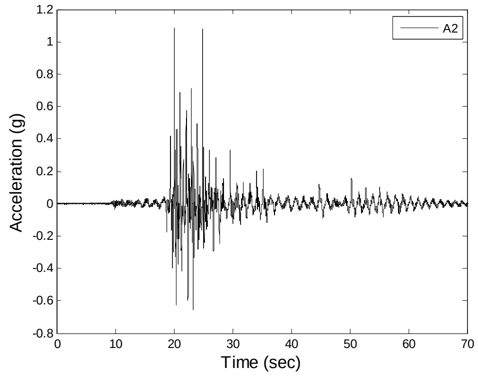



**Figure 3.8.** Time history of acceleration of sensor A2 subjected to the spectrum-compatible time history of acceleration with PFA of 408gal

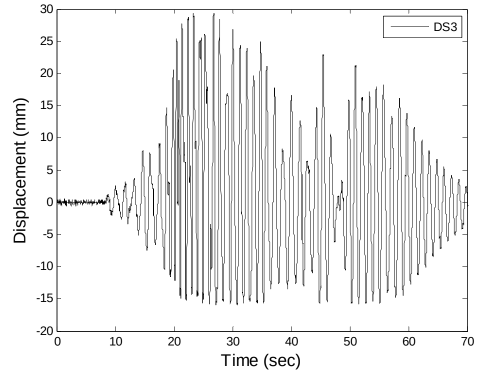
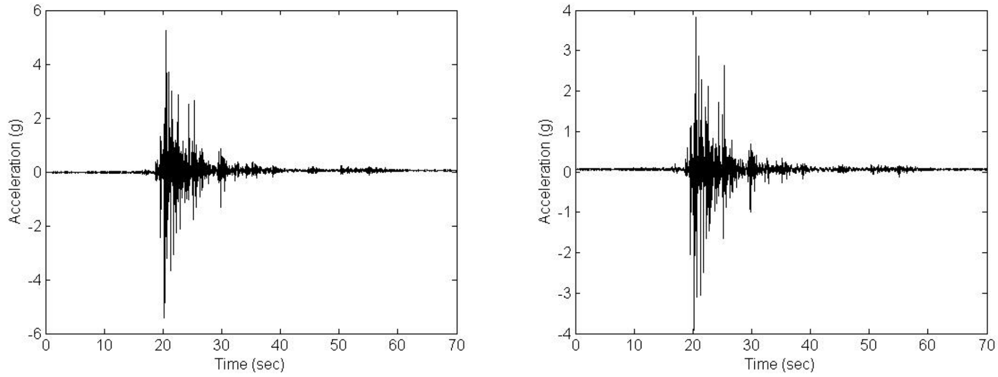



**Figure 3.9.** Time history of relative displacement of sensor DS3 subjected to the spectrum-compatible time history of acceleration with PFA of 408gal




(a) (b)

**Figure 3.10.** Time history of acceleration of sensor (a) A5 and (b) A15subjected to the spectrum-compatible time history of acceleration with PFA of 408gal

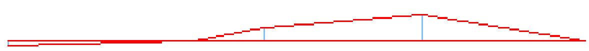


**Figure 3.11.** Deformation shape in Y-direction at the moment the displacement of DW2 attained maximum subjected to the spectrum-compatible time history of acceleration with PFA of 408gal

## 4. CONCLUSIONS

In this study, the seismic performance of hospital sprinkler system was investigated using shake table tests. The specimen was with threaded-joints and supported by unbraced hangers. Before the leakage of water occurred, slippage of hanger, crushing of ceiling and partition boards were observed, while cracking or visible bending deformation of the pipes was not observed. For the specimen with and without partitions, the natural frequencies obtained using white noise input were the same. However, subjected to earthquake motions, the response of the specimen was greatly influenced by the partitions and became much larger than that obtained at the corresponding frequency by the spectrum. Collision with partition should be properly taken into consideration. Crushing of ceiling around sprinkler head was observed, while breaking the sprinkler head did not occur.

**AKCNOWLEDGEMENT**

This work is supported by the National Center for Research on Earthquake Engineering (NCREE), Taiwan. This financial support is gratefully acknowledged.

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