

EXPERIMENTAL STUDIES OF A TYPICAL SPRINKLER PIPING SYSTEM IN HOSPITALS

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ABSTRACT

Based on the issue of life safety and immediate needs of emergency medical services provided by hospitals after strong earthquakes, this paper aims to introduce a research programme on assessment and improvement strategies for a typical configuration of sprinkler piping systems in hospitals. The study involved component tests and subsystem tests. Cyclic loading tests were conducted to investigate the inelastic behaviour of components including concrete anchorages, screwed fittings of small-bore pipes and couplings. Parts of a horizontal piping system of a seismic damaged sprinkler piping system were tested using shaking table tests. Furthermore, horizontal piping subsystems with seismic resistant devices such as braces, flexible pipes and couplings were also tested.

The test results showed that the main cause of damage was the poor capacity of a screwed fitting of the small-bore tee branch. The optimum improvement strategy to achieve a higher nonstructural performance level for the horizontal piping subsystem is to strengthen the main pipe with braces and decrease moment demands on the tee branch by the use of flexible pipes. The hysteresis loops and failure modes of components were further discussed and will be used to conduct numerical analysis of sprinkler piping systems in future studies.

INTRODUCTION

Based on the lessons learned from the 1999 Chi-Chi earthquake in Taiwan, the government promulgated a scheme for the seismic evaluation and retrofitting of buildings to comprehensively review the capacity of publicly owned buildings and critical facilities such as main hospitals. The purpose of this scheme was to improve the seismic performance of buildings to maintain life safety of general buildings and functionality of critical facilities during and after earthquakes. With the recognition that the immediate operation of critical facilities following strong earthquakes relies heavily on the performance of important nonstructural components, critical facilities are especially required to ensure seismic capability of the water supply, power supply, and fire suppression systems. However, with hospitals for instance, although their building structures have all been evaluated and parts of them have been strengthened prior to 2014, the mechanical/electrical systems have not been evaluated or retrofitted due to a lack of mature evaluation methods and a proven code of practice for seismic upgrading. In addition to the functionality of fire suppression systems, water leakages or floods resulting from broken sprinkler piping systems is of importance in critical facilities due to their effects on room fixtures below that could be related to the functionality of the facilities. This occurred at Olive View, Holly Cross Medical Center and Northridge hospital in the San Fernando Valley during the 1994 Northridge earthquake [1]. According to a literature review on earthquake damage [2], the common damage states of sprinkler piping systems include screwed fittings, broken anchorages, and sprinkler heads. One such situation was observed at a responsibility hospital during the 2010 Jiashian earthquake in Taiwan [3] (Figure 1) where a reduction in medical functionality was caused by serious flooding due to one segment of a broken small-bore pipe of the sprinkler system. For fire sprinkler systems in general

buildings, National Fire Protection Association (NFPA) provides a common code of practice for seismic installation. Instead of a stress analysis, a rule-based approach was proposed by the NFPA standard (NFPA 13 [4]). However, its effectiveness in seismic upgrading requires verification by more extensive studies.

In order to conduct a more accurate fragility analysis of sprinkler piping systems in the seismic performance assessment of critical facilities [5], it is necessary to establish reliable numerical models of the piping system. However, common numerical models for piping joints such as screwed fittings and couplings cannot simulate nonlinear behaviours accurately. Tian *et al.* [6] developed the analytical model accounts for inelastic behaviour of tee joints validated by the experimental results of tee subassemblies. Soroushian *et al.* [7] further established a comprehensive three dimensional model of a full fire sprinkler system layout with component analytical models for tee joints, hangers and wire restrainers. However, in both Tian's and Soroushian's studies, the tested piping joints of tee subassemblies resisted bending moment and shear force simultaneously. On the other hand, the standard specifications for pipes in Taiwan (Table 1) differ from the US standard ones [6]. In order to distinguish flexural and shear capacities of components to clarify the damage states of sprinkler piping systems in the earthquake experiences of hospitals in Taiwan [2][3], an ongoing research programme on assessment and improvement strategies for typical configurations of sprinkler piping systems in hospitals was organized by the National Center for Research on Earthquake Engineering (NCREE) in view of the immediate needs of emergency medical services provided by hospitals after strong earthquakes. Figure 2 depicts the overall flow of the research programme in three major levels: (1) Establishment of reasonable numerical models for selected components by means of component testing - these selected

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components, which include concrete anchorages, screwed fittings of small-bore pipes and couplings, were picked out based on observed common seismic weak points which likely exhibit nonlinear behaviour under design earthquakes; (2) Verification of the numerical model for the horizontal piping subsystems (i.e. parts of the complete fire sprinkler piping system) using shaking table testing and cyclic loading tests; and (3) Proposals of the seismic assessment method and improvement strategy for seismic performance via a proper numerical model for a complete fire sprinkler piping system.

This paper focuses on completed topics within the research programme and related preliminary findings, including basic behaviour of concrete anchorages, piping joints and horizontal subsystems of a sprinkler piping system. The effectiveness of

three types of seismic restraint devices for sprinkler piping systems was also validated by shaking table tests.



Figure 1: Flooding at a hospital due to an earthquake.

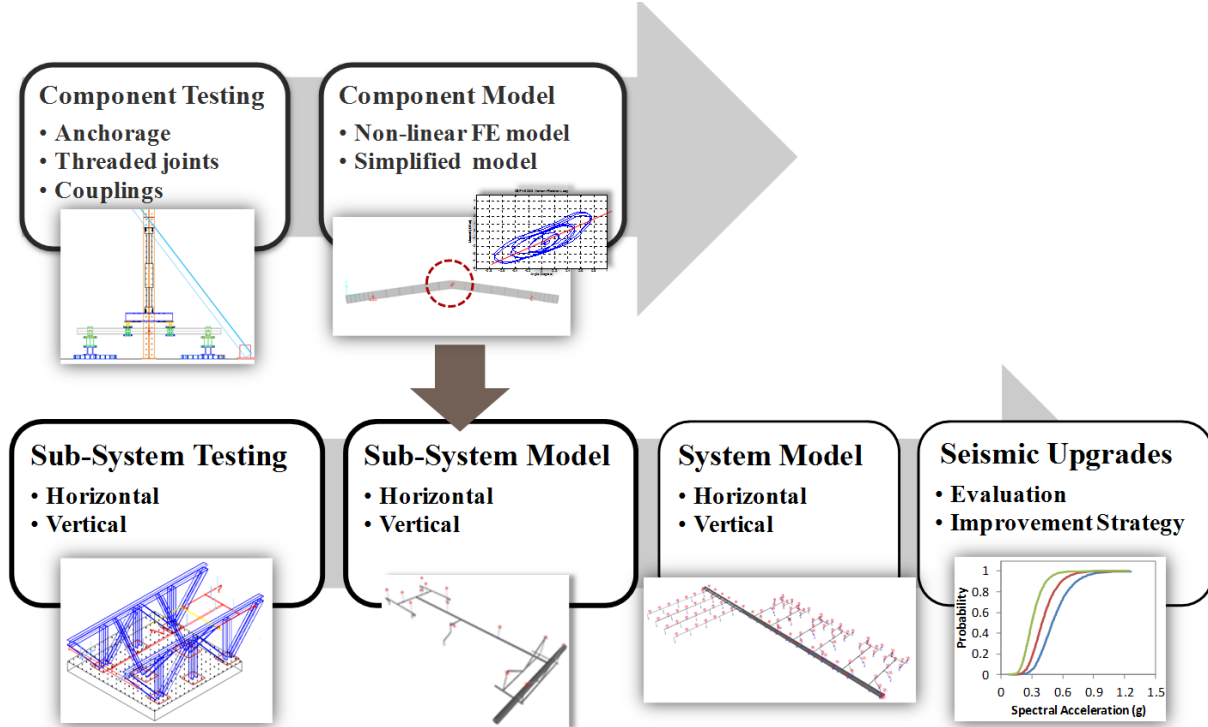


Figure 2: Overall flow of research for sprinkler piping systems.

COMPONENT TESTING: PIPING JOINTS

This study aims to investigate the seismic behaviour of mechanical joints including couplings and small-bore screwed fittings to effectively improve the seismic performance of sprinkler systems. According to NFPA13 [4], flexible joints are regarded as seismic resistance devices for piping joints and as substitutions for screwed fittings to accommodate excessive motions induced by strong earthquakes. One of the common flexible joint types is a coupling (Figure 3). Hence, this study conducted pure bending tests for couplings and small-bore screwed fittings (i.e., 1" screwed fittings) to investigate their flexural capacity. Based on the case studies of several hospitals in Taiwan [8], paired couplings with three common galvanized steel pipe dimensions (1", 4" and 6") were studied through monotonic and cyclic loading tests (Table 1). Furthermore, the vulnerability of small-bore piping joints observed in earthquakes and previous research [2] [3] [9] was considered by conducting flexural-shear tests for 1" screwed fittings and couplings to identify the difference between flexural and flexural-shear failure modes.

Figure 4 depicts the test configuration of pure bending tests for piping joints. The angular deflection θ of the pipe was measured by angle gauges, and the moment M was calculated based on the reaction forces at both ends of the pipe measured by load cells. The tested couplings are the commonly used

commercial types in Taiwan that are classified into rigid and flexible types according to their flexibility. In NFPA 13 [4] and ASCE 7-10 [10], flexible couplings for pipe sizes smaller than 8" are required to allow at least 1 degree of angular movement of the pipe without inducing harm on the pipe. The couplings are determined to be flexible according to flexibility tests with FM 1920 [11].

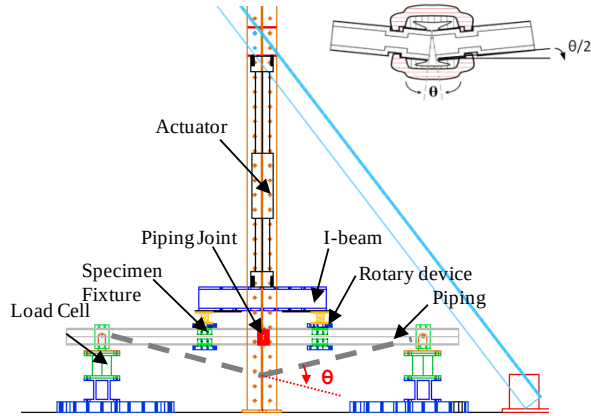
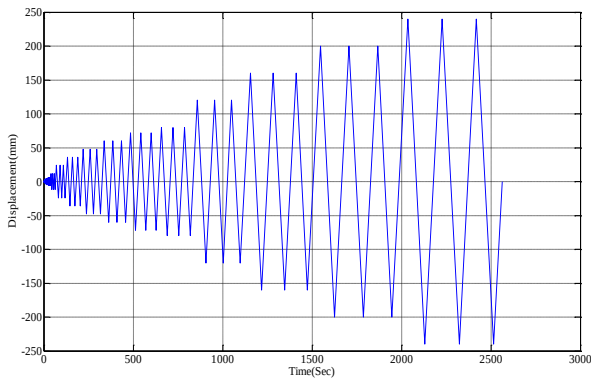


Figure 3: Couplings and screwed fittings.

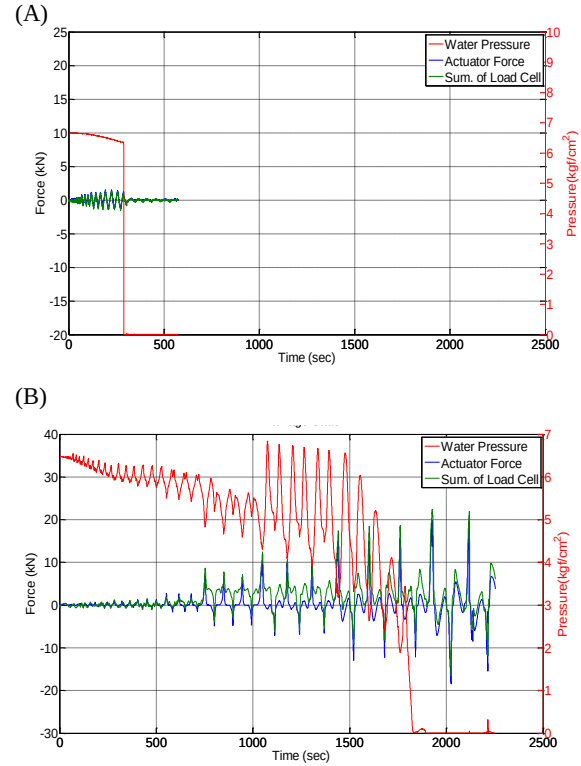
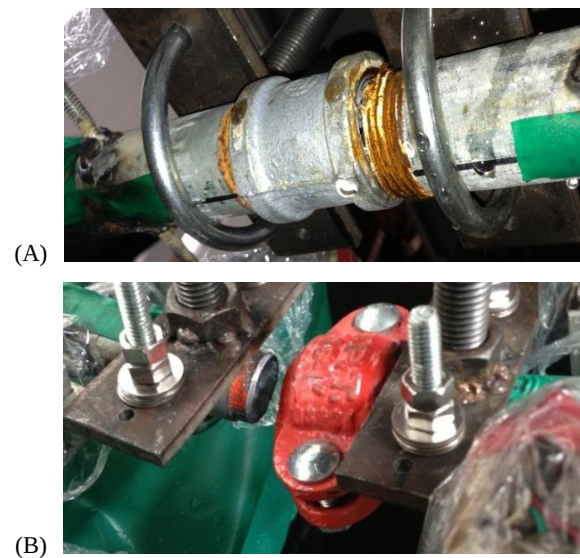
In this study, the flexibility of rigid and flexible couplings with three different diameters was tested according to FM 1920 [11] and all couplings achieved the flexible requirement of NFPA 13 [4] without failure. However, there was little difference between the seismic capacity of rigid and flexible couplings based on the test results. The four-point flexural tests were executed under monotonic and cyclic loading (Figure 5). When the diameter decreases, it is hard to distinguish a rigid coupling from a flexible one in seismic behaviour and capacity.

Table 1: Test programme of the pure bending tests.

Nominal pipe dia. (in.)	Outside pipe dia. (in.)	Pipe wall thickness (in.)	Connection types	No. of FM 1920 tests	No. of monotonic tests	No. of cyclic loading tests
1	1.34	0.13	Screw fitting/ Flexible coupling	3	1	2
4	4.50	0.18	Rigid/Flexible coupling	3	1	2
6	6.50	0.20	Rigid/Flexible coupling	3	1	2

**Figure 4: Testing configuration for piping joints.****Figure 5: Input motion of cyclic load tests.**

On the other hand, in monotonic and cyclic loading tests, the capacity of couplings at the first-leak state has better results compared with screwed fittings (Fig). The water pressure of the pipe with a flexible coupling reversed without leakage under a cyclic pure-bending loading, while that of the pipe with a screwed fitting was suddenly lost pressure due to a damaged thread of the fitting when the rotation angle θ was about 1.35° . Of the three flexible couplings tested for a 1" diameter piping, only one experienced failure when the value of θ was about 18.4° (Figure 7). Figure 8 depicts the Moment- θ curves for two types of joints under cyclic pure-bending loading. The stiffness of the screwed fitting was about 0.51 kN-m/degrees. For flexible couplings, bi-linear behaviour can be used to simplify the backbone curve of hysteretic response. The stiffness values in the first and second levels of the bi-linear behaviour were about 0.02 and 0.87 kN-m/degrees, respectively. The dramatically increasing stiffness was due to the contact of housing and the resulting higher stress may cause the failure of the piping with configurations of couplings in the shaking table tests.

**Figure 6: Loading and water pressure during tests: (A) screwed fitting and (B) flexible coupling.****Figure 7: Damage states: (A) screwed fitting and (B) flexible coupling.**

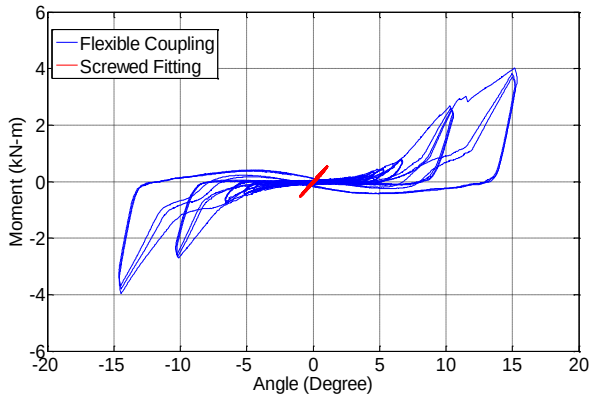


Figure 8: Moment- θ curves of the flexible coupling.

In addition to pure-bending tests, shear tests under a monotonic loading for screwed fittings and flexible couplings of a 1" diameter piping were conducted to further investigate the shear capacity of piping joints (Figure 9A). From the force-displacement curves of shear tests in Figure 10, it can be seen that the initial stiffness of the screwed fittings was higher compared with flexible couplings, but these screw fittings were damaged due to brittle failure under a shear force. Table 2 shows the averaged results and associated standard deviation (σ) of strength and initial stiffness under a moment or shear force loading. The moment strength of the screwed fittings at a leakage point can also be regarded as their ultimate strength. The mean ultimate shear strength of the coupling was not adopted since the damage in the test was at the piping or the welding between the piping and the adapter plate plates (Figure 9C).

The experimental results were compared with the seismic demands from static and dynamic analyses to evaluate the seismic performance of joints.

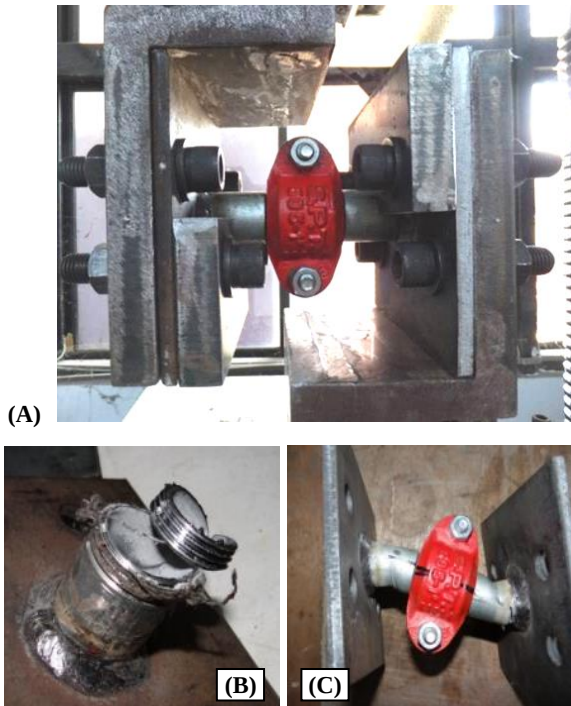
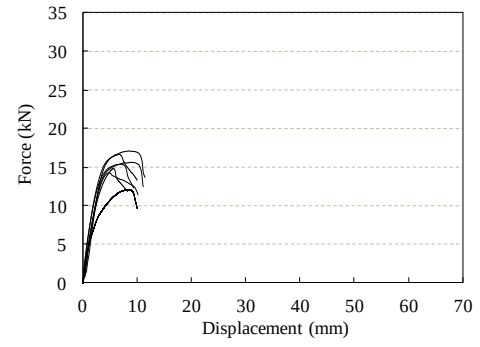
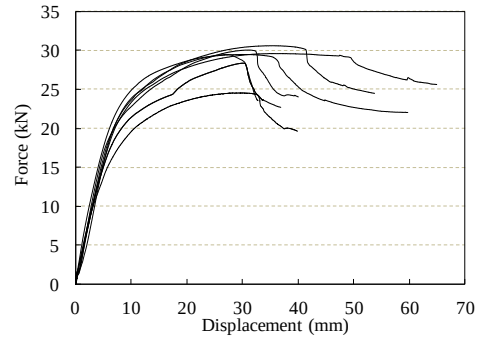


Figure 9: Shear tests: (A) configuration; damage of the (B) screwed fitting and (C) flexible coupling.



(A)



(B)

Figure 10: Force-Displacement curves: (A) screwed fitting and (B) flexible coupling.

Table 2: Leakage/ultimate strength and stiffness.

		Joint Type	Screwed Fitting	Flexible Coupling
Loading Type				
Moment	Strength at Leakage (kN-m)	average	0.61	6.18*
		σ	0.03	.*
	Initial Stiffness (kN-m/ degree)	average	0.51	0.02
		σ	0.01	0.00
Shear Force	Ultimate Strength (kN)	average	15.15	-
		σ	1.54	-
	Initial Stiffness (kN / mm)	average	4.53	3.28
		σ	0.39	0.29

* The Leakage of coupling only happened once in bending tests.

COMPONENT TESTING: EXPANSION ANCHORS

Post-installed expansion anchors have been widely used for the installation of nonstructural components on reinforced concrete structures due to their convenient installation and adjustability. According to *in-situ* investigation results, drop-in anchors with a nominal diameter of $\frac{3}{8}$ " are commonly used to suspend sprinkler piping systems (Figure 11). However, seismic damage to this type of anchorage was observed and resulted in instability of the suspended piping. In order to realize the seismic performance of the drop-in anchors for the hanging of the sprinkler piping system, tension and shear cyclic loading tests were conducted according to ACI 355.2 [12] to simulate the seismic loading effects, but without spacing and edge effects. Both cracked and uncracked reinforced concrete (RC) blocks were used as the base material to discuss the effects of cracked concrete on the performance of the drop-in anchors. Figure 12 describes the accomplished test configurations. The 25-ton capacity hydraulic actuator was used for monotonic and seismic tests. The RC specimens were constructed according to the specification of common RC floor slabs with a thickness of 20 cm and a compressive strength of concrete (f'_c) of 3000 psi (20.7 MPa). The top and bottom steel rebars were laid to

simulate general RC floor slabs and control the crack width from 0.5 mm to 2.0 mm. The nominal diameter and embedment of the tested drop-in anchors were $\frac{3}{8}$ " and 40 mm, respectively. The excitations of seismic tests were conducted under force control (Figure 13), and the amplitudes of input actions were defined according to the mean shear or tension capacity (F_u or N_u), which was determined by the former reference test under a monotonic loading. The amplitudes in sequence were $0.5F_u$, $0.375F_u$ and $0.25F_u$ for the shear tests, and $0.5N_u$, $0.375N_u$ and $0.25N_u$ for the tension tests. Figure 13 also depicts the number of cycles of each amplitude complied with ACI 355.2 [12]. After seismic tests, additional monotonic tests were performed to observe the residual strength and stiffness of the drop-in anchors.

Figure 14 depicts the force-displacement curves of the tested drop-in anchors during seismic shear and tension tests. As the cyclic number of shear loading increased, the initial stiffness gradually decreased and the force-displacement curves tended towards elastic behaviour, which could be simplified as a bi-linear response (Figure 14A). The initial response with a lower stiffness was due to the gap between the top part of the sleeve of the anchor and the surrounding concrete. Meanwhile, the force-displacement relation remained elastic during tension loading with a slight residual displacement of 0.06 mm (Figure 14B). Figure 15 describes the shear and tension damage states of the drop-in anchors subjected to the monotonic loading after seismic tests. The failure modes for drop-in anchors were steel failure proceeded by concrete spalling and concrete breakout under the shear and tension loadings, respectively.

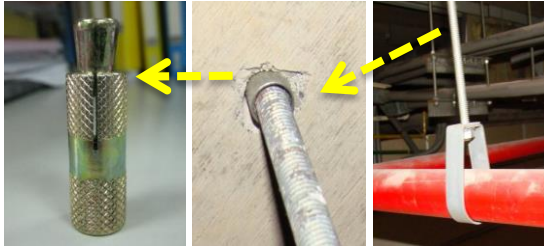


Figure 11: The common type of fasteners for piping.

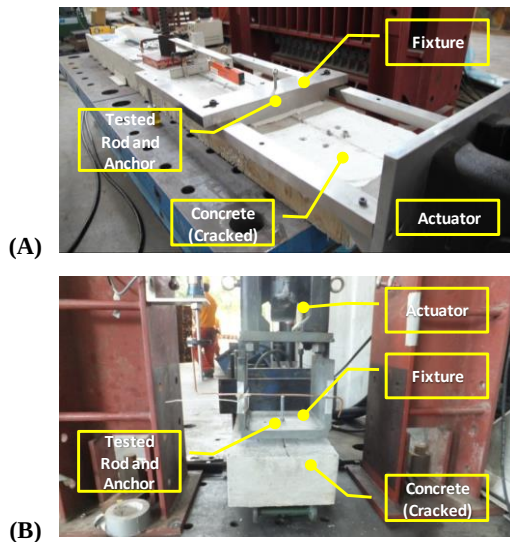


Figure 12: Test configuration: (A) shear and (B) tension.

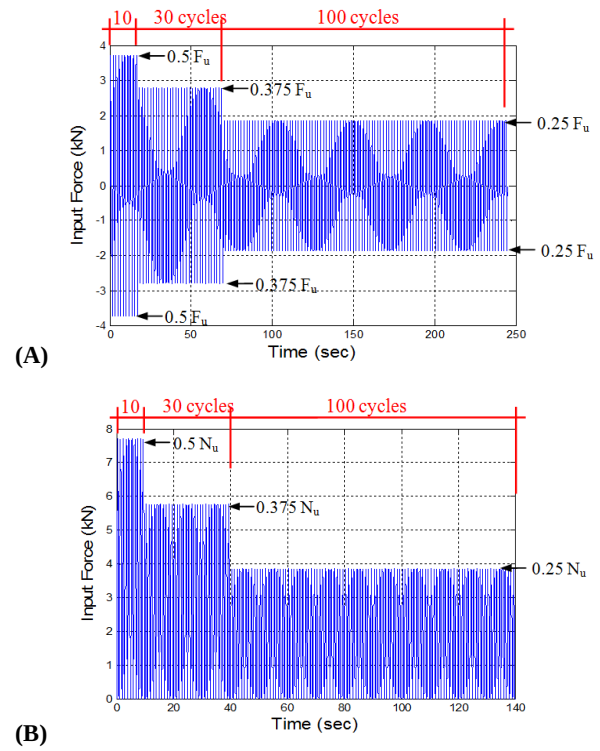


Figure 13: Seismic loading: (A) shear and (B) tension.

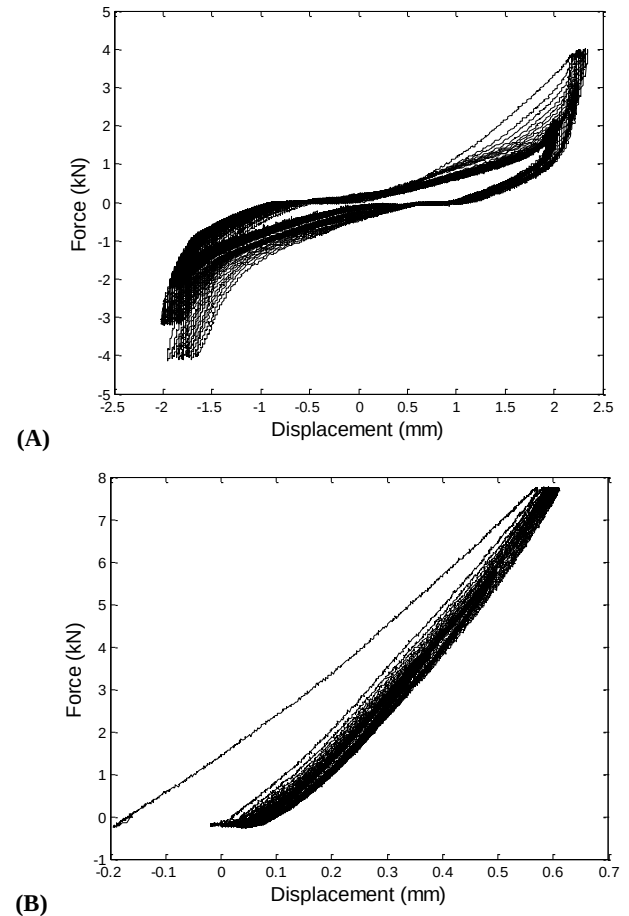


Figure 14: Seismic test results of the anchorage in uncracked concrete: (A) shear and (B) tension.

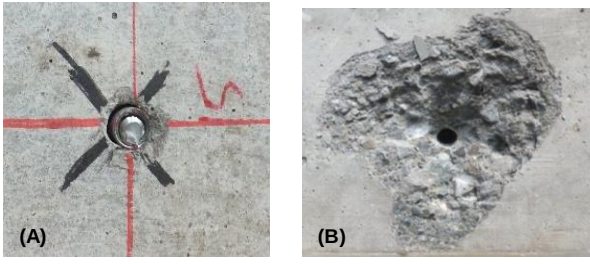


Figure 15: Damage states: (A) shear and (B) tension.

Table 3 shows the values of mean ultimate strength and mean elastic stiffness of the tested anchors under a monotonic loading and a seismic loading, respectively. The ultimate strength of the anchors embedded in cracked concrete was much lower than that of the anchors embedded in uncracked concrete. Although the failure mode under shear loading was mainly steel failure, the additional rotational response and the interaction between bending and shear would reduce both the stiffness and ultimate strength of the anchors in cracked concrete.

Table 3: Ultimate strength and stiffness of anchors.

Base Material	Tension Test		Shear Test	
	Strength (kN)	Stiffness (kN/mm)	Strength (kN)	Stiffness (kN/mm)
Uncracked Concrete	17.71	17.94	13.47	3.63
Cracked Concrete	15.22	13.62	9.40	3.08

IN-SITU INVESTIGATION

In order to realize the typical configuration of the fire sprinkler piping system at hospitals, an *in-situ* investigation was carried out at the hospital building where the fire sprinkler piping system was damaged during the 2010 Jiashian earthquake [3]. As shown in Figure 16, the broken segment of the piping system was located in a patient room at the top floor of the 6-storey building. Restricted by the confined space above the suspended ceiling system, four pipes along the corridor with diameters of 6", 2-1/2", 6" and 4" (from left to right) were carried by the same trapeze frame supports, where

the left 6" diameter pipe was the cross main of the sprinkler piping system (

Figure 17). Based on the results of ambient vibration tests and impact hammer tests, the fundamental frequency of the building structure was identified to be about 2.0 Hz in both horizontal directions, while that of the piping was 5.37 Hz in the transverse direction of the cross main pipe.

Limited to the scale of the shaking table, only a part of the sprinkler piping system was duplicated in the laboratory, including branches in the area of the patient room and a part of the cross main pipe along the corridor (Figure 18). To obtain a reasonable assumption about the boundary conditions of the tested segment of the cross main in shaking table tests, preliminary numerical models of the complete piping system at the 6th floor and the test specimen were both established according to the *in-situ* investigation on the configuration and restraint conditions in the hospital and that of the actual test specimen (

Figure 17 and 18). Comparing the system identification results of ambient vibration tests and numerical analysis, it was found that the restraint conditions of boundaries might be different under ambient vibration or strong motions. For example, to obtain the fundamental frequency in the transverse direction of the cross main pipe, the restraints of sprinkler heads adjacent to ceiling systems are assumed to be hinges. However, it is more reasonable to regard sprinkler heads as free ends of pipes while the mineral fibre ceiling board ceiling boards are torn during strong earthquakes.

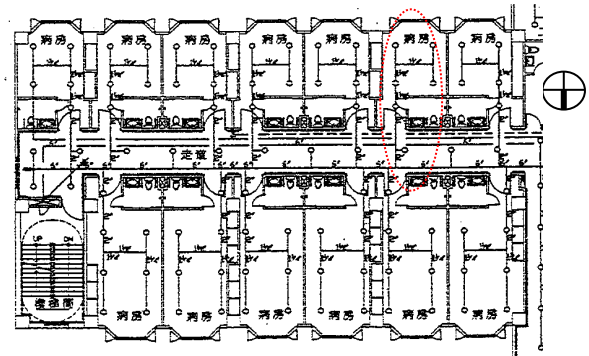


Figure 16: The plane of the sprinkler piping system.

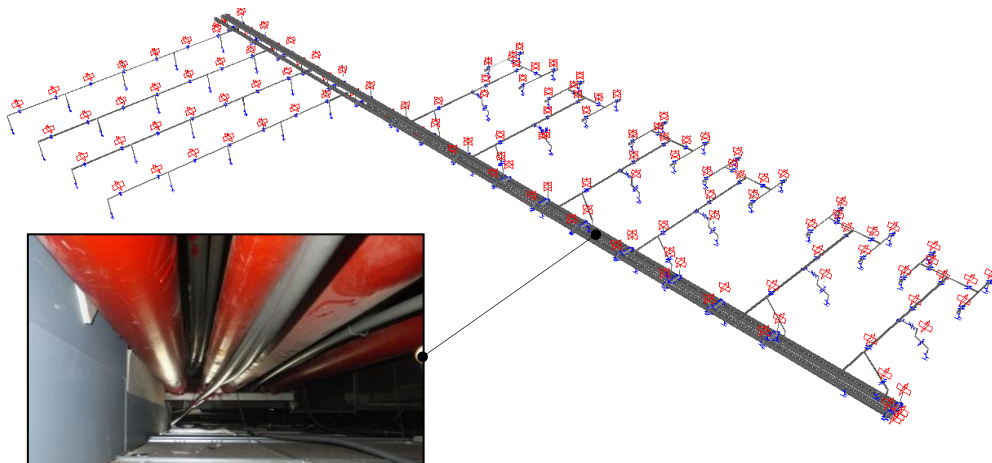


Figure 17: The numerical model of the horizontal piping system.



Figure 18: The numerical model of the test specimen.

SUBSYSTEM TESTING: SHAKING TABLE TESTS

The objective of this test was to identify the failure modes of a typical sprinkler piping system in hospitals and to propose the appropriate improvement strategies for higher seismic performance (Figure 20, Figure 21A). It was attempted to reproduce the same damage that occurred in the 2010 Jiashian earthquake for the test with the original configuration of screwed fittings. In addition, the modified configurations with proposed seismic restraint devices including braces, flexible hoses and couplings were also arranged at the proper positions to verify their improvement efficiencies (Table 4 and Figure 21). The tested subsystem was hung by a rigid steel frame, which was designed to be stiff enough to transfer the motion of the shaking table without significant effects. Figure 21 and Figure 23 depict two types of horizontal motions measured in tests near hang points on the steel frame. The purpose of the Type A motion was to verify whether seismic restraint devices satisfy the requirement of the building code in Taiwan [13], while that of the Type B motion was to simulate the floor response in the hospital during the Jiashian earthquake. Figure 24 shows the layouts of instruments including accelerometers, magnetic transducers, and strain gages in the DBF testing case. With the assumption that ceilings moved with the floor in this experiment, the rigid frames accommodating ceiling boards were installed on the reference frame directly (Figure 19).

Table 4: Testing Configurations.

OC	Original configuration	FH	Flexible hose
CT	A coupling near the tee branch	CB	A coupling between the tee branch and partition
DB	Double braces	DBF	Double braces with a flexible hose

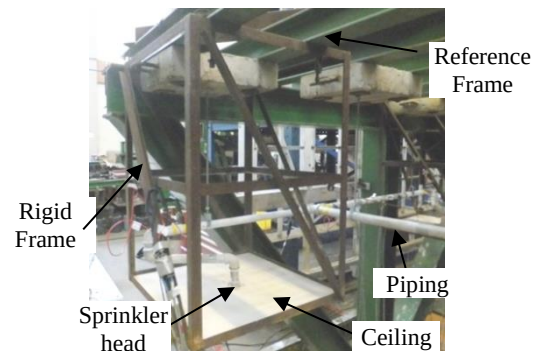


Figure 19: Ceiling installed details.

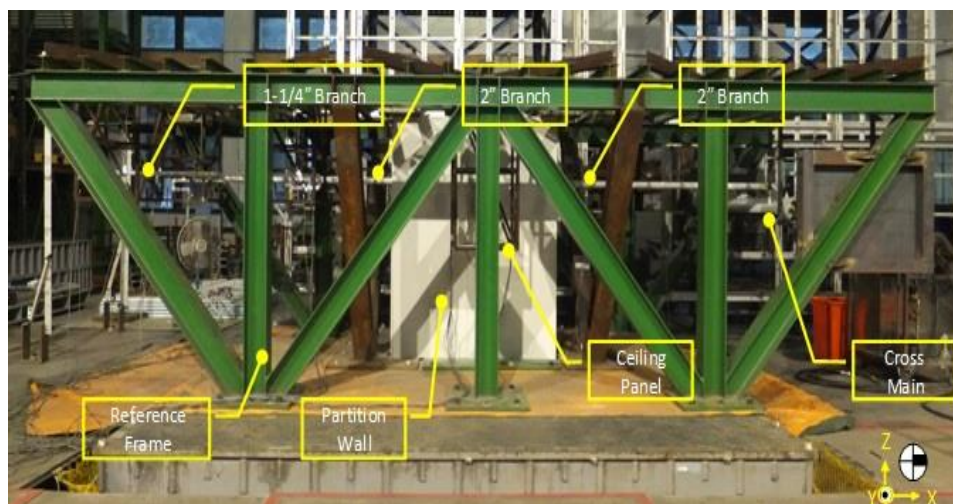


Figure 20: Shaking table testing for the subsystem.

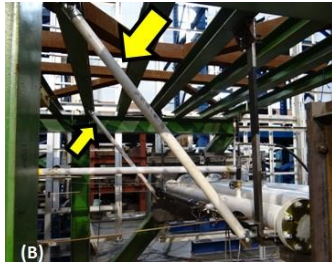
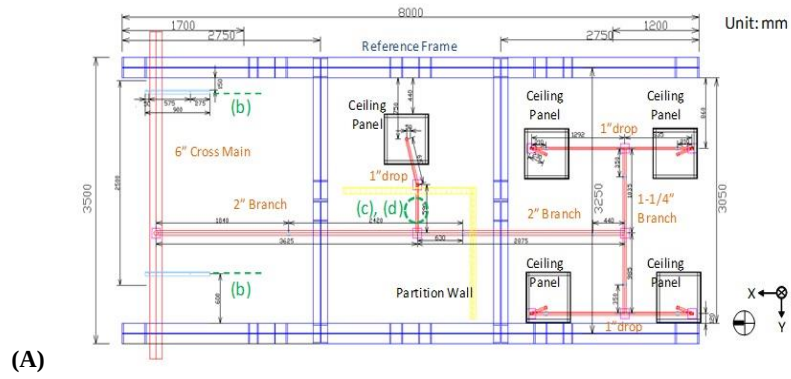


Figure 21: Test configuration and seismic restraint devices.

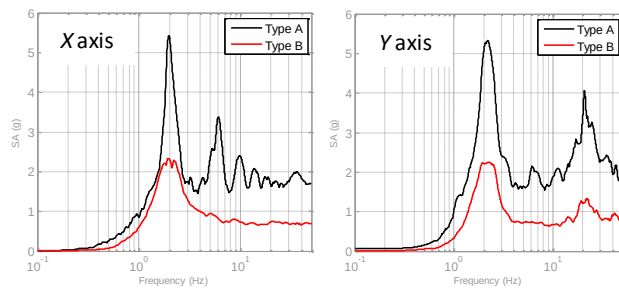
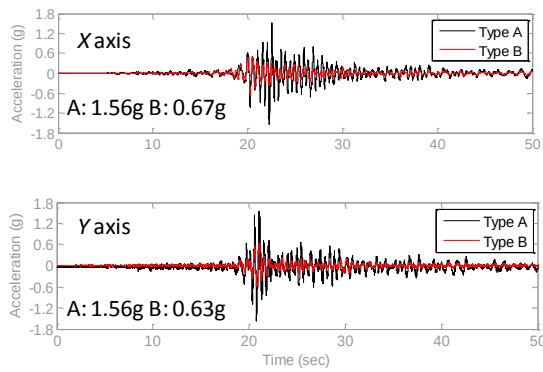


Figure 22: Acceleration time series at the steel frame along the x-axis (top) and y-axis (bottom).

Figure 23: Response spectra along the x-axis and y-axis.

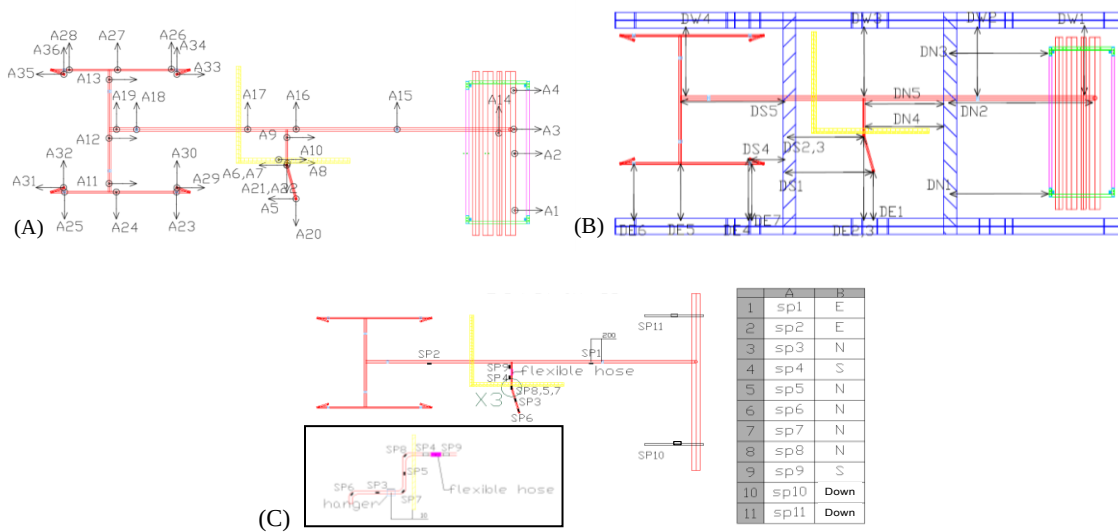


Figure 24: Layouts of (A) accelerometers, (B) transducers and (C) strain gauges for DBF case.

Table 5: Experimental Protocols for specimens.

Test Config.	Peak acceleration of input motion (g)								
	WN* (Tri.**)	15%Type B (Tri.)	WN (Tri.)	48%Type B (Tri.)	WN (Tri.)	100%Type B (Tri.)	WN (Tri.)	Type A (Tri.)	WN (Tri.)
OC	0.107	0.091	0.111	0.323	0.100	0.670 (1)	-	-	-
CT	0.111	0.095	0.099	0.316	0.099	0.671 (1)	-	-	-
CB	0.101	0.096	0.102	0.319	0.095	0.683 (1)	-	-	-
FH	0.140	0.109	0.118	0.318	0.101	0.755	0.123	1.255 (2)	0.094
DB	0.093	0.089	0.083	0.320	0.075	0.646	0.055	1.396 (3)	-
DBF	0.094	0.093	0.082	0.312	0.061	0.666	0.096	1.557	0.110

*WN: White noise motion, 0.05g

** Tri.: Tri-axial input

(1): The 1" drop at tee branch failed

(2): Only ceiling boards failed

(3): Leakage happened at the 1" drop at tee branch

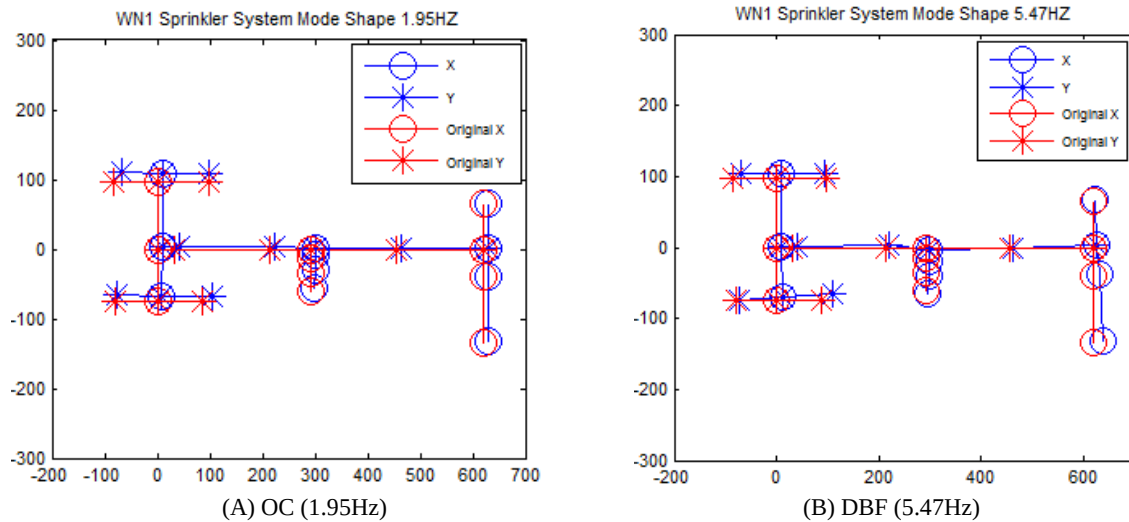


Figure 25: The first mode shape and natural frequency along the x-axis of OC and DBF test configurations.

SHAKING TABLE TEST RESULTS

Six test configurations were tested under expected input motions (Table 5). Figure 25 depicts the natural frequency identified and the first mode shape along the x-axis of each test configuration, i.e. the transverse direction of the cross main pipe, from the results of resonant frequency survey tests. The natural frequencies and mode shapes are established according to the magnitude and phase of transfer functions from responses of the reference frame to those of the tested subsystems. The test specimen which simulated the original configuration (OC) in the hospital was designed using conservative assumptions regarding the resonance with the floor response. The natural frequency of the test specimen (OC) was 1.95 Hz, which was close to the expected value 2.0 Hz. It can be seen that braces increased the natural frequencies significantly (DBF), while couplings and flexible hoses decreased the natural frequencies and changed the stress distribution of local segments. Meanwhile, Figure 25 shows the torsional behaviour of the DBF specimen due to the unequal stiffness provided by two sets of braces.

In order to avoid leakages of the sprinkler piping system and associated damage of the adjacent architectural components

due to seismic interactions, three performance indexes were examined during and after each test: (1) the damage of the piping segments; (2) enlarged diameters of the reaming on ceiling boards and partition walls due to impacts caused by sprinkler heads and piping segments; and (3) the leakage of contained water. The test results of the original configuration showed that the screwed fitting of a 1" drop at the tee branch was the most vulnerable part of the tested piping system and was damaged at a 100% intensity of the Type B test (Figure 26A). Although there was no leakage in the tests of the configuration with the flexible hose (FH, Figure 27), all ceiling boards were broken and could seriously damage the medical services (Figure 26B and Figure 28). On the other hand, due to the brittle failure caused by the screwed fitting and couplings, the mechanical behaviour of both devices should be further studied (Figure 26C and Figure 26D). The optimum improvement strategy to achieve a higher nonstructural performance for the piping system is to strengthen the main pipe with braces and decrease moment demands on the small-bore piping at the tee branch by a flexible hose. However, well designed attachments of braces were needed to avoid the damage observed in the DBF tests (Figure 26E).



Figure 26: Damage states of each test configuration: (A) OC; (B) FH; (C) CT; (D) CB; and (E) DBF.

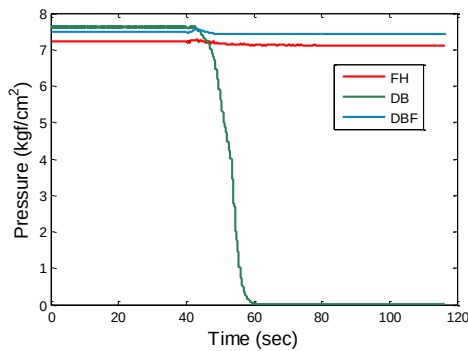


Figure 27: Leakage conditions in the Type A tests.

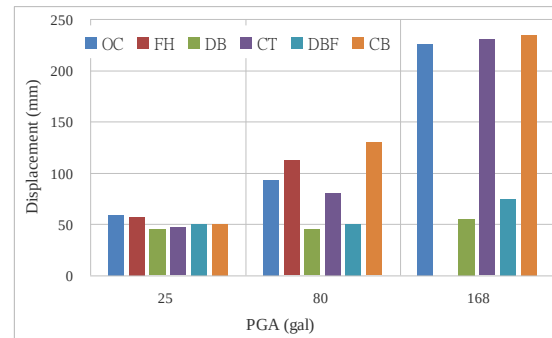


Figure 28: Diameter of the reaming on the ceiling board in the Type B tests.

Figure 29 to Figure 31 depict the seismic behaviour observed in Type A and B tests of different configurations. Note that leakages occurred at 20.4 seconds and 40 seconds in the Type B test (Figure 29 and Figure 30) of the original configuration (OC) and in the Type A test (Figure 31) of the configuration with double braces (DB). Comparing the responses of the 6" cross main (Figure 29A and Figure 30A) and the damaged 1" drop (Figure 29B and Figure 30B) in the OC test, it was seen that the partition wall partially restrained the displacement response of the 1" drop but enlarged its acceleration response. Compared to the OC test, the configurations with braces (DB and DBF) successfully reduced the displacement response of the entire piping system (Figure 29) while also reducing the

impact effects on the 1" drop (Figure 30). The strain responses of the 1" drop in the DB, FH, and DBF configurations (Figure 31A) proved that using both braces at the main pipe and flexible hoses at the drops near partition walls can effectively decrease the internal force of small-bore pipes and reduce the possibility of leakages. However, it should be noted that the braces and related attachments in the DBF configuration were subjected to more seismic forces than those in the DB configuration due to less restraint offered by the partition wall (Figure 31B). Better and more-detailed design of the attachments of braces is required to avoid the damage observed in the Type A test of the DBF configuration (Figure 26E).

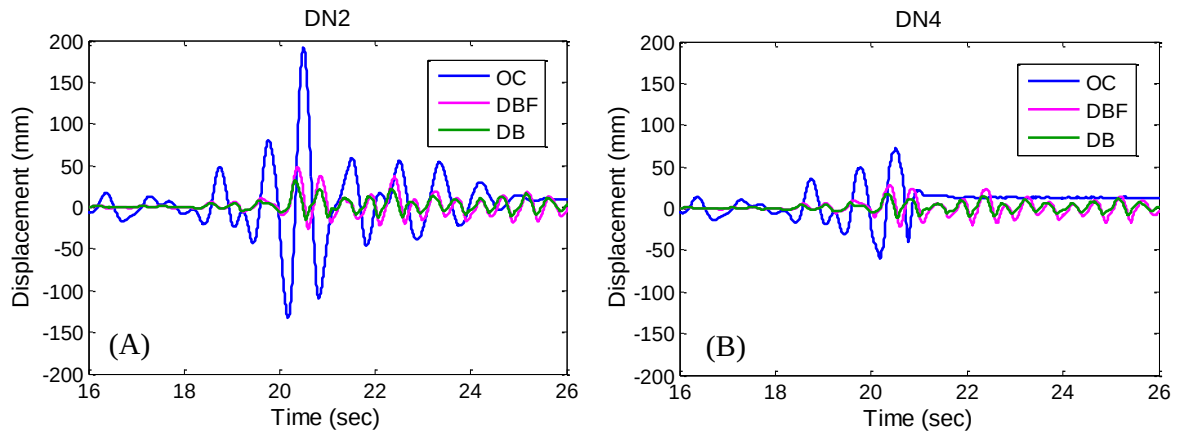


Figure 29: Displacement response in the Type B tests of OC, DB, and DBF: (A) 6" cross main and (B) 1" drop.

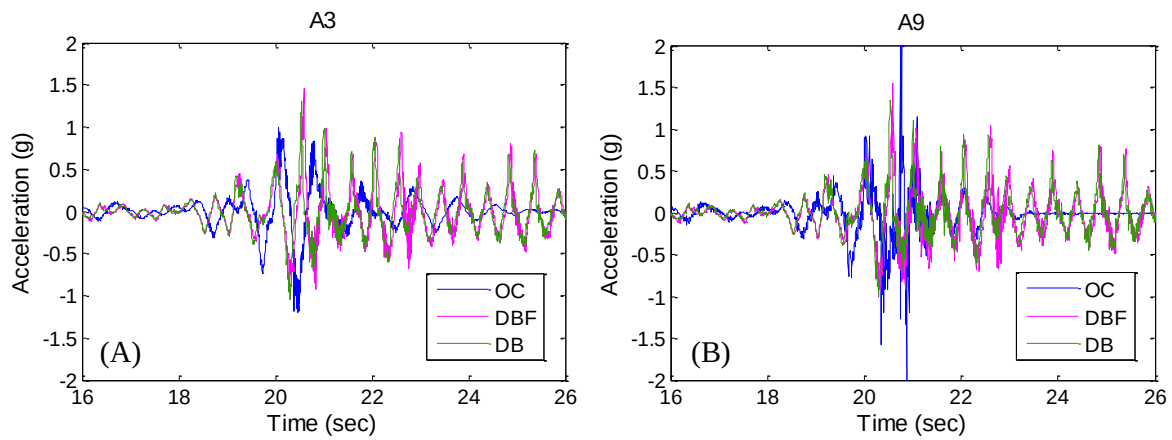


Figure 30: Acceleration response in the Type B tests of OC, DB, and DBF: (A) 6" cross main and (B) 1" drop.

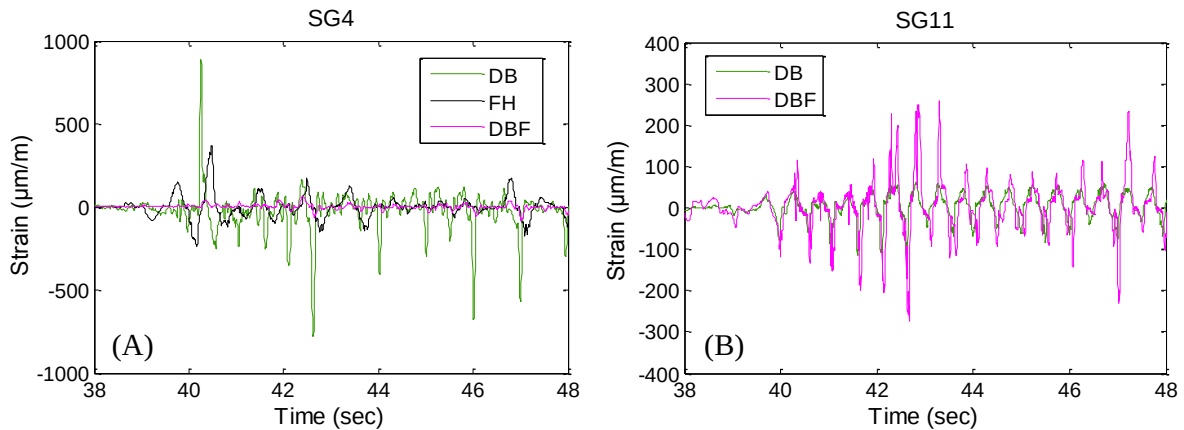


Figure 31: Strain response in the Type A tests of DB, FH, and DBF: (A) 1" drop and (B) Bracing.

CONCLUSIONS

In view of the immediate needs of emergency medical services provided by hospitals after strong earthquakes, an ongoing research programme on assessment and improvement strategies for a typical configuration of a sprinkler piping system in hospitals was organized by NCRE. Presently, the completed topics within the research programme include component testing of expansion anchors and piping joints and shaking table tests for a typical subsystem of horizontal

sprinkler piping. The preliminary findings are summarized as follows:

1. The drop-in anchors with a nominal diameter of $\frac{3}{8}$ " were commonly used to suspend sprinkler piping systems. According to the component tests under a monotonic loading, the failure modes for the drop-in anchors were steel failure preceded by concrete spalling and concrete breakout under a shear and tension loading, respectively. Based on the results of seismic shear tests, the force-displacement relationship in the elastic stage can

be simplified by a bi-linear response. Meanwhile, the cracks of concrete where the tested anchors were embedded significantly affected their ultimate strength and stiffness under shear or tension loading. That should be noted since most sprinkler piping systems are hung at the tension side of concrete floor slabs where cracks might gradually occur in existing buildings.

2. Based on the shaking table test results, a screwed fitting of a 1" drop at the tee branch was the most vulnerable part of the damaged sprinkler piping system with the original configuration of the hospital during the 2010 Jiashian earthquake. The effectiveness of three types of seismic restraint devices for a sprinkler piping system, namely braces, couplings and flexible hoses, were also tested. Although a seismic bracing can reduce the damage of adjacent architectural components, the optimum strategy to avoid leakages is to strengthen the main pipe with braces and to use flexible hoses near the tee branch to decrease both the shear and displacement demands on screwed fittings.
3. Brittle failure associated with a screwed fitting and couplings was observed in the shaking table tests. Further component tests were conducted to study the mechanical behaviour of both devices. It was seen that the screwed fittings exhibited brittle failure under moment or shear actions. Although the capacity of screwed fittings and couplings can sustain the seismic demands from static and dynamic analyses, the dramatic change in stiffness could be the reason for failure for piping configurations with couplings in shaking table tests.

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