OPTIMIZED SEISMIC STRENGTHENING STRATEGIES FOR A TYPICAL SPRINKLER-PIPING SYSTEM IN A HOSPITAL

F.-R. Lin[(1)], J.-F. Chai[(2)], Y.-A. Tsai[(3)], S.-C. Tseng[(4)], P.-R. Wu[(5)],C.-Y. Su[(5)] Zhen-Yu Lin[(6)], Zhi-Yu Lai[(7)] and Tzu-Chieh Chien[(8)]

[(1)] *Associate Researcher, National Center Research on Earthquake Engineering (NCREE), frlin@ncree.narl.org.tw*
[(2)] *Research Fellow, NCREE, chai@ncree.narl.org.tw*
[(3)] *Research Assistant, NCREE, yatsai@ncree.narl.org.tw*
[(4)] *Graduated Student, NCKU, n76071178@mail.ncku.edu.tw*
[(5)] *Graduated Student, NTUT, t107428057@ntut.edu.tw ; t107428016@ntut.edu.tw*
[(6)] *Assistant Researcher, NCREE, Taipei, Taiwan, zylin@ncree.narl.org.tw*
[(7)] *Assistant Researcher, NCREE, Taipei, Taiwan, zylai@ncree.narl.org.tw*
[(8)] *Assistant Researcher, NCREE, Taipei, Taiwan, tcchien@ncree.narl.org.tw*

Abstract

Based on recent earthquakes experiences in Taiwan, losses do not necessarily result from damages of building structures but non-structural components and systems. For instance, the leakage of the fire protection sprinkler systems in hospitals during small earthquakes could results in shortage of medical function and fire protection, and malfunction and repairs of medical equipment. The break of sprinkler systems caused by strong earthquakes could even harm the life safety in buildings.

Taking a sample sprinkler piping system in a medium-scale hospital as an example, this research aims to verify seismic strengthening strategies based on NFPA 13 to improve seismic performance of the fire protection sprinkler system in critical buildings. The design concepts, which include numerical analysis simulating original piping, design of input motion and test specimen, and strengthening strategy established based on the consideration of improving seismic performance of specific damage states were introduced. Meanwhile, preliminary results of shaking table tests for four strengthening strategies are discussed as well to propose a more applicable seismic design guideline for sprinkler piping system in Taiwan.

Keywords: sprinkler-piping, failure mode, seismic evaluation, strengthening strategies

1. Introduction

In recent years, the major disasters and economic losses in critical buildings in Taiwan caused by the earthquake have changed from structural to non-structural systems, which include piping systems. For instance, the leakage of the fire protection sprinkler systems in hospitals during small earthquakes could results in shortage of medical function and fire protection, and malfunction and repairs of medical equipment. The break of sprinkler systems caused by strong earthquakes could even harm the life safety. On 4 March 2010, a moderate-scale earthquake with magnitude M_L 6.4 occurred at Jiaxian in Kaohsiung city, namely Jiaxian earthquake, and shook the southern Taiwan. A middle-scale hospital (hereinafter called the sample hospital), locates at the Douliou City in Yunlin County, encountered strong ground motion with the peak acceleration between 80 gal and 250 gal. On the six floor in one of the buildings belonging to the sample hospital, almost half area is flooded after Jiaxian earthquake due to the leakage of suspended sprinkler piping system. As shown in Fig. 1, one-inch drop above a sickroom has been replaced after Jiaxian earthquake immediately due to the pressurized water aggravate the flood problem. Besides, it can be seen that the wall penetration was enlarged by the impact between sprinkler piping and the partition panel. Tears in partition walls and suspended ceiling panels adjacent to piping and sprinkler heads respectively were observed as well. In 2014, The damaged sprinkler piping system in the range of the sickroom in the sample hospital mentioned above was duplicated on the shaking table to identify the failure modes of piping [4]. From the results of the tests, the main cause of leakage was found to be the poor moment capacity of the screwed fitting of the one-inch drop. The movement of the one-inch pipe cannot be consistent with two-inch branch due to the constraint of the adjacent partition wall.

Fig. 1 – The damaged sprinkler drop in the sample hospital

In Taiwan, there is no mandatory requirement for seismic design of nonstructural components in the Building Act [1]. For fire sprinkler systems at general buildings, NFPA 13 [2] provides a common code of practice for seismic installation. Instead of stress analysis, a rule-based approach is proposed by the NFPA standard. However, the efficiency of seismic strengthening improved by NFPA method is questioned due to the stress concentration effect on the piping at the bracing point [3]. In order to upgrade seismic performance of sprinkler piping systems efficiently, a long-term research program on assessment and improvement strategies for typical configuration of sprinkler piping systems in hospitals was organized by National Center for Research on Earthquake Engineering (NCREE). The content of this research is summarized below:

1. Definition of failure modes for performance design: Based on the seismic experiences of sprinkler piping, three damage states were defined for the critical components of a sprinkler-piping system: (1) failure

© The 17th World Conference on Earthquake Engineering

of the ceiling caused by the impact of the sprinkler head if the resulted force applied to the ceiling panel from the sprinkler head under Design Based Earthquake (DBE) exceeds the yield strength; (2) leakage of the threaded joint of the branch if the resulted moment on the joint under DBE exceeds the capacity; and (3) drop-off of the piping system due to the damaged hangers if the resulted moment of the hanger under DBE exceeds the yield strength. All the capacities of the critical components are determined by experiments previously [5].

2. Numerical analysis of seismic strengthening sprinkler piping systems: the sample sprinkler piping system is used as a case to discuss the effects of seismic strengthening strategies recommended by NFPA13 or proposed by this study. Strengthening strategies include braces of main pipes, seismic hangers of branch lines, steel wire of sprinkler heads, and flexible hoses at possible impact regions. Detailed numerical analyses were conducted to compare seismic performance of before- and after-strengthened systems under DBE. The results of a series of component tests were conducted to verify simplified numerical models with SAP2000 v.20 software for critical piping components and seismic devices. Four groups of input motions, i.e. floor responses anchored at DBE level, were established according to the results numerical analysis of the six-floor RC hospital and a fourteen-floor SC building under near-fault and far-field earthquakes respectively.

3. Shaking table tests of the sample sprinkler piping system: In order to verify the accuracy of numerical results, a series of shaking table tests has been conducted in October 2019. According to the numerical analysis mentioned above, a test region of 10m by 10m area of the sample sprinkler piping system is picked out to compare the efficiency of seismic strategies. The observed effects of seismic spatial interactions caused by an adjacent ceiling system and partition walls will be quantified to remedy the differences with the numerical results. Based on the comparison of test results of strengthening and original sprinkler piping system, the seismic efficiency, installation applicability and economic consideration of seismic strategies for sprinkler piping systems will be discussed with fire protection engineers as well.

Taking the fire protection sprinkler system in the sample hospital as an example, this paper aims to introduce the design concepts first, which include numerical analysis simulating original piping, design of input motion and test specimen, and strengthening strategy established based on the consideration of improving seismic performance of specific damage states. Meanwhile, preliminary results of shaking table tests for four strengthening strategies are discussed as well to propose an applicable seismic design guideline for sprinkler piping system. The research results will be applied to propose an applicable seismic design guideline for sprinkler piping system in Taiwan.

2. Design of test specimen

2.1 Sprinkler Piping System

In the sample hospital, the main pipe of the southern part of the fire suppression system is T-shaped distributed along the corridor and the central elevator hall. Fig. 2 depicts the layout of the main pipe above the corridor ceiling. The four galvanized steel pipes size from left to right in the Fig. 2 are 6”, 2-1/2”, 6” and 4” are placed on the same trapezes. As shown in Fig. 3, although only 6” pipe belongs to the sample sprinkler system, another three ones are still counted into the numerical analysis to reflect the real mass and stiffness of piping. Boundary conditions of the piping system are also corresponding to in-situ observation, such as the location marked with a red circle in Fig. 3 is regarded as a fixed end of main pipe in the numerical model. Numerical model of the sprinkler-piping system in the example hospital was established for fragility analysis using SAP2000 v.20 software. . Fig. 3 depict the modal shape at the fundamental frequency in transverse

© The 17th World Conference on Earthquake Engineering

direction. It is noted that the damged branch is above the sickroom marked by red circle, at which the siginificant modal response is. The accuracy of the fundamental frequency (1.3Hz) of the numerical model is verified by in-situ ambient vibration tests as well in previous studies[7][8]. In reality, seismic response of sprinkler piping systems in buildings typically contain non-linear behavior, especially at the interface between the end of sprinkler piping and adjacent components, such as ceiling systems or partition walls. Therefore, appropriate parameters to simulate the gap between adjacent partition walls or ceiling systems were proposed and verified through the results of component tests and shaking table tests [9].

Fig. 2 – Piping layout in the corridor

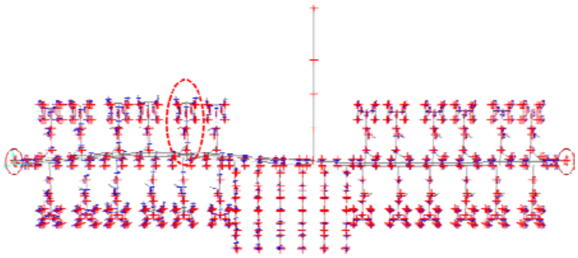
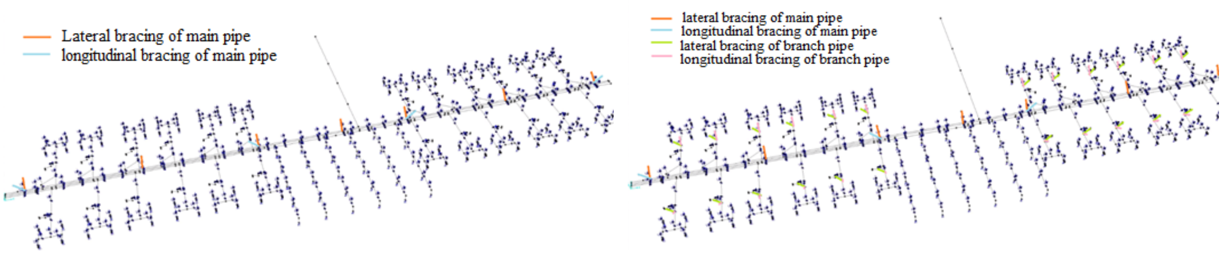


Fig. 3 – Fundamental modal shape of the piping system (1.3 Hz, Mass participation ratio of 0.31)

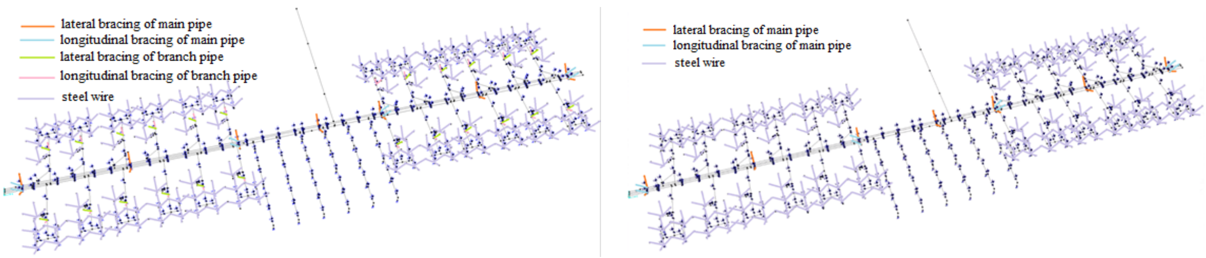
2.2 Strengthened cases of the sprinkler piping system

Based on NFPA13, this research proposes four strengthened cases of piping system. First of all, the earthquake-resistant diagonal bracing is installed on the main pipe as shown in Figure. 4(a). The purpose is to suppress the displacement of the main pipe. The position of the main pipe bracing and the affected area and distribution are calculated according to the NFPA 13 or the strengthen guideline for hospitals (Chai et al., 2015) [6]. However, the proposal using NFPA13 did not effectively inhibit the displacement of the sprinkler head, To prevent possible impact and tear of ceiling boards caused by adjacent sprinkler head, this study added three additional schemes. According to the NFPA13 recommendation, as shown in Figure. 4(b), the second scheme is to add braces to the branch pipes besides the braces for main pipes. As shown in Figure. 4(c), the third scheme is to add four steel wires to each sprinkler head in addition to the above mentioned seismic strengthening devices. In order to understand the effect of the steel wire on suppressing the displacement of the sprinkler head, the fourth scheme is added in this study. As shown in Figure. 4(d), the fourth scheme is to add four steel wires to each sprinkler head and to add earthquake-resistant diagonal bracing on main pipe. Table 1 lists the strengthening components of each scheme, the modal frequency and mass partition ratio of the numerical model.



(a) (b)

© The 17th World Conference on Earthquake Engineering



(c) (d)

Fig. 4 – Configuration of each strengthened case (a) case 1;(b) case2; (c) case3; (d) case4

Table 1 Configuration of sprinkler-piping systems

Conf.	Main pipe bracing	Branch pipe bracing	Sprinkler head w/ steel wire	1-inch pipe replaced by Flexible Hose	Complete System Analysis	
					Fundamental Freq. of transverse mode (Hz)	Mass participation ratio
Original	-	-	-	-	1.30	0.31
Case 1 (AXX)	V	-	-	-	3.07	0.2
Case 2 (ABR)	V	V	-	-	8.71	0.3
Case 3 (SBH)	V	V	V	-	8.75	0.3
Case 4 (AHL)	V	-	V	-	4.23	0.25
AXF	V	-	-	V	-	-

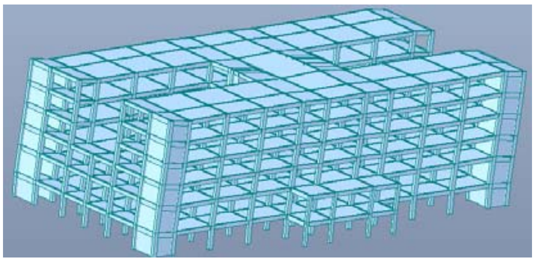
V : installed devices

2.3 Input motion of piping system (Floor response)

The sample hospital is a shear-wall reinforced concrete (RC) structure with six floors above ground and one floor under ground. In order to obtain the floor response as the input motion for dynamic analysis of the sample sprinkler piping, the hospital structure is simulated using the finite element analysis software MIDAS Gen 2018 v2.1 to execute nonlinear time-history analysis of the RC structure under strong ground motion. Fig. 5a depicts the fundamental modal shapes at the frequency of 2.4 Hz and 2.73 Hz in longitudinal (along "flanges") and transverse (along the "web") directions of the floor plan respectively. These natural frequencies can be found as the main frequency contents of floor responses derived in following analysis since the mass participate ratios of both modes exceed 70%. On the other hand, in order to investigate possible resonant behavior of the suspended piping system in the top roof level of a mid-rise building, a numerical model of a fourteen-level SC building was adopted to obtain flexible floor response (Fig. 5b). The numerical model and verification are supported by Prof. Liao [10]. The simulated floor responses were generated from the roof level of the two numerical models under three types of ground motions. Table 2 depict more detailed data about designated ground motions. In order to simulate the scenario happened in the

© The 17th World Conference on Earthquake Engineering

sample hospital during Jiashian earthquake, first one is the measured ground motion at the nearest seismic station. Referring to FEMA P695[11], Other two ground motions are picked out from PEER West NGA database [12] and all measured at Duzce, but one is near-fault ground motion (RSN 1605) and the other one is far-field ground motion (RSN1158). Three types of ground motion s are normalized to 320 gal based on the geometric mean value of Horizontal PGA and then were input to those building models. Finally, the floor response at the roof level were obtained (Fig. 6) and further checked to be smaller than the limitation of the shaking table in NCREE Tainan Laboratory (**Table 3**).

(a) 

(b) 

Fig. 5 – Numerical models of Buildings -- (a) the sample RC hospital; (b) a 14-floor SC building

Table 2 Input motion for numerical analysis of building

Event RSN No. or Station	Item	PGA(gal)* geomean(H1,H2)	PGA(gal)* max(H1,H2)	PGA(gal)* EW | NS PGA	PGV(cm/s) geomean(H1,H2)	PGV(cm/s) max(H1,H2)	Direction Ground-building-Piping (Trans. of Pipe = Y dir. of Table)	Floor Response
Kocaeli (RSN1158Duzce)	FQ9(320gal)	319.77	345.35	296 | 345	55.27	56.79	EW-Lateral-Y	FDH
Duzce (RSN1605Duzce)	NQ12(320gal)	319.75	416.94	245 | 417	58.65	63.97	EW-Lateral-Y	NDH
Kocaeli (RSN1158Duzce)	FQ9(320gal)	319.77	345.35	296 | 345	55.27	56.79	EW-Lateral-Y	FDL
Duzce (RSN1605Duzce)	NQ12(320gal)	319.75	416.94	245 | 417	58.65	63.97	EW-Lateral-Y	NDL
20100304 JiaShan (CHY103)	FQ24(320gal)	326.2	368.14	289 | 368	32.92	39.17	NS-Lateral-Y	FCL
	FQ24(320gal)			289 | 368			NS-Lateral-Y	FCH

*Geometric mean value of Horizontal PGA Scaling to 320gal

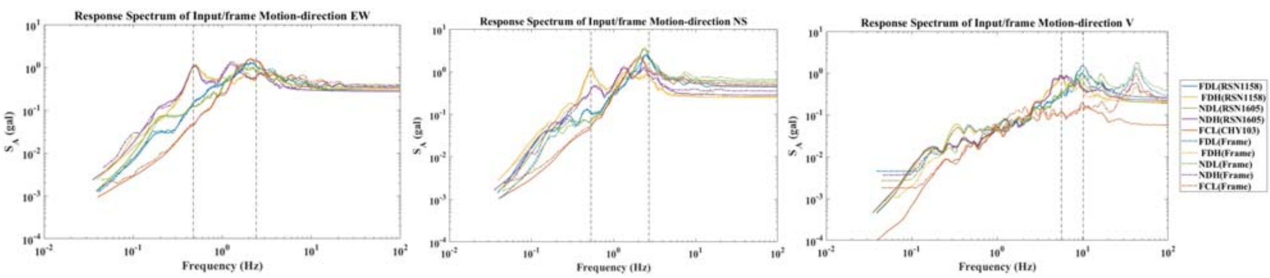


Fig. 6 – Floor response spectrum in EW, NS and Vertical directions

Table 3 – Performance of the shaking table

Axis	**X axis**	**Y axis**	**Z axis**
Stroke	±1.0 m	±1.0 m	±0.4 m
Velocity	±2.0 m/sec	±2.0 m/s	±1.0 m/s
Acceleration			
250t specimen	±0.75 g	±0.75 g	±0.5 g
100t specimen	±1.4 g	±1.4 g	±0.8 g
Bare Table	±2.5 g	±2.5 g	±3.0 g

Overturning Moment Limit: 500 ton-m (biaxial), 1000 ton-m (uni-axial)

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 (Fig. 7). To obtain a reasonable assumption about the boundary conditions of the tested segment of the cross main in shaking table tests, detailed numerical models of the complete piping system at the 6th floor and preliminary analysis for 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 (Fig. 7). The boundary of the test specimen was carefully designed to simulate the unduplicated part of main pipe (Fig. 8). On the other hand, 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 fiber ceiling board ceiling boards are torn during strong earthquakes.

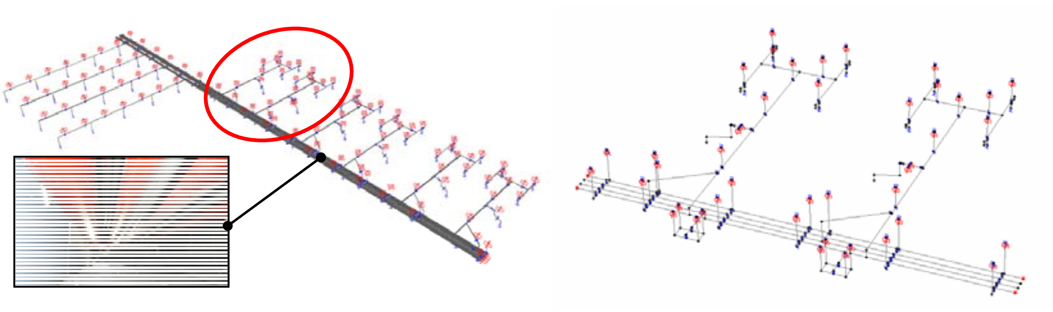


Fig. 7 – Test range of piping system

© The 17th World Conference on Earthquake Engineering


Fig. 8 – Boundary of test specimen

3. Shaking table tests

The objective of this testing is to identify the failure modes of a typical sprinkler piping system in hospitals and to propose the appropriate improvement strategies for higher seismic performance. During this test, the same damage as it occurred during the earthquake event was reproduced for the original configuration with screwed fittings. In addition, the modified configurations with proposed seismic restraint devices, including braces, attachment for braces, flexible hoses and steel wires were also tested to verify their improvement efficiencies (Fig. 12). From the results of resonant frequency survey, the first mode of the original configuration of the sub-system was translation along *Y*-axis (Table 4). Braces increased the natural frequency of piping significantly, while the steel wires and flexible hose slightly changed the natural frequencies of the whole specimen. The effectiveness of devices was mainly reflected by the stress distribution of local pipe segments.

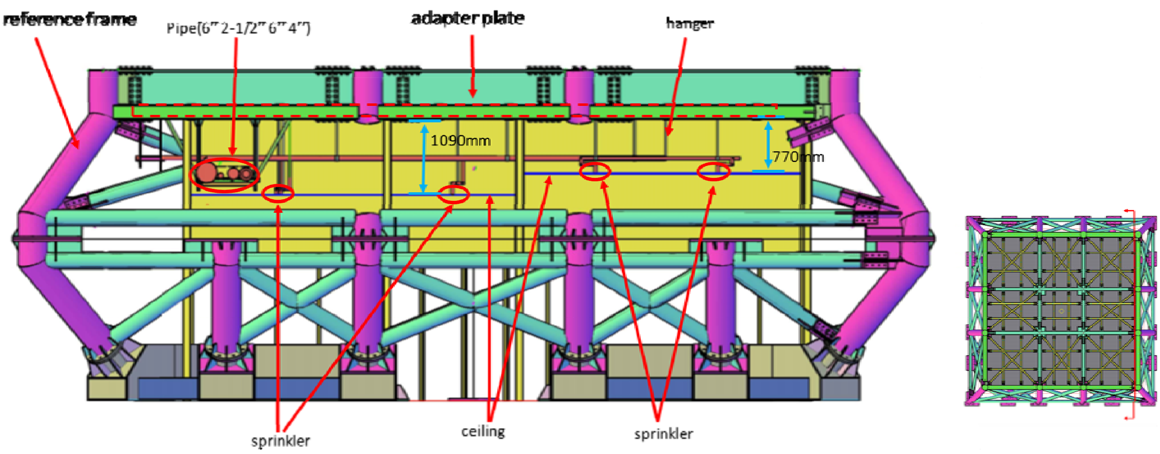


Fig. 9 – Test Configuration (Lateral View)

© The 17th World Conference on Earthquake Engineering

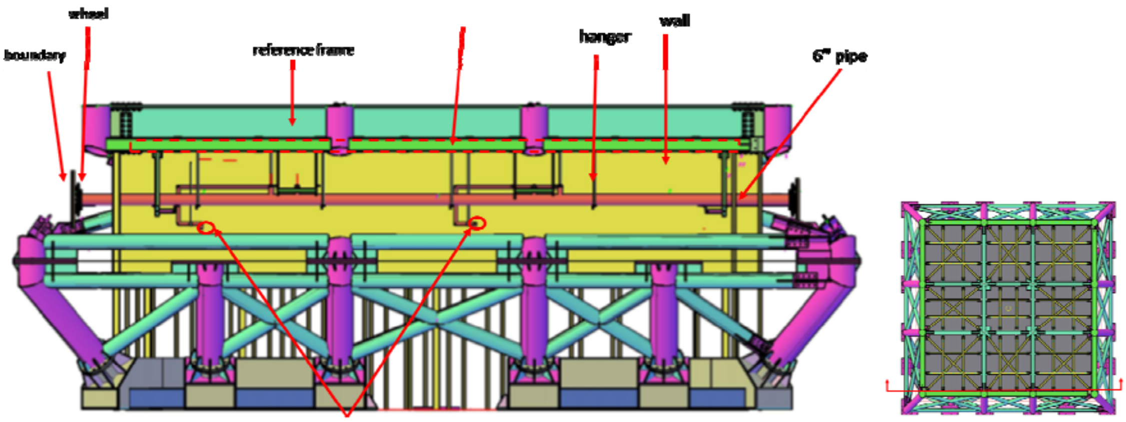


Fig. 10 – Test Configuration (Front View)

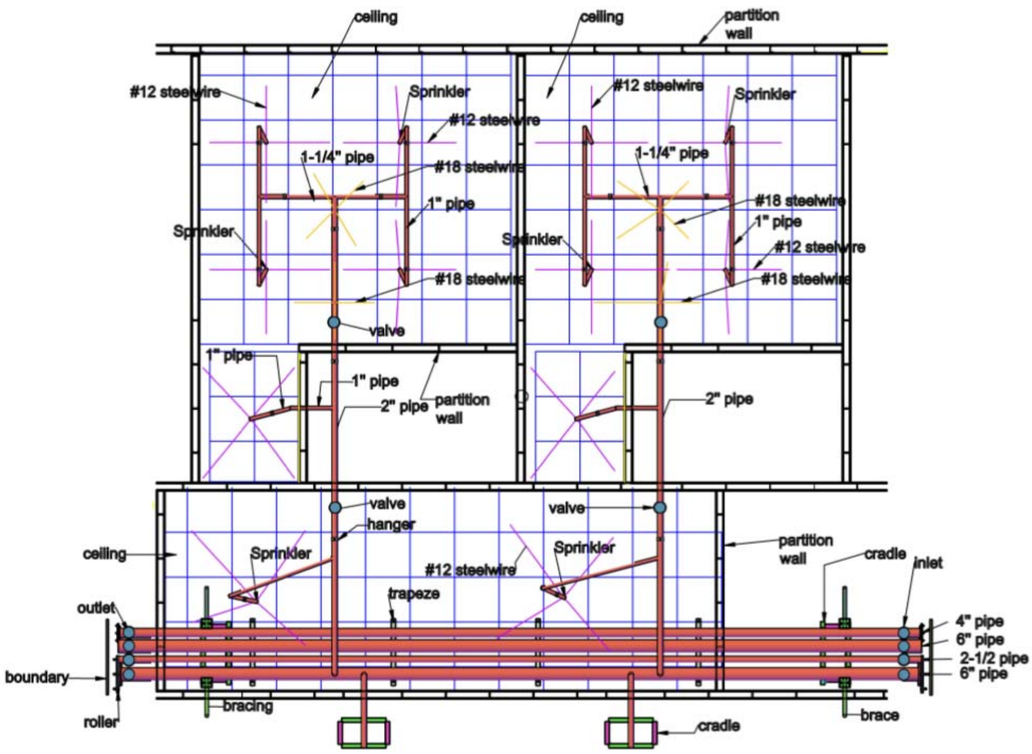


Fig. 11 – Test Configuration (Plan View)

© The 17th World Conference on Earthquake Engineering

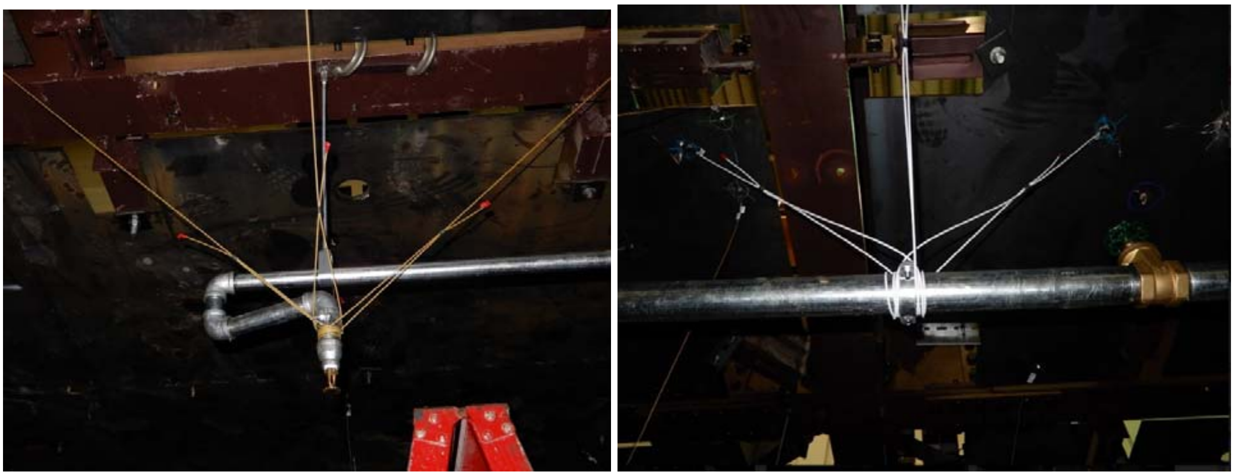


Fig. 12 – Steel Wire for sprinkler head and branch

Table 4 Configuration of sprinkler-piping systems

Conf.	Main pipe bracing	Branch pipe bracing	Sprinkler head w/ steel wire	1-inch pipe replaced by Flexible Hose	Fundamental Freq. of transverse mode (Hz)		Performance
					Complete System Analysis	Test Specimen	
XXX	-	-	-	-	1.30	2.8	Leakage at 10%
AXX	V	-	-	-	3.07	5.0	Deformed attachment
ABR	V	V	-	-	8.71	4.7	Leakage at 60%
SBH	V	V	V	-	8.75	5.0	No Leakage / Deformed attachment
AHL	V	-	V	-	4.23	4.7	No Leakage
AXF	V	-	-	V	-	4.0	No Leakage / Deformed attachment

V : installed devices

Conclusions

In view of the immediate needs of emergency medical services provided by hospitals after strong earthquakes, an ongoing research program on assessment and improvement strategies for a typical configuration of a sprinkler piping system in hospitals was organized by NCREE.

© The 17th World Conference on Earthquake Engineering

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. Brittle failure associated with a screwed fitting and couplings was observed in the shaking table tests. The effectiveness of three types of seismic restraint devices for a sprinkler piping system, namely braces with well-designed attachments for main pipe, steel wires for branch lines, and flexible hoses for penetrations, 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, or use braces and steel wires to limit the movement of main pipe and branch lines respectively. Based on the results of finite element analysis and component tests, simulate parameters of prototype and modified types of attachments under different loading directions are proposed for the application on seismic design of piping systems as well.

4. References

[1] Ministry of the Interior (MOI), *the Building Act*, Taiwan, 2011.

[2] National Fire Protection Association (NFPA), *Standard for the Installation of Sprinkler Systems*, NFPA 13, U.S, 2010.

[3] G&E Engineering Systems Inc., "Fragility of Non-Structural Components: A.1 fire sprinkler systems", FEMA P-58/BD-3.9.12, Federal Emergency Management Agency (FEMA), Washington, D.C, 2009.

[4] Lin ZY, Lin FR, Chai JF and Chang KC, Experimental studies of a Typical Sprinkler Piping System in Hospitals, Bulletin of the New Zealand Society for Earthquake Engineering 2016; 49 (1): 1-12.

[5] Chai JF, Lin FR, Tsai YA, Yeh CC, and Chang KC, *Seismic evaluation methods for fire protection sprinkler piping systems in buildings*, PVP2019-93443, ASME Pressure Vessels & Piping Conference, San Antonio, USA, 2019.

[6] Juin-Fu Chai, Jemm-shin Hwang et al. ,Seismic Evaluation and Strengthened Guidelines for Hospital Buildings 2015

[7] Lin ZY, Lin FR, Chai JF and Chang KC, *Experimental studies of a Typical Sprinkler Piping System in Hospitals*, Bulletin of the New Zealand Society for Earthquake Engineering 2016; 49 (1): 1-12.

[8] Lin FR, Yeh CC, Hu PW, Chai JF and Chang KC, *Fragility analysis of typical sprinkler-piping systems in hospitals*, Proceedings of the 11th National Conference in Earthquake Engineering, EERI, Los Angeles, CA. 2018.

[9] Lin FR, Chang KC, Chai JF, Lin ZY et al., *Experimental study on seismic behavior of a typical sprinkler piping system in hospitals*, PVP2014-29114, ASME PVP Conference, Anaheim, California, USA, 2014.

[10] Su YS, Lin FR, Chai JF and Liao WI, *A research on analysis of seismic demands for non-structural components of system in Mid- to High-Rise Buildings*, Paper No. 22011, the 14th National Conference on Structural Engineering, Taichung, Taiwan, 2018

[11] Applied Technology Council, Quantification of Building Seismic Performance Factor, FEMA P-695, FEMA, Washington, D.C., 2009.

[12] PEER Center, University of California, PEER NGA West database, https://ngawest2.berkeley.edu

© The 17th World Conference on Earthquake Engineering