Experimental studies of a typical sprinkler piping system in hospitals

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2017 NZSEE Conference

ABSTRACT: Based on the issue of life safety and immediate needs of emergency medical services provided by hospitals after strong earthquakes, this paper is to introduce a research program on assessment and improvement strategies for a typical configuration of sprinkler piping systems in hospitals. Shaking table tests were executed for a part of a horizontal sprinkler piping system under both original and improved configurations, i.e. the original system with additional seismic resistant devices such as braces, flexible pipes and mechanical couplings. The test results show that the main cause of the damaged case is the poor capacity of the screwed fitting of the small-bore tee branch. The optimum improvement strategy to achieve higher non-structural performance level for the horizontal piping subsystem is to strengthen the main pipe with braces and to decrease moment demands on the tee branch by flexible pipes. However, the piping system in attachment of bracing was damaged. The initial suggestion for the damaged attachments of braces was proposed as well, and the attachment model was established by finite element program.

1 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 (FEMA P-58, 2009). According to a literature review on earthquake damage (Huang, 2003), 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 (Lin et al., 2016) 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, 2010). 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, 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 behaviors accurately. 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 (Huang, 2003; Lin et al., 2016), an ongoing research program 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.

This paper focuses on completed topics within the research program and related preliminary findings, including horizontal subsystems of a sprinkler piping system and the initial improvement for the damaged attachments of braces. The effectiveness of three types of seismic restraint devices for sprinkler piping systems was also validated by shaking table tests.

2 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 (Lin et al., 2016). 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-story 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" were carried by the same trapeze frame supports, where the left 6" diameter pipe was the cross main of the sprinkler piping system (Figure 1). 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 1). 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 1). 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.

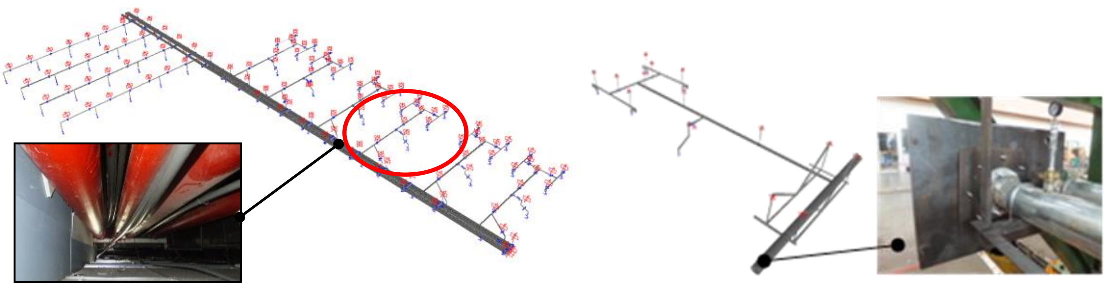


Figure 1. The numerical models of the horizontal piping system and the test specimen

3 SHAKING 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 2, Figure 3a). 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 (Figure 3, Table 1). 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 4 and Figure 5 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 (MOI, 2011), while that of the Type B motion was to simulate the floor response in the hospital during the Jiashian earthquake. Figure 6 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.

Table 1. 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 flexible hose

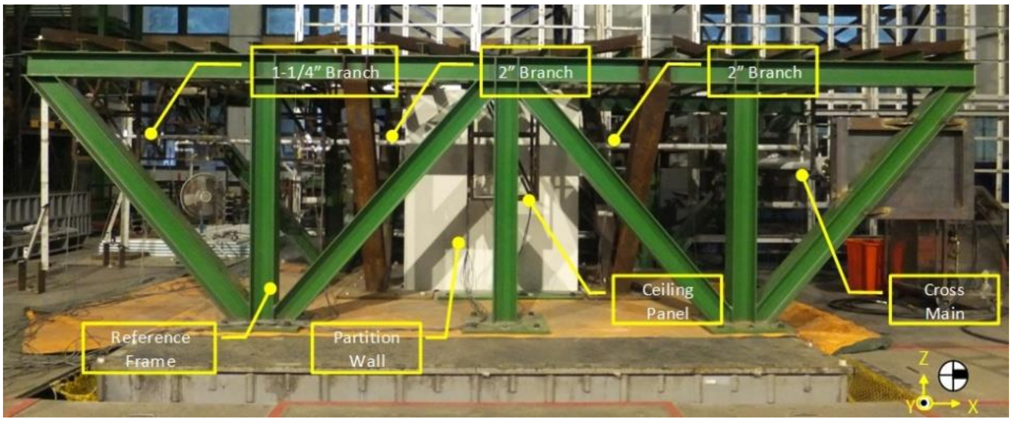


Figure 2. Shaking table testing for the sub-system

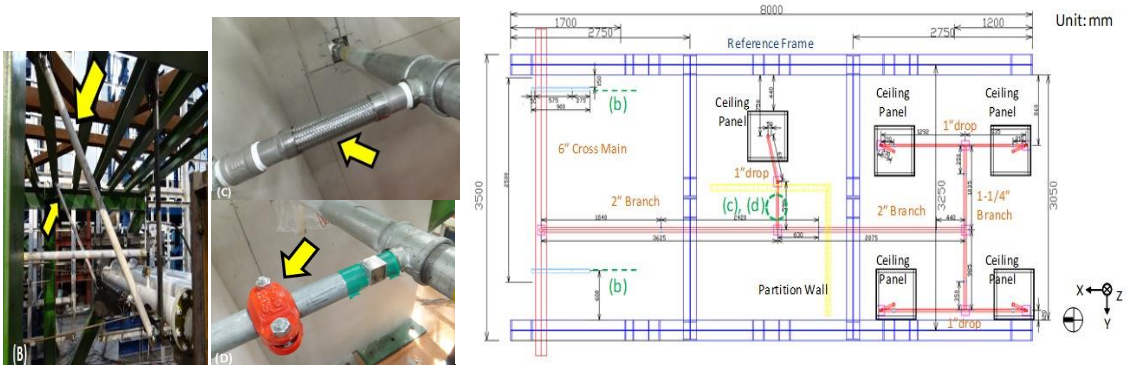


Figure 3. Test configuration and seismic restraint devices:

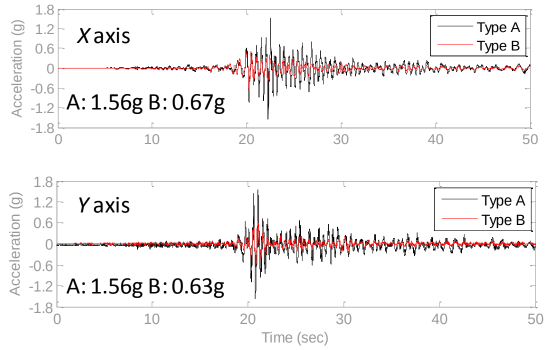


Figure 4. Acceleration time series at the steel frame along X axis (top) and Y axis (bottom)

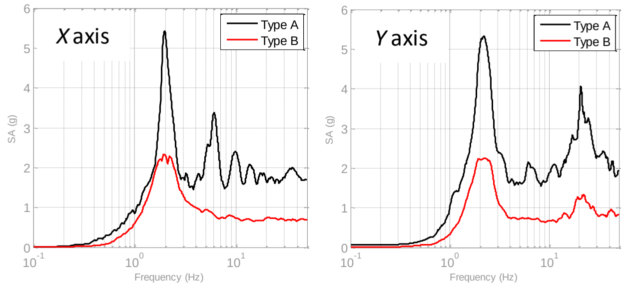


Figure 5. Response spectra along X axis and Y axis

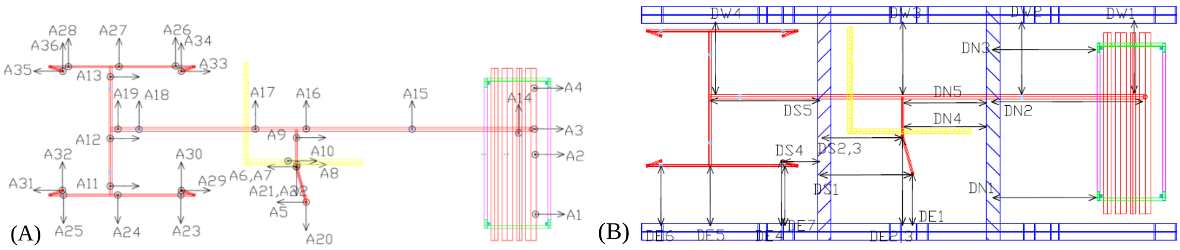


Figure 6. Layouts of (a) accelerometers and (b) transducers

4 SHAKING TABLE TEST RESULTS

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 7a). Although there was no leakage in the tests of the configuration with the flexible hose (FH, Figure 8), all ceiling boards were broken and could seriously damage the medical service (Figure 7b and Figure 9). On the other hand, due to brittle failure caused by the screwed fitting and couplings, the mechanical behaviors of both devices should be further studied (Figure 7c and Figure 7d). 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 7e).

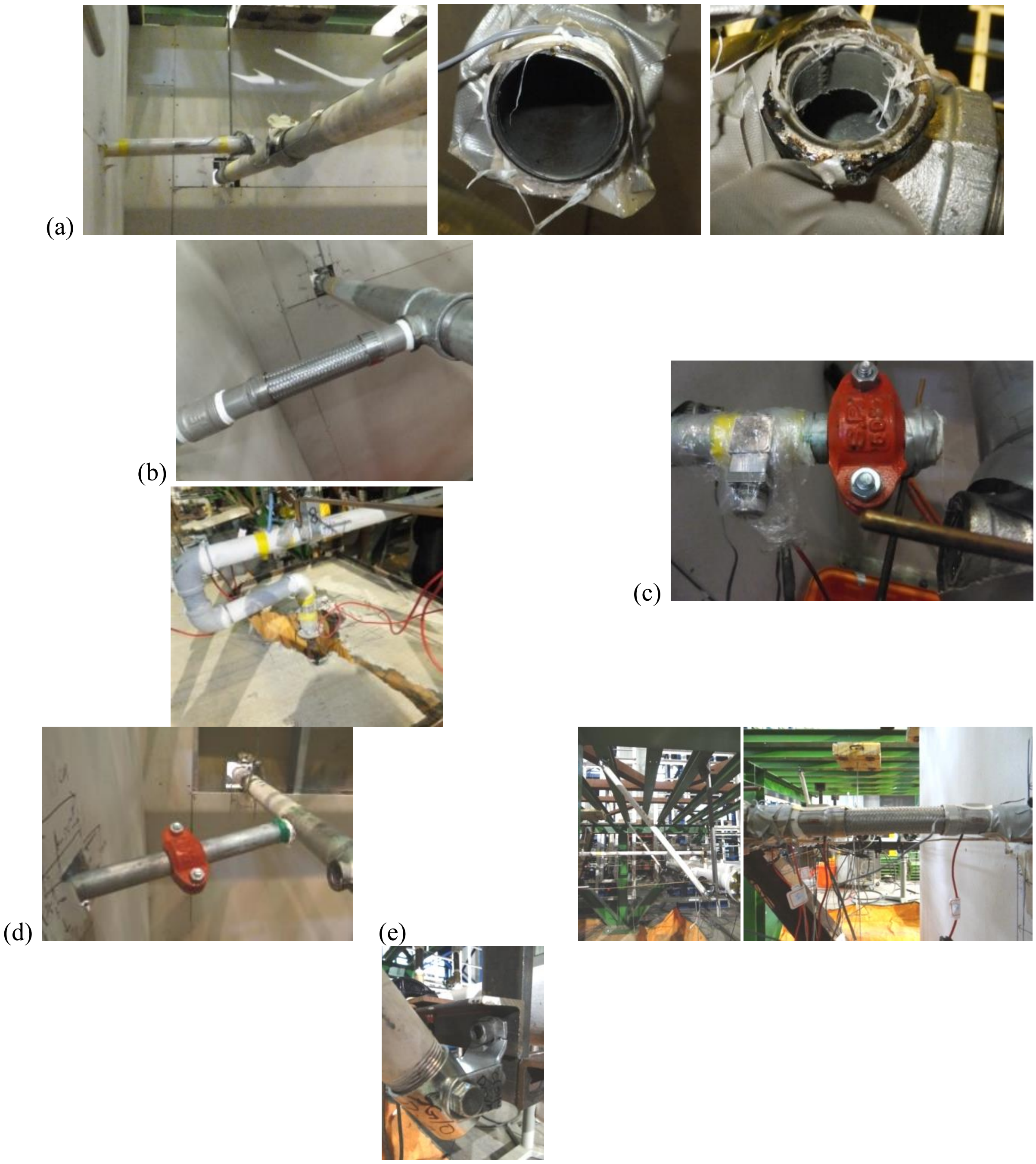


Figure 7. Damage states of each test configuration: (a) OC; (b) FH; (c) CT; (d) CB; and (e) DBF.

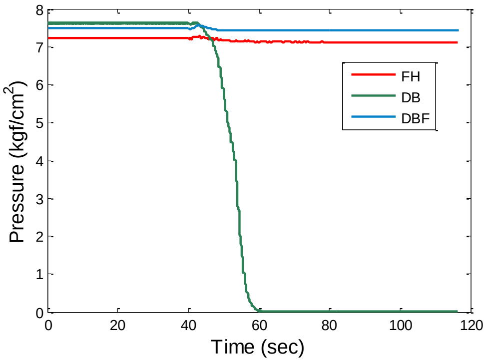


Figure 8. Leakage conditions in the Type A tests.

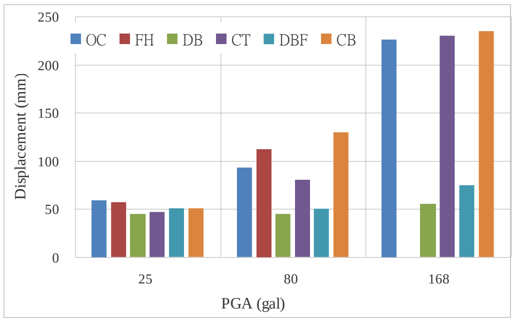


Figure 9. Diameter of the reaming on the ceiling board in the Type B tests.

Figure 10 to Figure 12 depict the seismic behavior 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 10 and Figure 11) of the original configuration (OC) and in the Type A test (Figure 12) of the configuration with double braces (DB). Comparing the responses of the 6” cross main (Figure 10a and Figure 11a) and the damaged 1” drop (Figure 10b and Figure 11b) 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 10) while also reducing the impact effects on the 1” drop (Figure 11). The strain responses of the 1” drop in the DB, FH, and DBF configurations (Figure 12a) 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 12b). Better and more-detailed designs of the attachments of braces is discussed in the next section to avoid the damage observed in the Type A test of the DBF configuration (Figure 7e).

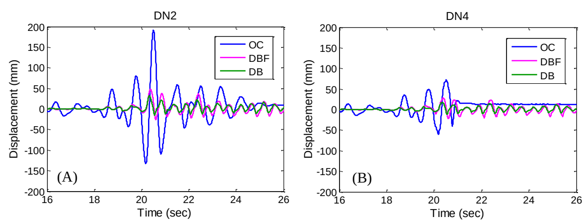


Figure 10. Displacement response in the Type B tests of OC, DB, and DBF: (a) 6” cross main and (b) 1” drop.

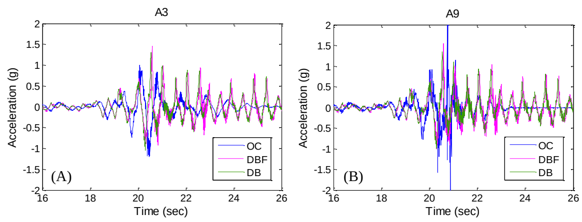


Figure 11. Acceleration response in the Type B tests of OC, DB, and DBF: (a) 6” cross main and (b) 1” drop.

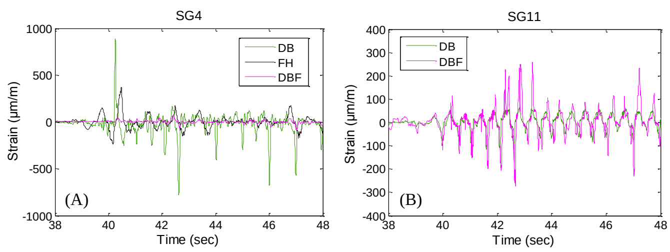
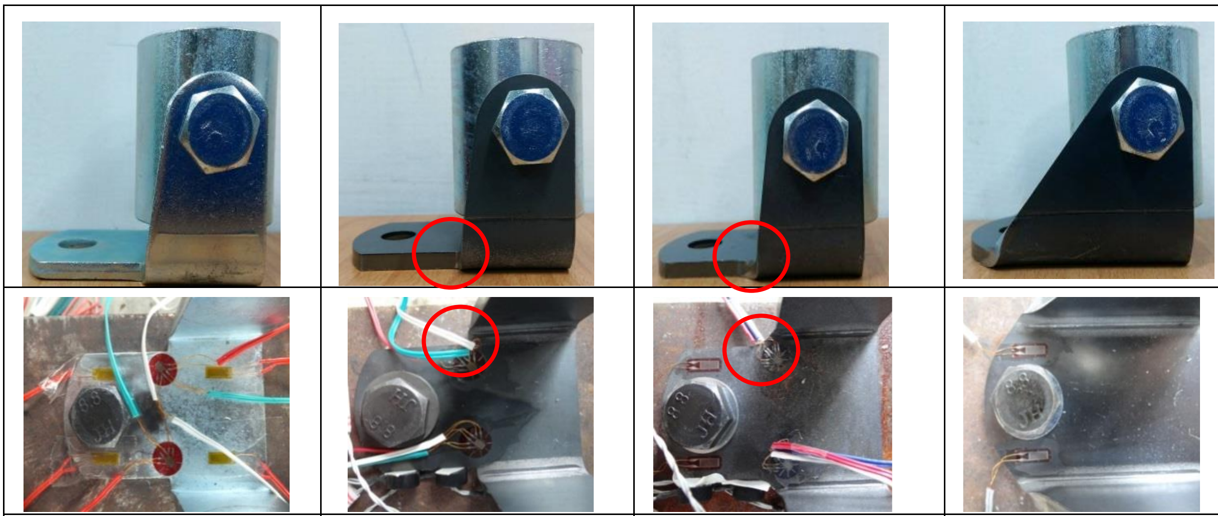


Figure 12. Strain response in the Type A tests of DB, FH, and DBF: (a) 1” drop and (b) Bracing.

5 COMPONENT TESTING: ATTACHMENT TESTING

In the DB and DBF tests, the seismic capacity of the piping subsystem is controlled by the attachments of braces, which are commercial products of a large-scale hardware company in Taiwan (Figure 7e). In order to improve the seismic performance of attachments effectively, tension and shear tests were conducted for four types of attachments, including the prototype ones (PT, Figure 13a) used in shaking table tests and three modified types (MT1 to MT3, Figure 13b to Figure 13d) made of a higher-strength steel material (Table 2). The dimension of MT1 keeps the same as PT to obtain the effect of material on tensile and shear behaviour. Strengthening corner gussets were added at the stress concentration area (MT2) or fulfilled between the base and vertical plates (MT3). From test results (Figure 14), it can be seen that only higher material strength (MT1) can improve ultimate strength of PT. Under tensile force (Figure 14a), MT3 offers the highest ultimate strength and stiffness when the deformation is larger than 10 mm, while MT2 has better ductility than others. On the other hand, MT3 improves the initial stiffness and yielding strength of PT most effectively under shear force (Figure 14b).



(a) Prototype, PT | (b) Modified Type 1, MT1 | (c) Modified Type 2, MT2 | (d) Modified Type 3, MT3

Figure 13. Four types of attachments of braces

Table 2. Specifications of four types of attachments

	Material of base plates	Corner gusset
PT	Steel (E < 200 GPa)	None
MT1	A36 steel (E=200 GPa)	None
MT2	A36 steel (E=200 GPa)	Arc-shaped
MT3	A36 steel (E=200 GPa)	Full-filled

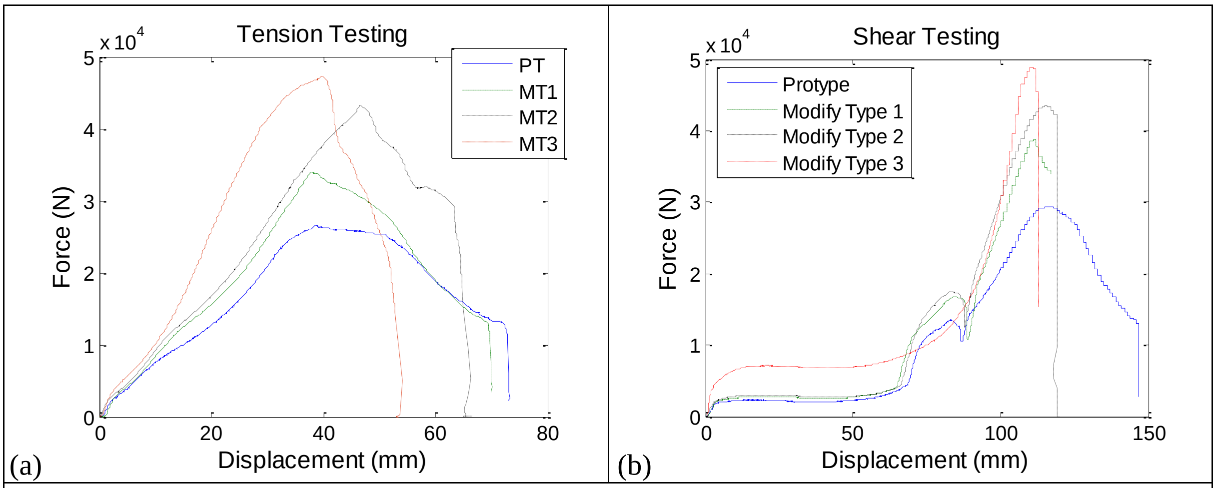


Figure 14. Force-displacement curves of attachments under (a) tensile loading and (b) shear loading

6 FINITE ELEMENT ANALYSIS OF ATTACHMENT

The loading direction of a bracing attachment (namely the axial direction of the connected brace) is decided by the engineer according to the seismic design for piping and in-situ situation. Based on the results of component tests, it is recognized that the behaviour of attachment is dependent on the loading direction. Hence, detailed finite-element models of the bracing attachments were established with ABAQUS to provide simulate parameters of attachments along different loading directions (Figure 15). The accuracy of finite-element analysis was verified by comparing the force-displacement curves of the attachment under tensile or shear loading to the results of component tests (Figure 16).

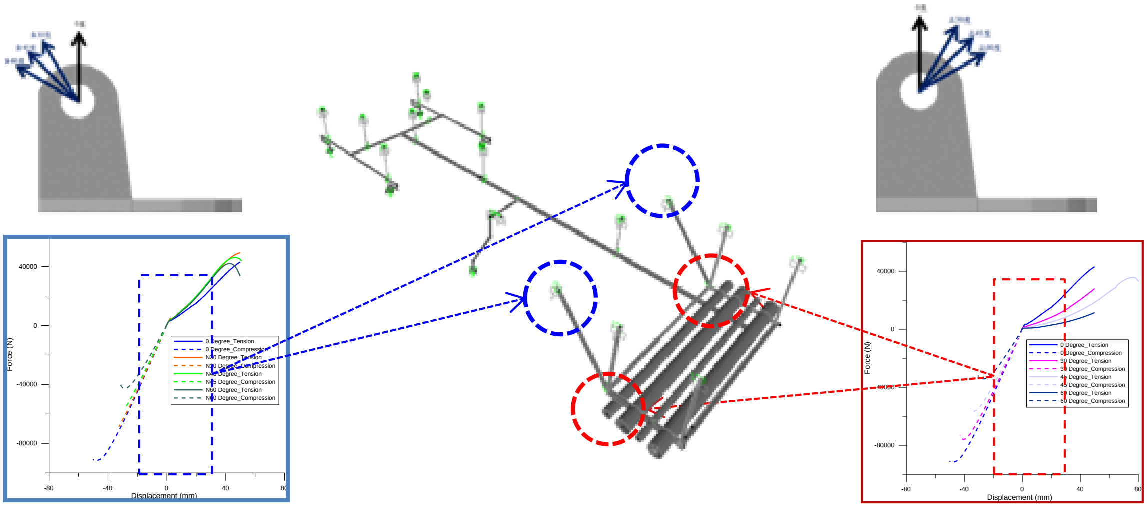


Figure 15. Application of finite-element analysis of bracing attachments to the model of piping systems

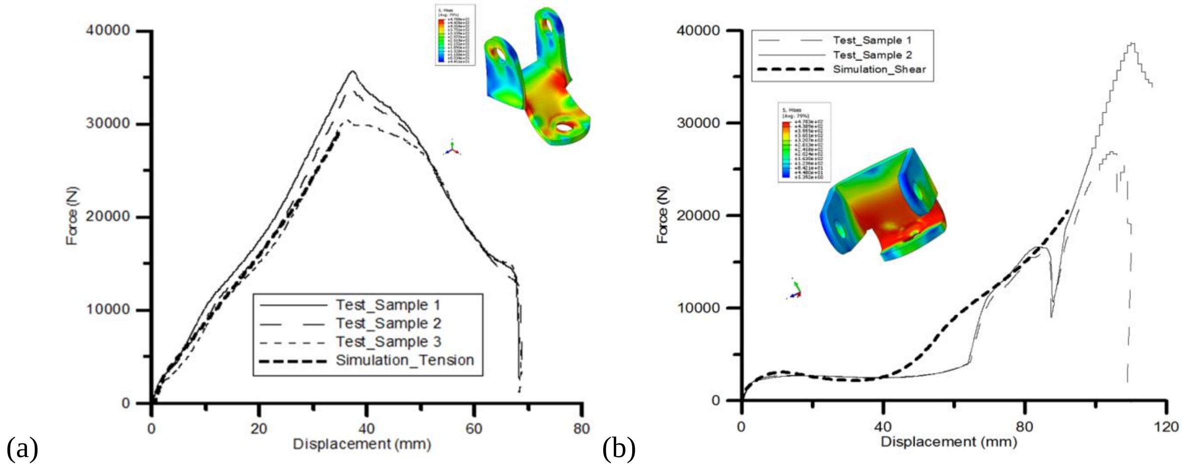


Figure 16. Comparison of Analysis and test results of MT1 under (a) tension and (b) shear loadings

7 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.

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. Further component tests were conducted to study the mechanical behavior of both devices. It was seen that the screwed fittings exhibited brittle failure under moment or shear actions (Lin et al., 2016). 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.

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. Three improvement suggestions for bracing attachments were proposed according to their weakness point found in component tests. 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.

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