



## A STUDY ON SEISMIC BEHAVIOR OF MECHANICAL COUPLINGS FOR FIRE PROTECTION SPRINKLER PIPING SYSTEMS IN HOSPITAL

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### ABSTRACT

Based on the experiences learned from recent earthquakes, it is recognized that the immediate operation of a hospital after strong earthquakes relies heavily on the functional integrity of critical nonstructural components. Unfortunately, the seismic performance of existed hospital sprinkler systems in Taiwan was unsatisfactory. From the literature review of earthquake damages, the reduction of medical functionality has been caused by serious flooding due to broken sprinkler head and screwed fittings of sprinkler system. According to NFPA13, the flexible couplings are regarded as seismic resistance devices for piping joints to accommodate excessive motions induced by strong earthquakes. One of the common flexible coupling types is the mechanical coupling joint, and hence, the objective of this paper is aimed to the seismic behaviors of mechanical coupling joints to improve the seismic performance of sprinkler systems effectively. The seismic capacities of mechanical coupling joints in pair with various pipe dimensions were studied through cyclic loading tests. In addition, one of the actually damaged sprinkler piping system in a responsibility hospital during the Taiwan Jiashian earthquake in 2010 was reproduced for shaking table tests. Both the original configuration with screwed fittings and the modified configuration with mechanical coupling joints were tested to verify the efficiency of mechanical coupling joints for the sprinkler piping system.

### INTRODUCTION

The Emergency Medical Care Law indicates that the emergency care responsibility hospitals must provide patients with medical care for 24 hours continuously. It is recognized that to maintain functionality of an important building such as a hospital after an earthquake struck, both structural components and critical Mechanical/Electrical systems should have well seismic performance. As shown in Fig. 1, although the building maintained structural integrity, the hospital was forced to be evacuated after the 1999 Chi-Chi earthquake owing to the interior nonstructural damage.

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Figure 1. Evacuation of the Hospital after Chi-Chi Earthquake (provided by G. C. Yao)

Among the numerous problems due to seismic damage of nonstructural components, water leaks or flooding resulting from broken sprinkler piping systems is an important issue for hospitals because of the effect of water damage on the suspended ceiling systems and other room fixtures associated with medical functionality. The earthquake experiences show that piping rarely collapsed entirely, but once the first leak occurs in fire protection sprinkler system, amount of water will flow out and cause flooding, secondary injury, and loss of medical function. Such damage occurred at the Olive View Medical Center, the Holy Cross Medical Center, and Northridge Hospital in the San Fernando Valley during the 1994 Northridge earthquake (G&E, 2009). From a literature review of earthquake damage, common failures of sprinkler piping systems occur at the screwed fittings, anchorages, and sprinkler heads. As shown in Fig. 2, the most frequently seismic damaged part of the sprinkler piping systems is the screwed fittings of the small-bore drops neighboring suspended ceiling systems (Ju et al., 2011; Arash et al., 2012). An example was observed in a critical hospital during the 2010 Jiashian earthquake in Taiwan, where a reduction of medical functionality was caused by flooding due to a broken small-bore pipe of the sprinkler system (Fig. 3).

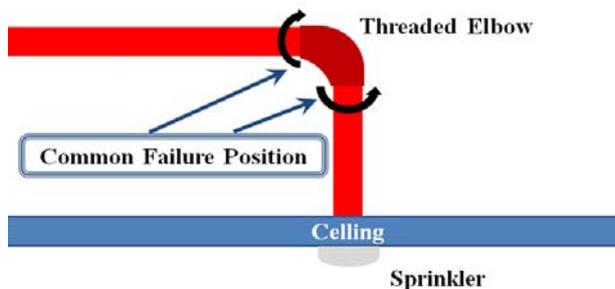


Figure 2. Common Failure in Screwed fittings



Figure 3. Flooding at a hospital caused by the leakage of the sprinkler system.

Based on the aforementioned experiences, the seismic damages to the screwed fittings might result from the excessive angular movement or surging shear loadings. According to NFPA13 (NFPA, 2010), the “flexible joints” are regarded as seismic resistance devices for piping joints to accommodate excessive angular movement induced by strong earthquakes. Following the definition in NFPA 13, hereinafter a flexible joint is the one that allows axial displacement, rotation, and at least 1 degree of angular movement of the pipe without inducing harm on the pipe.

Grooved couplings belonging to mechanical joints are the common types of flexible joints (Fig. 4b). As mentioned in the section C13.6.8 of the 2010 edition of ASCE 7 (ASCE, 2010), couplings could be recognized as flexible joints through the seismic evaluation as specified by FM 1920 (FM Approval LLC, 2007). However, the dynamic performance of flexible couplings presented in the shaking table tests of a partial piping system was unanticipated (Lin et al., 2014). In order to improve

the seismic performance of sprinkler systems effectively, the objective of this study is aimed to the mechanical behaviors of grooved couplings and to establish more accurate numerical models of piping joints for seismic design and analysis. Considering the damage of piping joints might be controlled by flexure or shear failure, the flexibility tests according to FM 1920 and the fragility tests under pure bending or shear loads were conducted to obtain the mechanical behavior, failure mechanism and capacity of joints. The seismic capacities of mechanical coupling joints in pair with various pipe dimensions as well as 1.0 in. screwed fittings (Fig. 4c) were studied through quasi-static cyclic and monotonic loading tests. At the end of this paper, the test results were compared with the seismic demands derived from static and dynamic analyses in the cause of seismic evaluation of piping joints.



Figure 4. Piping joints: (a) rigid and (b) flexible mechanical joints; (c) screwed fitting.

## PURE BENDING TESTS

The program of pure bending tests was depicted in Table 1. Based on the results of an in-situ investigation into the practice of piping joints for sprinkler piping systems, three typical manufactures of piping joints including small-bore screwed fittings with piping diameters of 1 in. (25mm), rigid and flexible grooved couplings with piping diameters of 6 in. (150mm), 4 in. (100mm) and 1 in. (25mm) were studied in this paper (Fig. 4). As shown in the circled area in Fig. 4a and 4b, little difference exists between the appearance of rigid and flexible mechanical joints except the shape of the recess of couplings. In order to validate the flexibility characteristics of these sampled coupling manufactures, the flexibility tests were executed under specified cyclic pure bending loads according to FM 1920.

The fragility testing was conducted in sequence to investigate the nonlinear behavior under cyclic pure bending loads (Table 1). The main purpose of fragility testing was to obtain the relationship between internal moment and rotation angle ( $\theta$ ) in the elastic and plastic stages (Fig. 5). In addition, the leakage of contained water and structural integrity were regarded as performance indexes of piping joints to judge the capability of resisting excessive angular movement.

Table 1. Test Program

Specimen No. (Nominal Pipe Diameter)	Piping Joint <sup>1</sup>	Testing Sequence <sup>2</sup>
CSP6 (6")	RGD / FLX	1 <sup>st</sup> : FM 1920 Testing 2 <sup>nd</sup> : Fragility Testing (Case 1) 3 <sup>rd</sup> : Fragility Testing (Case 2)
CSP4 (4")		
CSP1 (1")	THR / FLX	

**Note:**

1. THR: screwed fitting ; RGD: rigid mechanical joints ; FLX: flexible mechanical joints.

2. For fragility testing, Case 1 and Case 2 were under monotonic loading and under the cyclic loading complied with ISO-16670 (ISO, 2003) respectively.

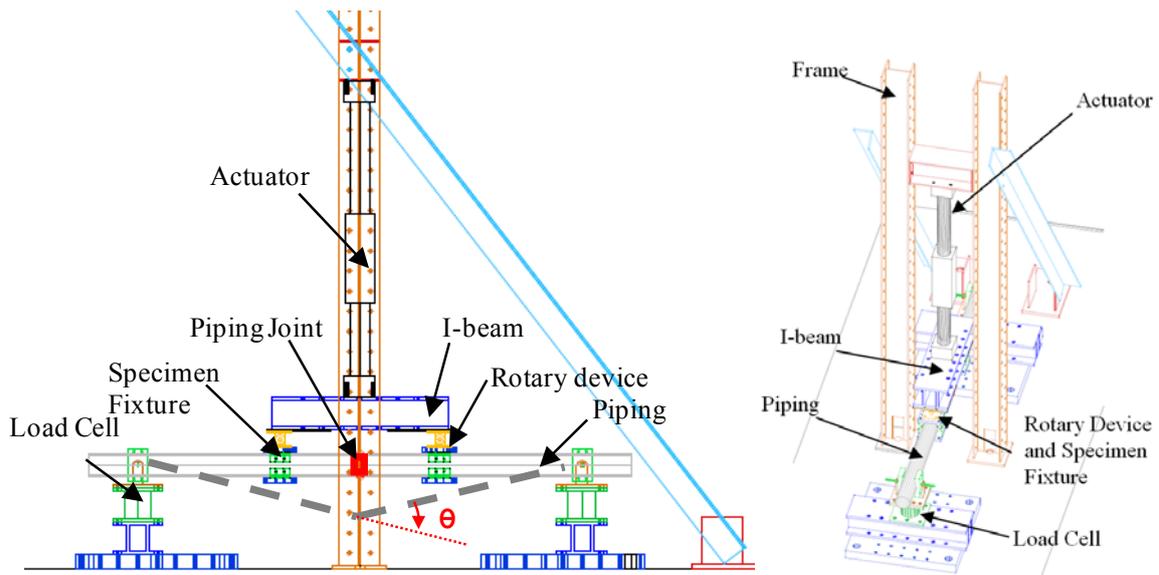


Figure 5. Configuration of bending tests in front view and isometric view

Figure 5 and Figure 6 depict the configuration for cyclic pure bending tests. Based on the four-point configuration, the tested piping joint at the middle of each specimen was subjected to a cyclic pure bending under displacement control. From top to bottom, the test configuration was composed of a reference frame with a height of 5.0 m, a 25-ton capacity hydraulic actuator, a force-adapter assembly connecting the actuator to the tested specimen, the tested specimen with internal pressure approximately equal to the rated working pressure of  $7.0 \text{ kgf/cm}^2$ , a hinge support at one side of the specimen and a roller support at the other side, and one load cell under each support. Although the maximum distance between hangers specified in NFPA 13 are 3.66 m and 4.57 m for 1.0 in. pipe and 1-1/4 in. pipe or larger respectively, the support spacing in the test was adjusted to be 3.0 m for all sampled pipe dimensions based on the space limitation of the laboratory.

In order to apply vertical forces without imposing additional moment upon specimens, the force-adapter assembly between the actuator and the specimen was composed of a horizontal I-beam with a length of 1.3 m, rotary devices and specimen fixtures. Pure bending area was formed between the specimen fixtures with a center-to-center distance of 1.15 m. In addition, as a result of the significant stress concentration effect on the loading points for 1.0 in. pipe, the specimen fixtures were replaced with U-bolts to mitigate the imposed deformation within the fixture contacting area.

### Flexibility Testing

In accordance with the requirement of FM 1920 and ASCE 7-10, the flexibility testing should be executed under cyclic loading with the fixed amplitude of 1 degree of angular movement. The displacement-controlled loading was applied in 15 cycles with frequency of 1.0 Hz. The tested coupling will be regarded as a flexible joint if no leakage, cracking, or rupture occurs during the test.

The flexibility of rigid and flexible couplings in three different diameters was tested according to FM 1920. As a result of flexibility tests, all of the couplings, without respect to flexible or rigid coupling manufactures, achieved the flexible requirement of ASCE 7-10.

### Fragility Testing

The fragility of piping joints were investigated under monotonic and cyclic pure bending loads. According to the cyclic displacement schedules proposed by ISO-16670 (ISO, 2003), the loading protocol was designed based on the ultimate displacement ( $v_u$ ) obtained from monotonic testing. Figure 7 depicts an example of cyclic loading protocols of fragility testing and the amplitude of each reversed cycle in the percentage of  $v_u$ . The reverse loading with each amplitude was applied for three cycles. The amplitude of the loading protocol varied from 1.25% of  $v_u$  to 120% of  $v_u$ .



Figure 6. Actual test configuration

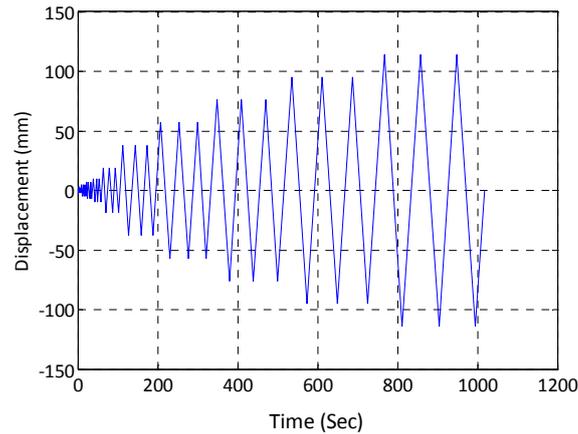


Figure 7. Input motion of cyclic testing for CSP6 specimens

Step	No. of cycles	Amplitude
1	3	1.25% of $v_u$
2	3	2.5% of $v_u$
3	3	5% of $v_u$
4	3	7.5% of $v_u$
5	3	10% of $v_u$
6	3	20% of $v_u$
7	3	40% of $v_u$
8	3	60% of $v_u$
9	3	80% of $v_u$
10	3	100% of $v_u$
11	3	Increments of 20% of $v_u$

### (a) Comparison of rigid and flexible mechanical joints

From the results of fragility tests, it is noted that when the diameter gets small, the rigid couplings and the flexible ones are hard to be distinguished in seismic behavior and capacity. Hence, following paragraphs focus on the differences found in tests between the largest rigid and flexible mechanical joints, i.e. 6 in. couplings.

In terms of the first leakage performance, the rigid and flexible mechanical joints presented quite close capacity in the fragility tests under pure bending loads. Figure 8a and 9a depict the time series of the contained water pressure, the applied actuator force and the summation of vertical reaction forces measured by load cells in two examples of the fragility tests for 6 in. rigid mechanical joints (CSP6-RIG) and 6 in. flexible mechanical joints (CSP6: FLX) respectively. The rigid and flexible joints leaked at similar testing time namely similar angular loading, which were 4.45 degree and 4.65 degree respectively. However, the damage states at the first leakage of two kinds of joints were quite different. As shown in Figure 8b, the rigid mechanical joint leaked owing to the broken housing. However, the leakage at flexible joints resulted from the gap between gasket and grooved pipe, not the damage of coupling or piping.

The structural integrity performance of flexible mechanical joints was superior to rigid ones. Although the rigid joints provided higher stiffness due to the tighter shape of the recess of couplings (Figure 4a), the houses were broken at the same time of first leakage. On the other hand, the structural integrity of flexible mechanical joints maintained after leakage until the loading achieved the ultimate displacement ( $v_u$ ) obtained from monotonic testing. The damage state of flexible joints was that the grooved pipes were separated from housings (Figure 9b and 9c).

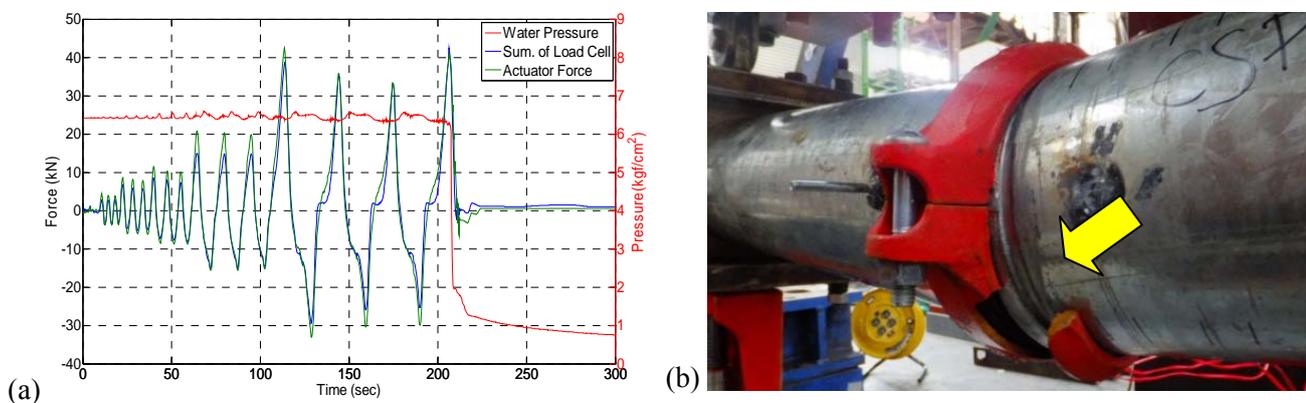


Figure 8. Test results of CSP6-RIG: (a) Loading and water pressure; (b) The damage state at first leakage.

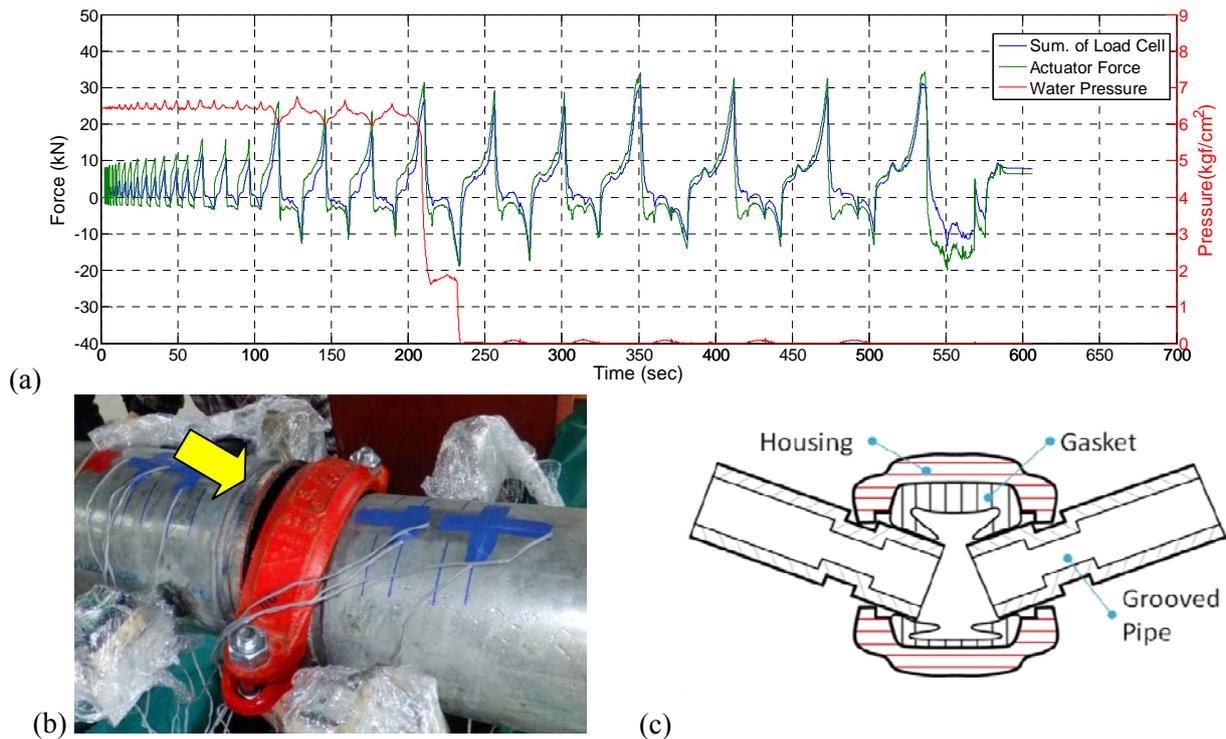


Figure 9. Test results of flexible coupling specimens: (a) Loading and water pressure; (b) The damage state of structural integrity; (c) The cross section sketch of the damaged coupling.

(b) Comparison of flexible mechanical joint and screwed fittings

In the case of piping joints for 1 in. pipe, the flexible couplings could resist much higher moment imposed under cyclic pure-bending loading against both the first-leak and structural-failure states compared with the performance of screwed fittings. Figure 10 depicts the time series of the contained water pressure, the applied actuator force and the summation of vertical reaction in two examples of the fragility tests for flexible mechanical joints and 1 in. screwed fittings. The water pressure of the pipe with flexible coupling reversely changed without leakage under cyclic pure-bending loading, while the one of the pipe with screwed fitting remained stable but suddenly dropped at the rotation angle ( $\theta$ ) of  $1.35^\circ$  due to the damaged thread of the fitting (Fig. 10 and Fig. 11a). Among three tested samples of flexible coupling for 1 in. pipe, only one failed at the rotation angle ( $\theta$ ) of  $18.4^\circ$  owing to the separation of the coupling from the piping, while no structural damage occurring on the coupling and piping (Fig. 11b).

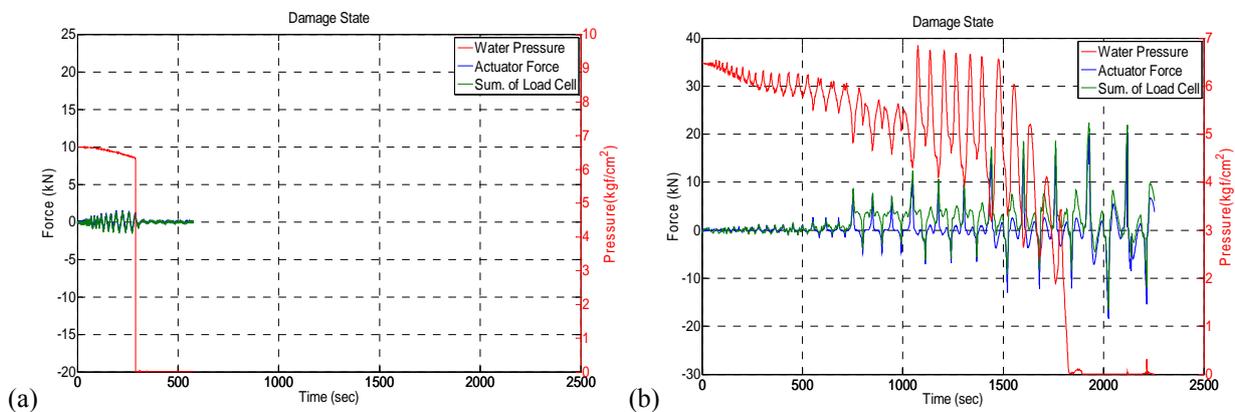


Figure 10. Loading and water pressure during tests: (a) screwed fitting; (b) flexible coupling.

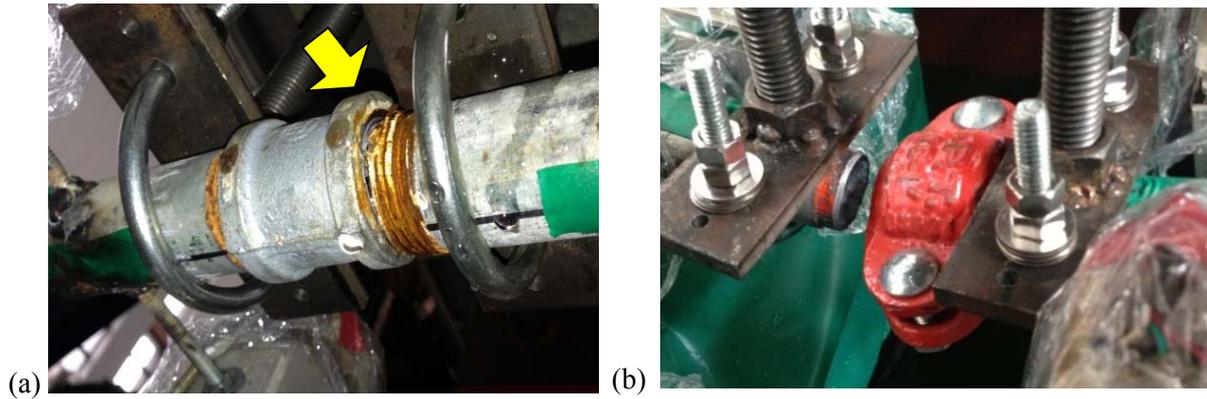


Figure 11. Damage states under pure bending loads: (a) screwed fitting; (b) flexible coupling.

Figure 12 depicts the Moment- $\theta$  curves for two types of joints under cyclic pure-bending loading. The stiffness of the screwed fitting is about 1657.85 kN-m/degree. For flexible couplings, the behavior of the hysteresis curve can be simulated by a bi-linear model with stiffness of 81.93 and 2853.33 kN-m/degree for the first and second linear ranges respectively. The dramatically increasing stiffness was owing to the contact of two separated housings and the resulted higher stress may cause the failure of piping with such flexible couplings as observed in the shaking table tests (Lin et al., 2014).

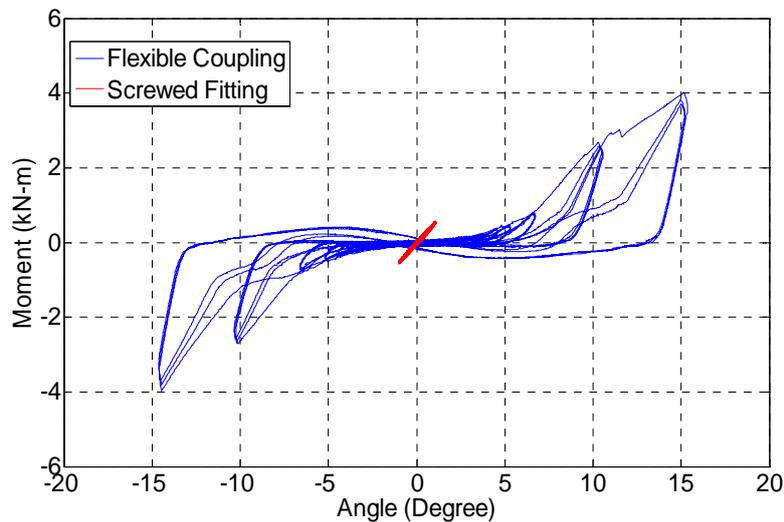


Figure 12. Moment- $\theta$  curves of a flexible coupling and a screwed fitting with piping diameters of 1 in.

## SHEAR TESTS

In addition to pure-bending tests, the monotonic shear tests for screwed fittings and flexible couplings of 1 in. diameter piping were conducted to further investigate the shear capacity of piping joints (Fig. 13a). From the force-displacement curves of shear tests in Fig. 14, it can be seen that the initial stiffness of screwed fittings is higher than that of flexible couplings; however, these screw fittings were damaged with brittle failures under shear force. Table 2 shows the average and associated standard deviation ( $\sigma$ ) of strength and initial stiffness determined from the pure-bending or shear force tests. The moment strength of screwed fittings at leakage point can be also regarded as their ultimate strength. The ultimate shear strength of the flexible coupling is not adopted since the damage in the test occurred at the piping or at the welding between piping and adapter plates, but not on the coupling itself (Fig. 13c).



Figure. 13 Shear tests: (a) configuration; damages of (b) screwed fitting; (c) flexible coupling.

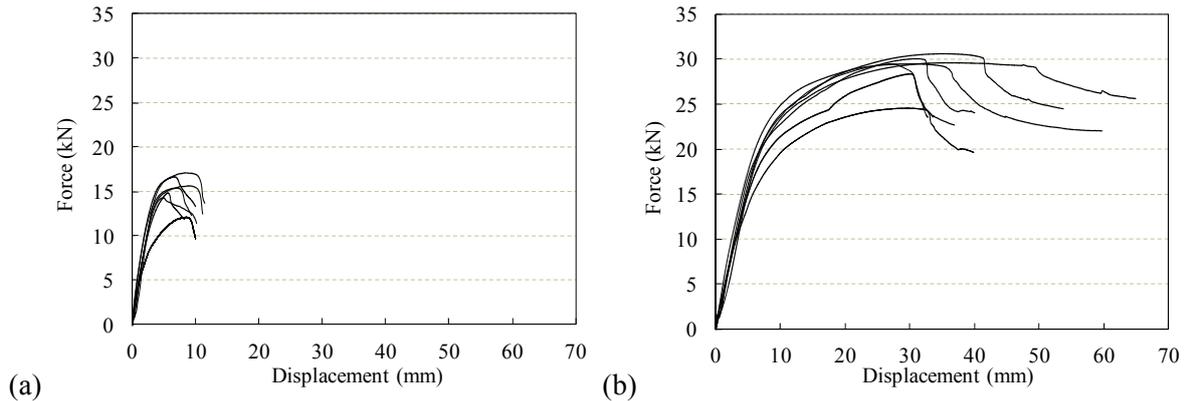


Figure. 14 Force-displacement curves: (a) screwed fitting; (b) flexible coupling.

Table 2 Strength and stiffness values in pure bending and shear tests

Loading Type		Joint Type	Screwed Fitting	Flexible Coupling
Moment	Strength at Leakage (kN-m)	average $\sigma$	0.61 0.03	6.18* -*
	Initial Stiffness (kN-m/degree)	average $\sigma$	1657.85 23.09	81.93 0.01
Shear Force	Ultimate Strength (kN)	average $\sigma$	15.15 1.54	- -
	Initial Stiffness (kN/mm)	average $\sigma$	4.53 0.39	3.28 0.29

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

## COMPARISON OF NUMERICAL SIMULATION AND TESTING RESULTS

The experimental results were compared with the seismic demands determined from static and dynamic analyses to evaluate the seismic performance of piping joints. The moment and rotation demands were calculated based on the building codes in Taiwan (MOI, 2011), NFPA 13 and ASCE 7-10 respectively. It is noted that both the sampled screwed fittings and couplings satisfy the design requirement, because the capacities determined by the pure bending or shear force tests are larger than the associated seismic demands according to the design codes.

There is an experiment in NCREE to simulate the piping system of the hospital shown in Figure 15 (Kuo et al., 2012). The results of this experiment determine the dynamic characteristics and seismic behavior of the hospital sprinkler piping system. Various failure modes can be observed in this experiment, the slip of hanger, the damage of ceiling and partition wall and the rupture of screwed

fitting which causes leakage, shown in Figure 16. This study established SAP2000 numerical model shown in Figure 17, and used dynamic analysis to simulate the experimental results of the research.

Use SAP2000 to simulate this experiment and changing the system partition wall with GAP-Link to, and the displacement of failure point shown in Figure 18, it can be seen 19.8 seconds the simulation is great but after 19.8 seconds the model can't capture the displacement from experimental. It could be the joint destruction and lose its strength. However, in 19.4 seconds at the moment the value shown in Figure 19, has been implemented over the threaded couplings moment capacity 590 kN-mm of cyclic experiment. From the parameters analysis of the vibration table, stiffness of partition wall is about 0.4 kN/mm. In addition, in this linear dynamic analysis simulations, the T-joints bending moment is larger than its capacity of the cyclic experiment, and elbow bending moments and not. It is same as shaking table test results.



Figure 15. Configuration of the shaking table test



Figure 16. Damaged screwed fitting

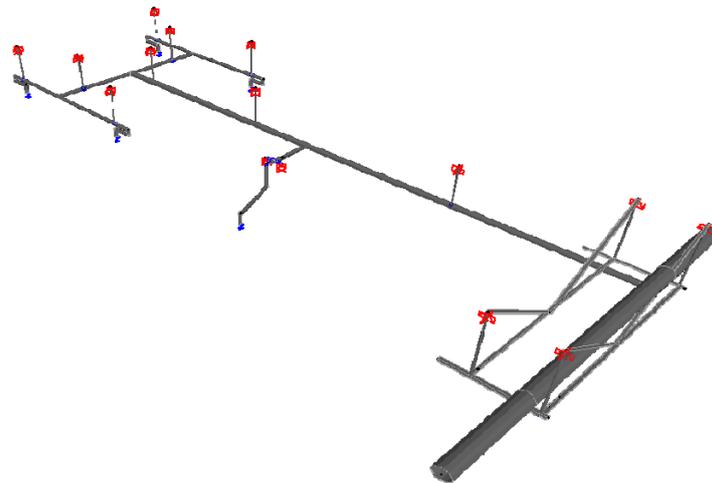


Figure 17. The numerical model simulating the specimen in shaking table tests

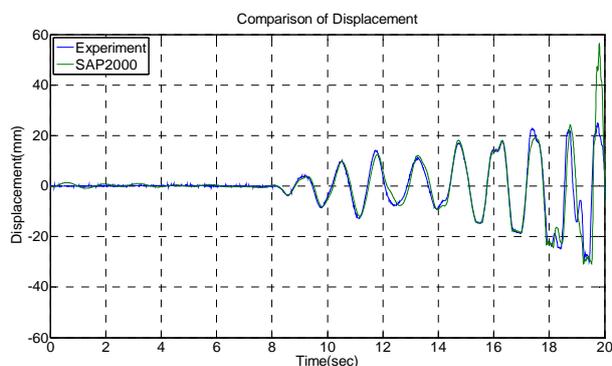


Figure 18. Time series of displacement

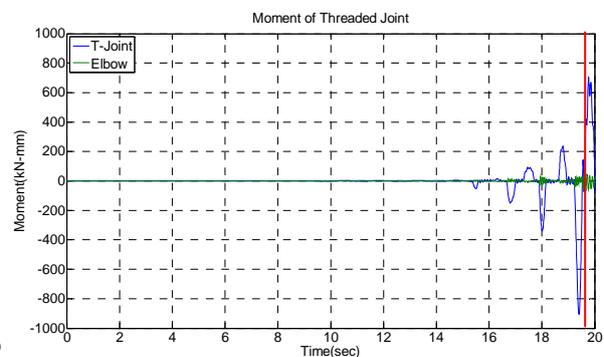


Figure 19. Time series of internal moment

In the dynamic analysis, the strength from ceiling to the sprinklers of the pipeline is hard to capture in the earthquake. Therefore, the parameter analysis is well to analysis the kind of situation. Figure 20 is for the whole hospital piping system model. Table 3 is for the model without partition walls in the parametric analysis. In Case 1 and Case 6 frequency of 1.53Hz frequency of 4.18Hz, and then to change the ceiling sprinklers stiffness to let the frequencies fall in 2, 2.5, 3, 3.5 Hz. When the beam is completely free from the sprinkler system, its displacement of elbows is up to 30 cm, which was unreasonable; And when the ceiling for sprinkler stiffness increases, the moment of joints are rising and then began to decline. Then join the effect of partition wall and set the spacing is 10 mm. The results are shown in Table 4. After adding partition walls, the displacement was decreased.

Table 3 Parameter analysis of the numerical model (without partition walls)

Case	Sprinkler (kN/mm)	Frequency (Hz)	Displacement of Elbow(mm)	Moment of T-Joint(kN-mm)	Moment of Elbow (kN-mm)
1	Free	1.53	308	107	33
2	4.60E-03	2.00	215	616	350
3	1.39E-02	2.50	96	482	267
4	3.40E-02	3.01	31	204	108
5	8.80E-02	3.50	17	130	68
6	Hinge	4.18	9	71	37

Table 4 Parameter analysis of the numerical model (with partition walls)

Case	Sprinkler (kN/mm)	Frequency (Hz)	Displacement of Elbow(mm)	Moment of T-Joint (kN-mm)	Moment of Elbow (kN-mm)
7	Free	1.53	28	4876	2091
8	4.60E-03	2.00	27.6	2722	988
9	1.39E-02	2.50	32.1	222	80
10	3.40E-02	3.01	19.7	123	55
11	8.80E-02	3.50	14.6	114	49
12	Hinge	4.18	9	71	37

In order to establish of a complete model with fire protection sprinkler piping system, this study in the southern Taiwan Y hospital of 7 floor fire protection sprinkler piping systems are to impact testing, and obtained system natural frequency. Testing result displayed the frequencies are 2.7 Hz and 5.37 Hz. Base on the result, can provide to establish pipeline system model (show in Fig. 24). This model can also be used for future evaluation the seismic performance of the whole pipeline system benchmarks.

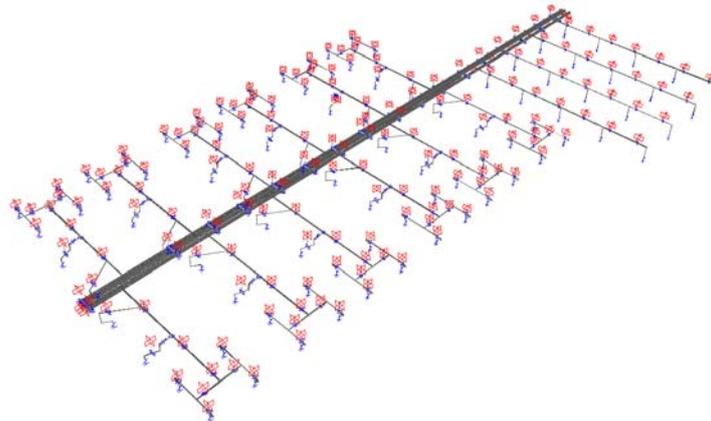


Figure 20. The numerical model of the horizontal piping system

## CONCLUSIONS

From the earthquake experiences of sprinkler piping systems, the one-inch screwed fittings usually fail during earthquakes. To improve the seismic performance of piping system, the original concept was to replace the screwed fittings at critical positions by mechanical joints. However, the dynamic performance of flexible couplings as presented in the shaking table tests was unanticipated. In order to realize the basic characteristics of mechanical joints and small-bore screwed fittings, the pure bending tests and shear tests were completed to obtain the seismic behavior and capacity of piping joints. In the end, the experiment results were compared with the seismic demands determined from static and dynamic analyses to evaluate the seismic performance of joints. Summary of research results is as follows:

1. Flexibility testing of mechanical joints: The flexibility of both rigid and flexible mechanical joints in three different diameters was tested according to FM 1920, and the test results showed that all of the sampled mechanical joints achieved the flexible requirement as specified by NFPA 13.
2. Fragility testing: The four-point bending tests were executed under monotonic and cyclic loadings, and the shear tests of mechanical joints and screwed fittings for 1.0 in. pipes were executed under monotonic loading. There is little difference of seismic capacity between the rigid and flexible couplings in terms of the first leakage performance. When the diameter gets small, it's hard to distinguish the rigid couplings from the flexible ones in seismic behavior and capacity. For 1.0 in. pipes, the mechanical joints perform well compared to the screwed fittings. The shear and moment capacities of mechanical joints against the first leakage are higher than those of screwed fittings, and further, the screwed fittings exhibit brittle failure under moment or shear actions.
3. Static analyses: The moment and rotation demands were calculated based on the building codes in Taiwan, NFPA 13 and ASCE 7-10 respectively. Both the capacities of mechanical joints and screwed fittings determined by the test results satisfied the required seismic demands for design.
4. Dynamic analyses: In order to obtain the seismic demands of piping joints, the sprinkler piping system in a hospital, which was damaged at one-inch screwed fitting in Jiashian earthquake, was simulated using SAP 2000 software. Similar to the shaking table test results, the most vulnerable point of the numerical model is located at the T-joint due to flexure failure. Although the mechanical joints can sustain the seismic demands determined by dynamic analysis, the dramatically changed stiffness of mechanic joints might be the reason to bring out the failure for the piping with couplings in shaking table tests.

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