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Experimental study on flexible pipelines used in base isolated buildings

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Abstract

The flexible pipeline connection is one of the key components for the water supply and drainage system in a base-isolated building. It is able to accommodate the large displacement between the superstructure and the ground. Its seismic performance is extensively examined in this study by a series of tests. Three types of seals, namely rubber-based seals, metal-based seals and asbestine-based seals, and three types of connections, union joints, ferrule fitting connections, and grab-type joints, are examined. The specimens were tested cyclically with the pipes filled with pressurized water, ranging from 1.0MPa to 2.5MPa. It is observed from the test results that the asbestine-based seal leaks earlier than the other two types of seals, and the union joint is not easy to realize the complete boundary of infilled liquids.

Keywords: Flexible pipe; Base isolation; Leakage; Seismic performance; Quasi-static test

1. Introduction

The cost of nonstructural components is the majority of the construction cost of a modern public building. Their damages during recent earthquakes, such as 1994 Northridge earthquake and 2008 Wenchuan earthquake, have not only caused massive economic losses, but suspended the routine function of a building which exerted serious influence on the immediate rescue and the post-earthquake re-construction. During the Ms.7.0 Lushan earthquake, the county had fallen into chaos for more than one month because most of the public buildings were evacuated temporarily due to the nonstructural failures, while the structural components were generally fine. Similar nonstructural failure was also observed in the 1994 Northridge earthquake, water leakage from damaged fire sprinkler piping systems forced a number of buildings out of function, including one hospital[1]. As one of the most important nonstructural components, not until very recently has the pipeline system been extensively studied to evaluate its seismic performance when sustaining severe earthquakes.

A series of full-scale earthquake tests and finite element analysis (FEA) of a water piping system were conducted by Martínez (2007) [2] to study its seismic behavior and examine the differences between coupled and welded piping system models. It was found that flexible couplings make the system more flexible by modifying the stiffness properties. Goodwin et al. (2007) conducted a series of shake table tests to understand the seismic behaviors of the typical welded and threaded hospital piping systems under braced and unbraced conditions. Their failure modes and drift capacities were identified. It was noticed that the welded pipe system had a much better performance than the threaded system due to the superior ductility. The seismic bracing systems were effective to reduce the displacement response of both piping systems, but did not significantly reduce the accelerations [3]. Hoehler et al. (2009) examined the performance of suspended pipes and the forces applied on the post-installed anchors in a full-scale 7-story reinforced concrete building subjected to different types of ground motions. They found that with the increase of the seismic intensity, the amplification of the ground accelerations measured on the pipes decreased due to the nonlinearity in the structure [4]. Filiatrault et al. (2014) tested a large number of commonly used sprinkler piping components. The long armovers with tee joint connections to the branch lines are of the most vulnerability among components of piping systems with grooved fit joints [5]. Zhong et al. (2015) conducted quasi-static and dynamic testing on ductile iron pipeline specimens reinforced with the cured-in-place-pipe (CIPP) liner. The test results demonstrate that pipelines reinforced with the CIPP liner substantially improve the seismic performance of the deteriorated underground pipelines under transient ground deformation (TGD) [6]. Bursi et al. (2015) conducted a performance-based seismic analysis of petrochemical piping systems through two realistic case studies. Proper seismic inputs were selected, and two realistic piping systems were analyzed nonlinearly for limit states suggested by modern performance-based earthquake standards. It was found maximum stress and strain values in both the piping systems remained below their yield strengths and allowable limit values even at the collapse limit state [7].

Although several studies mentioned above studied the pipe systems experimentally and analytically, the seismic performance of one type of pipes remains unknown, which is the pipeline system in a base-isolated building, particularly, those within the base-isolation layer used to connect the pipes in the superstructure with those to the gas or water stations mounted directly on the ground. Base-isolation technique has been strongly suggested for hospital building applications because it is commonly deemed resilient in terms of structural and non-structural protection and immediate occupancy. However, hospital buildings are often equipped with many types of pipe systems to transfer water, gas, poisonous material, and so on. If they fail during an earthquake, the function of the hospital building may be significantly affected and the emergency rescue activity may have to be interrupted, so that the resilience of the entire society would be decreased sharply.

As one of the most important components, the flexible pipe is used to connect the pipes of the superstructure and those fixed on the ground. It is able to provide a large deformation capacity to accommodate the displacement in the base isolation layer when being caught by a huge earthquake, which is commonly less than 60 cm as the rule of thumb in Japan [8]. The mechanical behavior, deformation capability and failure mode of the flexible connections, however, are not fully investigated up to now. In this study, a series of tests were conducted on the flexible pipelines used in the base isolation layer. The specimens were tested cyclically in-filled with pressurized water. Three types of seals and three types of connections, specifically, rubber-based seals, metal based seals, and asbestine-based seals, union joints, ferrule fitting connections, and grab-type joints, were examined respectively. The test results were summarized in this paper.

2. Flexible pipeline system

2.1 Requirements of flexible pipeline in Isolation structures

Flexible connections used for pipeline systems through the isolation layer are suggested in many regulations. In a huge earthquake, they deform following the large displacement between the superstructure and the foundation, releasing the force caused by the seismic deformation, thus protecting both the hard pipelines in the superstructure and those connected to the ground. According to the regulations of CECS126:2001, Technical specification for seismic-isolation with laminated rubber beating isolators [9], pipeline systems through the isolation layer should adopt flexible connection or other effective measures to adapt to the seismic forces and seismic relative displacements of isolation layer when suffering rare earthquakes. Similar requirement is also found in ASCE7 [10] which suggests either flexible pipelines or connections having sufficient deformability are needed to avoid failure of the connection. Mechanical devices that add flexibility, such as bellows, expansion joints, and other flexible apparatus, are permitted to be used where they are designed for seismic displacements and defined operating pressure.

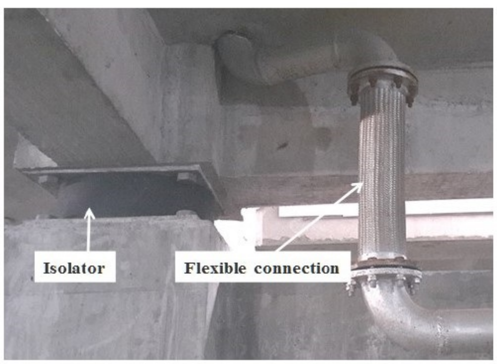


Fig. 1 – Flexible pipe in base-isolated buildings

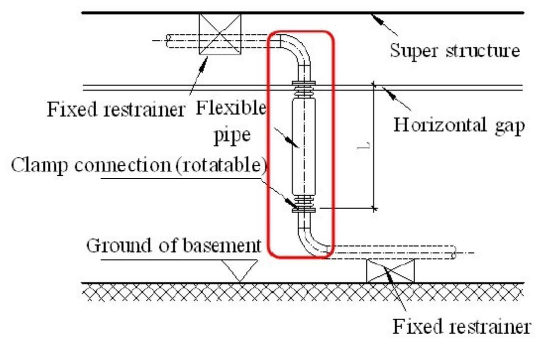


Fig. 2 – Typical design of flexible pipe system

2.2 Flexible hoses

Typical design of the flexible pipe system is illustrated in Fig. 2. The flexible pipe is connected with hard pipes fixed on the restrainers connected to the superstructure or the basement ground. Although the clamp connections are inserted between the flexible pipe and hard pipes, the rotation capacity of them is very limited. Therefore, the horizontal displacement between the superstructure and the ground is primarily accommodated by the elongation of the flexible pipe line. The length of the flexible pipe line determines the allowable horizontal displacement, which however, has to be selected based on the designer's experience since the mechanical properties and deformation capacity are not explored up to now.

The flexible pipe typically consists of the internal metal bellows and two layers of external stainless steel wire mesh, as shown in Fig. 3. Both are flexible and fabricated using standard commercial materials and methods. The metal bellow is used to maintain complete liquid boundary but cannot resist water pressure, while the two layers of external wire mesh provide radial confinement to the internal metal bellow, so that the pressure can be maintained.

In this study, three types of seals, i.e., rubber-based seals, metal based seals, asbestine-based seals, as shown in Fig. 4 (1)~(3), respectively, and three types of connections, i.e., union joints, ferrule fitting connections, grab-type joints, Fig. 4 (4)~(6), respectively, are examined using six specimens. Each has a length of 1200mm long. The inside nominal diameter of the flexible pipe is 100mm and its working pressure is 0.6MPa~2.5MPa. All seals can sustain a pressure of 2.5 MPa, while three types of joints at mid-span work under the pressure of 1.0MPa. When connecting the joints, the Teflon tape is used to seal the thread for fear of any unnecessary leakage. Three specimens with mid-span joints are shown in Fig. 5.

When being installed on the test frame, each end of the specimen is connected to one elbow hard pipe with two flanges, as shown in Fig. 6. The hard pipe at the left end is connected to a fixed jig with an orifice through which water can be injected into the specimen to maintain the working pressure at either 1.0MPa or 2.5MPa. The pressure is monitored by use of a hydraulic pressure gauge installed on the top of the left hard pipe. The hard pipe at the right end is connected to an adapter jig which is loaded horizontally in perpendicular to the axis of the specimen. Each flange of the hard pipe is connected to its counterpart by use of high-strength bolts with one piece of seal inserted at the interface. Totally four seals are installed in one specimen.

Fig. 3 – Configuration of flexible pipes

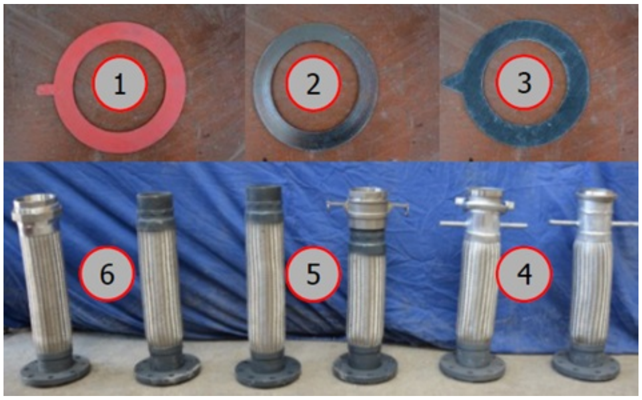


Fig. 4 – Seals and joints of flexible pipes

Fig. 5 – Specimens with mid-span joints

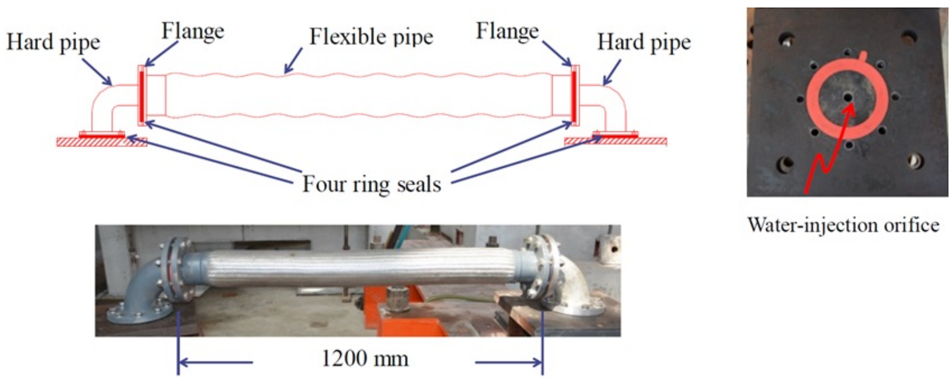


Fig. 6 – Specimen installed on the test frame

3. Test scheme

3.1 Loading frame and facility

Fig. 7 shows the loading frame and facility of the experiment. A dynamic actuator fixed on a rigid support structure is used to apply load to the flexible pipe. The stroke of the actuator is ±250mm. To achieve a larger loading capacity, a displacement amplifier is designed based on the lever principle. The short arm of the lever is connected with the actuator, while the long arm connected with the adapter to the pipe specimen. The length of the long arm is twice of the short arm, so that the loading capacity is amplified to ±500mm, compared with the design displacement of the base isolation layer, 440mm. The adapter is fixed on the sliding block of a linear roller bearing with a neglectable friction. A water pump with the pressure capability ranged from 0~16MPa is used to provide pressure inside the specimen.

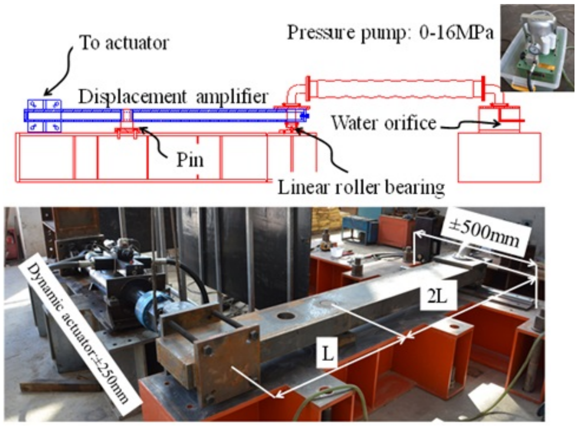


Fig. 7 – Loading frame and facility

3.2 Loading history

The quasi-static tests were conducted using the Interim Testing Protocol suggested by FEMA 461[11], as shown in Fig. 8. It is specifically developed for the seismic performance assessment of nonstructural components and equipment to quantify all damage states used for the development of fragility functions. The loading protocol consists of repeated cycles of step-wise increasing deformation amplitudes. The amplitude of the current step is 1.4 times that of the previous step after the initial damage state is observed. Two cycles of loading are conducted at each amplitude level at a frequency of 0.1Hz. When it comes to the design deformation of the base isolation layer, 50 cycles of loading will be conducted. Meanwhile, the specimen is filled with pressurized water at its maximum working pressure. Supplement pumping might be needed once the pressure on the monitor gauge decreases more than 10% of the maximum working pressure.

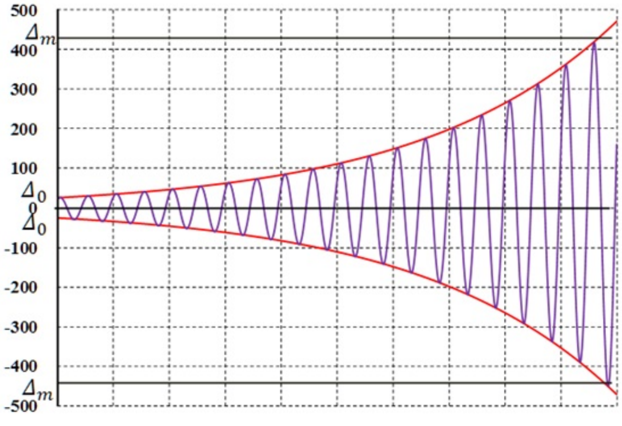


Fig. 8 – Typical interim testing protocol by FEMA 461

4. Summary of test results

Table 1 – Summary of damage and failure mechanisms of test specimens

Specimen ID	Main Damage/Failure Observed	Photographs of damage
1	±320mm slight plastic elongation; ±360mm break of steel mesh; ±400mm significant plastic elongation; ±440mm(50cycles) plastic crack and leakage at 17th cycle	
2	±320mm leakage at the left seal and slight plastic elongation; ±360mm break of steel mesh; ±400mm significant plastic elongation; ±440mm(50cycles) plastic crack and leakage at 20th cycle	
3	±200mm leakage at both end seals; ±400mm break of steel mesh; ±440mm(50cycles) plastic crack and leakage at 47th cycle	
4	±280mm slight plastic elongation; ±320mm leakage at the joint; ±400mm break of steel mesh and significant plastic elongation; ±440mm(50cycles) plastic crack and leakage at 2nd cycle, complete disconnection at 3rd cycle	
5	±200mm joint failure and leakage; ±280mm complete disconnection	

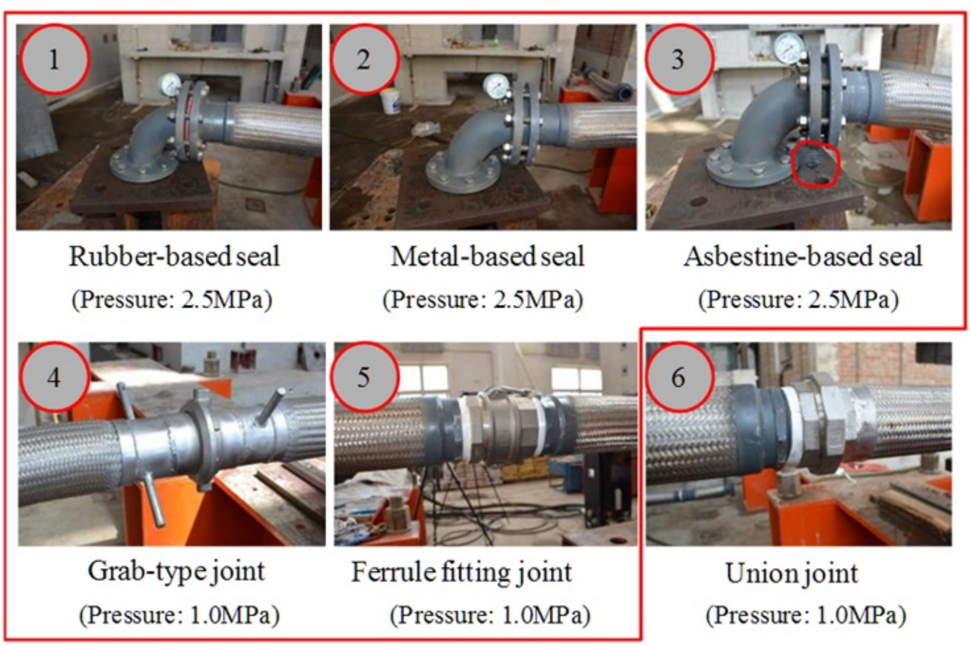
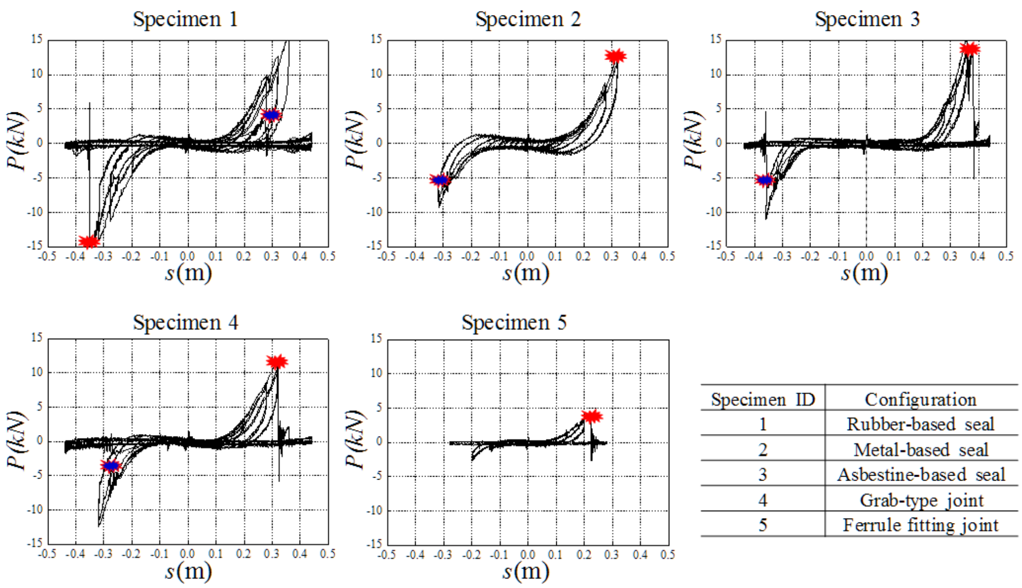


Fig. 9 – Pictures of all test specimens

Table 1 summarizes the main damage observed and shows photographs of the observed damage of all test specimens during the tests. It is obvious that asbestine-based seal (leakage at both end seals at the amplitude of 200mm) failed much earlier than other types of seals and rubber-based seal is the most effective one in terms of the leaking displacement it reached. Grab-type rapid joint is acceptable as it didn't suffer complete disconnection until the displacement reached 440mm while ferrule fitting joint completely failed at 280mm. Specimen 6 with union joint was not tested as a result of serious leaking at the beginning. Fig. 9 shows pictures of all test specimens.

Fig. 10 presents the hysteretic curves of the tested specimens. Two Damage States (DS) are defined as the leakage state and the fracture state. The Damage State DS_1 represents the occurrence of the first significant leakage, and is indicated by a blue dot on each plot. The Damage State DS_2 is defined as the physical fracture of the pipe/joint accompanied with complete pressure loss, and is indicated by a red dot. It is observed that all the tested specimens exhibited a very pinched hysteresis behavior associated with small energy dissipation. And the hysteretic curves show that the loading stiffness of the specimen increases at larger displacement amplitudes. The stiffness of all specimens except specimen 5 increases sharply as a result of significant plastic elongation at the larger displacements than 200mm.



Specimen ID	Configuration
1	Rubber-based seal
2	Metal-based seal
3	Asbestine-based seal
4	Grab-type joint
5	Ferrule fitting joint

Fig. 10 – Hysteretic curves of the tested specimens

5. Summary and conclusions

With rapid application of isolation technique in China, the seismic inspection of associate non-structural components becomes especially important to realize resilient isolation buildings. This paper presented the testing results of different seals and joints used in flexible pipe system. The following conclusions highlight the findings of this study:

1. Rubber-based seals and metal based seals are effective to prevent leakage. Asbestine-based seal leaks very early at a relatively low level of displacement.

2. Grab-type rapid joint is acceptable to be used for flexible pipe line connection. Union joints and ferrule fitting connections can't provide equally good seismic performance.

3. Straight-line flexible pipes all damaged at a displacement close to the design displacement in the base isolation layer, implying that they may be vulnerable when suffering severe earthquakes because of the large displacement between the superstructure and the ground.

There are still some possible future research works ahead of us. More types of connections and patterns need to be tested to explore the mechanical behavior, deformation capability and failure mode of the flexible connections of flexible pipelines to build up the experimental fragility curves. Also to be developed are analytical models for the flexible pipes which will be used in the seismic assessment and performance-based design procedures. Finally, structure-pipe interaction analysis can be conducted, and development of innovative technologies to enhance the seismic performance is needed.

6. Acknowledgements

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