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SHAKING TABLE TEST OF SEISMIC BRACINGS IN PIPING SYSTEMS

X.Q. Ning [(1)], J.W. Dai [(2)], D.Z. Wang [(3)] and W. Bai [(4)]

[(1)] *PhD Student, Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, 453472140@qq.com*

[(2)] *Professor, Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, jwdai@iem.cn*

[(3)] *Assistant Professor, Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, wangdz_iem@126.com*

[(4)] *PhD Student, Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, 781090853@qq.com*

Abstract

The seismic damage caused by strong earthquakes worldwide has highlighted the importance of functional resilience of nonstructural components. Directing at seismic bracings used in piping systems, this paper firstly introduces the classification, construction and design steps of seismic bracings. The seismic code requirements for design method and load performance testing of seismic bracings are mentioned. Relevant seismic research of bracings is also reviewed. The shaking table test of seismic bracings in a 6-meter full-size piping system was conducted and responses of both floor and pipes were measured on the longitudinal and lateral directions under the table input levels. In addition with theoretical analysis and specification comparison, the seismic performance of bracings and the acceleration amplification coefficient of pipes are studied. The test results indicate that the seismic performance of bracings is good enough to satisfy the seismic code requirement. But the problem of bolt looseness occured in connection parts may further cause the rotation or shift of bracings under continued earthquakes or aftershocks. Based on the results, both technical improvement measures to enhance weak connections and design optimization suggestions considering cost need to be put forwarded.

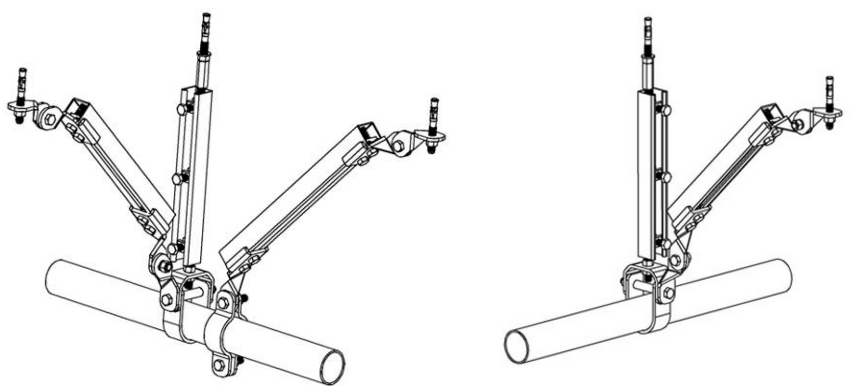
Keywords: Seismic bracing, Piping system, Functional resilience, Shaking table test

1. Introduction

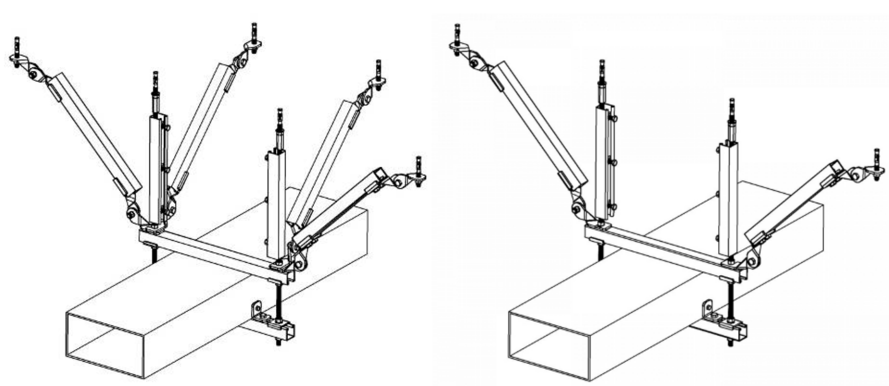
For modern architecture, the post-earthquake function loss is mostly embodied in the nonstructural system. The low resilience of buildings due to the high vulnerability of nonstructural components has been widely observed. Functional resilience is expected to achieve during and after earthquakes such as in hospitals. The good operation of piping systems in buildings is the foundation to ensure the whole function implementation. Seismic bracings are important parts to connect structure and nonstructural components like piping systems, which should have enough stiffness and strength to surfer earthquake actions and to make piping systems restored quickly, in order to achieve the goal of building function resilience. However, the specialized study and information about seismic bracings are very little, and applicable codes and guidance greatly depend on past experience, engineering judgment and intuition, rather than test and analysis results. Therefore, it becomes necessary to study the seismic response characteristics of seismic bracings.

1.1 Types and design of seismic bracing

The types of seismic bracing mainly include bidirectional and lateral seismic bracing, single tube and door-shaped seismic bracing (Fig. 1), which is primarily composed of U-steel, seismic connecting component, limit fastener, expansion bolt and other parts (Fig. 2). The design of seismic bracing is divided into four steps: firstly, determine the location and orientation of bracing; secondly, determine the design load requirements; thirdly, select the correct shape, size and maximum length of bracing; finally, choose the appropriate type and specification of fastener to fix bracing on the building structure.



(a) Bidirectional single tube bracing (b) Lateral single tube bracing



(c) Bidirectional door-shaped bracing (d) Lateral door-shaped bracing

Fig. 1 –Types of seismic bracing

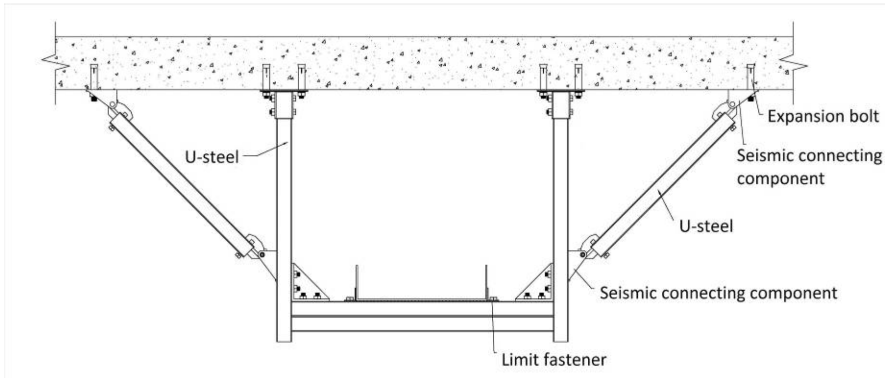


Fig. 2 –Construction of seismic bracing

1.2 Seismic code requirements

China's code for seismic design of mechanical and electrical equipment [1] has made corresponding provisions for design and calculation of seismic bracings. The spacing of lateral and longitudinal seismic bracings shall be calculated by Eq. (1), and comprehensive coefficient of horizontal seismic force can be calculated by Eq. (2). Seismic bracings should be checked based on the load to satisfy the requirements through spacing adjustment.

$$l = \frac{l_0}{\alpha_{Ek} \cdot k} \tag{1}$$

$$\alpha_{Ek} = \gamma \eta \zeta_1 \zeta_2 \alpha_{\max} \tag{2}$$

Where l is the spacing of lateral and longitudinal seismic bracings, l_0 is the largest spacing of seismic bracings, α_{Ek} is comprehensive coefficient of horizontal seismic force, k is angle adjustment coefficient, γ is nonstructural function coefficient, η is nonstructural category coefficient, ζ_1 is condition factor, ζ_2 is location factor, $\alpha_{\max}$ is the maximum of earthquake influence coefficient.

Specification of seismic supports for mechanical and electrical components in China [2] has made corresponding provisions for load performance testing of components. If the expected test load of a single set of bracing is less than 2.25kN, the initial load on the specimen shall be 2.25kN. In the test, after 15 times of the same amplitude of cyclic loading, the increasing amplitude of cyclic loading is applied to the specimen, until the complete 55 times of cyclic loading. The entire load formulas are as Eq. (3) and Eq. (4), in which F stands for the loading force, X stands for the initial force, and N stands for the number of cyclic loading. As there are four sets of bracings needed in the test apparatus, the test load should be divided by four to get the load of a single set of bracing.

$$F = X, \quad N \le 15 \tag{3}$$

$$F = X \times \left(\frac{15}{14}\right)^{\frac{N-15}{2}}, \quad 15 < N \le 55 \tag{4}$$

1.3 State-of-the-art research

Recently, horizontal piping subsystems with seismic resistant devices such as braces were tested, showing the importance to strengthen the main pipe with braces [3]. A connector was designed for connecting a seismic brace to a support rod, such as for a cable tray, to inhibit movement of the rod during seismic activity [4]. A bracing apparatus was designed for bracing a flexible pipe extending between a fire sprinkler header pipe and a sprinkler and for holding the sprinkler in a desired location [5]. A sway brace fitting clamp was used for lateral bracing of sprinkler or other types of pipe (designated the service pipe) to a structure, to prevent movement of the service pipe perpendicular to the axis of the pipe relative to the structure to which it is attached [6]. An apparatus was disclosed which provides connection points on a piping system to facilitate motion restraint using external motion-restraining systems [7].

2. Shaking table test

2.1 Test setup and specimens

The shaking table test of seismic bracings in a 6-meter full-size piping system is carried out at the Key Laboratory of Earthquake Engineering and Engineering Vibration of China Earthquake Administration. The 5m ×5m square shake table is characterized by three DOF along the two horizontal and one vertical directions. The maximum payload of the shake table is 300kN with a frequency ranging between 0.4 and 40 Hz, acceleration peak equal to 1g, velocity peak equal to 0.6m/s, and total displacement equal to 160mm (±80mm).

The tested bracings were installed in three steel single-story framed structures with reinforced concrete floor which were designed to simulate the floor response. Considering the shaking table's size limit, the whole test model with two 6m length pipes was placed along the table diagonal (Fig. 3, Fig. 4 and Fig. 5). The total weight of the whole test model was 61.6kN, consisting of three structures 57.9kN and pipes 3.7kN.

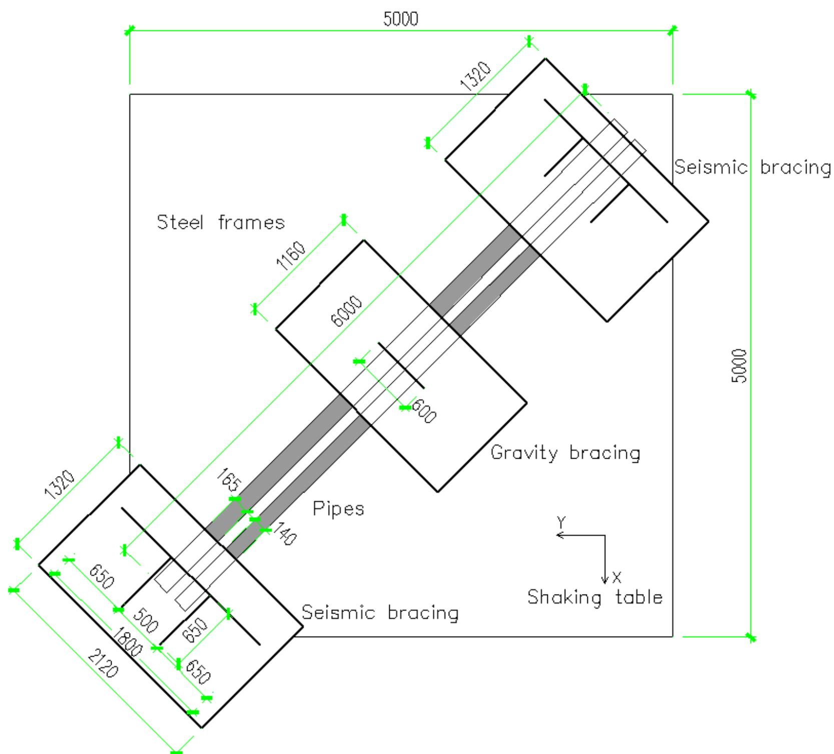
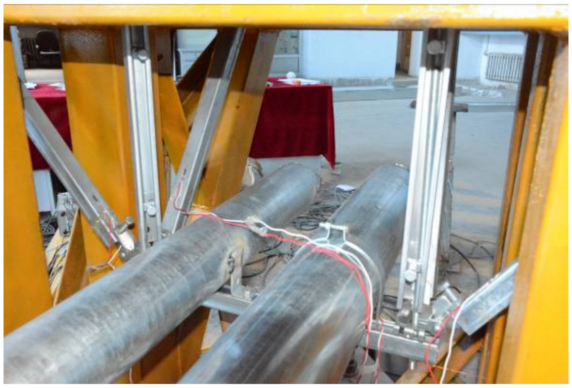


Fig. 3 –Test model layout

Fig. 4 –Test model



(a) Seismic bracing

(b) Gravity bracing

Fig. 5 –Tested bracings

2.2 Test input and program

According to the Chinese code for seismic design of buildings [8], five accelerograms were used as input in the test, consisting of three ground motions– the 1995 Kobe ground motion, the 1999 Chichi ground motion and the 2008 Wolong ground motion, and two sine resonance waves (9.5Hz, 11.0Hz). The table input levels range from PGA=0.053g to 0.898g along two horizontal directions, in order to compose diagonal direction input as floor response levels (Table 1).

Table 1 –Table input levels

Test ID	Table Input PGA(g)	
	Table X	Table Y
1	0.053	0.061
2	0.161	0.156
3	0.328	0.307
4	0.610	0.766
5	0.721	0.898

2.3 Test results and analysis

The white noise frequency sweep was conducted before and after each input level, obtaining the natural frequency and damping ratio of pipes (Table 2). Responses of both floor and pipes were measured on the longitudinal and lateral directions under the table input levels (Table 3).

After the input of test level 3, the movement of structure was basically consistent with the shaking table, behaving as rigid motion. In the input of test level 4, the amplitude of structure increased obviously, while seismic bracings shake slightly due to bolt looseness. In the input of test level 5, as seismic bracings shake violently with frames, one of the supporting U-steel rotated about 45 degrees along the vertical axis. Nevertheless, at the end of the test, neither seismic bracings nor piping systems occurred obvious damage, which means good seismic performance of bracings.

With the increase of input PGA, the acceleration amplification coefficient of pipes (the ratio of peak acceleration between pipes and floor) decreased gradually due to the degradation of model stiffness and the increase of damping ratio. The lateral acceleration amplification coefficient of pipes is always larger than the longitudinal one, with the maximum of which is 1.455 (Fig. 6). The maximum displacement of seismic bracings relative to the floor is 68mm, while the strain of bracings is 58.74E-6, calculating the stress is 121MPa, less than the allowable stress 160MPa, which means that bracings have no stress damage.

Table 2 –Natural frequency and damping ratio of pipes

Test ID	Natural frequency(Hz)		Damping ratio(%)	
	Longitudinal	Lateral	Longitudinal	Lateral
Pre-test	12.85	9.47	3.13	2.17
3	11.27	9.07	3.63	3.30
4	10.64	8.85	3.96	4.14
5	10.15	8.65	4.16	4.72

Table 3 –Responses of floor and pipes

Test ID	Table Input PGA (g)		Response of Floor (g)		Response of Pipes (g)	
	Table X	Table Y	Longitudinal	Lateral	Longitudinal	Lateral
1	0.053	0.061	0.059	0.089	0.067	0.126
2	0.161	0.156	0.202	0.254	0.210	0.369
3	0.328	0.307	0.452	0.481	0.479	0.640
4	0.610	0.766	0.931	0.957	0.984	1.247
5	0.721	0.898	1.228	1.343	1.295	1.708

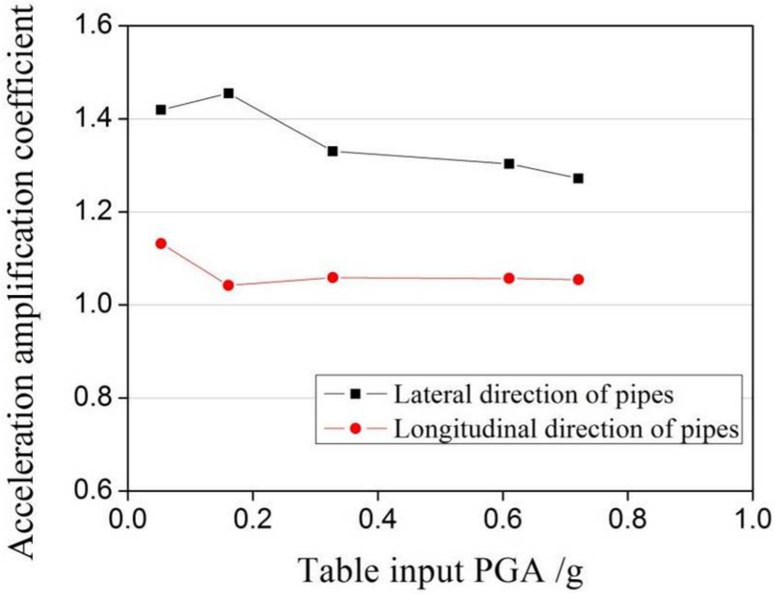


Fig. 6 –Acceleration amplification coefficient of pipes

2.4 Comparison of maximum load between specification and shaking table test

In accordance with the specification requirements involved in section 1.2, in load performance testing, the initial load and maximum load applied to a single set of bracing should be calculated by Eq. (5) and Eq. (6). In the shaking table test, based on the acceleration results of the pipes, the actual maximum load applied to a single set of bracing is calculated by Eq. (7) and Eq. (8).

According to the comparison (Table 4), the maximum load applied to a single set of bracing in the shaking table test is more than that in the specification requirements, which indicates that the load of shaking table test conforms to the specification, and the test results are conservative.

Specification requirements：the initial load $F_1 = \frac{1}{4} F_1' = \frac{1}{4} \times 2.25 = 0.56kN$ (5)

Specification requirements：the maximum load $F_{55} = \frac{1}{4} F_{55}' = \frac{1}{4} \times 2.25 \times \left(\frac{15}{14}\right)^{\frac{55-15}{2}} = 2.24kN$ (6)

Longitudinal bracing：the maximum load $F_{lo} = \frac{1}{2} F_{lo}' = \frac{1}{2} m a_{lo} = \frac{1}{2} \times 373 \times 1.295 \times 9.8 = 2.37kN$ (7)

Lateral bracing：the maximum load $F_{la} = \frac{1}{2} F_{la}' = \frac{1}{2} m a_{la} = \frac{1}{2} \times 373 \times 1.708 \times 9.8 = 3.12kN$ (8)

Table 4 –Comparison of maximum load between specification and shaking table test

Comparison	Specification requirements	Shaking table test	
		Longitudinal bracing	Lateral bracing
Maximum load	2.24kN	2.37kN	3.12kN

3. Conclusion

According to the shaking table test results, neither seismic bracings nor piping systems occurred obvious damage, which means the seismic performance of bracings is good enough to satisfy the seismic requirements. As the load of shaking table test conforms to the specification, the test results are conservative.

Nevertheless, the problem of bolt looseness is easy to occur in the seismic connection parts, which may further cause the rotation or shift of bracings under continued earthquakes or aftershocks, therefore technical measures need to be improved and innovated to enhance weak connections.

Meanwhile, the test results show that the longitudinal acceleration response of pipes is basically identical to the floor response. If cost saving is taken into account, designers and engineers can give priority to choose the type of lateral seismic bracings, on the basis of meeting seismic requirements.

4. Acknowledgement

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