Research Article

Shaking Table Test of a Full-Scale RC Frame Structure with an Indoor Gas Piping System

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To investigate the seismic behavior of a two-story RC frame structure with an indoor gas piping system, a shaking table test was performed and the data obtained from the shaking table test were analyzed in this paper. The detailing of the structural elements was compliant with the Chinese seismic design code, whereas minor modifications were applied to the pipe materials and joint arrangements. In the test, three kinds of pipe materials (galvanized steel, thin-walled stainless steel, and polyethylene) combined with three types of joint arrangements were selected. The filling materials of the joint were epoxy resin, batched jute, and asbestos cement. A series of full-scale shake table tests were performed by gradually increasing the three ground motions for reaching to the near collapse limit state. The dynamic characteristics and the responses of the model were investigated via analyzing shaking table test data and the observed damage. The test results also indicated that different joint arrangements had a different impact on the dynamic response of the pipes when subjected to strong ground motions. The peak acceleration of metal pipes with a rigid joint was higher than that of flexible ones, and the peak acceleration of plastic pipes with flexible joint connection was higher than that of rigid ones.

1. Introduction

Nonstructural components include nonstructural components of buildings and auxiliary electromechanical equipment attached to buildings, and the indoor gas piping system is an example. Because a gas pipe transports a number of inflammable gases, serious secondary accidents or disasters can occur if it is damaged in an earthquake. According to GB50011-2016 [1], the anti-seismic target of nonstructural components that may cause secondary disasters should not be lower than that of the main structure. Figure 1 shows a typical damage caused by an earthquake to the indoor piping system. Researchers have systematically studied such nonstructural components of buildings as infilled walls, suspended roofs, and parapets, and seismic response analysis of indoor pipe systems is a part of this work [2–5].

FEMA E74 [6] proposed the anti-seismic construction measures applicable to various types of indoor pipe systems. FEMA 273 [7] proposed that the weak points of gas pipes in high-rise buildings were mainly concentrated in the joints and welds of pipes. FEMA 414 [8] proposed the anti-seismic construction measures that should be paid attention to when installing indoor pipe system. Sun [9] used Idarc-2D, a software for static elastoplastic analysis, to establish a dynamic analysis model of gas pipes in high-rise buildings. The model assumed that the riser was connected to each floor through a support and the seismic response of the main structure was transmitted to the pipe through the support. By deducing the mass, stiffness, and damping matrices of elements of the pipe and calculating the displacement response of the main structure at the support, they analyzed the seismic response of the riser. The results showed that
appropriately using the flexible connections in weak floors can help reduce seismic damage to pipes. Sorace and Terenzi [10] carried out an experiment and a finite element simulation on water and gas pipes in a basic isolation structure and found that even if earthquakes are rare, the normal functioning of the water and gas pipes across the floor can be ensured by using a flexible joint. Guo et al. [11] studied a pipe system supported by the main structure by using the equivalent linearization method. Their model analyzed the influence of the nonlinear characteristics of the main structure on the seismic response and optimal location of the pipe attached to it. FEMA E74 [11] proposed the anti-seismic construction measures applicable to various types of indoor pipe systems. Sato et al. [12] carried out a shaking table test of a five-floor full-scale steel frame to study the seismic performance of the system of pipes of its fire sprinklers. The results showed that the pipe itself had barely sustained any damage, and the system failed primarily due to damage to the support system and the fire sprinkler. He et al. [13] used a pseudostatic test to compare the seismic performance of a PPR pipe with that of a galvanized steel pipe. The results showed that the PPR pipe had stronger deformation capability than the galvanized steel pipe but its bending moment was much smaller. Ju et al. [14] studied the effects of the diameter of the pipe, thickness of the wall, and different types of coupling on the seismic vulnerability of household pipes. The results showed that the type of coupling used significantly affected their seismic performance, where threaded coupling was more vulnerable than grooved coupling. Tian et al. [15] carried out an experimental program designed to evaluate the seismic behavior of fire extinguishing sprinkler piping systems and examined the efficiency of a number of hysteresis models to simulate the nonlinear moment-rotation behavior of sprinkler piping tee joints made of various materials and connection types. Perrone et al. [16] discussed the results of an experimental program designed to evaluate the seismic behavior of suspended piping restraint installations. Blasi et al. [17] studied the seismic performance assessment of two types of piping systems installed in RC-framed buildings (i.e., medical gas distribution and fire-fighting system) through cascading analysis. The piping systems were modeled accounting for the nonlinear response of both pipe joints and suspended piping seismic restraints.

At present, few scholars have studied the influence of joint arrangements on the seismic response of pipes. In case of a strong earthquake, the horizontal displacement of the RC frame might be large, and easily damage nonstructural piping systems. Therefore, a full-scale model of a two-story RC frame with indoor gas piping systems was employed in this study. It was designed and tested on the shaking table in the Key Laboratory of Earthquake Engineering and Engineering Vibration in China. The damage and dynamic characteristics of the RC frame and the gas pipes were investigated. The results were discussed to evaluate the effects of different joint arrangements.

2. Design of the Shaking Table Test

2.1. Experimental Model. The test model was a two-floor RC frame structure and the infilled wall was chosen to be 120 millimeters thick steam-pressurized concrete bricks using M7.5 mixed mortar. A steel bar was used between the infilled wall and the column of the frame, and reinforced concrete lintels were set at the openings of the doors and windows. The floor slab, beam, and column were composed of C30 concrete. The model and section sizes and the reinforcements of the floor slab, beam, and column are shown in Figures 2 and 3, respectively. The testing method of the specimens strictly followed the requirements of the Standard for Test Methods of Concrete Structures (GB50011-2016) [1].
Galvanized steel (GS) pipes, 304 thin-walled stainless steel (TSS) pipes, and polyethylene (PE) pipes with a nominal diameter of 40 millimeters (DN40) were used in the test for gas piping system investigation. To consider the impact of gas pressure on the seismic performance of the pipe, and for convenience of observing the experimental phenomena, each pipe was pressurized 0.5 MPa water during the test. When the pipes passed through the floor slab, to render them shake and leakage proof, they were equipped with casings filled with a fireproof filler. The joint was made of casing pipe, steel wing ring, and filler. Epoxy resin, batched jute, and asbestos cement were used as fillers to study the effect of different ways of pipe joint arrangements to the seismic response of the piping system.

Table 1 lists the different combinations of pipes and fillers used. According to JGJ339-2015 [18], the bottom of each casing was flush with the bottom of the floor slab and its top was 20 mm higher than that of the floor slab. The control valve was located at an elevation of 0.3 m, and the intake pipe was located at 0.2 m below the floor.

The model was constructed in the order of the foundation, columns of the frame, beams, floor slabs, infilled walls, and pipes. The PE pipe was connected through melting, the TSS pipe was connected using argon arc-welding, and the GS pipe was connected by threading. Pipe straps were used to fix the pipes.

During the pipeline installation, the risers were fixed using U-shaped pipe straps. GS and TSS pipes were installed using two U-shaped pipe straps at the elevation of 0.3 m, 1.5 m, and 4.25 m, respectively, while the PE pipes were installed using four U-shaped pipe straps at the elevation of 0.1 m, 1.5 m, 2.1 m, 3.7 m, and 4.7 m, respectively. The view

Figure 2: Model size (in millimeters). (a) Plan view. (b) Elevation view. (c) Front view. (d) Back view.
of the pipes and the detailed structure of the casing are shown in Figures 4 and 5. The construction of the model is shown in Figure 6. Materials used in the model are summarized in Table 2.

2.2. Ground Motions and Instrumentation. By referring to the method of ground motion selection in ASCE/SEI 7–16 [19], three ground motion records were selected from the PEER Strong Vibration Database: the El-Centro ground motion, Chichi ground motion, and San Fernando ground motion. After adjusting the PGA of the three ground motion records to 70 cm/s², a response spectrum analysis of acceleration was carried out at a damping ratio of 0.05. Figure 7 shows the comparison between the acceleration response spectrum of the three ground motion records and the design spectrum proposed in GB50011-2016.

A two-way ground motion input was chosen in this test. According to the provisions of GB50011-2016, the ratio of the amplitudes of acceleration in the X and the Y directions was set as 1:0.85. The input sequence of the ground motion was determined according to the method suggested by Zhou.
et al. [20]. Before and after loading each level of the ground motion, white noise was input to sweep the test model. Table 3 shows the working conditions.

According to the characteristics of the model and test conditions, acceleration sensors were used to measure the acceleration of the floors and pipes, and displacement sensors were used to measure displacement in the floor. Three types of sensors were installed at the key positions of the model: (1) nine bidirectional Integrated Circuits Piezoelectric accelerometers (ICPA) (Beijing Heng Odd Instrument, Beijing, China) were distributed on the gas risers to measure the pipe accelerations, (2) six 941B accelerometers (Institute of Engineering Mechanics, China Earthquake Administration, Harbin, China), having a measuring range of 2000 gal, frequency passband of 0.25–80 Hz, and resolution of $5 \times 10^{-3}$ gal, were installed at the base, first and second floor to measure the acceleration of the model, and (3) six pull-line displacement sensors (Beijing JLMOOM Technology, Beijing, China), with a measuring range of 0–500 mm and resolution of 0.01 mm, were installed on the base, first and second floor beams to measure the model displacement. Figure 8 gives the layout details of the installed sensors on the model. A total of fifteen acceleration sensors and six displacement...
Figure 5: Detailed structure of pipe-floor joint (in millimeters).

Figure 6: Model construction: (a) RC frame concreting, (b) steel wing ring, (c) GS pipe threading, (d) TSS pipe argon arc welding, (e) PE pipe hot melting, (f) pipe strap, (g) indoor gas pipes, and (h) model completion.
### Table 2: Materials for the model.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (MPa)</th>
<th>Poisson ratio</th>
<th>Strength (MP)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C30 concrete</td>
<td>$3.2 \times 10^4$</td>
<td>0.2</td>
<td>30</td>
<td>2500</td>
</tr>
<tr>
<td>HRB 335</td>
<td>$2.0 \times 10^5$</td>
<td>0.3</td>
<td>300</td>
<td>7800</td>
</tr>
<tr>
<td>HPB300</td>
<td>$2.1 \times 10^5$</td>
<td>0.3</td>
<td>270</td>
<td>7800</td>
</tr>
</tbody>
</table>

### Table 3: Test conditions.

<table>
<thead>
<tr>
<th>Test condition serial number</th>
<th>Earthquake excitation</th>
<th>Peak acceleration in the X direction (g)</th>
<th>Peak acceleration in the Y direction (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>First white noise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>El-Centro wave</td>
<td>0.07</td>
<td>0.0595</td>
</tr>
<tr>
<td>3</td>
<td>Chichi wave</td>
<td>0.07</td>
<td>0.0595</td>
</tr>
<tr>
<td>4</td>
<td>San Fernando wave</td>
<td>0.07</td>
<td>0.0595</td>
</tr>
<tr>
<td>5</td>
<td>Second white noise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>El-Centro wave</td>
<td>0.2</td>
<td>0.17</td>
</tr>
<tr>
<td>7</td>
<td>Chichi wave</td>
<td>0.2</td>
<td>0.17</td>
</tr>
<tr>
<td>8</td>
<td>San Fernando wave</td>
<td>0.2</td>
<td>0.17</td>
</tr>
<tr>
<td>9</td>
<td>Third white noise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>El-Centro wave</td>
<td>0.4</td>
<td>0.34</td>
</tr>
<tr>
<td>11</td>
<td>Chichi wave</td>
<td>0.4</td>
<td>0.34</td>
</tr>
<tr>
<td>12</td>
<td>San Fernando wave</td>
<td>0.4</td>
<td>0.34</td>
</tr>
<tr>
<td>13</td>
<td>Fourth white noise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>El-Centro wave</td>
<td>0.62</td>
<td>0.527</td>
</tr>
<tr>
<td>15</td>
<td>El-Centro wave</td>
<td>0.527</td>
<td>0.62</td>
</tr>
<tr>
<td>16</td>
<td>Chichi wave</td>
<td>0.62</td>
<td>0.527</td>
</tr>
<tr>
<td>17</td>
<td>Chichi wave</td>
<td>0.527</td>
<td>0.62</td>
</tr>
<tr>
<td>18</td>
<td>Fifth white noise</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 7:** Comparison of the response spectrum of acceleration: (a) X direction and (b) Y direction.
Table 4: Instrument layout.

<table>
<thead>
<tr>
<th>Types of instruments</th>
<th>Decorate position</th>
<th>Numbers</th>
<th>Sensor type</th>
<th>Measurement content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement sensor</td>
<td>Base</td>
<td>2</td>
<td>Unidirectional</td>
<td>The horizontal displacement of the base in X/Y direction</td>
</tr>
<tr>
<td></td>
<td>First floor</td>
<td>2</td>
<td>Unidirectional</td>
<td>The horizontal displacement of the first floor in X/Y direction</td>
</tr>
<tr>
<td></td>
<td>Second floor</td>
<td>2</td>
<td>Unidirectional</td>
<td>The horizontal displacement of the second floor in X/Y direction</td>
</tr>
<tr>
<td>Accelerometers</td>
<td>Base</td>
<td>2</td>
<td>Unidirectional</td>
<td>The horizontal acceleration of the base in the X/Y direction</td>
</tr>
<tr>
<td></td>
<td>First floor beam</td>
<td>2</td>
<td>Unidirectional</td>
<td>The horizontal acceleration of the first floor in X/Y direction</td>
</tr>
<tr>
<td></td>
<td>Second floor beam</td>
<td>2</td>
<td>Unidirectional</td>
<td>The horizontal acceleration of the second floor in X/Y direction</td>
</tr>
<tr>
<td></td>
<td>All risers (Elevation 1.5 meters)</td>
<td>9</td>
<td>Bidirectional</td>
<td>The horizontal acceleration of the risers in X/Y direction</td>
</tr>
</tbody>
</table>

Figure 8: Layout details of the installed sensors on the model (A for accelerometers, D for pull-line displacement sensors, and ICPA for Integrated Circuits Piezoelectric accelerometers): (a) elevation view and (b) plan view.
Figure 9: Cracks around the point of contact between the infilled wall and the frame: (a) inside of north wall and (b) south wall.

Figure 10: Cracks appeared under ground motion of 0.4 g: (a) east wall, (b) south wall and column, (c) the column of the frame damaged, and (d) partial enlargement of figure (c).
sensors were used. The layout of the instruments is detailed in Table 4.

3. Experimental Phenomena

Under a ground motion of 0.07g, the model had no observable cracks and there was no damage on the gas piping system. The infilled wall and periphery of the frame were bonded together as a whole. Under ground motion at an amplitude of 0.2g, cracks appeared around the point of contact between the infilled wall and the frame and progressed to the wall. See Figure 9.

Under a ground motion of 0.4g, the cracks on the wall on the first floor developed into penetrating cracks. There were inclined cracks along the brick gap. The cracks on the frame were also concentrated on the first floor, with almost no cracks on the second floor. See Figure 10.

The straps used to fix GS pipes were damaged first, and then the straps of TSS pipes and PE pipes were also loosened. There were 5 pipe straps damaged on the first floor, while no pipe strap was damaged on the second floor. The typical damaged characteristics of the pipe strap are shown in Figure 11.

Under a ground motion of 0.62g, some bricks of the infilled wall on the first floor were crushed, and it began to separate from the frame. Cracks in the beams and columns continued to develop, and the extending rate of the cracks on the first floor was significantly higher than that on the second floor. The number of damaged pipe straps increased, with 9 on the first floor and 5 on the second floor. The filler at the bottom of the first floor fell off from the GS pipe joint, but there was no damage on the pipe body until the end of the test. The typical damages are shown in Figure 12.

4. Seismic Response Analysis

4.1. Analysis of Dynamic Characteristics. By using the random subspace method [21, 22] to analyze the spectrum of the measured excitation response of acceleration to white noise, the first natural frequency of the test model was obtained. Table 5 lists the frequency and period information of the model. It is clear that the model’s natural frequency gradually decreased with increasing amplitude of ground motion.

4.2. Analysis of Dynamic Response of the Main Structure. Figure 13 shows the amplitude of story drift of the frame structure under the different seismic motions. The first floor of the model structure showed prominent characteristics of weak floors. Deformation was concentrated in the first floor and the displacement of the second floor was small. Under the ground motions of different amplitudes as input, the maximum story drift of the model increased with the amplitude of the input ground motion. When the Chichi wave acts at an amplitude of 0.62g, the maximum story drift of the model was 0.047 which is considerably larger than the limit of story drift of 0.02 that prevented the structure from failure in accordance with GB 50010–2016 [1]. The model for the experiment showed good ductility.

The peak value of the acceleration response of each floor divided by the peak acceleration measured at the base was used to calculate the amplification coefficient of the acceleration response of each floor of the model. The trend of change in this coefficient with the loading conditions could adequately reflect the degree of damage to each floor of the model. Figure 14 shows the acceleration amplification coefficient of the frame structure under different seismic waves. The coefficient of amplification in acceleration of the floor decreased with increasing load. This was due to the increasing structural damage, decreasing structural stiffness, and increasing damping ratio of the test model.

4.3. Dynamic Response of the Piping System. Figure 15 shows a comparison of the time histories of the acceleration of the pipes under the San Fernando wave at the amplitude of 0.4g. It can be found that the GS and the TSS pipes had the smallest acceleration response when using epoxy resin as a filler and was the largest when using asbestos cement as the filler. The PE pipe had the largest acceleration response when epoxy resin was used as the filler, and the smallest response was observed when asbestos cement was used as the filler.

The component amplification factor is recommended as the seismic performance index of indoor piping system in...
Figure 12: The damages under 0.62 g: (a) the eastern wall, (b) crushed bricks and mortar fell off the north wall, and (c) the filler at the bottom fell off the joint of No.3 GS piping system joint.

Table 5: Natural frequency and fundamental period of the model.

<table>
<thead>
<tr>
<th>White noise loading sequence</th>
<th>Test conditions</th>
<th>Period (s)</th>
<th>Frequency (Hz)</th>
<th>Frequency reduction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>Before the trial</td>
<td>0.256</td>
<td>3.906</td>
<td>1</td>
</tr>
<tr>
<td>second</td>
<td>After 0.07 g</td>
<td>0.267</td>
<td>3.748</td>
<td>0.96</td>
</tr>
<tr>
<td>Third</td>
<td>After 0.2 g</td>
<td>0.283</td>
<td>3.528</td>
<td>0.90</td>
</tr>
<tr>
<td>Fourth</td>
<td>After 0.4 g</td>
<td>0.339</td>
<td>2.954</td>
<td>0.76</td>
</tr>
<tr>
<td>Fifth</td>
<td>After 0.62 g</td>
<td>0.683</td>
<td>1.465</td>
<td>0.38</td>
</tr>
</tbody>
</table>
Figure 13: Envelope value of story drift under different seismic inputs.

Figure 14: Floor acceleration amplification coefficient under different seismic inputs.

Figure 15: Continued.
Figure 15: Comparison of time histories of acceleration of pipes with different joint arrangements under the 0.4 g San Fernando wave in the X direction: (a) GS pipes, (b) TSS pipes, and (c) PE pipes.

Figure 16: Comparison of component amplification factor of pipes with different construction measures under the El-Centro wave in the X direction: (a) GS pipe, (b) TSS pipe, and (c) PE pipe.

Figure 17: Comparison of component amplification factor of pipes with different construction measures under the Chichi wave in the X direction: (a) GS pipe, (b) TSS pipe, and (c) PE pipe.
kT_he equation of the component amplification factor of pipes with different construction measures under the San Fernando wave in Fig. 14: Comparison of component amplification factor of pipes with different construction measures under the San Fernando wave in the X direction: (a) GS pipe, (b) TSS pipe, and (c) PE pipe.

ASCE7-16 [19]. The equation of the component amplification factor is given by the following:

\[ a_p = \frac{a_1}{a_0} \]  

where \( a_p \) is the component amplification factor of the pipe, \( a_1 \) is the peak acceleration of the pipe, and \( a_0 \) is the peak acceleration of the main structure to which the pipe is attached. ASCE7-16 recommended \( a_p \) with a limit of 2.5. Figures 16–18 show the component amplification factor of pipes with different materials under different ground motions.

Under 0.07 g and 0.2 g, the component amplification factor of all gas risers were similar, and different piping joint arrangements did not cause significant differences in acceleration response between the pipes. The reason was the RC frame was undamaged and the input excitation transmitted to the pipes was small. Under 0.4 g and 0.62 g, the main structure gradually entered nonlinear state and the corresponding input excitation transferred to the pipe gradually increased. It can be found that the GS and the TSS pipes had the smallest \( a_p \) when using epoxy resin as the filler and was the largest when using asbestos cement as the filler. The PE pipe had the largest \( a_p \) when epoxy resin was used as a filler when crossing the floor, and the smallest \( a_p \) was observed when asbestos cement was used as a filler.

When peak ground acceleration (PGA) was small, the amplification effect of the frame structure on the input ground motion was not obvious, and the dynamic response of some pipes was even smaller than the frame structure. The component amplification factor of pipes increased with increasing PGA, and the frame structure significantly amplified the input ground motion. However, until the test end, except for a few of gas pipes, the component amplification factor was still less than the suggested limit in ASCE7-16. Observing the values of \( a_p \) in the figures, it can be found that the cases exceeding the limit of ASCE7-16 were basically combinations of metal pipes with rigid fillers and plastic pipes with flexible fillers. From the results, it is recommended to use flexible fillers with metal pipes and rigid fillers with plastic pipes in areas where strong earthquakes may happen.

The amplitude factor of metal pipes with rigid fillers was greater than that with flexible fillers, and the amplitude factor of plastic pipes with flexible fillers was greater than that with rigid fillers. The vibration of the indoor piping system is very complex and it is difficult to complete the theoretical derivation clearly. Maybe it can be roughly explained as follows:

When the material properties of the pipes are similar to those of the filler, resonance occurs, which amplifies the vibration amplitude. However, when the material properties of the pipes differ greatly from the material properties of the filler, forced vibration caused by structure vibration is dominant.

5. Conclusions

A full-scale two-story RC frame structure with a gas piping system was designed and tested to investigate the seismic performance of indoor gas pipes. A series of full-scale shake table tests were performed by gradually increasing the three ground motions for reaching to the near collapse limit state. The dynamic characteristics and the responses of the model were investigated via the analyzing of shaking table test data and the observed damage. The major findings of this study are as follows:

(1) After the working conditions of 0.62 g, the main structure of the model was seriously damaged, but the piping system remained in good condition. The damage of the piping system was mainly concentrated on the pipe straps.

(2) The first floor of the model structure showed prominent characteristics of weak floors. Damage was concentrated in the first floor. The failure of infilled wall showed obvious shear failure mode.

(3) Different combinations of pipe and filling materials led to significant differences on the seismic responses of the piping system. The amplitude factors of metal
pipes with rigid fillers was greater than that with flexible fillers, and conversely, the amplitude factors of plastic pipes with flexible fillers was greater than that with rigid fillers.

The test results provide some technical support and help for the design of the pipeline. However, because too many factors were considered in the test design, it was difficult to analyze the impact of a certain factor on the piping. Due to the lack of research on gas pipeline, there are still many problems to be further studied.

(a) In order to study the seismic performance of gas pipeline, simple structures and materials should be selected.
(b) At present, there are still many piping joints between pipeline and ground constructed with rigid connections. This gas piping system should be emphatically considered in future experiments and analysis.
(c) The collapse or partial collapse of the structure is a serious threat to the gas piping system, which can also be considered as one of the research contents of the future experiment.
(d) The security threat of the gas piping system is not mainly from earthquake, and the joint action of various disasters is also one of the research contents.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that there are no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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