Seismic Fragility of Water Supply Pipelines under Static and Dynamic Cyclic Loadings

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ABSTRACT
Pipelines are essential for water supply, sewage, fire extinguishing and central heating in buildings. Experimental seismic fragility of commonly-used water supply pipelines in buildings in China, including Polypropylene random copolymer (PPR) pipes and galvanized steel pipes, is investigated through cyclic loading tests on 12 groups of specimens that differ in diameter, wall thickness and water pressure. Each group included six identical specimens, three of which were subjected to static loading and the other three dynamic loading. A total of 72 cyclic-loading tests was performed. Both static and dynamic loading are conducted to investigate the influence of loading speed on the behavior of the pipe joints. The results show that the PPR pipes can sustain much larger deformation before they break under static loading than under dynamic loading, whereas the steel pipes exhibited the opposite. Fragility curves of the pipe joints are generated based on the test results, which can be used to assist the damage assessment of water supply pipes in buildings.

KEYWORDS: nonstructural components, PPR pipes, galvanized steel pipes, pipe joints, dynamic loading

1. INTRODUCTION
Nonstructural components are important for the functionality of buildings. This is especially true for modern buildings which are usually equipped with sophisticated nonstructural systems for various functions. Past earthquakes have demonstrated the seismic vulnerability of nonstructural systems, including piping systems, which are essential for water supply, drainage, fire distinguishing, gas supply, etc. In the 1994 Northridge earthquake, the damage to the fire sprinkler system and cooling water system in some medical facilities led to water leakage and flooding of rooms, leading to functional loss of the facilities [1]. Similar water damages were reported for the Santiago and Concepcion airports during the 2010 Chile earthquake [2]. Various types of pipes and piping systems have also been subjected to pseudo static or dynamic loading in lab tests. Most researches focus on the joints of pipes, which are usually the most vulnerable parts in a piping system [3, 4]. Large scale shake table tests were also performed on distributed piping systems to simulate the observed pipe damage in earthquakes [5, 6].

In the US, the Federal Emergency Management Agency (FEMA) has recommended seismic measures in FEMA 414 to enhance the seismic performance of pipes and ducts [7]. FEMA E-74 also summarized the damage patterns and their reasons for various types of pipe and proposed enhancement measures [8]. For the purpose of damage assessment and prediction, FEMA P58 provided fragility curves of various types of piping for cold, hot and water, steam, and drainage. The fragility data were obtained from either experimental results or expert judgement [9]. In China, the study on the seismic performance of nonstructural components is still very limited. There is yet no specific study on the seismic fragility of piping in the buildings in China. This paper presents an experimental study on the seismic fragility of water supply pipe joints for buildings in China. Special attentions are paid to the dependence of the deformation-sensitive behavior of the pipe joints on the loading speed.

2. TEST SPECIMENS AND TEST SETUP
In China, polypropylene random copolymer (PPR) pipes are widely used for the water supply system of hot and
cold water in multi-story buildings. Galvanized steel pipes are mainly used for the water supply for fire distinguishing system and central heating system [10]. The fundamental parameters of the specimens in the tests are summarized in Table 2.1. A total of 12 groups of specimens that are different in pipe material, diameter (D), thickness (t) and water pressure are prepared. There are six identical specimens in each group, three of which are subjected to static cyclic loading with increasing amplitudes, while the other three to dynamic cyclic loading. Each specimen is T-shaped, and is consisted of a T joint in the middle and a segment of straight pipe on each side of the joint (Fig. 2.1). For the PPR specimens, the straight pipes and the T joint are joined by heating both the joint and the pipe using a fusion welding iron. When welded, the two parts can be joined together to become one. For the galvanized steel specimens, the straight pipes and the T joint are jointed by threaded connections.

Table 2.1 Specimen parameters

<table>
<thead>
<tr>
<th>Group No.</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td></td>
<td>Polypropylene random copolymer (PPR)</td>
<td>Galvanized steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>40</td>
<td>50</td>
<td>75</td>
<td>40</td>
<td>50</td>
<td>75</td>
<td>50</td>
<td>75</td>
<td>42.4</td>
<td>48.3</td>
<td>76.1</td>
<td></td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>3.7</td>
<td>4.6</td>
<td>6.8</td>
<td>3.7</td>
<td>4.6</td>
<td>6.8</td>
<td>5.5</td>
<td>6.9</td>
<td>10.3</td>
<td>3.5</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

The far ends of the straight pipes in a specimen are connected to pin supports, which are fixed on a strong steel beam that is anchored to the strong floor of the lab as a test bed. The distance \( L \) between the two pin supports are adjusted for specimens of various diameters to keep the shear span-to-depth ratio \( L/(2D)=5 \). The foot of the T joint in the specimen is connected to a 500 kN dynamic actuator through a connection pipe, a load cell and a sliding pad in series. The sliding pad slides along a pair of linear rails on the steel beam. One end of the actuator is bolted to a reaction stub on the bottom steel beam and the other end is bolted to the sliding pad. The test setup is depicted in Fig. 2.1.

Before loading, the specimen is filled with water and pressurized by an electric pump through an outlet on the connection pipe. The T joint is then driven by the actuator to move horizontally along the axis of the connection pipe so that the joints between the T joint and the straight segments are bent. The loading is controlled by the horizontal displacement of the T joint. The loading protocol suggested by FEMA 461 [11] is adopted. Two cycles of loading are performed for each amplitude, and the current amplitude \( a_i \) is 1.4 times the previous one, \( a_{i-1} \). The amplitude for the initial step is \( 1/500 \ L \) for all specimens. The loading protocol for static loading is depicted in Fig. 2.2. Sine waves of the same protocol of displacement amplitudes and of a frequency of 1 Hz are used for dynamic loading.
The horizontal displacement of the T joint was measured by a displacement transducer behind the specimen and the force on the specimen was measured by a load cell that is put in series with the connection pipe. Another two pairs of miniature displacement transducers were mounted on the two pipe-to-T joint connection joints. The displacement data of each pair of transducers were then used to calculate the joint rotation, \( \theta \), which is used as the demand parameter in evaluating the fragility function. In addition, a water pressure sensor was installed on the connection pipe to monitor the water pressure inside the pipe (Fig. 3.2).

Two damage states (DS) are defined to categorize the damage observed for the pipes. The DS1 is deemed to initiate when the specimen starts to leak, and the DS2 is deemed to initiate when continuous leakage is observed or the water pressure drops to below 80% of the initial pressure. For most specimens of either PPR or galvanized steel, the breakage of the pipes in the test was sudden and the two damage states initiated almost simultaneously. Although a total of 54 PPR specimens are tested, only 48 were damaged as intended while the other 6 broke unexpectedly at the connection pipe. Among the 48 specimens, 44 exhibited sudden brittle fracture of the straight pipe immediately outside the T joint and the water pressure dropped to zero quickly (Fig. 3.1(a)). Among the other four specimens, all of which were subjected to static loading, two of 75 mm diameter fractured in the T joints (Fig. 3.1(b)), two exhibited gradual pullout of the straight pipes from the T joints (Fig. 3.1(c)), which suggests quality defects in the fusion connection.

On the other hand, a variety of failure patterns were observed in galvanized steel specimens. Among the 18 specimens, five failed because of brittle fracture of the T joints (Fig. 3.2(a)), eight fractured at the thread of the straight pipes immediately outside the T joints (Fig. 3.2(b)), and the other five, all of which are of 76.1 mm diameter, exhibited gradual pullout of the straight pipes after the threads were worn, in which case the water pressure dropped more gradually than in other cases (Fig. 3.2(c)). In addition, the pipe diameter seems to have a significant effect on the failure patterns of the galvanized steel specimens. The T joint fracture predominated the failure of the 42.4 mm diameter specimens; the pipe fracture predominated that of 48.3 mm specimens; while the pullout of worn thread predominated the 76.1 mm diameter.
Although the loading speed had little effect on the failure patterns of the specimens, either PPR or galvanized steel, it did make a difference in the hysteretic behavior and deformability of the joints. The galvanized steel specimens exhibited considerable plastic deformation before DS2 was initiated. Both the strength and deformability are much larger under dynamic loading than those under static loading.

Fig. 3.3(a) and (b) compare the hysteretic curves of two identical galvanized steel specimens but subjected to different loading speed. The moment immediately outside the T joint, $M$, is simply taken as $PL/4$, where $P$ is the force measured by the load cell. The maximum moment is 3.42 kN\cdot m under static loading, while it is 5.36 kN\cdot m under dynamic loading, a 57% increase in strength. This can hardly be explained by the strain rate effect in increasing the steel strength. In addition, the maximum rotation before DS2 is 0.023 rad. under dynamic loading, much larger than the 0.012 rad. rotation under static loading.

The opposite effect of load speed was observed for the PPR specimens. Fig. 3.3(c) and (d) compare the hysteretic curves of two identical PPR specimens but subjected to different loading speed before DS2 was initiated. The maximum moment is 0.50 kN\cdot m under static loading while it is only 0.28 kN\cdot m under dynamic loading. The maximum rotation before DS2 is 0.183 rad. under static loading while it is only 0.096 rad. under dynamic loading.

**4. FRAILITY CURVES**

The fragility functions of the specimens for DS2 are generated following the method described in FEMA P58. The
joint rotation $\theta$ is taken as the demand. The fragility function, $F(\theta)$, is expressed as Eq. 4.1.

$$F(\theta) = \Phi \left( \frac{\ln(\theta/\sigma)}{\beta} \right)$$  \hspace{1cm} (4.1)

where $\Phi$ is the standard normal cumulative distribution function, $\sigma$ is the mean of the demand at which DS2 is likely to initiate, and $\beta$ is the dispersion.

$\sigma$ and $\beta$ are given by Eq. 4.2 and Eq. 4.3, respectively.

$$\sigma = e^{\left( \frac{1}{M-1} \sum_{i=1}^{M} \ln(\theta_i) \right)}$$  \hspace{1cm} (4.2)

$$\beta = \sqrt{\frac{1}{M-1} \sum_{i=1}^{M} \left( \frac{\ln(\theta_i)}{\sigma} \right)^2 + \beta_u^2}$$  \hspace{1cm} (4.3)

where $\theta_i$ is the demand for each tested specimen; $M$ is the number of specimens tested, $M=3$ in this test; $\beta_u$ accounts for the uncertainty associated with quality of the test data to represent the true condition of the components in buildings. $\beta_u$ is taken as 0.25 following the suggestion by FEMA P58 [9].

The results are summarized in Table 4.1 and the corresponding fragility curves are depicted in Fig. 4.1. The groups P1 and P4 under static loading is unavailable because of unsuccessful test. The results show that the deformability of the pipes decreases for larger diameters. The PPR pipes exhibited much larger deformability than the galvanized steel ones. It is also worth noting that the deformability of PPR pipes is much smaller under dynamic loading than that under static loading, whereas the deformability of galvanized steel pipes increases under dynamic loading.

<table>
<thead>
<tr>
<th>Group No.</th>
<th>P1</th>
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<th>P9</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(%)</td>
<td>Static</td>
<td>17.3</td>
<td>15.4</td>
<td>-</td>
<td>14.8</td>
<td>13.3</td>
<td>25.2</td>
<td>18.6</td>
<td>15.0</td>
<td>1.8</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Dynamic</td>
<td>16.1</td>
<td>10.3</td>
<td>7.0</td>
<td>15.3</td>
<td>9.4</td>
<td>8.3</td>
<td>16.0</td>
<td>13.9</td>
<td>6.8</td>
<td>2.1</td>
<td>2.2</td>
<td>2.1</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Static</td>
<td>-</td>
<td>0.30</td>
<td>0.25</td>
<td>-</td>
<td>0.26</td>
<td>0.33</td>
<td>0.28</td>
<td>0.25</td>
<td>0.30</td>
<td>0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>Dynamic</td>
<td>0.26</td>
<td>0.28</td>
<td>0.30</td>
<td>0.26</td>
<td>0.25</td>
<td>0.26</td>
<td>0.25</td>
<td>0.26</td>
<td>0.26</td>
<td>0.32</td>
<td>0.30</td>
<td>0.30</td>
</tr>
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</table>

Assuming that the mean demand of a pipe is a function of its diameter which has the form of $\theta=x/D$. The assumption is simplistic and the water pressure and pipe thickness did have an effect on the fragility of the pipe joints. However, more test data are necessary before these factors can be appropriately taken into account. The coefficient $x$ in the assumed function is found for each type of the pipes by minimizing the square error.

For PPR pipes, the functions are given in Eq. 4.4.

$$\theta = 10/D \text{ for static loading} \hspace{1cm} (4.4a)$$

$$\theta = 6/D \text{ for dynamic loading} \hspace{1cm} (4.4b)$$

For galvanized steel pipes, the functions are given in Eq. 4.5.

$$\theta = 0.7/D \text{ for static loading} \hspace{1cm} (4.5a)$$

$$\theta = 1.1/D \text{ for dynamic loading} \hspace{1cm} (4.5b)$$

For all specimens, 0.3 can be taken as an approximate estimate for the dispersion $\beta$. Fragility curves for pipes of other diameters can be obtained by the above equations and $\beta=0.3$. 

Table 4.1 Fragility function parameters
Figure 4.1 Fragility curves for (a) thin wall PPR pipes of 0.6 MPa pressure, (b) thin wall PPR pipes of 1.0 MPa pressure, (c) thick wall PPR pipes of 1.0 MPa pressure and (d) galvanized steel pipe joints.

Fig. 4.2 compares the mean demand obtained in the test with the above equations. The square of Pearson product moment, $R^2$, is also given in the figure. It is worth noting that Eq. 4.5b yields a very low $R^2=0.06$, which corresponds to the fact that the test data suggest no trend of decreased deformability with the increase of the diameter for galvanized steel pipes under dynamic loading. This equation should be used with caution and more test data are necessary to improve the understanding.

Figure 4.2 Relationship of pipe diameter and mean demand for DS2

5. CONCLUSIONS

A series of pipe joints of various diameters, wall thicknesses, pressures and material were subjected to either static or dynamic cyclic loading to assess the deformability of water supply piping system. Most PPR specimens fractured at the pipes immediately outside the fusion connection, whereas the galvanized steel specimens with threaded connections exhibited a variety of failure patterns including pipe fracture, T-joint fracture and thread
pullout. The loading speed has a significant influence on the cyclic behavior of both PPR and galvanized steel specimens. The PPR specimens failed at much smaller deformation under dynamic loading, while the galvanized steel specimens can sustain larger deformation under dynamic loading. Fragilities of the pipes that are generated with the test data show that the pipe diameter and loading speed are the two main factors that influence the performance of the pipe joints. Equations for estimating the fragility function parameters are also suggested based on the test data.

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