Axial Behavior Characteristics of Pipe Joints Under Static Loading

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Research Objectives

The objective of this study is to perform physical testing on pipe joint segments to determine the axial static load behavior characteristics of various types of pipe joints typically used in both above ground and buried piping systems. The pipe joints considered include cast iron, steel, and ductile iron bell and spigot joints as well as newer types of restrained joints, and other types of pipe materials such as PVC and polyethylene. This effort is part of an overall research project to determine the dynamic behavior characteristics of pipe joints and to develop fragility information and risk assessment data.

Damage reports from past earthquakes have clearly revealed that buried and above surface pipelines are prone to severe damage in areas of strong shaking. Given the vital importance of this infrastructure system, understanding how pipe and pipe joints respond during an earthquake is a necessity. The proposed testing is the first phase of an overall research project designed to determine the static and dynamic strength characteristics of pipe joints, and to develop fragility information and risk assessment data. Such information is critical to determine potential damage of piping systems when subjected to seismic motion. Among the many well-documented pipeline failures under earthquake loading, a few important studies have been selected and summarized below.

O’Rourke (1996) reviewed the performance of and damage to pipelines following various earthquakes. In the 1989 Loma Prieta earthquake, the major damage was concentrated in areas of liquefaction such as the Marina district in San Francisco. San Francisco, Oakland, Berkeley, and the Santa Cruz area had almost 600 water pipeline failures. In the 1994 Northridge earthquake, over 1,400 failures were reported including 100 failures to critical large diameter pipelines. In the 1995 Kobe earthquake, as many as 1,610 failures occurred in distribution water mains and 5,190 failures occurred in distribution gas mains.
Trifunac and Todorovska (1997) reported on a detailed investigation of the amount of pipe breaks that occurred in the Northridge earthquake. They concluded that the “pipe breaks correlate well with the recorded amplitudes of strong ground motion....”. They presented empirical equations which related the average number of water pipe breaks per km of pipe length with the peak strain in the soil or intensity of shaking at the site.

O’Rourke and Palmer (1996) reviewed the historical performance of gas pipelines, steel and plastic, in southern California over a 61 year period. Statistics are provided for 11 major earthquakes starting from the 1933 Long Beach earthquake up to the 1994 Northridge earthquake.

Iwamatu et al. (1998) and Kitaura and Miyajima (1996) documented failures and the failure rate (per km) in the 1995 Kobe earthquake. These researchers provided a comprehensive summary of pipeline damage in terms of pipe material type, joint types, and the failure mechanisms that were observed. They reported that the majority of pipeline failures were at the joints, and the predominate modes of failure were slip-out of the joints and the intrusion of the spigot into the bell. For this reason, the emphasis of this testing is on axial loading behavior (compression and tension).

A thorough survey of the literature reveals that laboratory tests on pipe joints are limited. Singhal (1984) performed a number of static experiments on bell and spigot rubber gasketed joints to determine their strength and stiffness characteristics. The joints were subjected to axial and bending loading. In some tests, the joints were encased in a “sand box” that allowed the soil-pipe interaction and overburden pressures to be included. The author provided failure criteria in terms of deformations for various sizes of pipes. Wang and Li (1994) conducted studies on the damping and stiffness characteristics of conventional ductile iron pipe joints subjected to dynamic cyclic loading.

The documentation and results of this project will be useful to several different groups. Other researchers involved with physical testing of pipelines will be able to benefit from the methodologies and procedures that have been developed and used for this project. Manufacturers of pipe and joint restraint systems will have information on the behavior characteristics of their product. It will also benefit those who intend to consider using polyethylene pipe to replace conventional pipe material normally used for water supply. The project results will enable pipeline designers and manufacturers to effectively quantify the merits of relatively new products such as pipeline joint restraints and polyethylene pipe. Furthermore, pipeline owners can use fragility information and risk assessment data developed by this project to determine regions within their service area that may be vulnerable to damage from earthquakes. This will help them with upgrade and retrofitting plans of their piping systems.
This paper presents the initial pipe joint test results for a variety of pipe materials including ductile iron, welded steel, cast iron, PVC, and polyethylene. For ductile iron pipe, two different joint restraints were tested:

- reinforced gasket
- bolted restrained collars.

Figure 1 shows a sketch of a ductile iron pipe provided with bolted collar restraints. Details on the testing, configuration, loading procedures, and test results are described with accompanying plots and graphs.

Overview of Testing

The testing procedure used for this project consisted of developing a method of applying an axial load (compression and/or tension) to a pipe joint and recording the pipe barrel strains and the load-displacement relationship. Initially, a series of compressive loading tests (Phase I) were conducted on ductile iron pipe joint specimens in order to establish the range of axial load capacity for various diameters of pipe. This test series was conducted using a SATEC compression testing machine. The second phase (Phase II) of this testing consisted of applying compression and/or tension loading to pipe joint segments using a self-contained loading frame that was designed and constructed specifically for this testing. More details on this phase of the testing are presented subsequently.

Preliminary Compressive Testing on Ductile Iron Pipe Joints (Phase I)

In this testing phase, the ends of the ductile iron bell and spigot pipe joint segments of different diameters were milled to achieve smooth end surfaces. The specimens were placed in our SATEC compression testing machine and loaded until noticeable fracture occurred. The pipe sizes tested were 4”, 6”, 8”, and 10” diameter. The load-displacement values were electronically recorded and stored using a Megadac data acquisition system. The results of the testing are shown in Figure 2. It can
be seen that, except in the case of 8 inch diameter pipe, there are measurable amounts of seating distance that had to be overcome before the joints exhibited any resistance to load. As expected, the strength of pipe joints is proportional to the pipe diameter. At the end of the tests, one specimen was cut in half longitudinally to observe the failure mechanism (Figure 3). The failure mechanism can be described as a telescoping of the spigot end into the bell and a subsequent buckling and fracture of the spigot end.

Test Setup and Loading Configuration (Phase II)

A self-contained steel loading frame was designed and fabricated (Figures 4 and 5) that allows an actuator to apply axial compression and/or tension load to a test specimen without the use of reaction blocks. The loading and the anchoring setup were designed to readily accept various diameters of pipe specimens and to assemble them within a reasonable amount of time. Axial load, both in tension and compression, can be applied in incremental displacement control by an MTS 450k hydraulic actuator. Table 1 provides a list of the tests undertaken using this loading setup. Several pipes of one single pipe size of 8 inch diameter were tested.

The information obtained from testing included load-displacement characteristics of the joint assembly and strains on the pipe barrel. Typically, at some level of loading, noticeable fracture and buckling occurred, indicating pipe failure. However, failure in a pipeline is governed by the leakage which possibly can occur at some point well before fracture. A generalized criterion for leakage failure may be defined as “substantial
Axial Behavior Characteristics of Pipe Joints

and continuous leakage.” To detect such leakage failure, the test setup used completely sealed pipe joint specimens that contained water under a small pressure head (3-4 psi). A noticeable drop in water pressure and an observable amount of water leakage indicated leakage failure. The water pressure was monitored and correlated with the load and displacement values to determine load level at leakage.

Load-Displacement Behavior (Phase II)

Figures 6 through 11 provide the plots of load-displacement data recorded in Phase II testing. Tension loads were applied only to joints that were capable of resisting tension. These cases included two ductile iron pipes with joint restraints (Figures 7 and 8), welded steel pipe (Figure 9), and polyethylene pipe (Figure 11). The compressive capacity of the cast iron, ductile iron, steel, PVC, and polyethylene pipe can be interpreted from the plots as 460 k, 250 k, 85 k, 3 k, and 68 k, respectively. Similarly, the tensile capacity of ductile iron pipe with reinforced gasket, ductile iron pipe with bolted collars, welded steel, and polyethylene pipes are 125 k, 52 k, 125 k, and 52 k, respectively.

Conclusions/Future Research

This testing program establishes axial behavior characteristics and leakage failure levels due to axial (tensile and/or compression) static loading for several different types of pipe material and pipe joints. Static testing will continue for other diameters of pipe. Information gained, especially failure loads, can be used in the design of the next phase of our testing which will use shake-table testing to simulate dynamic loading.

Table 1. Test Matrix Describing Various Pipe Material and Joint Types (Phase II)

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter</th>
<th>Joint Type</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Cast Iron (see Figure 6)</td>
<td>8 in</td>
<td>Bell-spigot, lead caulked</td>
<td>Compression load only; fracture occurred in barrel; no distress in bell</td>
</tr>
<tr>
<td>Ductile Iron (see Figure 7)</td>
<td>8 in</td>
<td>Bell-spigot, reinforced gasket</td>
<td>Tension load only; max. load = 125 k; ultimate failure of metal teeth in gasket</td>
</tr>
<tr>
<td>Ductile Iron (see Figure 8)</td>
<td>8 in</td>
<td>Bell-spigot, bolted restraining collar</td>
<td>Tension load only; max. load = 52 k; fracture at collar wedge screw holes</td>
</tr>
<tr>
<td>Steel (see Figure 9)</td>
<td>8 in</td>
<td>Bell-spigot, lap welded</td>
<td>Bi-directional load; fracture occurred in barrel; weld joint very ductile; severe buckling at bell</td>
</tr>
<tr>
<td>PVC (see Figure 10)</td>
<td>8 in</td>
<td>Bell-spigot, push-on rubber gasket</td>
<td>Compression load only; spigot extruded into bell end; water seal maintained; no fracture; max. load = 3 k</td>
</tr>
<tr>
<td>Polyethylene (PE) (see Figure 11)</td>
<td>8 in</td>
<td>Butt-fused</td>
<td>Bi-directional load; fused joint remained ductile; severe buckling of pipe; fracture occurred at end flange</td>
</tr>
</tbody>
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“The project results will enable pipeline designers and manufacturers to effectively quantify the merits of relatively new products such as pipeline joint restraints and polyethylene pipe.”
References


