Author

Brian Olson's advice to future researchers is to find a project you enjoy, one that will keep you motivated throughout the life of your project. In keeping with his own advice, Brian became involved in this project: the design and testing of new bracing elements for suspended piping systems—elements that are better designed for withstanding seismic stresses, such as those applied in an earthquake. After receiving his B.S. degree, he started working with a consulting structural engineering firm, and he intends to pursue his Professional Engineer's license and a master's degree. Brian is also an avid fencer and has been eligible to attend the Summer National Championships two years in a row.

Key Terms

- Accelerometers
- Compression Spring
- Coupling
- Diaphragm
- Floor Level Motions
- Peak Horizontal Floor Acceleration
- Shake Table

Double Bracing Element for Reducing Seismic Demands to Suspended Piping Systems

Brian Olson
Civil Engineering

Abstract

Suspended piping systems are vulnerable to large displacements and accelerations resulting from seismic loading. Rigid bracing can accommodate seismic loads, but increased stiffness may result in larger forces, which can cause system failure. In this study, a special bracing element was designed to accommodate the seismic load, while leaving enough flexibility in the system for the resulting displacements. A no-hub cast-iron drain pipe was tested and analyzed under the effects of different simulated floor level accelerations. Connections were tested to establish an acceptable level of displacement, and to measure the force associated with this displacement. A preliminary tension-compression ("double") spring brace design was tested and compared with test results from a rigid-braced system and an unbraced system. Two different springs were tested and compared to determine brace performance with changing system stiffness. For this study, only transverse loading of the pipe was considered. The results show that increasing stiffness generally reduced the displacement and increased acceleration experienced by the braced section of pipe. These results substantiate the potential use of double spring designs to mitigate seismic demands on suspended piping systems.

Faculty Mentor

Brian's research touches on a subject area that has received limited attention by the earthquake research community. Namely, he focused on developing a mechanism for reducing seismic demands to suspended piping systems. Damage to piping systems during past seismic events has resulted in closure and eventual loss of entire structures, due to loss of functionality or extensive interior building water damage. Brian's solution for minimizing these effects is simple enough to be implemented quickly in the field, yet reliable enough to assure the response of these particular elements will be reduced during the next strong earthquake. His research methodology is well validated with component tests (to design the bracing solution) and shake table tests, using measured ground motions and a model suspended piping system.

Tara C. Hutchinson
Henry Samueli School of Engineering

Introduction

Modern design practices in structural engineering typically minimize the potential for structural failure of essential facilities following seismic events. However, failure of non-structural elements, such as piping systems, can render these facilities inoperable. When unrestrained, suspended piping systems can undergo significant displacements, resulting in impact with the structure or failure of the connections between elements. Figure 1 shows a section of pipe that separated following the Loma Prieta Earthquake of 1989. The vertical pipe stub and elbow are no longer connected; an example of local joint failure.

Figure 1
Failed joint connection following the Loma Prieta Earthquake. National Information Service for Earthquake Engineering photo.

The traditional solution to handling seismic load on suspended piping systems is to install rigid bracing, with a capacity determined through static analysis of the system. Rigid braces consist of short sections of thick walled pipe bolted to a floor diaphragm and fixed to a section of the suspended pipe (Figure 2). Typically, the diaphragm connection has a pin connection to allow rotation of the rigid brace for installation. The brace is either clamped directly to the suspended pipe or attached to a vertical hanger. Braces are often located at the most vulnerable sections of the pipe (elbows, bends, joints, etc.). Consequently, they have to resist additional forces, such as water pressure, within the pipe. The relatively high stiffness of rigid braces can actually attract more load to the system and localize it to the brace locations. This additional load, applied at the weakest locations, helps to promote system failure rather than prevent it.

Figure 2
Traditional rigid brace. Photo provided by the author.

To combat this effect, non-rigid brace systems have been developed. An example, using tension cables to brace the pipe, is shown in Figure 3. Cables, like rigid braces, are attached to the diaphragm and either directly to the pipe or to its vertical supports. Since compression is not an issue, the cables can be a fraction of the size of rigid braces and have lower stiffness. However, because two cables are required at every location, they require twice the labor for installation. In retrofit operations, the additional space required for the second cable may not be available, severely limiting the application of cable restraints.

Figure 3
Cable stayed bracing. Photo from Mason Industries, Inc.

The intent of this project was to design a brace that addressed both of these concerns. An ideal solution would be a brace that limited displacements by restraining the system, while minimizing the system reaction force. It should be designed to be easy to install, especially in retrofit operations, and be usable in a variety of situations. Additionally, the brace should be able to withstand several seismic events without requiring replacement, minimizing the costs of inspecting every brace after each seismic event.

Okeil and Tung (1995) explored the relationship between ductility of the piping system and the reaction forces induced at its supports. It was found that support reactions decreased as ductility increased for similar pipe displacements. Thus, a more ductile system would experience the same pipe displacement, but less stress than a stiffer system. Bakre *et al.* (2004) tested a mechanical friction damper to reduce the pipe displacements. The device worked, but not as well as analytically predicted.

An alternative design might incorporate a bracing element that would yield under a desired load. This would eliminate the problem of excessive stiffness. However, designing elements to work properly in tension and compression is difficult. Furthermore, if such a design were created, even small changes in field conditions would dramatically change the stiffness of the brace in compression. Upon yielding, the element would no longer restrain the system, and, in the event of aftershocks, the system would be effectively unbraced. While the system may survive an initial earthquake, large magnitude aftershocks could still result in failure. Following an earthquake, all of the yielding elements would need to be inspected and potentially replaced, which could be costly and time consuming, limiting the benefit of a yielding brace element.

Coupling Test

Setup

The coupling was assumed to be the system weak point, which would fail before the cast iron pipe. Therefore, it was necessary to determine the load and deformation capacity of the coupling in an existing piping system. The bracing element was designed to prevent the load or deformation from exceeding these guidelines.

The coupling/bracing element was subjected to a straight monotonic pull by applying a load to a 4” diameter, braced pipe in a Tinius-Olsen (TO) machine. The monotonic response would be similar to the cyclical response of the coupling before inelastic failure. Two couplings were tested simultaneously, and data was recorded for the first connection that experienced failure. Each end of the pipe was connected to another short section of pipe with a coupling. The end sections of pipe were blocked in place with medium density fiberboard (MDF) and clamped down. This established a connection that was essentially fixed, preventing rotation of the coupling and transferring the applied load as shear in the couplings. Displacement of the center section relative to the end sections of pipe was recorded by two precision linear potentiometers (PLPs), one located at either end of the short pipe segment. The PLPs used the top of the support beam as a reference. Trial runs showed that the MDF did not noticeably deform (less than .001 in) while the system was loaded, and the end sections did not displace relative to the support beam. The recorded displacement was averaged to account for any minor rotations that may have occurred during the test.

Three serviceability states were observed during testing: leaking of the pipe, buckling of the coupling, and significant leaking or “gushing” of the pipe. Minor leakage following an earthquake would be acceptable until repairs could be made, but catastrophic failure would not. Plastic deformations would cause the coupling to buckle, indicating that it was no longer behaving elastically and was violating one of the underlying assumptions. Leaking and gushing were determined by visual observation. Tests over a catch basin allowed the rate of leakage to be quantified. The coupling test was intended to determine the most probable mode of failure, not to test the system under serviceability conditions.

To establish when the first leak would occur, pipe sections were filled with water. The sections were non-pressurized to simulate drain piping, and there was approximately 18” of hydraulic head on the water in the pipes, the result of having filled the pipe stubs. All connections were checked prior to the start of every test to verify that no leaks had developed. The bolts on the couplings were hand tight, or no tighter than could be accomplished by hand with a wrench. This would be approximately the 60 in-lb specified for the couplings, and a reasonable approximation of field conditions where it is unlikely a torque wrench would be used on every coupling bolt.

Procedure

The TO machine was set to pull at a rate of 0.25 in/min for each test. This allowed failure modes to be observed and accurately documented without stopping the tests. Load and displacement data was recorded for each failure mode. The tests were allowed to run until after the coupling started to weaken—when additional displacement resulted in reduced loading. This was primarily a safety concern to prevent sudden failure of the system and possible damage to the equipment or injury to observers. The TO machine was then reversed, typically at a much higher rate, to unload the couplings and determine the plastic displacement that had occurred in the couplings.

Analysis and Discussion of Results

The load-displacement graphs for all five tests followed the same general trends. Figure 4 shows the Load vs. Displacement plots for all five tests and the three different failure modes. Figure 5 depicts the secant stiffness from the origin to the failure point of the coupling for each test. The

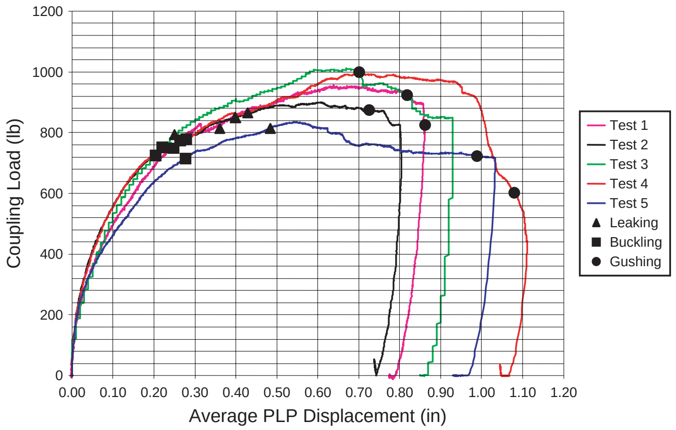

Figure 4
Load/Displacement plots

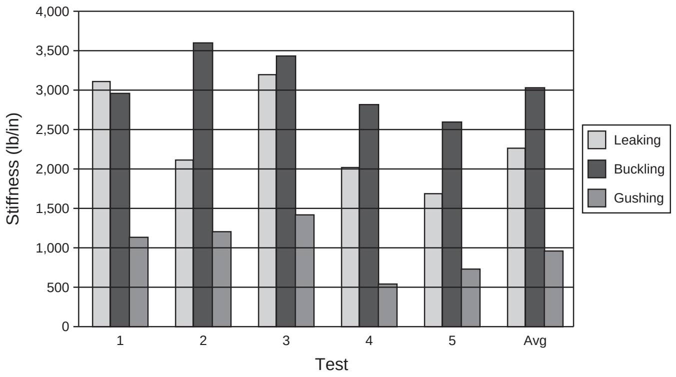

Figure 5
Average coupling stiffness at service criteria

initial stiffness of each system was approximately the same up to 250 lbs and 0.02 in of displacement. As more load was applied, the coupling stiffness degraded. At approximately 750 lbs of applied load per coupling and 0.25 in of displacement, buckling started to occur. This was consistent from test to test, with a standard deviation of 0.03 in. Leaking generally occurred at or before the load reached a plateau, with displacement varying from 0.25 to 0.67 in. Gushing was scattered with respect to both load and displacement. Because leaking could happen virtually anywhere on either of the couplings, and because of the risk of sudden failure, it was not possible to measure the flow rate. Engineering judgment was used to determine the difference between gushing and leaking, which could be a source of much of the scatter in the observed failures. Plastic distortion was very large, as evidenced by the minor displacement recovery during unloading. Visual observation of the couplings confirms that significant displacement did occur in the coupling (Figure 6). Evidence of buckling of the metal coupling can be seen in the profile view of the connection, which also gives an idea of the overall displacement of the coupling's ends.

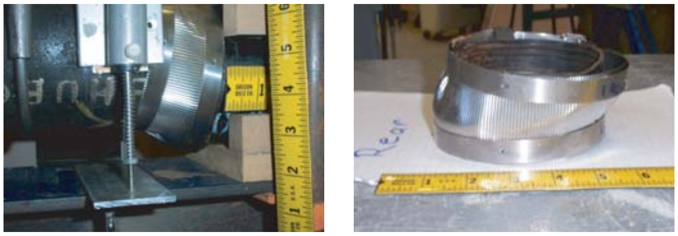

Figure 6
Deformation of the coupling following testing

In Test 4, there was evidence of strain softening. During this test, the pipe was allowed to continue displacing until gushing occurred. At the end of the yield plateau, the connections rapidly lost strength as they were subjected to increased displacements. Once gushing occurred, the connection was quickly unloaded to prevent catastrophic failure.

Test results indicated that buckling was the dominant failure mode for the connection; it typically occurred before both leaking and gushing. Buckling was also the most consistent measure of load and displacement at failure. Testing established loads and displacements for the different failure criteria identified for the connection. Having established a failure mode and corresponding load and displacement, the proposed brace would be designed to prevent the connection from approaching failure levels.

Spring Brace Testing

Brace Design

This work tested the merit of using springs to control the stiffness of the brace. Springs with stiffness lower than that of rigid pipe could be used, and their stiffness would be independent of the length of the brace. A system of springs could give the same stiffness whether the brace was in tension or compression. This would require only one brace to be installed at every location, an ideal solution for retrofit operations. By replacing springs, the stiffness could be adjusted for varying load levels. A prototype was created using one compression spring to provide resistance as the brace was extended and compressed (Figure 7). Figure 8 is a schematic of the components that make up the spring brace. The spring is restrained by bolts that can only travel

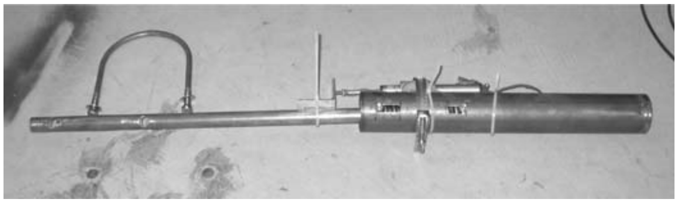

Figure 7
Spring brace prototype

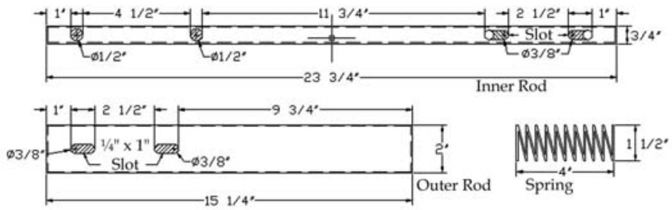

Figure 8
Spring brace schematic

within a set of slots. As the brace is extended or compressed, one of the bolts encounters the edge of the slot and is restrained. The other bolt is free to move and compress the spring. The stiffness is equal whether the brace is extending or contracting, because the same spring is compressed whether the element is in tension or compression.

Using one spring simplifies both the mechanics and the manufacture of the brace. With fewer parts, the materials for the brace are cheaper and easier to assemble. The brace consists of a pair of steel rods and the compression spring. Traditional connections can be used to attach the brace to the diaphragm and to the pipe. The length of the slots regulates maximum displacement; if both bolts are restrained, the spring cannot be compressed and the brace will act as a conventional rigid brace. Selecting springs that will remain elastic under the anticipated loads ensures that the brace will not undergo any plastic deformations, and it can be reused without modification. This spring has a relatively low, adjustable stiffness, can operate both in tension and compression, is no more difficult to install than conventional rigid bracing, and should not require inspection and replacement following every seismic event.

Testing Setup

Given the established criteria for joint failure in the system, it was possible to design the brace to limit the amount of load and displacement the joints needed to handle. A series of Floor Level Motions (FLMs), representing a service level event and a life-safety level event, were selected to use in the shake table testing of the piping. The estimated seismic load on the pipe was based upon the response of the diaphragm while subjected to loading. A limiting displacement of 0.5 in horizontal was used. This was determined by checking the displacement of the unrestrained system. There was 0.5 in of horizontal displacement before the pipe stubs encountered the concrete, thus this was deemed a reasonable maximum allowable displacement. Because each pipe was only 9 ft in length, only one brace was used near the middle of the pipe. Typical field spacing is greater than 9 ft on center, but this physical limit was imposed by the diaphragm on the shake table. Braces were attached to the underside of the diaphragm using a TOLCO Figure 980 – Universal Swivel Sway Brace Attachment. The narrower tube was attached to the suspended pipe with a U-bolt and lock nuts. Only one spring stiffness was used during each test. Two different springs, with spring constants of 465 lb/in (SB1) and 912 lb/in (SB2) were tested overall. It was assumed that any brace would be designed for a worst case scenario (a water-filled pipe), but the pipe could be empty during the event. Thus, the brace needed to function properly for both a filled and an empty pipe under the same seismic loading.

For testing of the rigid bracing, the same diaphragm connection was used. The rigid brace (RB) was a piece of 1 in diameter, Schedule 80 steel pipe, 33 in long, and having a tensile and compressive strength more than adequate for the anticipated loads. Connection from the rigid brace to the suspended pipe was made with a TOLCO Figure 1000 – Fast Clamp, for a 4 in pipe and 1 in brace. As a control case, the tests were also run on the system with no bracing installed (NB).

Testing Procedure

The diaphragm was subjected to a series of six separate FLMs, which were obtained from simulated computer models of two different building structures subjected to acceleration traces from the magnitude 6.2, 1984 Morgan Hill, California earthquake and the magnitude 7.2, 2000 Tottori, Japan earthquake (Ray Chaudhuri and Hutchinson, 2004). For the Morgan Hill earthquake, simulations from a four-story rigid building and 16-story flexible building were used. For the Tottori earthquake, only the four-story rigid building was considered. The piping system response was measured using accelerometers, precision linear potentiometers (PLPs), and string potentiometers (String Pots), as shown in Figure 9. Table 1 lists the FLMs in order of increasing peak horizontal floor acceleration (PHFA), which is the largest acceleration recorded at a specific floor level within the building. Peak horizontal floor velocity (PHFV) and peak horizontal floor displacement (PHFD) were likewise recorded. Each FLM was tested three times to study the repeatability of the system response. The data was used to verify the response of the diaphragm and to construct a model of the piping system. Displacements were applied transverse to the length of the piping system. The scope of this study is in this direction only, with load applied perpendicular to the pipe sections. Future experiments will consider testing in the orthogonal direction.

Tests were performed for each of the four different bracing systems: No Brace (NB), Spring Brace 1 (SB1), Spring Brace 2 (SB2), and Rigid Brace (RB). The spring braces were

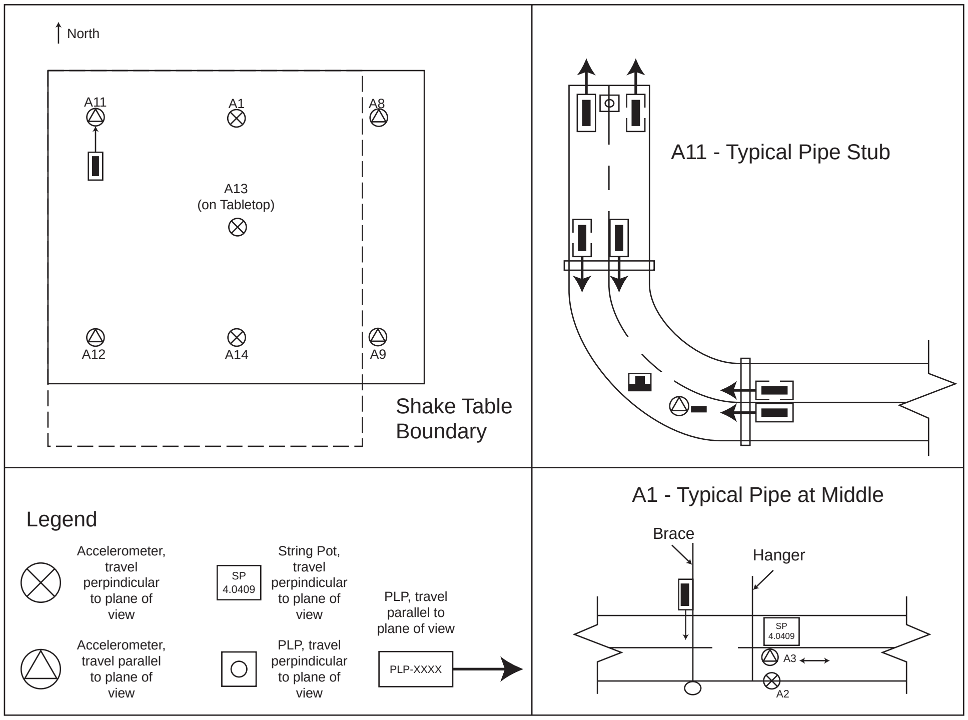

Figure 9
Overview of the instrument layout showing typical details of the instrumentation on the pipe stubs as well as at midspan on the pipes

Table 1
Floor level motions

Motion	Earthquake	Building	Floor	PHFA (g)	PHFV (cm/sec)	PHFD (cm)
1	Morgan Hill	16 story	Roof	0.17	30.59	10.84
2	Morgan Hill	4 story	2nd	0.19	18.08	3.72
3	Morgan Hill	16 story	2nd	0.23	16.30	3.69
4	Morgan Hill	4 story	Roof	0.29	27.55	4.91
5	Tutori	4 story	2nd	1.12	40.16	10.05
6	Tutori	4 story	Roof	1.33	68.01	10.87

fitted with PLPs to record the amount of travel of the spring brace, which could be used to determine whether the springs were operating within their elastic range by estimating the brace reaction force. The same bracing condition (NB, SB1, SB2, RB) was in place on both pipes during each simulation.

Test Results and Analysis

Prior to testing, the ends of the pipe stubs were sealed with firestop and surrounded by mineral wool, as is done in practice. Much of the mineral wool fell out during testing, and the firestop separated from the concrete and the piping. Failure of the firestop and mineral wool was realized after testing, but most likely did not contribute to the overall deflection of the system. This reduced the stiffness at the ends of the system, increasing the deformation of the system as a whole. The firestop and mineral wool were not replaced between each successive test simulation because replacement firestop requires two days to set properly. The deflection of the pipe stubs was controlled primarily by the diameter of the holes in the diaphragm. The load on the pipe stubs would not have caused significant bending in the pipe stubs. Hence, they could displace no more than the amount of clearance in the hole, approximately 0.75 inches in any direction.

The U-bolts used to attach the spring brace prototype to the pipe did not slip across the surface of the pipe. Prior to installation, the pipes were painted. Slippage in the connection would have resulted in scratching and deformation of the pipe surface, but no scratching was evident at the location of the U-bolts. The braces tended to buckle slightly when compressed. Because there is no support for the inner tube of the brace, it is easy for the two tubes to get out of alignment. When this happens, the brace still functions, but the slight shifts may introduce some error into the displacement readings. There is also the possibility that the springs suffered fatigue damage due to the repeated loadings. After the completion of all the tests, the springs had been subjected to about 15 magnitude 7.2 earthquakes from the Tottori motions alone. This is far beyond what a structure could reasonably expect to experience during its design life, and more than the braces were intended to handle. The original intent of the design was to make a brace that could survive three to five strong earthquakes before requiring replacement. This would allow the brace to experience the initial earthquake and several aftershocks that might follow, and still be in a functional condition. A brace designed to withstand 15 earthquakes of over 7.0 magnitude without a loss in performance would be overdesigned, as the probability of that many large earthquakes occurring within the life of a structure is negligible. Some of the error could be attributed to residual strain in the 0.5 in hangers from which the pipe was suspended. The bending stiffness of the hangers was ignored in calculating the stiffness of the system, but does contribute to resisting the horizontal displacements. Due to the large displacements induced by the stronger FLMs, residual strain would start to develop in the hangers, resulting in a nonlinear stiffness for the system.

Table 2 lists averaged displacement and acceleration data collected at the midspan of the pipe from FLM 4. Increasing stiffness in the brace did lead to a decrease in displacement at the midspan of the pipe run. FLM 4 was selected for comparison purposes because it had the greatest PHFA of the Morgan Hill motions; therefore, it represents the most extreme acceleration case. Acceleration data collected from FLMs 5 and 6 were beyond the range of the instruments and were not examined. Future experiments will re-examine the data from Floor Level Motions 5 and 6.

Table 2
Summary of FLM 4 test results

	Average Maximums			
Brace Setup	Displacement at Midpoint (in)	Acceleration at Midpoint *(g)*	Displacement of Brace (in)	Reaction of Brace (lb)
Empty Pipe				
No brace	1.02	0.88	N/A	N/A
Spring: 465 lb/in	0.34	1.22	0.26	120
Spring: 912 lb/in	0.21	1.02	0.14	129
Rigid	0.08	1.36	N/A	N/A
Filled Pipe				
No brace	1.54	1.37	N/A	N/A
Spring: 465 lb/in	0.47	1.05	0.18	85
Spring: 912 lb/in	0.17	0.88	0.11	97
Rigid	0.08	1.50	N/A	N/A
Ratio Filled/ Empty				
No brace	1.51	1.55	N/A	N/A
Spring: 465 lb/in	1.38	0.86	0.71	330
Spring: 912 lb/in	0.82	0.86	0.75	684
Rigid	0.98	1.10	N/A	N/A

The reaction of the spring braces was calculated from the recorded PLP displacement and the stiffness of the spring used. For the empty pipe, the PLP on SB 1 recorded nearly twice the displacement of the PLP on SB 2. SB 2 had a higher calculated reaction by about 8%. For the filled pipe, the PLPs recorded maximum displacements that were 65–75% of those recorded for the empty pipe. The reaction force in SB 2 was about 14% higher than that in SB 1. It was expected that the spring braces would deform more for the filled pipe, when they would be resisting the movement of a larger mass. Based on observations, the brace and the PLP did not fail. The PLPs mounted on the spring braces recorded lower displacements for the filled pipe than the empty pipe for all six FLMs (Figure 10). The maximum String Pot reading at midspan increased for Spring Brace 1 with the filled pipe, and decreased for Spring Brace 2 with the filled pipe. Based on the reduced PLP readings, it was expected that the maximum String Pot reading would also be lower, not greater. As the String Pot directly measured horizontal displacement of the pipe, it was a more accurate measure of displacement than the PLP mounted on the brace, which measured brace elongation/contraction, and could be used to find horizontal displacement indirectly.

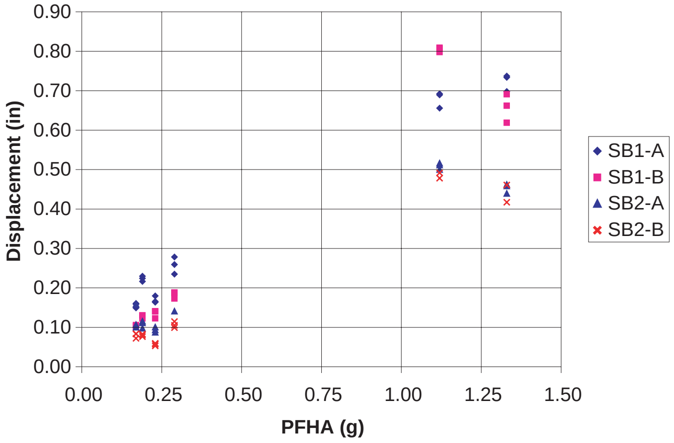

Figure 10
Displacement of the PLP on the spring brace

Table 3 lists displacement ratios for the three iterations of FLM 4. In general, the greater the stiffness of the brace, the less it displaced in comparison with the unbraced system, as anticipated. FLMs 3 and 4 experienced the largest displacement reductions due to bracing. The displacement ratios for FLMs 5 and 6, the strongest of the set, were lower. Having water in the pipe typically increased the displacement of the system, although, for motions 1 and 2, the empty pipe actually displaced more than the filled pipe. This is probably due to the large inertial force of the water in the pipe. Motions 1 and 2 may not have excited the system enough to cause much displacement in the heavier

Table 3
Horizontal displacement ratios from FLM 4

		Pipe A				
Motion	PHFA (g)	NB/RB	NB/SB1	NB/SB2	RB/SB1	RB/SB2
4.1	0.29	10.756	2.864	4.565	0.266	0.424
4.2	0.29	13.171	2.919	5.399	0.222	0.410
4.3	0.29	13.586	3.173	4.773	0.234	0.351

		Pipe B				
Motion	PHFA (g)	NB/RB	NB/SB1	NB/SB2	RB/SB1	RB/SB2
4.1	0.29	19.223	3.286	9.044	0.171	0.470
4.2	0.29	18.554	3.179	8.767	0.171	0.472
4.3	0.29	20.081	3.318	9.437	0.165	0.470

Motion	PHFA (g)	SB1-A/SB1-B	SB2-A/SB2-B	SB1-A/SB2-A	SB1-B/SB2-B
4.1	0.29	0.722	1.247	1.594	2.753
4.2	0.29	0.737	1.099	1.850	2.758
4.3	0.29	0.707	1.337	1.504	2.844

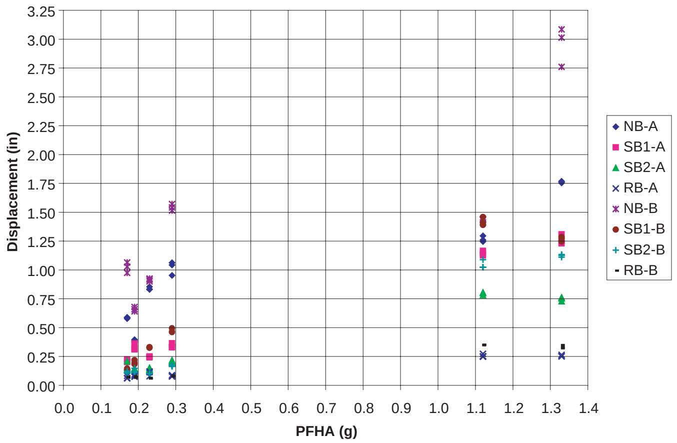

Figure 11
String potentiometer displacement at pipe midspan

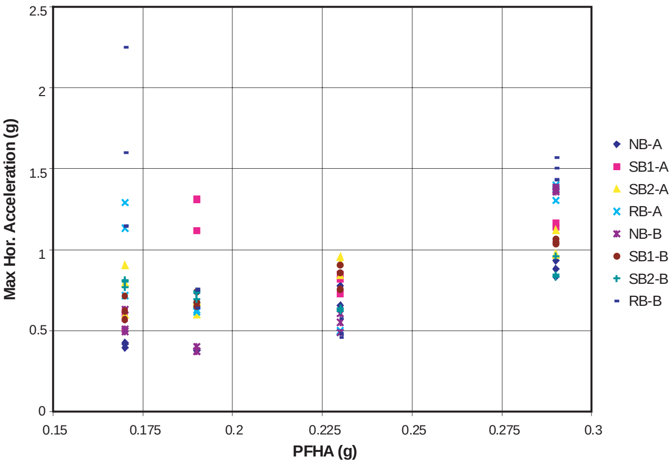

Figure 12
Midspan acceleration maximum accelerations, FLMs 1–4

filled pipe. However, the stronger motions could start the system moving, and the additional force due to the water would cause greater displacements in the system. The stiffer springs had the greatest effect for motions 3 and 4. For FLM 4, the weaker springs displaced from 1.5 to 2.8 times as much as the stiffer springs. At the higher motions, the stiffer springs showed less displacement than the weaker springs, but only by 30% (less for the filled pipe). For springs that were approximately twice as stiff, a 30% reduction in displacement caused the spring reaction to increase by 40%. For all the cases in which bracing was used, the maximum midspan displacement remained under 1.5 in (Figure 11). This is less than the 2.0 in of clearance Malhotra *et al.* (2004) assumed during their test of rigid bracing components. Assuming that 2.0 in of clearance is available, impact with adjacent structural or non-structural elements is not a probable cause of failure if the system is braced. Rather, the concern is the reaction induced in the brace when the system is accelerated. For a given displacement, increased stiffness would result in a larger reaction force. Based upon this, using the weaker spring in the brace is the preferable option. It results in greater horizontal displacement, but still within an amount that can be reasonably assumed to be present. Even though the weaker springs allow more displacement, they still result in a lower brace reaction than the stiffer springs. Systems with rigid bracing do not experience failure from excessive displacement, but from the larger reaction forces caused by the stiffness of the braces.

Table 2 shows the midspan accelerations for empty and filled pipes under the various bracing conditions for FLM 4. The stiffer bracing increased the maximum acceleration of the system. This corresponds to a higher reaction at the brace location, and increased probability of failure. Figure 12 is a graphical comparison of the maximum accelerations recorded at the pipe midspan for the three iterations of Floor Level Motions 1 through 4. Figure 13 shows the

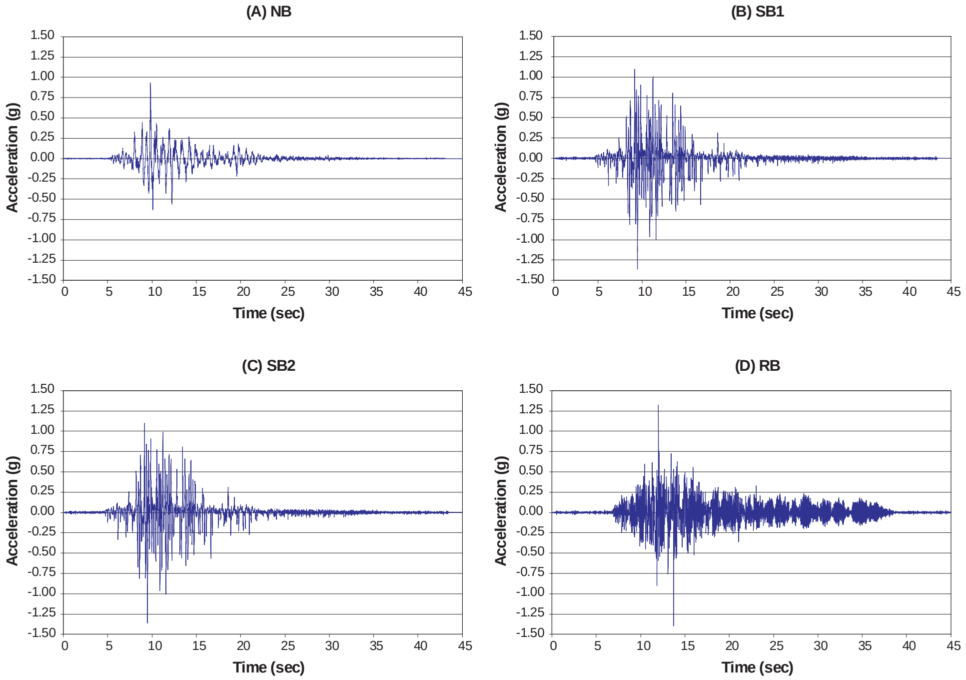

Figure 13
Midspan acceleration time history, FLM 4-2 empty pipe: (A) No Brace, (B) Spring Brace 1, (C) Spring Brace 2, (D) Rigid Brace

acceleration time history for the empty pipe from FLM 4-2 for the four separate bracing conditions. Note that the peak acceleration is highest for the rigid brace, and approximately the same for both spring braces. Thus, increasing the stiffness of the system does appear to increase the maximum acceleration. The similarity between the spring brace accelerations may be due to their relatively similar stiffness when compared to the rigid brace. The change in the shape of the graph for the rigid brace case is also of note. Both spring brace cases show the same relationship as the unbraced case, but with larger magnitudes. The rigid brace has a longer duration and passes through more load cycles. Malhotra *et al.* (2004) determined that one of the causes of system failure is the number of damaging load cycles that the system experiences. The rigid brace caused the pipe to experience more load cycles of higher magnitude than occurred in any of the other time histories. This corresponds to more damaging load cycles and increases the probability of system failure.

Conclusions

Applying a brace to a pipe greatly reduces the seismic induced displacements of the piping system as a whole. However, the reduction in displacement does not increase as rapidly as the increase in brace stiffness, and it is limited by the stiffness of any connections used to secure the brace to the diaphragm and to the pipe. As the stiffness of the brace increases, the acceleration experienced by the pipe system also increases, corresponding to an increase in reaction force in the brace. There is a trade-off between horizontal displacement of the system and system acceleration. Using a non-rigid brace allows the designer to restrict horizontal movement without producing large forces on the bracing elements. Further research may yield an analytical relationship between horizontal displacement and increase in brace reaction force. Using such a relationship, bracing design could be based upon the strength of the section to be braced and the allowable displacement of the section.

The prototype design for the spring braces should be modified to facilitate installation. The current design requires precision machining and installation to function properly. Field installations would be very difficult because even a small variation in field conditions would prevent the brace from being installed properly. Such braces would require special inspection, significantly increasing the cost and reducing their usefulness. The design of the telescoping tubes should also be improved to ensure that the tubes remain concentric while loaded. The prototype design provides only minimal guidance to the tubes, and they can easily come out of alignment. Regardless, this prototype's performance under simulated floor-level seismic loading showed the significant benefit a doubly spring-braced system can have in minimizing seismic deformation demands to suspended piping systems.

Acknowledgements

I would like to extend special thanks to Dr. Tara Hutchinson for agreeing to be a Faculty Mentor for this project. This project would not have been possible without the assistance of Robert Kazanjy, Lab Manager of the Structural Engineering Test Hall at UCI. Thanks are also owed to Dr. Charles Hamilton, Kalil Amin, Pierre Auza, Rebecca Chadwick, Samit Chaudhuri, and Irfan Kalhoro for their work on the related Four Seasons II project. Funding for the project was supplied in part by the Henry Samueli School of Engineering and the Undergraduate Research Opportunities Program at UCI.

Works Cited

Bakre, S.V., R.S. Jangid, and G.R. Reddy. (2004) "Seismic Response of Piping Systems with Isolation Devices." In the Proceeding of the 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada. August 1–6. Paper No. 2676.

Malhotra, Praveen K., P.E. Senseny, A.C. Braga, and R.L. Allard. (2003) "Testing Sprinkler-Pipe Seismic-Brace Components", Earthquake Spectra. Volume 19, No. 1, 87–109. Earthquake Engineering Research Institute, 2003.

Okeil, Ayman M., and C.C. Tung. (1995) "Effects of ductility on seismic response of piping systems and their implication on design and qualification," Nuclear Engineering and Design. Volume 166, 69–83. Elsevier Science S.A., 1996.

Ray Chaudhuri, S. and T.C. Hutchinson. (2004). "Distribution of Peak Horizontal Floor Acceleration for Estimating Nonstructural Element Vulnerability." In the Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, August 1–6. Paper No. 1721. 15 pages.