16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 817 (Abstract ID)

Registration Code: S- V1461900039

SEISMIC PERFORMANCE EVALUATION OF BURIED PIPELINES RETROFIT WITH CURED-IN-PLACE-PIPE LINING TECHNOLOGY

Z. Zhong[1], A. Filiatrault[2], A. Aref[3]

[1] Assistant Professor, Beijing University of Technology, zilanzhong@bjut.edu.cn

[2] Professor, State University of New York at Buffalo & Institute of Advanced Study (IUSS) Pavia, af36@buffalo.edu

[3] Professor, State University of New York at Buffalo, aaref@buffalo.edu

Abstract

Structural integrity of buried pipelines has been significantly compromised due to aging and corrosion, especially for those pipeline that have been in service longer than their design life. Seismic vulnerability and extensive damage to underground lifeline network, causing significant life and economic losses, have been observed and documented in past earthquakes. Seismic retrofit of critical underground pipelines has become an urgent need of our society to improve the performance and serviceability of these critical lifeline systems as well as to enhance public safety. The cured in place pipe (CIPP) lining technology consists of installing flexible polymeric liners with thermosetting resin inside existing pipelines. Compared to traditional expensive and disruptive excavation and replacement of aging and structurally unsound pipelines, CIPP lining technology provides an economic and environmentally friendly alternative for pipeline rehabilitation. However, the lack of verification and quantification of the seismic performance of CIPP liner-reinforced pipelines under transient ground deformations (TGD) remains a critical deficiency in current practice.

An experimental study was performed on water-pressurized ductile iron (DI) pipelines, 150 mm (6.0 in.) nominal diameter and 9.14 m (30 ft.) nominal length, reinforced with two different types CIPP liners commonly used in pipeline rehabilitation. This paper compares the behavior of DI pipelines strengthened with different types of CIPP liner under quasi-static loading and also investigates the seismic responses of CIPP liner-retrofitted pipelines under transient ground deformations induced by seismic wave propagations near the ground surface. The test results indicate that both types of CIPP liner provide substantial longitudinal strength to the joints of DI pipelines and improve significantly their seismic behavior under high intensity transient ground deformation.

Keywords: Cured in place pipe (CIPP); Transient ground deformations (TGD); Lifelines; Seismic retrofit; Strength degradation

1 Introduction

Widespread damage to buried pipelines caused by transient ground deformations (TGD), which are primarily induced by ground wave propagation and scattering near the ground surface, have been documented in the past earthquakes [1-7]. For water supply systems, extensive axial tensile and compressive damages at the pipe joints in the forms of joint pull-out failure, joint compressive telescope and circumferential cracks have been reported by many researchers, especially in regions with adverse soil conditions [8-12]. Wang and Cornell [13] pointed out that for buried pipelines subjected to TGD, the axial strain experienced by the pipelines are much more significant than the bending strain, and the latter is probably negligible in the engineering practice. In addition, water supply systems in the United States consist of a large amount of segmental pipelines made of brittle materials such as cast iron, asbestos and concrete that have been in service for over fifty years [14]. Deterioration of buried water distribution systems caused by corrosion and aging further increases the potential of life- and property-threatening hazards to our society. As a key component of the lifeline networks that maintain the economic well-being of the society, water supply systems is vital to emergency response and recovery of an industrialized city after disastrous events. Therefore, it becomes critical to develop efficient pipeline rehabilitation technologies that can effectively protect buried pipeline against adverse underground environments and improve the structural integrity of buried pipelines.

As shown in Fig. 1, the cured-in-place-pipe (CIPP) lining technology, consisting of installing flexible polymeric liners with thermosetting resin inside existing pipelines, is one of the promising trenchless technologies used in underground pipeline rehabilitation. Compared to traditional expensive and disruptive excavation of aging and heavily damaged pipelines, CIPP liner technology serves as an economic and environmentally friendly alternative with only limited digging at the two ends of the damaged pipeline. Previous experimental evidence confirms that after rehabilitation with CIPP liners, water pipelines with circumferential cracks and defective joints were able to resist repetitive axial loading [15]. However, the composite liner materials used by different manufacturers have significantly different mechanical properties. Current limited experimental study of different types of CIPP liners for seismic design and retrofit of buried pipelines cannot provide sufficient guidance for engineers to select proper CIPPP liner materials for pipeline rehabilitation in active seismic zones. This experimental study were performed on ductile iron (DI) pipeline specimens retrofit with two different CIPP liners that are commonly used in buried pipeline rehabilitation, with specific focus on CIPP lining technology for seismic retrofit of pipelines.

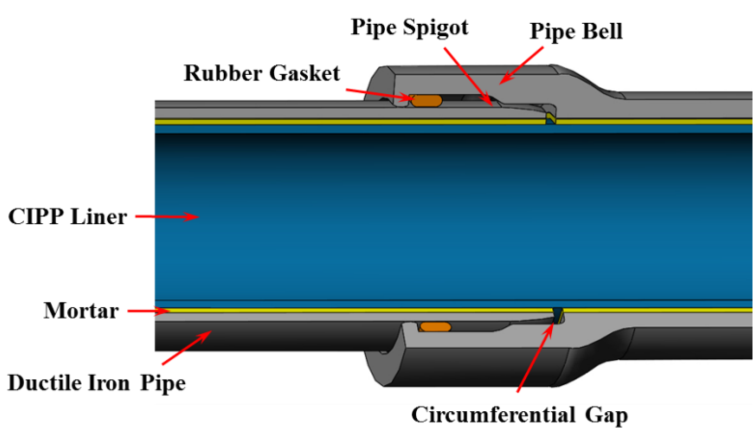


Fig. 1 CIPP lining technology (a) pipeline rehabilitation with CIPP liner (b) cross-sectional view of push-on joint of a ductile iron pipeline reinforced with CIPP liner-

2 Experimental Program

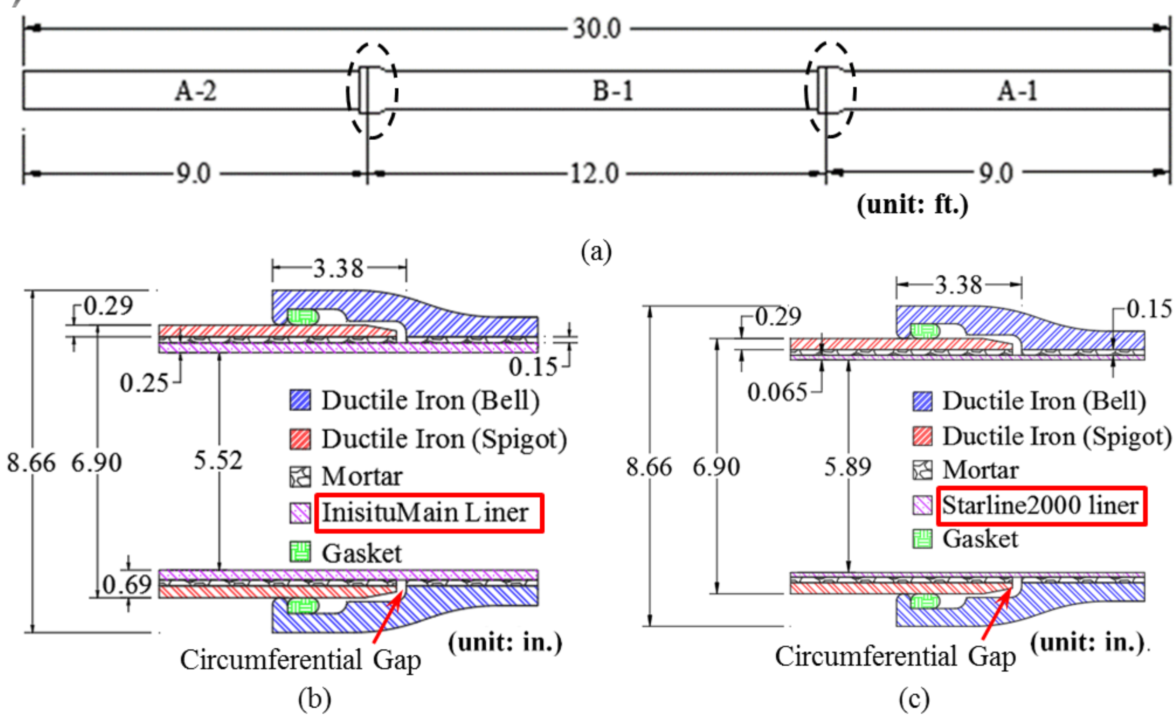
Two sets of full-scale quasi-static and dynamic tests were performed on the double-jointed pipeline specimens (9.14 m nominal diameter, and 150 mm nominal length) that were retrofitted with two types of CIPP liners—namely, the InsituMain® liner and the Starline® 2000 liner. The experiment was carried out utilizing the two re-locatable shake tables in the Structural Engineering and Earthquake Simulation Laboratory (SEESL) of the University at Buffalo (UB). The primary objective was to investigate the behavior and failure mechanism of the pipelines with weak joints or circumferential cracks after reinforced with CIPP liners subjected to quasi-static loading and their seismic performance under transient ground deformations (TGD).

In this experimental study, each pipeline specimen consisted of two push-on joints located at approximately its 1/3 span, as shown in Fig. 2a. A push-on joint is formed by simply inserting the spigot of one pipe segment into the bell of the adjacent pipe. A rubber gasket, pre-installed in the groove of the bell, is then compressed between the inside surface of the bell groove and the outside surface of the spigot to form a watertight seal. In the final installed position, a small gap always exists between the bell of one pipe segment and the spigot of the adjacent one in the push-on joint, as shown in Fig. 2b and c. This gap between the spigot and bell is used in this experimental study to represent the circumferential crack in the many existing underground pipelines due to aging, deterioration or external loadings. After the assembly of the pipeline specimens, the specimens were divided into two groups and reinforced with two different types of CIPP liners: the InsituMain® liner and the Starline® 2000 liner. These two CIPP liners were respectively manufactured by Insituform Technologies, LLC, Chesterfield, MI, and Progressive Pipeline Management (PPM), LLC, West Deptford, NJ. The geometries of a pipeline specimen and the detailed configurations of a typical section of a push joint after retrofit with CIPP liners are shown in Fig. 2. The wall of the DI pipeline specimen used in the tests consisted of three layers: the DI layer, the center mortar liner and the interior CIPP liner, as shown in Fig. 1b. The CIPP liner, applied inside the mortar liner as a reinforcing layer of the assembled pipeline, spanned across the gap of the push-on joint continuously without any trenches. The thickness of the InsituMain® liner is approximately 6.35 mm (0.25 in.). much larger than that of the Starline® 2000 liner (approximately 1.65 mm or 0.065 in.) after installation. Tensile and shear tests were performed on both types of CIPP liner specimens following the ASTM standards [16, 17]. Tables 1 and 2 summarize the mechanical properties of the CIPP liners obtained from the material tests. It can been found that the Starline® 2000 liner exhibits much higher ultimate longitudinal tensile strain than that of the InsituMain® liner.

Table 1 Mechanical Properties of InsituMain® Liner

Longitudinal Direction		Circumferential Direction		Shear Properties	
Longitudinal modulus, E_2 (psi)	481,000	Circumferential modulus, E_1 (psi)	707000	In-plane shear modulus, G_{12} (psi)	221,800
Longitudinal tensile strength, F_{2t} (psi)	6,100	Circumferential tensile strength, F_{1t} (psi)	11,200	Shear strength, F_s (psi)	5,530
Ultimate longitudinal tensile strain, ε_{2t} (%)	2.31	Ultimate circumferential tensile strain, ε_{1t} (%)	2.62	Ultimate shear strain, γ_s (%)	4.02

* 1.0 psi = 6.89 kPa



* 1.0 ft. = 305 mm; 1.0 in. = 2.54 cm

Fig. 2 CIPP liner-reinforced DI pipeline specimens (a) longitudinal dimensions; cross-sectional view of push-on joint reinforced with (b) InsituMain® liner; (c)Starline® 2000 liner

Table 2 Mechanical Properties of Starline® 2000 Liner

Longitudinal direction		Circumferential direction		Shear properties	
Longitudinal modulus, E_2 (psi)	377,000	Circumferential modulus, E_1 (psi)	139,000	In-plane shear modulus, G_{12} (psi)	45.78
Longitudinal tensile strength, F_{2t} (psi)	7,490	Circumferential tensile strength, F_{1t} (psi	2.14	Shear strength, F_s (psi)	1.01
Ultimate longitudinal tensile strain, ε_{2t} (%)	8.09	Ultimate circumferential tensile strain, ε_{1t} (%)	19.41	Ultimate shear strain, γ_s (%)	NA

* 1.0 psi = 6.89 kPa

A series of experiments consisting of both single-joint and double-joint tests were performed on the CIPP-liner-reinforced DI pipeline specimens in the longitudinal direction utilizing the twin shake tables in the SEESL at UB, as shown in Fig. 3. Each 30-ft-long pipeline specimen consisted of two push-on joints located approximately 2.74 m (9.0 ft.) from either end of the pipeline specimen. The central portion of the pipeline specimen was supported and restrained by a central concrete pedestal post-tensioned to the strong floor. For the single-joint tests, the central pedestal was connected to the east shake table using two hollow structural steel (HSS) beams with a cross section of 88.9 mm × 88.9 mm × 6.35 mm (3.5 in. × 3.5 in. × 0.25 in. to stiffen the central pedestal and reduce incidental rotation. One end of the pipeline specimen was restrained to the corresponding shake table with two steel clamps, while the other end rested freely on the other shake table. Both ends of the pipeline were sealed with mechanical end caps, and subsequently the pipeline was pressurized with municipal water before the tests. The internal water pressure was regulated manually during the quasi-static tests to maintain a constant pressure during the tests. Both shake tables were utilized to perform the double-joint tests to simulate a seismic wave propagation across a pipeline with two adjacent weak joints or circumferential cracks. The two HSS beams were removed for the double-joint tests. Each end of the specimen was restrained on one of the shake tables by two steel clamps. The water pressure was regulated only at the beginning of each test and both valves were closed at the two ends of the pipeline specimen during the seismic tests.

Over 100 sensors were deployed along each DI pipeline specimen to measure the pipeline and individual joint response during the tests. Strain gauge sets attached to the outer surface of the pipeline specimens to monitor the axial strain along the specimens. Each strain gauge set consists of four strain gauges, which were installed 90 degrees apart on the outer surface of the DI pipeline specimen at the same circular cross section. Most of the instrumentation sensors were located in the vicinity of the two push-on joints of each DI pipeline specimen. A close-up view of a typical instrumented push-on joint is shown in Fig. 4. Four potentiometers and eight LED sensors of the Krypton K600 Optical Measurement System [18] were placed around the joint to measure the joint opening and rotation in both the axial and transverse directions of the pipeline. Moreover, four string potentiometers were installed close to the joint as secondary instrumentation to measure the axial joint opening in the event that the potentiometers reached their capacity. Four accelerometers were installed close to the joints for the dynamic tests to measure the acceleration changes between the spigot and bell of the joint.

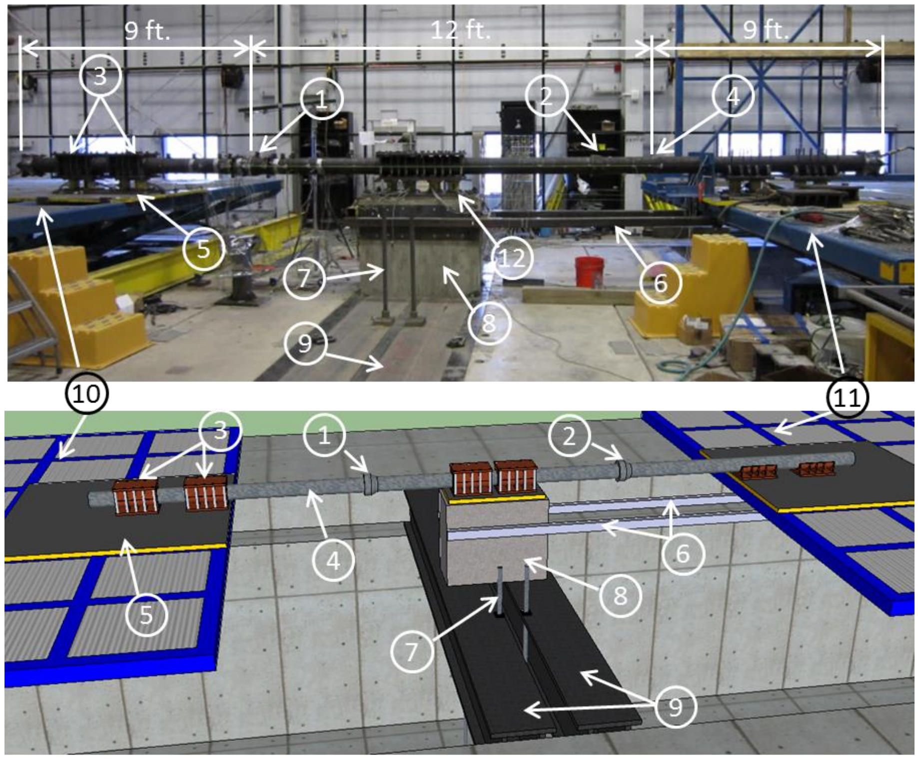
3 Experimental Results

This section compares the performance of the DI pipeline specimens strengthened with the two different types of CIPP liners (the InsituMain® and the Starline® 2000 liners) from both quasi-static tests and seismic tests under two markedly different ground motions (Rinaldi and Joshua Tree ground motions).

3.1 Cyclic Tensile Tests with Different Loading Rates

Two pipeline specimens reinforced with the two types of liners were tested under different loading rates increasing form 15.24 mm/min. (0.05 in./min.) to 1524 mm/min. (5.0 in./min.) with an target amplitude of approximately 61 mm (0.2 in.), respectively, to investigate the effects of loading rates on the CIPP liner reinforced joints. Moreover, for the both CIPP liner-reinforced pipeline, the internal water pressure was manually regulated at municipal water pressure of 331 kPa (48 psi.).

Figure 5a show the joint response under different loading rates for the DI pipeline specimens retrofitted with the Starline® 2000 liner (the Starline joint). From the joint response shown by the red curve in Fig. 5a, much higher axial stiffness and a yielding plateau can be observed in the loading cycle with a loading rate of 15.24 mm/min. (0.05 in./min.). The yielding plateau is primarily caused by liner debonding from the internal surface of the pipeline specimen. In the subsequent loading cycles on the Starline joint, no yielding plateau can be observed in the joint response, as shown by the green and blue curves in Fig. 4a, indicating that the debonded length of the Starline® 2000 liner primarily depends on the peak joint opening experienced by the joint. Moreover, similar joint responses can be observed as the loading rate increased from 152.4 mm/min. (0.5 in./min.) to 1524 mm/min. In general, the effects of the loading rates increasing from 15.24 mm/min. to 1524 mm/min. have insignificant effects on the Starline joint. Figure 5b presents the joint response of the DI pipeline specimens retrofit with the InsituMain® liner (the InsituMain joint) under different loading rates. In this test series, the achieved joint opening was low compared to the target joint opening due to the elastic rotation of the central concrete pedestal. The overlapping joint axial response indicates that the loading rates increasing from 15.24 mm/min. to 1524 mm/min. also has insignificant effect on the InsituMain joints.



1. West Joint
2. East Joint
3. Steel Clamp
4. Pipe Specimen
5. Mounting Plate
6. HSS Beam
7. Post-tension Steel Rod
8. Central Concrete Pedestal
9. Steel Girder
10. West Shake Table
11. East Shake Table
12. Load Cell

* 1.0 ft. = 305 mm

Fig. 3 Overview of shake table test setup

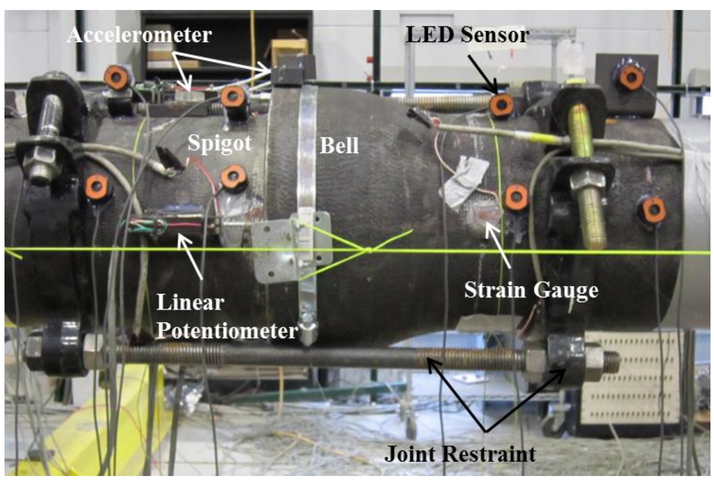
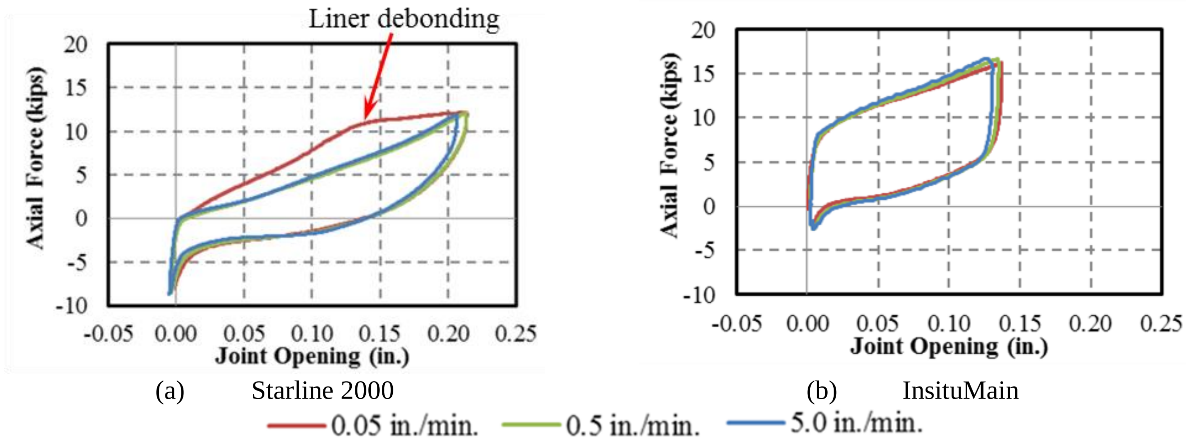


Fig. 4 Close-up view of instrumented push-on joint

Examining the response of two CIPP liner-reinforced joints in Fig. 5, the InsituMain joint exhibits an initial stiffness of approximately 175 kN/mm (1000 kips/in.) and a secondary stiffness of approximately 8.76 kN/mm (50 kips/in.) The peak tensile force reaches 72.1 kN (16.2 kips) at a peak joint opening of 3.3 mm (0.13 in.). The sudden decrease of the axial force after the joint opening reaches its peak value is primarily attributed to the friction between the liner and the DI pipeline. Small compressive force of approximately 11.12 kN (2.5 kips) can be observed at the end of each cycle with a final joint opening of approximately0.13 mm (0.005 in.). However, for the Starline joint under the cycles with the same loading rate, the joint exhibits reloading stiffness of approximately 60 kips/in. and a peak tensile axial force of approximately 53.4 kN (12.0 kips). Moreover, the Starline joint exhibits larger peak compressive axial forces when the joint closes compared to the InsituMain joint. This result is mainly attributed to the folding of the thinner and more flexible unbonded Starline® 2000 liner into the gap between the spigot and the bell of the push-on joint.



* 1.0 in. = 25.4 mm

Fig. 5 Axial force-joint opening hysteretic responses of DI joint retrofit with two types of CIPP liners under cyclic tensile loading with different loading rates

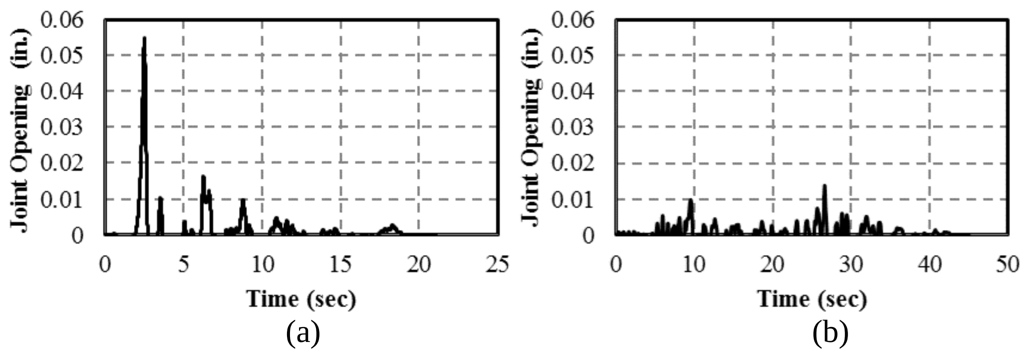
3.2 Seismic Tests with Near-fault Ground Motions

The input motions for the seismic tests were obtained from the numerical simulations of buried pipelines with circumferential cracks or week joints subjected to TGD, which were conducted by Bouziou [19] and Zhong et al. [20-22] the simulation model includes the soil-pipeline interaction during TGD induced by seismic wave propagation during an earthquake event [19]. The two acceleration time histories used for the numerical analyses were recorded by the Rinaldi receiving station during the 1994 Northridge earthquake and the Joshua Tree (J-T) receiving station during the 1992 Landers earthquake, respectively. The Rinaldi motion has the characteristics of a near-fault forward directivity seismic motion, which contains a displacement spike with large amplitude followed by a series of small vibrations. The J-T motion has the characteristics of a near-fault reverse directivity, which contains several spikes with different amplitudes. Since the bending strain of the pipeline under TGD is negligible and the weak joints absorb most axial deformation of the pipeline [13, 19], the relative axial motions of the pipeline joint were derived from the numerical model that were subsequently used to provide the input motions for the test specimens on the shake tables after removal of compressive displacements, as shown in **¡Error! No se encuentra el origen de la referencia.**, in order to protect the shake tables from damage. The following sections present the seismic test results from this experimental study.

3.2.1 Single-Joint Tests with Rinaldi Ground Motion

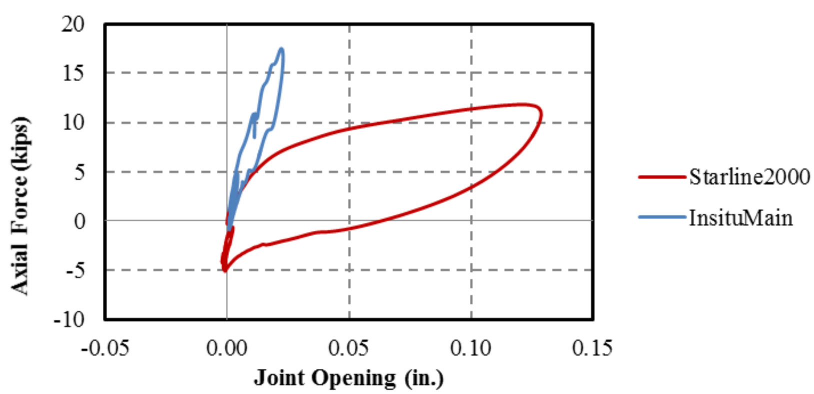
The seismic behavior of the DI pipeline retrofitted with the two types of CIPP liner under the full-scale (100%) Rinaldi input motion is compared in Fig. 7. The DI pipelines reinforced with both types of CIPP liners can accommodate the full-scale Rinaldi ground motion without failure but exhibit very different behaviors. The DI joint reinforced with the InsituMain® liner remains almost linear elastic with an initial stiffness of approximately 175 kN/mm (1000 kips/in.) and a secant stiffness of 133 kN/mm (760 kips/in.)

No residual deformation or axial compressive forces can be observed at the end of the test. However, the DI joint reinforced with the Starline® 2000 liner is much more ductile with a lower initial stiffness of 33.3 kN/mm (190 kips/in.) The joint starts to "yield" under an axial force of approximately 22.2 kN (5.0 kips) and the axial stiffness reduces significantly. A small residual deformation and a residual compression force of 22.4 kN (5.1 kips) are observed at the end of the test as shown in Fig. 7. Moreover, much more energy is dissipated by the Starline® 2000 joint than that by the InsituMain® joint. After the full-scale single-joint test, both DI joints reinforced with different CIPP liners were tested using higher intensities of the Rinaldi input motion. The InsituMain® joint was not damaged in the test with 125% Rinaldi input motion, but the liner failed during the malfunction of the shake table. The Starline® 2000 joint failed in the test with160% Rinaldi input motion [22].



* 1.0 in. = 25.4 mm

Fig. 6 Joint opening input motions scaled to 100% of their amplitudes: (a) Rinaldi; (b) Joshua Tree.

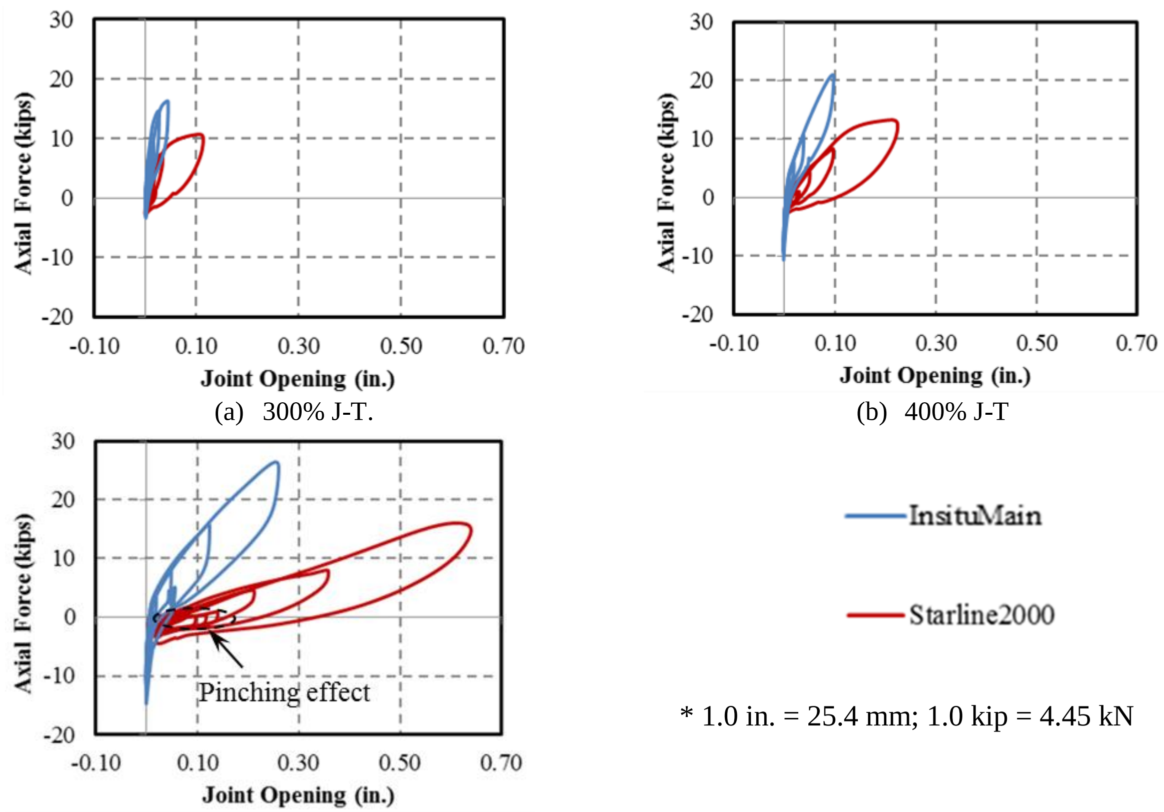


* 1.0 in. = 25.4 mm; 1.0 kip = 4.45 kN

Fig. 7 Axial force-joint opening hysteretic responses of DI joint retrofit with two types of liners under full-scale Rinaldi ground motion

3.2.2 Single-Joint Tests with Joshua-Tree Ground Motion

Figure 8 compares the seismic behavior of the DI pipelines reinforced with the two types of liners under the J-T ground motions at different intensities. The joints of both retrofitting strategies have exhibited a nonlinear plastic response under the amplified J-T ground motion. Evidently clear from the figure, the Starline joint is much more ductile and dissipates more energy than the InsituMain joint. Whereas the InsituMain joint experiences much higher peak tensile forces at smaller peak joint openings. Larger residual compressive forces are induced in the InsituMain joint than in the Starline joint. Finally, significant pinching effect with zero-resistance plateau under the same levels of tensile displacement in the liner are observed in the Starline joint as the J-T ground motion is scaled up to 550% of its full-scale intensity. This pinching effect is primarily attributed to the buckling and folding of the unbonded thin CIPP liner between the circumferential gap of the bell and the spigot, as shown in Fig. 2b, when the joint was unloaded. This portion of unbonded liner unfolded as the joint subjected to subsequent tensile loading, leading approximately to zero-resistance in the joint. However, for the InsituMain joint with thicker and more rigid liner as well as limited length of debonded liner, pinching effect cannot be seen in its axial response, as shown in Fig. 8.



(a) 300% J-T.

(b) 400% J-T

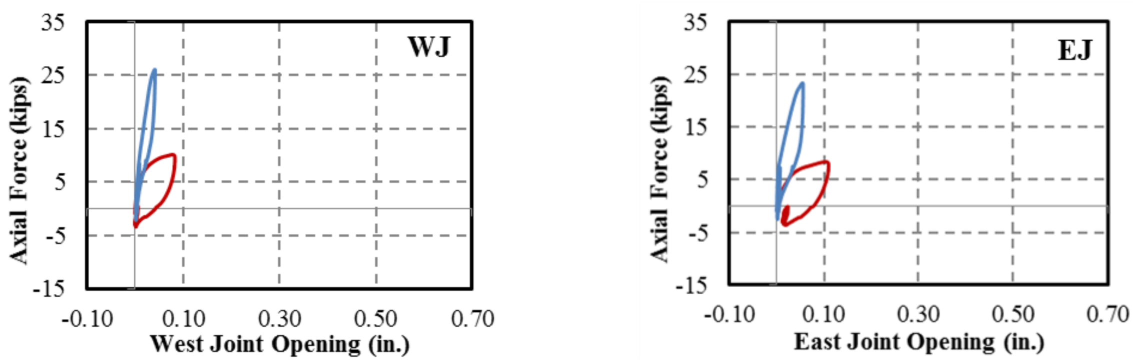
(c) 550% J-T

Fig. 8 Axial force-joint opening hysteretic responses of DI joint retrofit with two types of liners under J-T ground motion

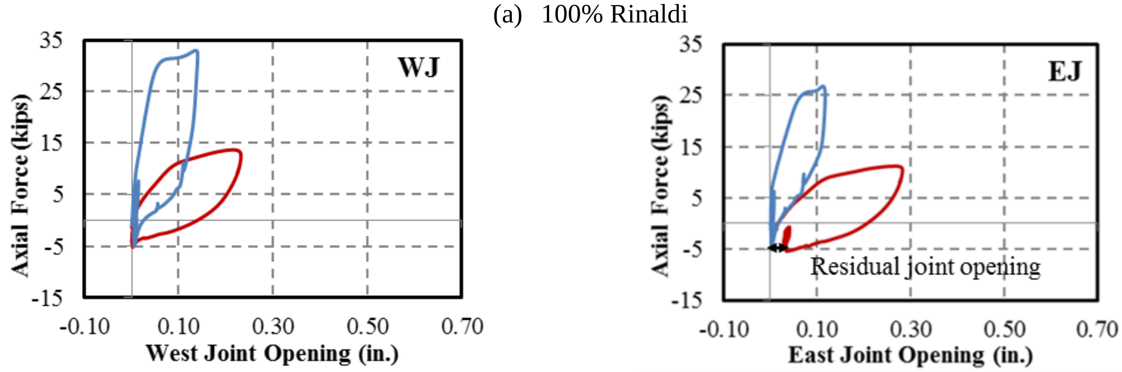
3.2.3 Double-Joint Tests with Rinaldi Ground Motion

The hysteretic responses of the DI pipelines reinforced with the two types of CIPP liners from double-joint seismic tests are compared in Fig. 9. Both joints of the specimen, namely the west joint (WJ) and the east joint (EJ), were tested at the same time using the asynchronous Rinaldi ground motion simulating a wave propagation across two adjacent weak joints or circumferential cracks along the DI pipeline.

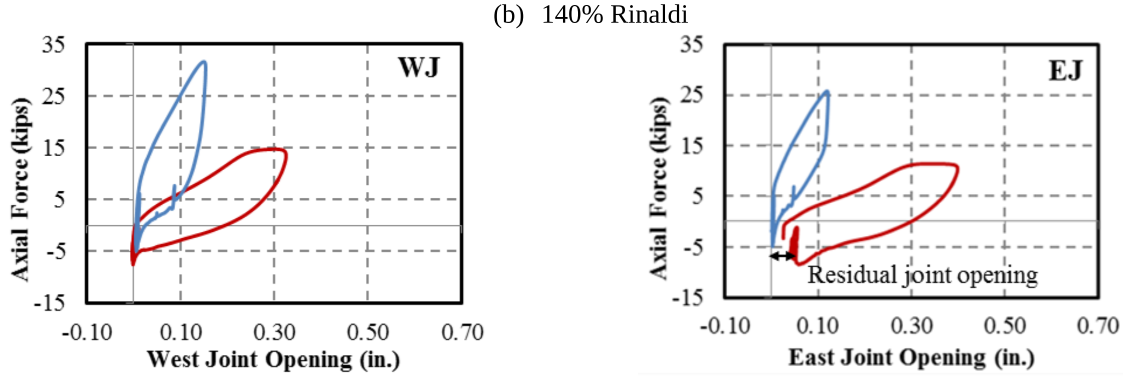
Similar to the single-joint seismic tests, ductile behavior is again observed in the Starline joint. Under the same intensity of input motion, the InsituMain joint experiences much higher peak axial tensile forces at a smaller peak joint opening. Moreover, for the Starline joints, especially the EJ, significant pinching effects and increasing residual joint openings are observed under high intensity of the Rinaldi ground motion (after scaled up to 190% or higher), which were mainly caused by liner folding into the gap between the spigot and bell of the joints. The west InsituMain joint failed under the 200% Rinaldi motion test while the east InsituMain joint of the same pipeline remained undamaged. However, both Starline joints remained water-tight under the same intensity of Rinaldi motion. Compared to the single joint tests with Rinaldi ground motions as discussed in section 3.2.1, the pipeline specimens with double weak joints/circumferential cracks strengthened by the CIPP liners were able to resist high intensity of ground motions. The presence of double joints/cracks redistributes the joint opening between the joints and thus mitigates the seismic damage to the entire pipeline under TGD.



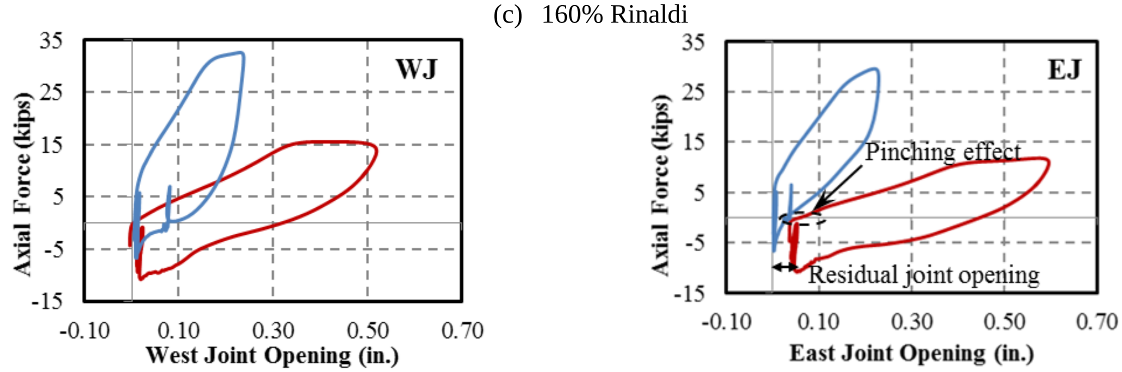
(a) 100% Rinaldi



(b) 140% Rinaldi



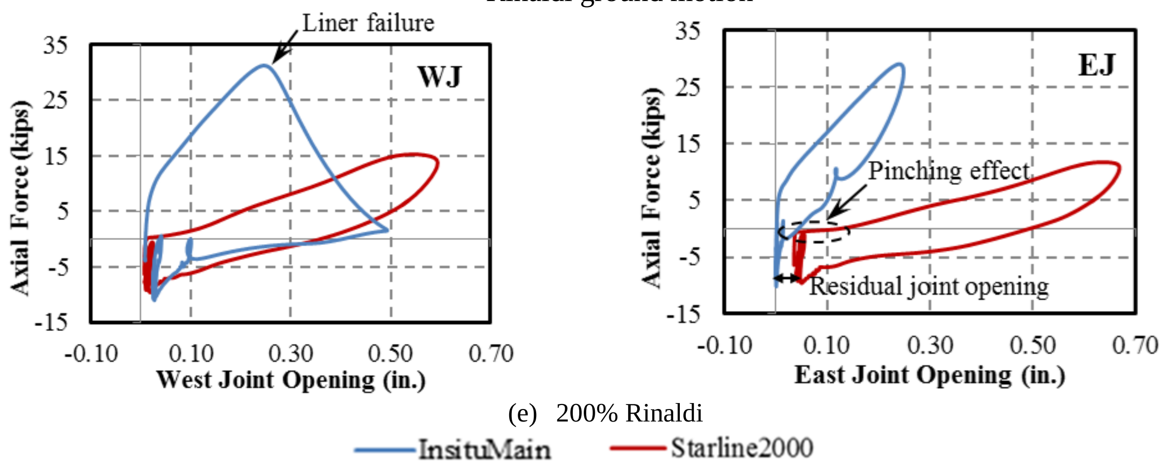
(c) 160% Rinaldi



(d) 190% Rinaldi

Fig. 9 Axial force-joint opening hysteretic responses of DI joints retrofit with two types of liners under

Rinaldi ground motion



(e) 200% Rinaldi

* 1.0 in. = 25.4 mm; 1.0 kip = 4.45 kN

Fig. 9 Axial force-joint opening hysteretic responses of DI joints retrofit with two types of liners under Rinaldi ground motion (cont.)

4 Conclusion

A series of experiments consisting of both quasi-static and dynamic tests were conducted to characterize the dynamic behavior and failure mechanism of CIPP-liner-reinforced ductile iron pipelines with circumferential cracks or weak joints in the longitudinal direction. The following conclusions can be drawn based on the results of this experimental study.

(1) Pipelines with circumferential cracks/weak joints after reinforced with both types of CIPP liners can accommodate high intensities of transient ground deformations induced by seismic wave propagation.

(2) The ductile iron joints reinforced with the Starline® 2000 liner are more ductile and could accommodate higher intensity of seismic ground motions compared with those reinforced with the InsituMain® liner. However, for the Starline® 2000 liner, pinching effect was observed when the joint was subjected high intensity ground motions. This is not favorable for seismic behavior of the joint, because partial damage accumulation occurs when the liner is repeatedly folding into the gap between the spigot and the bell of the push-on joint, which is likely to accelerate the damage in the CIPP liner.

(3) Debonding between the liner and the ductile iron pipelines confirms that it is advantageous to the seismic response of the lined joints because it increases the apparent ductility deformation capacity of the joints, and promotes the joints to dissipate more energy during an earthquake event.

(4) The presence of double joints/cracks redistributes the joint opening between the joints, and thus, mitigates the seismic damage of the entire pipeline under transient ground deformations.

5 Acknowledgements

The work reported in this paper was supported by the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program of the National Science Foundation (NSF), grant CMS-421142. Any opinions, findings and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of NSF. Sincere thanks are extended to Professor Thomas D. O'Rourke, Professor Harry E. Stewart and Dr. Dimitra Bouziou formerly from the School of Civil and Environmental Engineering at Cornell University for providing input motions and sharing important opinions in performing shake table tests. The Los Angeles Department of Water and Power is also gratefully acknowledged for providing the pipeline specimens as well as Insituform Technologies, LLC, and Power Progressive Pipeline Management, LLC, for lining the pipeline specimens.

6 References

[1] O'Rourke, T.D., Roth, B.L., and Hamada, M. Large Ground Deformations and Their Effects on Lifeline Facilities; 1971 San Fernando earthquake. NCEER-92-0002, 1992. p. 3:1-85.

[2] Ayala, A.G., O'Rourke, M.J., and Escobar, J.A. Evaluation of the Effects of the 1985 Michoacan Earthquake on the Water Systems in Metropolitan Mexico City. Earthquake Spectra, 1990. 6(3): p. 473-496.

[3] O'Rourke, T. D., Stewart, H. E., Blackburn, F. T., and Dickerman, T. S. (1990). Geotechnical and lifeline aspects of the October 17, 1989 Loma Prieta earthquake in San Francisco. National Center for Earthquake Engineering Research State University of New York at Buffalo: Buffalo, NY.

[4] Jeon, S.-S., and O'Rourke, T. D. (2005). Northridge earthquake effects on pipelines and residential buildings. Bulletin of the Seismological Society of America, 95(1), 294-318. doi: 10.1785/0120040020

[5] EQE International. (1995). The January 17, 1995 Kobe Earthquake: An EQE Summary Report: San Francisco: EQE International.

[6] Risk Management Solutions and Failure Analysis Associates (1995). Japan: The great Hanshin earthquake, January 17, 1995.

[7] O'Rourke, T. D., Jeon, S. S., Toprak, S., Cubrinovski, M., Hughes, M., Ballegooy, S., and Bouziou, D. (2014). Earthquake response of underground pipeline networks in Christchurch, NZ. Earthquake Spectra, Vol. 30 (1):183-204. doi: doi:10.1193/030413EQS062M.

[8] Ariman, T. A Review of the Earthquake Response and Aseismic Design of Underground Piping Systems, Proc. of Current State of Knowledge of Lifelines Earthquake Engineering Conference, ASCE, Los Angeles, CA, Aug. 1977, pp. 282-292.

[9] Kachadoorian, R. Earthquake: Correlation between Pipeline Damage and Geologic Environment, Journal of AWWA, March, 1976, pp. 165-167.

[10] Katayama, T., Kubo, K. and Sato, N. Earthquake Damage to Water and Gas Distribution Systems, Proc. of U.S. National Conference on Earthquake Engineering, Ann Arbor, MI, EERI, 1975, pp.396-405.

[11] Wang, L. R. L. and O'Rourke, M. J. State of the Art of Buried Lifeline Earthquake Engineering, Proc. of Current State of Knowledge of Lifeline Earthquake Engineering Conference, ASCE, Los Angeles, CA. Aug. 1977, pp. 252-266.

[12] Wang, L. R. L., O'Rourke, M. J. Overview of Buried Pipelines under Seismic Loading, Journal of Technical Councils, ASCE, Vol. 104, No. TC1, Nov. 1978, pp.120-130.

[13] Wang, L. R. L. and Cornell, H. A. Evaluating the Effects of Earthquakes on Buried Pipelines. Journal of AWWA, 1980, 72(4):201-207.

[14] O'Rourke, T. D. Geohazards and large, geographically distributed systems. Geotechnique 60, No. 7, 505–543 [doi: 10.1680/geot.2010.60.7.505]

[15] Jeon, S.-S., O'Rourke, T. D., and Netravali, A. N. (2004). "Repetitive loading effects on cast iron pipelines with Cast-in-Place-Pipe lining systems." Journal of Transportation Engineering, 130(6), pp. 692-705.

[16] ASTM. (2007). "Standard test method for in-plane shear properties of polymer matrix composite materials by the rail shear method", ASTM D4255 / D4255M - 01: American Society for Testing and Material, West Conshohocken, PA.

[17] ASTM. (2008). "Standard test method for tensile properties of polymer matrix composite materials", ASTM D3039 / D3039M - 08: American Society for Testing and Material, West Conshohocken, PA.

[18] Nikon Metrology, I. (2014). Krypton K600 Optical Measurement System. Retrieved August 2, 2014, from http://www.nikonmetrology.com/Products/Portable-Measuring/Optical-CMM/K-Series-Optical-CMM/(key_features)

[19] Bouziou, D. "Earthquake-induced ground deformation effects on buried pipelines." Ph.D. Dissertation, Cornell University, Ithaca, NY, USA

[20] Zhong, Z., Bouziou, D., Wham, B., Filiatrault, A., Aref, A., O'Rourke, T. D., and Stewart, H. E. (2014) "Seismic testing of critical lifelines rehabilitated with cured in place pipeline lining technology." Journal of Earthquake Engineering. Vol. 18 (6):964-985. doi: 10.1080/13632469.2014.916632.

[21] Zhong, Z., Bouziou, D., Wham, B. P., Filiatrault, A., Aref, A., O'Rourke, T. D. and Stewart, H. E. (2014) "Performance evaluation of water pipelines retrofitted with cured in place pipe lining technology under transient earthquake motions." Proceedings of the 10th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

[22] Zhong, Z. (2015). "Earthquake response and rehabilitation of critical underground lifelines reinforced with cured in place pipe liner technologies under transient ground deformations." Ph.D. Dissertation, University at Buffalo, Buffalo, NY, USA.