Earthquake Response and Rehabilitation of Critical Lifelines

D.Bouziou, B.P.Wham, T.D.O'Rourke, H.E.Stewart & M.C.Palmer
Cornell University, Ithaca, New York, USA

Z.Zhong, A.Filiatrault & A.Aref
University at Buffalo, Buffalo, New York, USA

15 WCEE
LISBOA 2012

SUMMARY
The earthquake response and rehabilitation of critical lifelines can be enhanced substantially by in situ pipe lining technologies that involve the installation of polymeric linings inside existing, underground pipelines through trenchless construction procedures. In situ linings are not used currently for earthquake protection, and the absence of experimental validation and analytical procedures for seismic loading is a serious barrier to the adoption of in situ linings for improved earthquake performance. This paper focuses on cured in place pipe (CIPP) lining technology for seismic retrofit. The CIPP process involves the installation and curing of fiber reinforced composites inside existing pipelines. The paper describes large-scale testing at the Cornell University and University at Buffalo equipment sites of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). The modeling of seismic wave effects on aging and defective pipelines, strengthened with CIPP linings, is discussed. The results of special tests on lined pipe specimens to characterize their response to earthquake induced ground motions are presented.

Keywords: Lifelines, Geotechnical earthquake engineering, Soil structure interaction, Ground motion, Seismic retrofit.

1. INTRODUCTION

Over the past two decades in situ pipe lining technologies have evolved into a well-established industry that increases the service life of existing utilities without expensive and disruptive excavation and replacement. It involves the installation of polymeric linings remotely inside existing, underground pipelines with minimum disturbance to the surrounding infrastructure through trenchless construction procedures. The linings provide continuity of pipeline flow, prevent leakage and intrusion, and provide variable degrees of structural reinforcement. Table 1.1 summarizes existing pipe lining technologies with brief descriptions of their general advantages and disadvantages.

Current design and construction practices do not include in situ lining technologies for seismic risk mitigation, and the adoption of such methods for this purpose require experimental validation and analytical procedures. Experimental evidence exists that confirms the ability of pipelines reinforced with cured in place (CIPP) linings to resist ground deformation and repetitive axial displacements at cracks and defective joints. For example, experimental and analytical work described by Jeon et al. (2004), demonstrate the effectiveness of fiber reinforced polymer (FRP) linings for pipelines that have full circumferential cracks and weak joints.

This paper focuses on the application of CIPP lining technology for seismic retrofit. Full-scale testing and numerical simulation using the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) to study the seismic performance of pipelines reinforced with FRP linings is discussed. Finite element (FE) models are developed for simulating seismic wave interaction with buried pipelines. The results of special tests on lined pipe specimens to characterize their response to earthquake-induced ground movement are presented. Full-scale dynamic test results are presented for simulations of seismic wave/pipeline interaction with the twin – relocatable shake table facility of the Structural Engineering and Earthquake Laboratory (SEESL) at the University at Buffalo (UB).

Table 1.1. Summary of in situ pipe lining technologies.

Method	Advantages	Disadvantages
Cured in Place Pipe (CIPP): Insertion of flexible tube saturated with thermosetting resin into existing pipeline.	● Adaptable to bends and various cross-sections. ● Flexible rapid installation.	● Needs interior cleaning. ● Installation rate depends on resin cure time.
Folded and Deformed Lining: Insertion of folded or deformed HDPE or PVC into existing pipeline.	● Rugged and/or ductile continuous linings. ● Oversized linings may be installed for tight fit and composite action.	● Limitation on angle of bends and pipe size. ● Residual strains and change in shape from folding.
Slip Lining: Insertion of factory-made piping into existing pipeline.	● Broad range of materials and sizes. ● Flexible installation, best suited for larger pipelines.	● Difficulties with bends and changes in size and shape. ● Relatively expensive.
Spray Lining: Mortar or resin coating on interior pipe surface.	● Rapid application. ● Relatively low cost.	● Limited strength/ductility of mortar or resin coating. ● Needs interior cleaning.
Carbon Fiber Composite Sheet Lining: Carbon-fiber composite sheets on interior pipe surface.	● Adaptable to changes in alignment, shape, and size. ● Suitable to large diameter pipelines (>3m) and tunnels.	● Not suitable for smaller diameter pipelines. ● Labor intensive, expensive.

2. TESTING AND RESEARCH PROGRAM

A primary goal of the research is to quantify how in situ linings affect the seismic performance of lifelines through systematic full-scale testing and numerical modeling of response to transient and permanent ground displacement (TGD and PGD, respectively). The research involves a university-industry partnership in which NEES equipment sites at Cornell University and the University at Buffalo (UB) are working with the California State University at Los Angeles (CSULA) with support from the Los Angeles Department of Water and Power (LADWP) and Insituform Technologies, Inc. (ITI), one of the largest international companies specializing in in situ linings. Figure 2.1 shows the organizational flow chart for the research program.

2.1. Full-scale testing

2.1.1. PGD tests at Cornell

The test basin at Cornell consists of a fixed and movable section displaced by four hydraulic actuators. The basin is 3.2m wide and 13m long, with a maximum 2.1-m depth and it can contain up to 100 tonnes of soil. The system can be configured to test multiple full-scale pipelines simultaneously, in either tension or compression, with various fault, or ground rupture, crossing angles. Currently, it is split in the center along a 50-degree sliding plane, which can be seen in Fig. 2.2a.

2.1.2. TGD tests at UB

Full-scale dynamic testing of underground lifeline systems is conducted in the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at UB. This NEES facility, shown in Fig. 2.2b, consists of two high-performance six-degrees-of-freedom shake tables that can be positioned such that they are closely adjacent to one another or up to 30m apart.

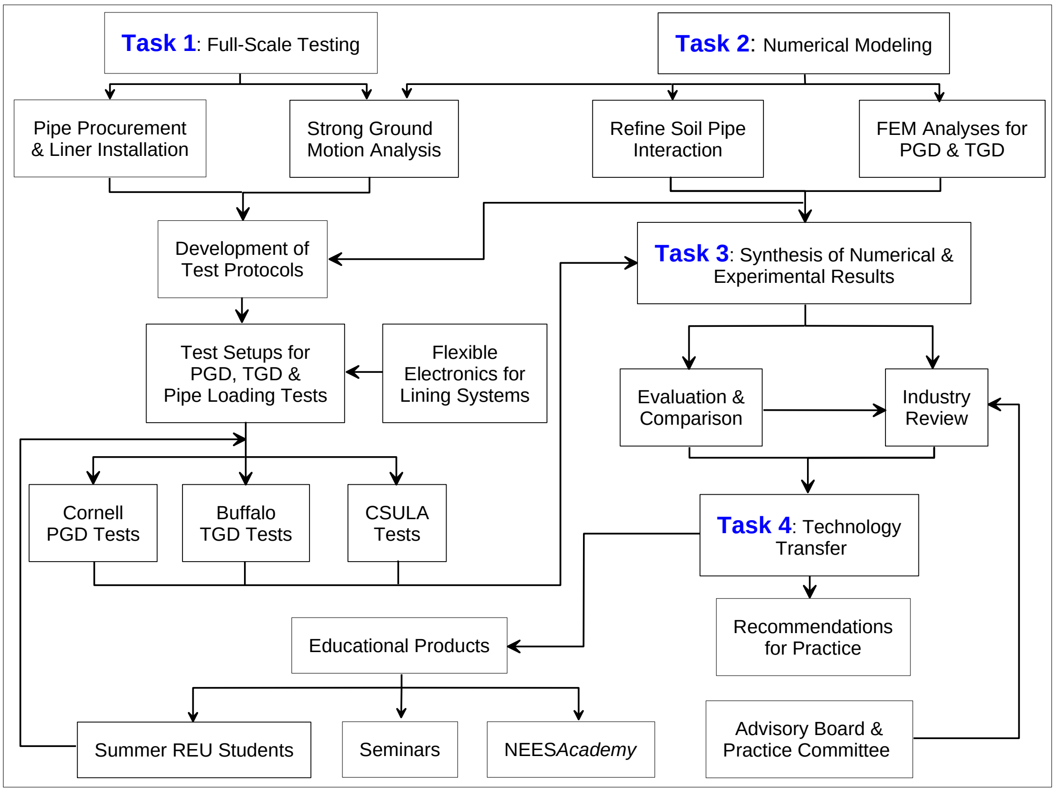
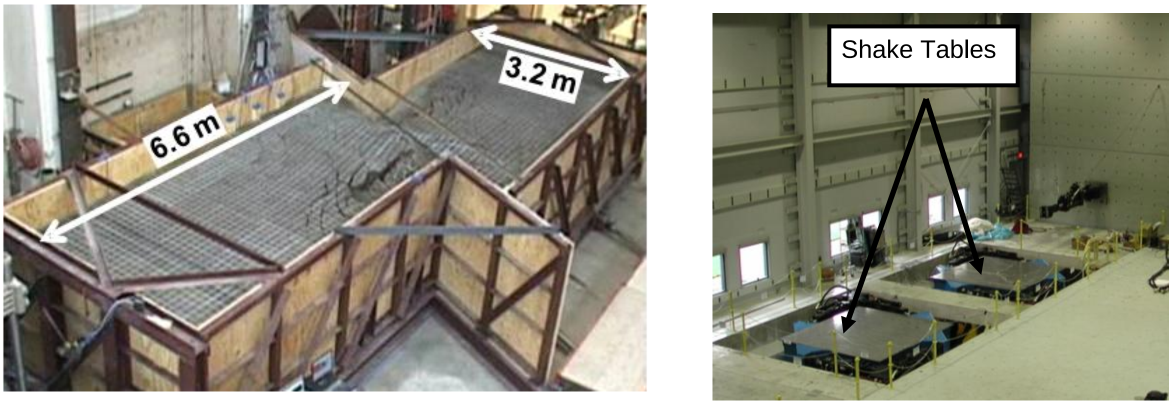


Figure 2.1 Organizational structure for proposed research.



(a) **(b)**

Figure 2.2 (a) Cornell NEES large-scale lifelines laboratory. **(b)** UB NEES shake table facility.

2.1.3. Tests at CSULA

Tests at CSULA investigate combined lining and pipeline behavior under failure conditions induced with four-point loading equipment in the Strength of Materials Laboratory. The tests focus on continuous lined pipe specimen failure under shear and moment conditions similar to the strike slip ground rupture simulated at Cornell.

2.2. Numerical modeling

Numerical modeling involves strong ground motion analyses to establish TGD test protocols, as well as soil-pipeline interaction analyses with soil spring/slider elements or soil continuum modeling, both with FE analyses of PGD and TGD effects. At Cornell, soil-pipeline interaction modeling developed by O'Rourke, et al. (2004) is performed to evaluate both underground pipeline response to seismic waves and to help design the dual shake table tests using ground records. Advanced computational models are being developed at UB and validated against experimental results from Cornell, UB and CSULA. The models will account for the composite behavior of the soil-pipe-liner (SPL) system under the effects of TGD and PGD, and will include simulation of the nonlinear, viscoelastic properties of the fiber-reinforced polymer (FRP) lining.

3. MODELING THE SEISMIC RESPONSE OF UNDERGROUND LIFELINES

3.1. Literature review

3.1.1 Seismic wave interactions with pipelines

Body wave effects on underground pipes are generated primarily by S-waves that intersect the pipeline at an angle of incidence, γ_i, illustrated in Fig. 3.1. The ground strain parallel to the pipeline, ε_g, is

$$\varepsilon_g = V_a / C_a \tag{3.1}$$

where V_a and C_a are the particle velocity and apparent wave propagation velocity, respectively, along the longitudinal axis of the pipeline:

$$C_a = \frac{C}{\sin \gamma_i} \tag{3.2}$$

$$V_a = V \cos \gamma_i \tag{3.3}$$

Combining Eqns. 3.1 through 3.3 provides the maximum ground strain, ε_g, parallel to the pipeline, which is

$$\varepsilon_g = \frac{V \sin 2\gamma_i}{2C} \tag{3.4}$$

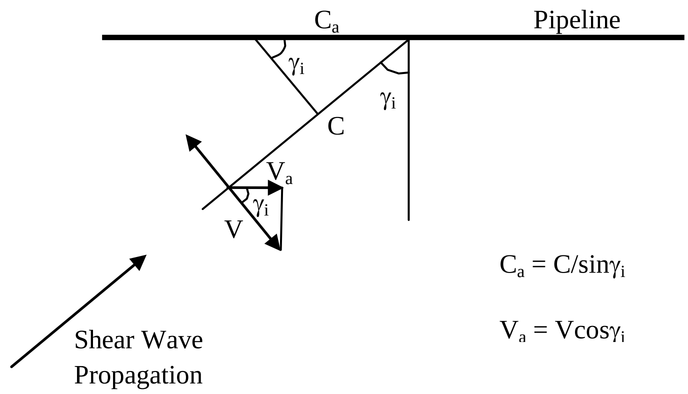


Figure 3.1 Pipeline subjected to shear wave propagation.

3.1.2 Analytical modeling

When a pipeline is axially flexible with respect to ground strain accumulation, no relative displacement occurs between the surrounding soil and the pipeline, and, hence, the pipeline deforms as much as the ground surrounding the pipeline, resulting in $\varepsilon_p = \varepsilon_g$ everywhere the pipeline is continuous. O'Rourke, et al. (2004) developed a model for the axial displacement of a locally weak joint in response to seismic wave train location and orientation relative to the pipeline. The pipeline either side of the weak joint is assumed to have full capacity joints and behave as a continuous pipeline. The concept is illustrated in Fig. 3.2, which shows the ground strain, ε_g, as expressed in

Eqn. 3.4 vs distance, X, along the pipeline determined as the product of wave propagation time, t, and C_a. Because the pipeline is fully flexible, $\varepsilon_p = \varepsilon_g$ everywhere the pipeline is continuous. At the weak joint, the maximum axial force, P_u, the pipeline can sustain corresponds to the pullout strain, $\varepsilon_u = P_u/EA$, where E is the pipe material modulus, and A is the cross-sectional pipe area. After P_u occurs at the weak joint, the joint yields. As the seismic wave passes across the weak joint, strain in the pipeline on each side of the weak joint will accumulate linearly from $\varepsilon_p = \varepsilon_u = P_u/EA$ to $\varepsilon_p = \varepsilon_g$ at a slope of f/EA where f is the axial shear resistance between pipe and soil. The shaded area in the figure is the integration of the differential strain between pipeline and ground, which equals the relative joint displacement.

The model simulates the geometric nonlinear performance of any number of weak joints in any position along the pipeline, accounts for both body wave [P- and S- wave] and surface wave [R- an L- wave] effects, and has been extended to joints with bilinear force-displacement characteristics as well as welded slip joints subject to buckling (Shi & O'Rourke, 2008; Wang & O'Rourke, 2008).

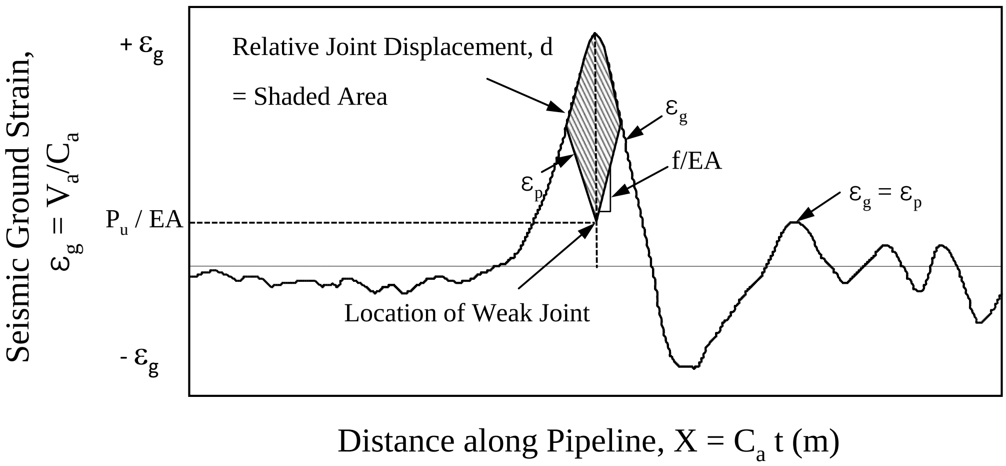
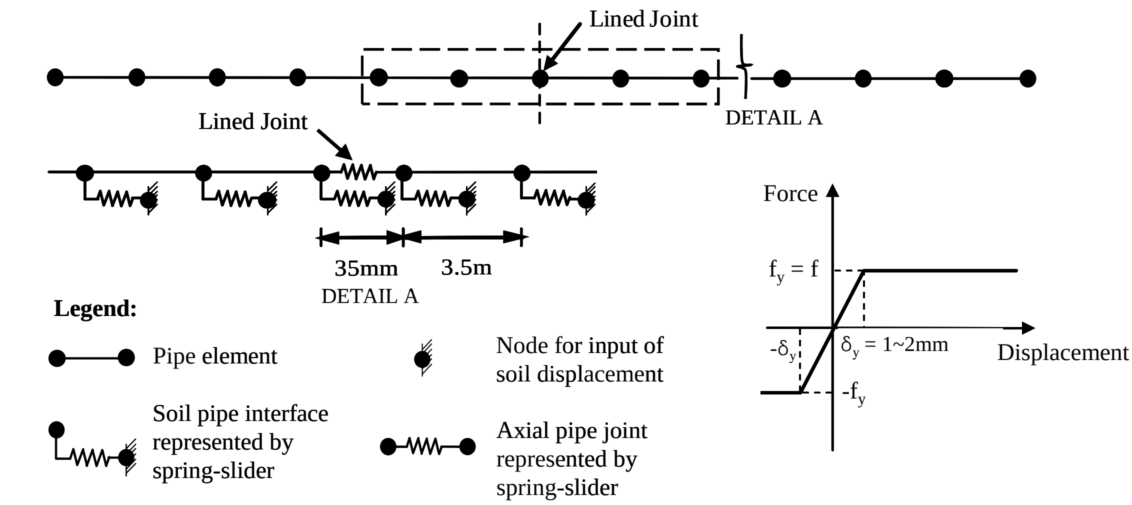


Figure 3.2 Relative joint displacement from seismic wave interaction for a CIPP.

3.2. Simplified model for segmented CIPP

A finite element (FE) model for seismic wave interaction with segmented CIPPs was developed, using the numerical code ABAQUS 6.9-2. Figure 3.3a shows a schematic of the FE model. The pipeline consists of 175-mm outer diameter and 6.35-mm wall thickness ductile iron pipes with axial deformation stiffness EA=556,740 kN, and is modelled with pipe elements that are connected to the ground by spring-slider elements with elasto-plastic behavior capable of representing shear transfer. Ground motion time records are converted to displacement versus distance records by assuming that $X = C_a t$, in which X is distance, t is time from the strong motion recording, and C_a is calculated from Eqn. 3.2, using C = 2.5 km/sec, which is the wave propagation velocity frequently used for crustal conditions in California. The seismic displacement versus distance record is superimposed on the spring-slider elements, which then conveys ground movement to the pipeline by means of spring-sliders, as recommended by O'Rourke (1998). The pipeline was assumed to be buried at 1.22m depth to the top of the pipe in partially saturated sand with an effective friction angle $\phi' = 38^o$ and unit weight $\gamma = 19.64$ kN/m^3. Figure 3.3b shows the relation between f and relative pipe-soil displacement modeled as a bilinear relationship with linear rise to f at a relative displacement of 1~2 mm and constant f thereafter.

Pipelines strengthened with CIPPs were modeled with the analytical procedures described above. In all analyses it was assumed that the CIPP lining was installed across an open joint or circumferential crack in the pipeline. Axial pull tests were performed on lined pipe specimens (see Section 4) to characterize the axial force vs displacement relationship for the lined joints. The modeled CIPP had 150mm outer diameter and 7.11mm wall thickness, with axial deformation stiffness EA = 15,840 kN,

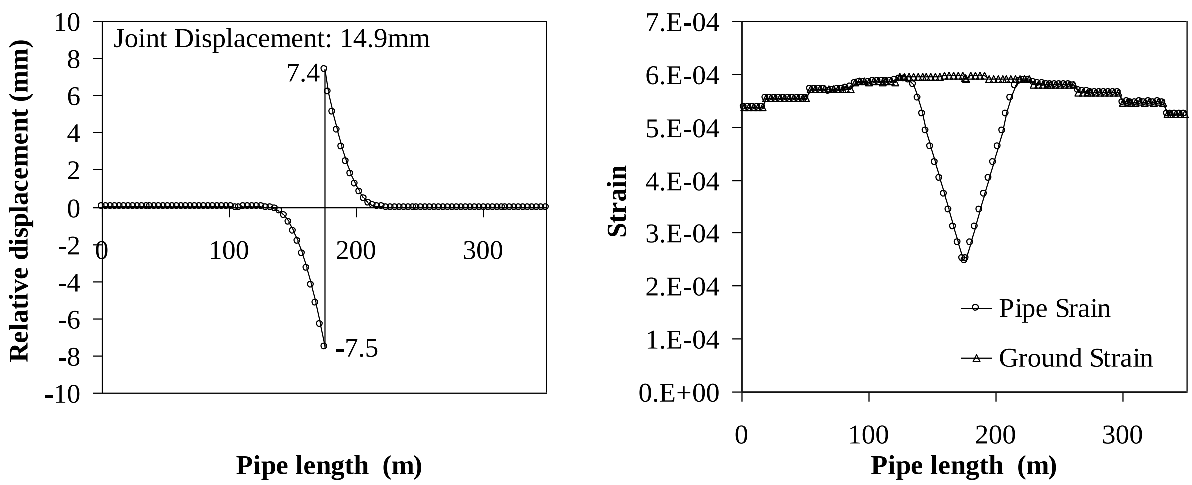


(a) **(b)**

Figure 3.3 (a) Finite element model for seismic wave and pipeline interaction. **(b)** Shear transfer and soil-pipe relative displacement relationship.

when cured. Ground motion records at the Rinaldi and Joshua Tree stations during the 1994 Northridge and 1992 Landers earthquakes, respectively, were converted to displacement versus distance records. The records were obtained from the NGA Database in the PEER library of ground motions (PEER NGA, 2011). The maximum recorded velocities, corresponding to fault normal motions were assumed to intersect the lined pipeline at $\gamma_i = 45^o$ with C = 2.5 km/sec to produce maximum strain and deformation in the pipeline. The motions were selected to represent large near-field velocity pulses as well as wave trains of varying duration and number of velocity pulses. The amplitudes of the velocities were scaled from approximately 50% to more than 200% of the measured magnitude to explore the sensitivity of lined joint response to variable ground motion.

Figure 3.4a shows the maximum relative joint displacement from FE analysis for seismic wave interaction effects using the Rinaldi ground motion records scaled to 200% of the recorded amplitudes. The maximum analytical pullout is 14.9 mm, which is distributed in a slightly asymmetric manner either side of the cracked joint to reflect the shape of the ground strain pulse. Figure 3.4b shows the analytical pipe and ground strains surrounding the lined joint, similar to the seismic wave interaction diagram in Fig. 3.2.



(a) Ground-pipeline Relative Displacement. **(b)** Ground and Pipe Strains.

Figure 3.4 FE results for CIPP subjected to 200% of the Rinaldi record from 1994 Northridge Earthquake.

4. CHARACTERIZATION OF CIPP RESPONSE TO GROUND DEFORMATION

4.1 Axial pull tests

Figure 4.1a is a cross-section of a standard push-on joint of a nominal 150-mm-diameter ductile iron (DI) pipeline. The DI joint is equipped with a rubber gasket that prevents leakage, but provides negligible resistance against pullout and rotation to about 5°. There is normally a small gap (1~4 mm) where the spigot of one pipe adjoins the bell of the adjacent pipe, as shown in the figure. Because the DI joint lacks both pullout and moment capacity with a small separation between bell and spigot, it is used in the research as a mechanical equivalent of a weak joint or circumferential crack that would be found in an aging cast iron (CI) pipeline. In situ linings are used to strengthen and provide continuity in aging CI pipelines, and will reinforce DI pipelines against pullout under seismic loading.

Axial pull tests were performed on several specimens of 150 mm nominal diameter DI pipe joints with lengths ranging between 2.14 m and 2.65 m. The test setup for an axial pull test is presented in Fig. 4.1b for which the pipe specimen has been fabricated with a 4-mm gap to simulate a circumferential crack. Each test joint was lined by ITI following typical field installation procedures. The 7.1-mm-thick lining was composed of unwoven polyester fabric impregnated with epoxy resin and reinforced with a central layer of fiber glass. The lining is bonded to the interior pipe surface by an epoxy that cures in place during and after installation. As shown in Fig. 4.1b axial pull forces were applied with a 25-tonne MTS actuator, while displacement across the circumferential gap was measured with DCDTs. Characteristic results from the testing of one specimen are presented in Fig. 4.1c. This specimen was subjected to two cycles of increasing axial force, after which the liner broke at 6.02 mm axial displacement and a force of 143 kN. The force vs displacement plots from the axial pull tests were used to develop representative tri-linear curves that capture joint behavior during TGD and PGD in the FE simulations.

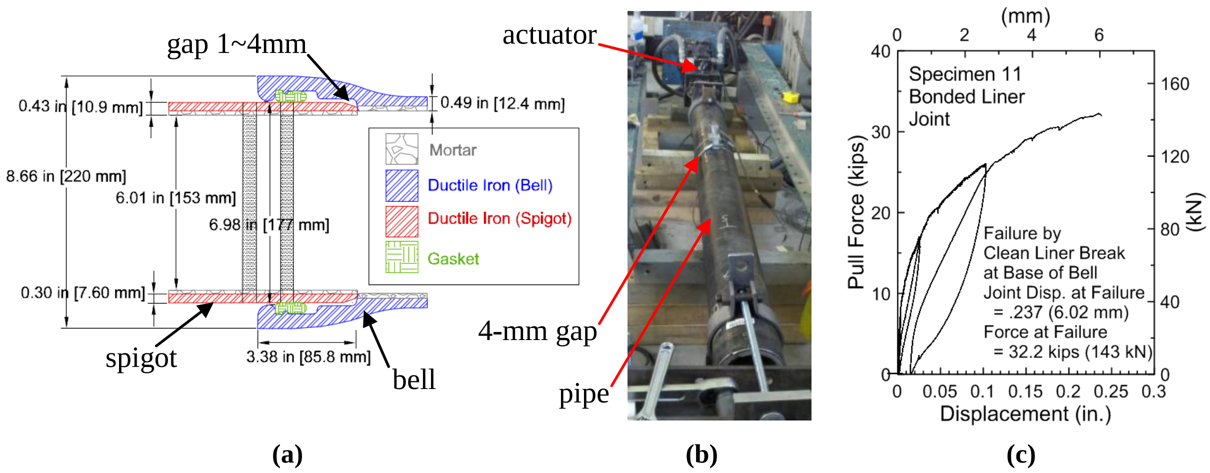


Figure 4.1. **(a)** Ductile iron joint cross-section. **(b)** Experimental setup for lined pipe pullout test. **(c)** Force vs displacement plot from lined joint pull test.

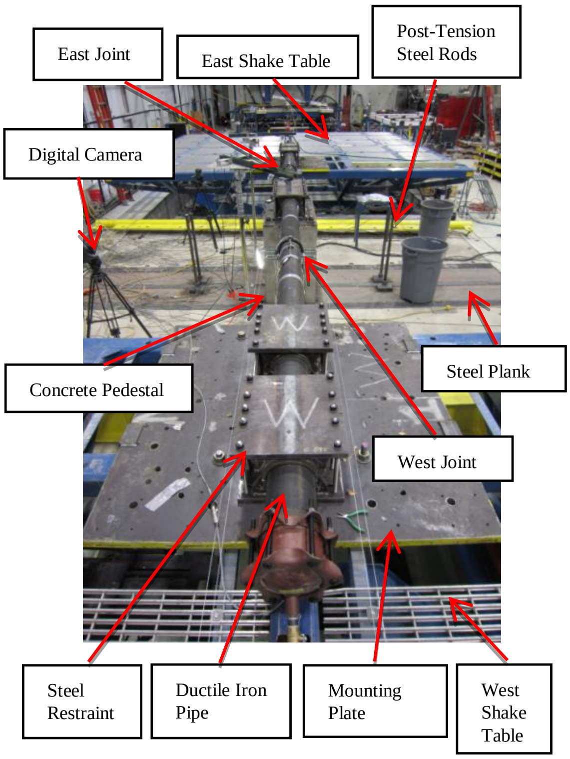
5. FULL SCALE TESTING AT UB

5.1 Test setup

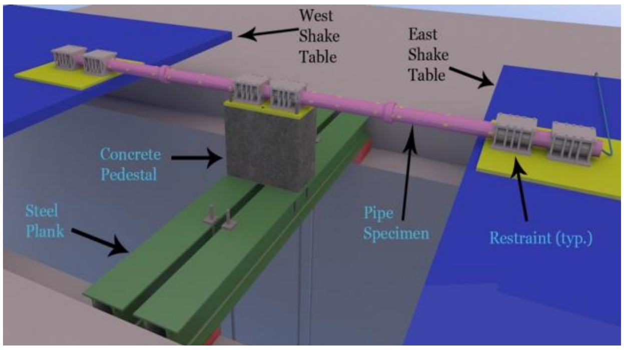
Full-scale dynamic tests on five pressurized 9.14-m-long test sections of DI water pipelines retrofitted with CIPP linings, were performed with the twin re-locatable shake table facility of the SEESL at UB. The DI specimens were provided by LADWP and lined in accordance with typical field installation procedures by ITI. Each specimen contained two lined DI joints, which could be subjected to earthquake ground motions individually or simultaneously. Joint movements for testing were derived from the FE simulations of seismic wave interaction with jointed CIPPs, as discussed in Section 3. Because the joint input motions account for soil-pipeline interaction, no soil was required for the UB tests. The pipes were pressurized internally at 345 kPa before and during each test. Figures 5.1a and 5.1b show a photo and 3-D view of the test setup, respectively. Strain gages, displacement transducers, accelerometers, differential pressure cells, and several video cameras were installed to monitor the seismic response. Furthermore, acoustic emission and ultrasonic guided waves inspections were carried out for each test to evaluate the extent of debonding between the DI pipe and the liner. Figure 5.1c shows a photo of a DI joint with acoustic monitors, strain gages, and DCDTs. As shown in Figs. 5.1a and 5.1b, the test pipeline was clamped to two shake tables with a support pedestal at the center of the test specimen. Lined DI joints were located 1.87m to 1.97m from the east and west clamping locations, respectively. The pipe length between the two joints was 3.75m.

Seismic wave/pipeline interaction analyses were performed, as described in Section 4, for the Rinaldi and Joshua Tree recordings at a number different scaled amplitudes. The analytical time records for the axial displacements of the CIPP- lined joints were used as input motions for the single and dual shake table tests. Both single and dual lined joint response to seismic motion was tested. The dual joint response represents an important case in which lined pipe with two adjacent weak joints or cracked sections is subjected to seismic wave effects. Under these conditions, the CIPP liners may debond over the pipeline length separating the locations of existing weakness. Tests that simultaneously subject the lined pipeline to ground motion are needed to understand and quantify the interaction between two lined, weak locations in the pipeline. This testing can only be performed with a dual shake table facility, such as the one at SEESL.

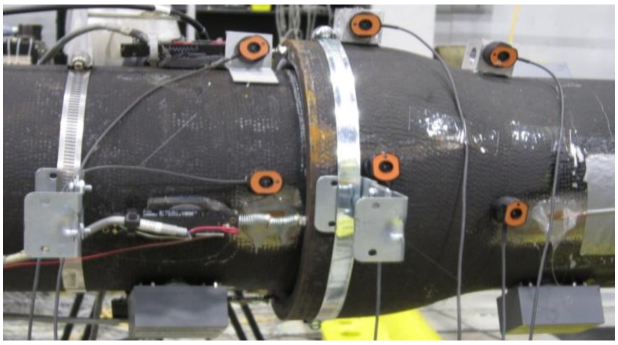
Asynchronous translational motions using lined joint displacement time records from the FE simulations were applied to each shake table causing differential axial movements at the joints. The ground displacement amplitudes were scaled from a minimum of about 50% to approximately 200% and 500% of the full-scale Rinaldi and Joshua Tree recordings, respectively. The scaled amplitudes were increased in stages until failure of the lining occurred.



(a)



(b)



(c)

Figure 5.1 (a) Overview of dual table tests. **(b)** 3-D view of shake table setup. **(c)** Close-up view of tested joints and instrumentation.

5.2 Test results

Figure 5.2a shows results derived from the dual shake table tests on two lined CIPP joints that were simultaneously subjected to asynchronous ground motion. It can be observed that the liner in the west joint reached failure when the joint displacement time history from 200% of the Rinaldi record was applied. The joint opening when the liner failed was 6.6 mm at a force of 148 kN. The east joint did not fail, and its force vs displacement plot is shown in Fig. 5.2b. The west joint test results at failure are compared in Fig. 5.2a with the tri-linear force vs displacement model for the lined joint used in the numerical simulations, showing very good agreement. The test results after failure show the absence of axial load capacity and stiffness at the lined joint. Some debonding between the joints occurred before failure which was confirmed by the acoustic emission and guided ultrasonic wave inspections. Tests are being performed on the shake table test pipeline section to characterize the physical conditions along the interface between the lining and pipe interior surface and correlate these conditions with acoustic emission results.

Fig. 5.2b shows the final force vs displacement plot for the east joint at 200% of the Rinaldi velocity amplitudes record. Also shown are the axial pull test results described in Section 4 and the tri-linear force vs displacement curve that was used in the FE simulations. The tri-linear force vs displacement model used in FE simulations compares well with both the axial pull and shake table results. The data in Figs. 5.2a and 5.2b show that the smaller lab test results match the dynamic behavior of the lined joints under large-scale shake table loading.

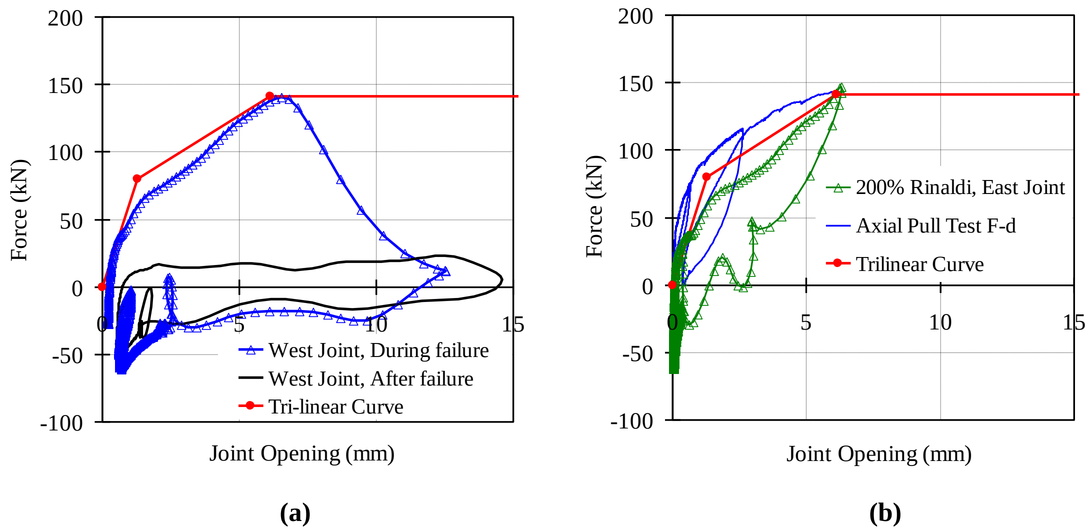


Figure 5.2 Force vs joint opening hysteretic response from dynamic testing: **(a)** West joint liner during failure at 200% of Rinaldi, liner after failure at 200% of Rinaldi, and tri-linear force vs displacement curve. **(b)** East joint liner at 200% of Rinaldi and comparison with tri-linear curve and axial pull test force vs displacement curve.

6. CONCLUDING REMARKS

The research undertaken through NEES on the earthquake response and rehabilitation of critical lifelines is a unique university-industry partnership focused on the use of in situ lining technology for the seismic retrofit of pipelines without disruptive excavation and replacement. Analytical models developed at Cornell for seismic wave interaction with underground lifelines have been successfully harnessed to full-scale tests with the dual shake table facility at the University at Buffalo (UB) to simulate the earthquake performance of pipelines retrofitted with CIPP technology. The results show that the retrofitted pipelines are able to accommodate very high levels of ground motion. Thus, the in situ lining technology is able to provide substantial benefits for seismic strengthening in addition to rehabilitation of aging and deteriorated underground infrastructure. Research results also show very favorable agreement between the axial force vs displacement performance of lined pipeline joints tested at large-scale with the dual shake tables and at smaller scale with tests on individual lined joints. The analytical force vs displacement relationship developed for numerical simulations are in excellent agreement with the test results. Future work will involve tests on pipelines retrofitted with CIPP technology subjected to permanent ground deformation with the Cornell Large-Scale Lifelines Test Facility, as well as analytical model development at UB, Cornell, and CSULA. The combined research results for transient and permanent ground movement effects will provide a comprehensive framework for design and system planning to utilize in situ lining technology for earthquake risk reduction.

AKCNOWLEDGEMENT

The work on which this paper was based was supported by the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program of the National Science Foundation (NSF) under Grant No. CMMI-1041498. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. Sincere thanks are extended to Insituform Technologies, Inc., including Messrs. S. Pearson, L. Osborn, and T. Driver, and to the Los Angeles Department of Water and Power, including Dr. C. Davis, Mr. Al. Gastellum, and Dr. J. Hu.

REFERENCES

Jeon, S.S., O'Rourke, T.D. and Netrevali, A.N. (2004). Repetitive Loading Effects on Cast Iron Pipelines with Cast-in-Place Lining Systems. *Journal of Transportation Engineering*, ASCE, **130:6**, 692-705.

O'Rourke, T.D., Wang, Y. and Shi, P. (2004). Seismic Wave Effects on Water Trunk and Transmission Lines. *Proceedings of the 11th International Conference on Soil Dynamics and Earthquake Engineering, and 3rd International Conference on Earthquake Geotechnical Engineering*. **Vol 2:** 420-428.

O'Rourke, T.D. (1998). An overview of Geotechnical and Lifeline Earthquake Engineering. *Geotechnical Special Publication No.75, Proceedings of Geotechnical Earthquake Engineering and Soil Dynamics Conference.* **Vol 2:** 1392-1426.

Pacific Earthquake Engineering Research Center, NGA Database. (PEER NGA, 2011). Available at: http://peer.berkeley.edu/nga/

Shi, P. and O'Rourke, T.D. (2008). Seismic Response Modeling of Water Supply Systems. *Technical Report MCEER-08-0016*. Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY.

Wang, Y. and O'Rourke, T.D. (2008). Seismic Performance Evaluation of Water Supply Systems. *Technical Report MCEER-08-0015*. Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY.