Research Objectives

The overall goal of this research is to achieve substantial improvement in seismic reliability of water supply systems through advanced technologies, notably fiber reinforced composites (FRC’s) to strengthen the welded slip joints of critical steel trunk lines. The research objectives are: 1) acquisition of full-scale welded slip joint specimens for laboratory testing, 2) development of simplified shell and 3-D FEM analytical models for performance of welded slip joints under compressive load, 3) full-scale testing of welded slip joints without FRC’s, 4) refinement and validation of analytical models, 5) full-scale testing of welded slip joints with FRC’s, 6) development and validation of analytical models for compressive load performance of FRC-reinforced welded slip joints, and 7) implementation of FRC reinforcement at Los Angeles Department of Water and Power (LADWP) and other water utilities.

In addition, the seismic performance of internal FRC linings will be assessed. This research will take advantage of work already supported by gas utility companies on the chemical and mechanical aging of FRC linings used to rehabilitate cast iron distribution mains. The improved performance of cast iron pipelines strengthened with FRC linings to both transient and permanent ground deformations during an earthquake will be quantified through full-scale tests on industry supplied specimens.

The 1994 Northridge earthquake resulted in the most extensive damage to a U.S. water supply system since the 1906 San Francisco earthquake. Los Angeles Department of Water and Power and Metropolitan Water District (MWD) trunk lines (nominal pipe diameter greater than 600 mm) were damaged at 74 locations, and the LADWP distribution system required repairs at 1,013 locations. An analysis of Northridge earthquake performance shows that approximately 60% of critical trunk line damage in the Los Angeles Department of Water and Power (LADWP) system occurred because of compressive failure at welded slip joints.
A welded slip joint is fabricated by inserting the straight end of one pipe into the bell end of another and joining the two sections with a circumferential fillet weld. The bell end is created by the pipe manufacturer by inserting a mandrel in one end of a straight pipe section, and expanding the steel into a flared, or bell casing. Large diameter pipelines can be constructed rapidly and economically in the field by joining the bell and spigot (straight) ends of connecting pipe segments.

Figure 1 shows a compressive failure at a welded slip joint on the Granada Trunk Line, a 1,245 mm (49 in.) diameter steel pipeline with 6.4 mm (1/4 in.) wall thickness that failed during the Northridge earthquake because of lateral ground movement triggered by liquefaction near the intersection of Balboa Boulevard and Rinaldi Street in the San Fernando Valley. Similar compressive failures were observed in trunk lines during the 1971 San Fernando earthquake and in the adjacent 1,727 mm (68 in.) diameter, (9.5 mm (3/8 in.) wall thickness) Rinaldi Trunk Line during the Northridge earthquake. Loss of both the Granada and Rinaldi Trunk Lines cut off water to tens of thousands of customers in the San Fernando Valley for several days.

As illustrated in Figure 2, failure of welded slip joints can be initiated by compressive forces that induce buckling and outward deformation at the location of maximum curvature in the bell casing. Compressive forces sufficient to fail welded slip joints can be generated...
by near source pulses of high particle velocity as well as permanent ground deformation generated by surface faulting, liquefaction, and landslides.

Fiber Reinforced Composite (FRC) wrapping can be used to confine the welded slip joint against outward deformation of the bell, (see Figure 2). This type of reinforcing not only can be used to retrofit existing welded slip joints, but to strengthen new joints during fabrication in the field. As new pipelines are constructed, the pipeline surface at and adjacent to the fillet weld needs to be wrapped to provide corrosion protection. If the wrap used to protect against corrosion can also strengthen the pipeline against compressive failure, then the seismic performance of the critical trunk lines can be enhanced at relatively little additional cost.

Research at MCEER has focused on developing robust analytical models that can emulate buckling in straight pipe and welded slip joint sections. The research also includes a comprehensive laboratory test program to quantify the improvements in axial load capacity achieved with FRC wrap relative to that of unwrapped specimens. The laboratory tests are also used to qualify and validate the analytical models.

A comprehensive study of analytical modeling with DIANA™ and ABAQUS™ was undertaken, and ABAQUS™ was adopted as the finite element method (FEM) package of choice for evaluating welded slip joint and pipeline performance. Benchmark analytical studies were performed with ABAQUS™, and the sensitivity of the solutions to initial imperfections was investigated by bifurcation buckling techniques. The most appropriate element type chosen was a linear, four node, reduced integration shell element. Circumferential weld representation was found to have a significant effect on the finite element solutions, and an appropriate weld representation technique was developed for the analytical work with a technique known as multi-point constraints (MPC). The MPC technique connects nodes around the circumference of the bell to their counterparts on the inserted straight pipe. A rigid weld is then simulated by enforcing identical degrees of freedom in each pair of connecting nodes.

Figure 3 shows profile views of the FEM mesh in the vicinity of a 305 mm (12 in.) diameter welded slip joint before and after the application of axial compressive load. The FEM mesh which was configured to simulate the 610 mm coordinated with MCEER-supported studies of the LADWP electric power system supervised by M. Shinozuka, University of Southern California.

- New York Gas Group, New York City, New York.
- In-Situ Form Technologies, Inc. St. Louis, Missouri.
- Miller Pipeline Co., Columbus, Ohio.

![Figure 2. Compressive response of welded slip-joint and FRC reinforcement](image)
(24 in.) long experimental specimens, was modeled as a quarter section to take advantage of the symmetrical loading condition and geometry. Based on mesh refinement studies, 7,260 elements were used with 66 equi-dimensional elements along the circumference of each quarter section in the region of refined mesh coverage.

Analytical studies were performed for a prismatic section of pipe with no welded slip joint so that the analytical results could be compared with published solutions and experimental measurements. The buckling limit of a prismatic, or straight, pipe section establishes the maximum capacity of the pipe. The upper bound of performance with FRC wrapping is the buckling limit of the straight pipe. If FRC strengthening of a welded slip joint increases the load carrying capacity to the buckling limit of a straight pipe section, then the FRC technology has been successful in achieving the maximum possible improvement.

Specimens of 305 and 610 mm (12 and 24 in.) diameter welded slip joints were fabricated by LADWP and shipped to the George Winter Structures Laboratory for Structural Engineering Research, at Cornell University. Full cooperation and support from LADWP was established early in the experimental process allowing for immediate feedback between the two parties in project definition and direction. The choice of specimen size (diameter and pipe wall thickness) and joint construction (exterior vs. interior welded slip joint) has had direct input from LADWP to reflect their concerns for existing and future inventory. In addition, close coordination with FRC designers and contractors has progressed in parallel with testing. Laboratory tests have been performed on FRC reinforced as-built specimens that were prepared by two vendor teams participating in the experimental program. The vendor teams are: 1) Structural Preservation Systems, Inc, Baltimore, MD, and Master Builders, Inc., Cleveland OH, and 2) Fyfe, Inc., La Jolla, CA, and R.J. Watson, Inc., Buffalo, NY.

The types of tests that have been performed on 305 mm (12 in.) diameter pipe are: 1) compression of a prismatic section, 2) compression of unreinforced welded slip-joints, and 3) compression of FRC-reinforced welded slip-joints. As previously discussed, the performance of the prismatic section establishes the baseline, i.e., the maximum, for comparison with all other test results.

The experimental testing facilities consisted of a custom designed MTS load frame, with a load capacity of 2,700 kN (600 kips). Data was acquired by a personal computer controlling several data acquisition systems. Axial forces

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**Figure 3.** Finite element mesh of welded slip-joint
were cycled on sections of strain-gaged pipe at levels needed to seat the specimen, and at approximately 30 and 60 percent maximum capacity. The pipe was loaded to the yield capacity and cycled, after which axial load was applied as far as the hydraulic ram could move (100 mm (4 in.)).

Figure 4 shows the prismatic section in the test frame. For this test a total of 48-strain gage rosettes were bonded to the pipe, 24 on the outside and 24 on the inside matching the location and orientation of the associated gage on the outside.

Many researchers (e.g., Donnell and Wan, 1950) have shown that initial imperfections due to the manufacturing and handling have a strong influence on the buckling limit. Imperfections were measured systematically across the prismatic pipe specimen on a 25 mm (1 in.) grid, utilizing a digital dial gage. The periodicity of the imperfections was analyzed with fast Fourier transform functions, and the imperfection spectra generated was used to model the imperfection amplitude and wavelengths. The maximum imperfection amplitude was approximately three percent of the pipe wall thickness. Close agreement between the experimentally observed buckling pattern and numerically simulated pattern was achieved.

Figure 5 shows the axial load vs. displacement plots for the prismatic test specimen and the numerical simulation. There is a remarkably close agreement between the experimental and analytical results. The peak predicted and measured loads are 2,200 and 2,175 kN (495 and 489 kips), respectively, which are two to three percent greater than the theoretical yield load of the specimen. As shown by the inset images, there is close agreement with respect to the location of buckling in the experimental and analytical results.

Figure 6 shows the axial load vs. displacement plots for a welded slip joint specimen and the numerical simulation. Again, there is remarkably close agreement between the

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Figure 4. Prismatic pipe specimen in load frame

Figure 5. Comparison of test and FEM results for prismatic pipe
force vs. displacement relationships and patterns of buckling.

Figure 7 shows the axial load vs. displacement plots of the prismatic and the welded slip joint specimens. The maximum loads carried by the welded slip joints were 1,670 and 1,740 kN (375 and 390 kips), which are between 77 and 79 percent of the buckling limit of the prismatic pipe section.

Figure 8 shows the axial load vs. displacement plots for the welded slip joint specimen, Slip Joint 3, and the FRC wrapped slip joint specimens prepared by the SPS/MB (FRC Wrapped-2) and Fyfe/Watson (FRC Wrapped-1) teams. In each case, the FRC wrap resulted in an increased capacity of approximately 25 percent. When the wrapped specimen results are compared with those of the prismatic section, it can be seen that FRC strengthening achieves a compressive capacity virtually equal to the buckling limit of a straight pipe section. Moreover, as the inset images in Figure 7 and Figure 8 show, the FRC wrapped specimen “FRC Wrapped–2” failed by buckling at the same location and manner as the prismatic specimen.

The close agreement between the analytical and experimental results indicates that the model developed in the research work is robust and sufficiently reliable for evaluating the response of welded slip joints with different geometries. Figure 9 shows the analytical results of welded slip joint axial load capacity, expressed as $P_R$, the ratio of maximum to theoretical yield load, plotted relative to pipe diameter-to-thickness ratio, $D/t$. The results for various pipe diameters are plotted. The yield load is simply the product of the steel compressive yield stress and cross-sectional area of the pipe. As discussed previously, the yield load is very close to the buckling capacity of a prismatic pipe section so that it may be taken as the maximum achievable capacity of the pipe.

The analytical results in Figure 9 allow one to scale the current findings to larger $D/t$ ratios, representative of larger diameter pipe. For example, the Granada and Rinaldi Trunk Lines described previously, have $D/t$ ratios 160 to 180. Welded slip joints in this $D/t$ range would
be expected to mobilize only about 50 percent of the maximum axial capacity of the pipe. Hence, FRC strengthening can result in nearly a 100 percent increase in compressive load capacity of a pipe with these geometric characteristics.

The FEM results are also plotted relative to the results from a simplified shell model developed by Tawfik and O’Rourke (1985). Although the simplified shell model provides a good representation for $D/t \geq 300$, it tends to underpredict the axial compressive capacity for the $D/t$ range most frequently encountered in water supply trunk lines ($75 \leq D/t \leq 200$).

**Conclusions and Future Research Needs**

The full-scale tests being performed at Cornell University are focused on the effectiveness of FRC strengthening for steel pipeline with welded slip joints. The experimental and numerical simulation work in progress will clarify: 1) influence of diameter to pipe wall thickness ($D/t$) on overall performance, 2) surface irregularities and their effects on performance, 3) local buckling deformation of exterior welded joints versus interior welded joints, and 4) different vendor FRC designs and installation procedures. As-constructed welded slip joints (bell housing and spigot) are tested to investigate the reduction of axial compressive capacity due to the joint. Participating vendors wrap the joint regions of test specimens with proprietary FRC materials. All specimens are tested to large plastic strains that investigate the failure process through successive local buckling modes.
be made. At the request of LADWP, an assessment will be made of the performance of slip joints with exterior and interior fillet welds at a D/t ratio identical to that of the new 2.44 m (96 in.) diameter City Trunk Line currently in design.

Large diameter pipes (762 and 914 mm) will be tested at the Taylor Devices facilities in North Tonawanda, New York. Taylor Devices will donate the use of its equipment at no charge, except for time required by Taylor personnel to assist in test preparation. This represents exceptional cost and time savings relative to previous plans for fabricating the appropriate testing equipment at Cornell. It also represents an excellent example of industry cooperation in the MCEER research effort. The capacity of the load frame at their facilities is roughly 6,700 kN (1500 kips). This load can be applied in either compression or tension. The test machine is capable of rapid loading with velocities similar to those recorded during the Northridge earthquake. Figure 10 shows the frame being used for testing a large seismic damping device.

A similar approach with internally applied FRCs for improving the seismic performance of gas and water distribution mains is being pursued. In this case, MCEER researchers are taking advantage of research already in progress and funded by the New York Gas Group (NYGAS) at Cornell. This work involves mechanical and chemical aging tests on full-scale specimens of cast iron (CI) distribution pipe prepared and lined with FRCs under the supervision of gas utility personnel and contractors specializing in FRC lining technologies. Specimens of cast iron gas mains, provided by the New York Gas Group, have been lined with the FRCs and tested under conditions in which the cast iron pipe has ruptured with the internal lining intact. The tests involved the simulation of vertical offsets and relative rotations of fractured pipe lengths consistent with the type of deformation experienced in liquefied ground. The lining was able to sustain low-pressure service without disruption.

Because this research involves the qualification of FRC linings for damaged pipe under cyclic and permanent deformations, the results can be readily adapted to evaluate the seismic performance of FRC-reinforced distribution mains. Additional tests are planned.
to load the FRC-lined pipes to failure and to assess dynamic deformations consistent with near field strong motion records. Cooperation in this testing has been obtained from the New York Gas Group, In-situ Form Technologies Inc., St. Louis, Missouri and the Miller Pipeline Co., Columbus, Ohio.

To evaluate the impact of FRC technology, improvements in system reliability will be evaluated by means of probabilistic hydraulic network simulations. These analyses will be used to quantify the effects on system performance of pipe and welded slip joints strengthened by FRCs. The systems analyses will take advantage of the inventory development and GIS modeling of the Los Angeles water supply being performed concurrently with the FRC research.

References

