FULL SCALE TESTING AND SEISMIC QUALIFICATION OF CEMENT MORTAR LINED CARBON STEEL PIPE

F R HAND (I)
C N SUN (II)
J M HOSKINS (III)
PRESENTING AUTHOR: F R HAND

SUMMARY

A full-scale testing program consisting of laboratory tests, field tests and vibration measurements was conducted for seismic qualification of cement-mortar lined carbon steel pipes. Pipe samples 30-inch and 18-inch in diameter were subjected to three-edge-bearing, cyclic loading, torsion, drop, impact and bending tests. A 90-degree elbow was subjected to bending tests. The results of the tests are presented. Based on these data a conventional, commercially produced cement-mortar lined pipe is fully adequate for its intended function in a low to moderate seismic area.

INTRODUCTION

Corrosion and incrustation in carbon steel raw water pipes have been found to be problems at many existing facilities. Lining existing and new carbon steel raw water pipes with cement mortar is one way to correct these problems. However, the performance of the cement-mortar lining under a variety of loading conditions, including earthquake, is either not well known or well documented. This paper described a full-scale testing program to structurally qualify the cement-mortar lined carbon steel pipes for both nuclear and non-nuclear applications. The testing program consists of laboratory tests, field tests and vibration measurements during shipping. Pipe sizes are 18- and 30-inch diameters. The pipes were lined by a commercial firm.

LINING OPERATION AND PREPARATION OF PIPE SPECIMENS

A total of 100 feet of 30-inch diameter pipe, 20 feet of 18-inch diameter pipe and a 90-degree elbow of 30-inch diameter were lined in accordance with AWWA C602 requirements. The 30-inch diameter pipes and elbow are ASME SA155-KCF70, Class 2, electric-fusion-welded carbon steel pipes fabricated from ASTM A516, Grade 70 steel plate with a minimum tensile strength of 70 ksi and a minimum yield strength of 38 ksi. The 18-inch diameter pipe is ASME SA106, Grade B, seamless carbon steel pipe with a minimum tensile strength of 60 ksi and a minimum yield strength of 35 ksi. The pipes were bought new and had been in yard storage for approximately 12 months. The interior surface condition was similar to Grade B carbon steel by the Steel Structures Preparation Standards for Painting Steel Structures (SSPC-Vis 1-67 T). Minimal cleaning effort was required to remove loose mill scale by wiping with a burlap bag.

The cement-mortar was composed of cement, sand and potable water. The cement was Portland Cement, Type II, conforming to ASTM C 150 and weighing

(I) Civil Engineer, F R Hand Consultants, Jackson Michigan, USA
(II) Civil Engineer, Tenessee Valley Authority, Knoxville Tenessee, USA
(III) Civil Engineer, Tenessee Valley Authority, Knoxville Tenessee, USA

94 pounds per bag. A manufactured sand conforming to ASTM C 144 and weighing 100 pounds per bag, was used. Proportion of cement to sand was 1 part cement to 1.1 parts sand by weight (approximately 1 bag to 1 bag). Water was adjusted as needed for workability. Estimated water to cement ratio was 0.3 by weight. A slump of 5½ inches was recorded using a 12-inch cone. Tests on mortar samples, both from fog-room cured and cured inside the 30-inch pipe, yielded ranges for compressive strength of 8 to 11 ksi, tensile strengths of 440 to 610 psi and modulus of elasticity of 3950 to 5240 ksi.

Mixing of the cement mortar was accomplished in a continuous operation that included immediate pumping, through a rubber hose, to the lining machine. The mortar was centrifugally applied onto the interior surface of the pipe by a rapidly revolving head. The mortar was thrown in a tangential direction and stuck to the wall upon contact. Immediately following this, the troweling operation was accomplished by means of rotating steel trowels (for 30-inch pipes) or conical-shaped drag trowel (for 18-inch pipe). The 90-degree elbow was lined by machine and troweled by hand. A relatively smooth surface was obtained after troweling. No excess water appeared on the surface (bleeding). All pipes were lined horizontally.

Water and curing compounds were used on separate pipe sections. Curing was found to be the most important factor in the entire lining operation. Both methods were effective and the water curing was simple to carry out with no undesirable side effects. Specimens were either fully moist curried, moist curried for 4 days and then air dried, or completely air dried. All fully curried linings showed no sign of any hairline cracks. The 4-day cured specimens developed large cracks soon after exposure to the environment. The air dried specimens developed cracks and separation between the lining and steel pipe wall after two days. This clearly indicates the importance of curing on the condition of the lining. However, the presence of these defects did not adversely effect the tested performance of the linings.

The lining thickness at the top is usually less than that at the bottom. Among 112 checked locations on the ends of the pipe specimens, 15 locations had a thickness less than the specified ¼ inch. Three of the 15 locations were from the 30-inch pipes, the rest were from the 18-inch pipe sections. The maximum thickness was 19/32 inch and the minimum thickness was 3/16 inch.

VIBRATION MEASUREMENTS DURING SHIPPING

Two accelerometers were mounted on the 30-inch diameter pipes to monitor vibrations experienced by the pipes during the 100-mile trip from lining to laboratory site. The vibrations of the 30-foot pipe (bottom) and a 2-foot section (top) were measured and recorded on tape for later analyse. The acceleration time histories and their corresponding Fourier amplitude spectra at certain high acceleration locations on the record were analyzed. The maximum acceleration experienced by the bottom pipe (30 feet long) was 0.6 g and the experienced by the top pipe (2-foot section) was 2.1 g. The recorded maximum peak to peak accelerations were 1.2 g and 3.8 g respectively. Dominant frequencies ranged from 15 to 70 Hz, mostly concentrated in the range of 15 to 50 Hz.

For most large earthquakes the dominant frequencies are in the range of 0.5 to 10 Hz. Lower frequencies indicate that a buried pipe would experience less number of cycles of vibration during actual earthquakes. Since a pipe has to move with its surrounding soil, vibration amplification due to structure properties is minimal. No crack due to vibration was found in any of the linings after unloading. The 90-degree elbow had a large circumferential shrinkage crack due to the loss of an end cover during transportation. No crack was found before shipping. It is concluded that the linings had experienced more severe vibrations than any recorded earthquakes in terms of magnitude and number of cycles. The vibration measurements were considered as effective as shaking table tests.

LABORATORY TESTS

The 2-foot sections were subjected to three-edge bearing, cyclic loading, torsion, drop and impact tests. The 30-foot section was subjected to bending, cyclic loading and drop tests. The 90° elbow was subjected to bending test. In general, these tests were continued either until the failure of the lining or pipe occurred or until the load or deformation capacity of the testing equipment was reached.

Three Edge Bearing Tests

A procedure similar to ASTM C 497 was used. The 2-foot pipe was placed on two wooden bearing strips and a vertical load was applied to the top of the pipe through a hardwood block. Six 30-inch pipe sections and five 18-inch sections were tested. The three-edge bearing tests showed that the cement-mortar linings were flexible. The lining cracked without falling even at the maximum loading stage when plastic hinges formed in the steel and the load could not be increased. The average maximum load, change in diameter at maximum load and permanent change in diameter were 12.3 kips, 3 inches and 1.5 inches, respectively, for the 30-inch pipe sections and 22.7 kips, 1.8 inches and 1.0 inch for the 18-inch pipe sections. The maximum deformation corresponds to approximately 10% ovaling.

For the 30-inch pipes, generally, visible hairline cracks appeared at the bottom when the load reached approximately 1 kip. The 0.01-inch crack, mostly in bottom, appeared under loads between 3.5 and 6.1 kips. Most of the cracks concentrated in the top and bottom areas. The largest crack recorded without complete failure was 0.06 inch in the bottom area of the lining of the 4-day cured specimen. For the 18-inch pipes, generally, visible hairline cracks appeared at the top when the load reached approximately 3 kips. The 0.01-inch crack, mostly in the bottom, appeared under loads between 12.5 to 19.0 kips. Most of the cracks concentrated in the top and bottom areas. Strain gauges on a 30-inch section clearly show that plastic hinges initially formed at centerline level on both sides of the steel pipe under a load of 8 kips (about 2/3 of the maximum load).

Cyclic Loading Test

The cyclic loading test is a three-edge-bearing test with repeated loads applied at an average rate of once every 12 seconds. A complete loading cycle was: zero to maximum load, then to zero. The loading rate is not rapid enough for a dynamic loading test.

A 30-inch pipe section was tested 32 days after lining. No visible cracks were observed at start of the test. The pipe was loaded to 4 kips first, unloaded and then cyclic loading was applied. Shortly after applying the static load, a hairline crack appeared in the bottom at 1-kip load and a second in the top at 2 kips. Bond break at the top was also observed at 2 kips. At 4 kips a crack close to 0.01 inch appeared in the bottom. The pipe was then cycled 20 times to 4.0 kips. At the eleventh cycle bond break between lining and pipe was indicated by a loud bang. The pipe was then cycled another 20 times to 7.0 kips. The 0.01-inch crack appeared in the bottom during the first cycle to 7 kips. More bond break occurred during the first cycle. More cracks appeared at top and bottom. The condition of the specimen at this stage is shown in Photo 1. The pipe was then cycled another 20 times to 10.0 kips and bond break developed at the eleventh cycle. Also, cracks and spalling appeared in top and bottom. Then the pipe was cycled four times to 12 kips. The top lining started to fall during the second cycle and more failure at top occurred after four cycles. Test was stopped after complete failure of the liner.

Another 30-inch pipe section with strain gauges was tested 33 days after lining. The pipe was loaded to its maximum load 12.2 kips first, unloaded and the cyclic loading was applied. During application of the static load, the 0.01-inch crack appeared at 3.5 kips. The pipe was cycled 20 times to 8 kips with no new cracks observed. The pipe was then cycled two times to 12.2 kips and complete failure occurred at the end of the second cycle. The stress reversal effects were evident from the strain gauge data.

An 18-inch pipe section was tested 32 days after lining. No visible crack was observed at the start of the test. The pipe was cycled 20 times to 12 kips, and small cracks appeared in the top at 3.5 kips and in the bottom at 4 kips, and bond break at 5 kips during the first cycle. The pipe was then cycled 20 times to 16 kips without showing any new cracks. The pipe was cycled 20 times to 20 kips with the 0.01-inch crack appearing in the bottom at 19 kips during the first cycle. The pipe was then cycled to 23.5 kips. More cracks appeared in top and bottom after the second cycle, top lining started to fall after the fourth cycle and complete failure occurred after the seventh cycle.

Impact Tests

Impact tests were performed on both 30-inch and 18-inch pipe sections 40 days after lining. A 35.5-pound missile was dropped onto the pipe from heights up to 40 feet. Two 30-inch pipe specimens and one 18-inch pipe specimen were used for 14 impact tests at different locations on the pipes. Impact loading was considered to have only local effects on the pipe. Damage to steel was not severe. Damage to lining was dependent on drop height and stiffness of the lining. The spalling damage from a 40-foot drop height is shown in Photo 2. For the 30-inch diameter pipe sections, there was no spalling for a drop height of 13 feet or less. Both axial and circumferential cracks appeared for a drop height of 15 feet or less, only axial cracks appeared for a drop height of 16 feet or more. For the 18-inch diameter pipe sections, no crack appeared in the lining for all drop heights tested.

Drop Tests

The drop tests were performed 40 days after lining. Two-foot pipe sections were lifted to various heights up to 15 feet and then dropped on a rigid concrete slab. All cracks appeared in the bottom impact area. No lining failed.

Drop tests on the 30-foot pipe were performed 53 days after lining. The pipe for the bending tests was also used for the drop tests. The cracks in the lining due to dropping the pipe from a certain height were, as expected, confined to the impact area however, no lining failed. After each drop, the pipe was rotated by approximately 45 degrees then dropped again. Drop heights were 1, 2, 4, 6, 8 and 10 feet. The pipe was kept as level as possible. Permanent change in diameter was approximately 0.5 inch for each drop regardless of the drop height (10 feet maximum).

Torsion Tests

The torsion tests were conducted 90 days after lining. One end of a 30-inch-diameter pipe section was welded to a steel plate to simulate a fixed end of a shaft. A twisting couple was applied at the free end of the pipe section by using two identical hydraulic jacks to deliver two equal but opposite forces at the two ends of a loading beam (Photo 3). The distance between the two loading points was 5.25 feet. The torsion test was intended to simulate conditions imposed upon the pipe due to change in pipeline geometry such as at elbows. At these locations, a deflection in one part of the pipe may induce torsional load in the other part of the pipe.

Cracks concentrated in the areas close to the loading beam (a boundary condition effect) and other cracks generally ran in the vertical direction (axial). Cracks appeared at 15, 35 and 45 kips. No crack exceeded 0.01 inches. The lining near the welds started to spall and one weld failed at a load 60 kips. At the higher loads ovaling of the pipe circular section was evident. At 60 kips the minor diameter reduced to 27 1/8 inches for approximately 10% ovaling.

Bending Tests

Static and cyclic loadings were applied to the 30-foot pipe (30-inch diameter) at two loading points near the midspan for pure bending tests. The pipe was held down by anchor blocks and the loading was applied upwards. The clear span between support points was 26 feet and between load points was 30.5 inches. Four strain gauges and two deflection gages were installed. Three tests were conducted on different days.

The first test was performed 34 days after lining. It was intended to be a trail test. Crack pattern was checked at 5-kip load increments. Only minor cracking occurred up to a load of 20 kips. The load was increased to 21 kips and then cycled 20 times at 20 kips; no additional cracks appeared. At 18 kips, the steel was stressed to +7.11 ksi (compression) at the bottom (where loads were applied) and -3.12 ksi (tension) at top. The cement lining was stressed to 0.98 ksi at the bottom and -0.65 ksi at the top. The tensile stress in the lining was close to, if not exceeding, the tensile strength of the mortar at age 34 days.

The second test was performed 47 days after lining. A large number of circumferential cracks appeared after the load was increased to 30 kips.

Local failure in the lining (scabbing) and local deformation in the steel appeared at one load point at the maximum load, 80 kips. At 60 kips the steel was stressed to +13.05 ksi at bottom (where loads were applied) and -23.35 ksi at top. The cement lining was stressed to +1.7 ksi at bottom and -0.25 ksi at top. Low stresses in the lining were due to circumferential cracks which relieved most of the bending stress.

The third test was performed 52 days after lining. The pipe was rotated 180 degrees so the loads could be applied to the relatively undamaged half of the pipe. The loading beam pads were enlarged so that scabbing of the lining due to load concentration could be avoided. The pipe was loaded to 90 kips and then cycled 10 times to 75 kips. Under the 90-kip load, the beam deflection at midspan was 0.36 inch and the changes in diameter were 0.94 inch vertically and 0.38 inch horizontally. The steel was stressed to +84.1 ksi at bottom (where loads were applied) and -20.3 ksi at top. The lining was compressed to +4.13 ksi at the bottom and no data was obtained for the top stress due to broken strain gauge.

<u>Tests on Elbow</u>

The 90° elbow was tested three times. The loading was applied inwards at the ends of the built-up section (Photo 4). The elbow was loaded to 10 kips to test the equipment 57 days after lining. In was then loaded to 50.6 kips 61 days after lining. It was finally loaded to 54 kips 65 days after lining and this resulted in failure of the lining and the steel pipe.

At 54 kips the distance between loading points was shortened by 5 inches and a permanent shortening of 1-½ inches was recorded after unloading. The changes in diameter at center of the elbow were +3/4 inch vertically and -1-½ inches horizontally. The steel pipe was under compression at all times: +13.92 ksi at the inside and +4.06 ksi at the outside. The lining was stressed to +2.9 ksi inside and -0.45 ksi (tension) outside. This stress distribution resulted because the center of the elbow was subjected to both axial load and bending moment. At small load, the entire section was under compression; but at maximum load (54 kips), local deformation had an important effect on the stress in the lining. The stress in the lining at the outside portion of the elbow then changed from compression to tension. The circumferential crack had an unknown effect on the strength of the elbow.

FIELD TEST

A field loading test was conducted 46 days after lining. The 30-inch diameter, 40-foot long pipe with exterior coating was installed in a trench, covered with 3 feet of compacted clay and subjected to loads from a large vibratory roller. Strain gauges and deflection gauges were installed at about midspan of the pipe to measure the flattening effects of the cross section. Beam action of the pipe which would induce longitudinal strains was considered to be negligible. A Dynapac CA-25 vibratory roller was used for applying loads on the pipe. The CA-25 vibratory roller has a smooth drum with 60-inch diameter and 84-inch width. The drum weighs 10,250 pounds and delivers a dynamic force of 36,000 pounds at 28 Hz.

A complete loading cycle contained a backward pass for static load with vibrator off and a forward pass for dynamic load with vibrator. The roller moved in both directions at an approximate speed of 2 miles per hour. After each loading cycle, lining crack pattern was checked and 6 inches of soil cover was removed. A new loading cycle was then begun. A total of seven passes were made (six cuts). After seven passes, only a thin layer (less than 1 inch) of soil remained on top of pipe. A sustained dynamic loading was applied to the pipe by parking the roller directly on top of pipe with the vibrator turned on. The sustained dynamic load was applied to the pipe for 15 minutes.

There were no visible cracks in the lining before tests began. There were no visible cracks after the roller made seven passes. When the roller was parked on top of the pipe with its vibrator turned on, cracks started to appear after 12 minutes of continuous vibration. Changes in pipe diameter due to static load from the roller were negligible and due to vibratory load were small. The maximum changes in vertical and horizontal diameters were approximately 1/8 and 1/16 inch respectively. Both maximum changes occurred when the roller was parked on top of the pipe with the vibrator turned on. The pipe had almost no soil cover for both the seventh pass and the continuous vibration loading conditions, but the changes in diameter due to continuous vibration were three times the changes due to the seventh pass. In addition, the pipe also moved vertically with the surrounding soil as a rigid body. The amount of movement was not recorded, but it was observed to have a maximum magnitude of ½ inches.

The maximum stresses in steel were 15.95 ksi compression (top) and 6.67 ksi tension (side). The maximum stresses in mortar were 1.5 ksi compression and 0.90 ksi tension. The steel stress was much lower than the 38 ksi minimum yield strength of the ASME SA155 steel. The compressive stress in the mortar was much lower than the 10 ksi compressive stress of the mortar specimen. The maximum tensile stress in the mortar exceeded the tensile strength of the mortar specimen by a factor of two. No crack was observed in areas directly under the load. This indicated that the dynamic tensile strength of the mortar may be much higher than the static tensile strength.

CONCLUSIONS

A full-scale testing program consisting of laboratory tests, field tests and vibration measurements was conducted for seismic qualification of the cement mortar lined carbon steel pipes. In general, these tests were continued either until the failure of the lining or pipe occurred or until the load or deformation capacity of the testing equipment was reached. Based on these test, the generated data and the observed performance, a conventional, commercially produced cement mortar lined pipe is fully adequate for its intended function in a low to moderate seismic area. In addition four specific conclusions are:

1. Cracks in the lining of some pipe sections existed prior to testing and did not influence the failure pattern of the linings. Thus, a perfectly uncracked lining is not required. The presence of some cracks in the inplace and cured lining is anticipated.

2. The three-edge-bearing tests showed that the cement mortar linings were flexible. The lining underwent considerable cracking prior to separation and falling of the lining. Linings only fell after the formation of the

plastic hinges in the steel.

3. The curing procedure is the most important step in the entire lining operation. This is required to control shrinkage cracks in the cement rich mortar used. A minimum of 4- to 7-day uninterrupted moisture cure is recommended.

4. Slight variation in lining thickness did not significantly affect the test data. Thus, strict control of the lining thickness is not required. The thickness tolerances given in AWWA C602-76 are adequate.

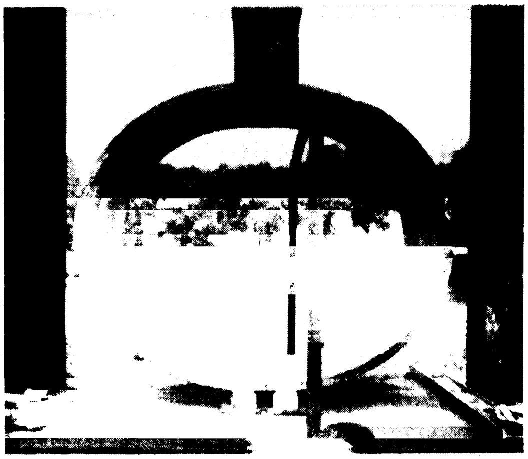

Photo 1-Cyclic test-30" pipe, fully cured (32 days)-after 20 cycles to 7k

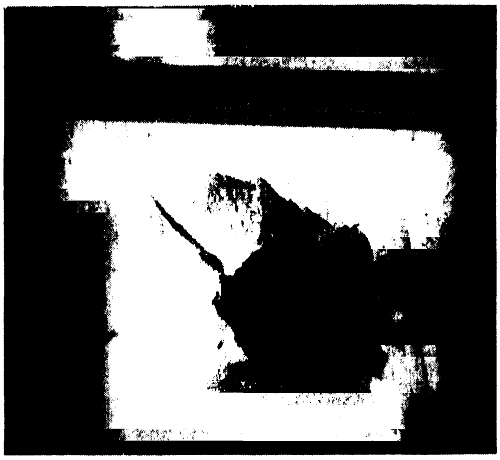

Photo 2-Impact test-30" pipe 40' drop

Photo 3-Torsion test-Initial setup

Photo 4-Tests on elbow-Initial setup