Seismic Fragility Pipe Testing

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ABSTRACT

Responding to the needs of emerging research programs, Energy Technology Engineering Center (ETEC), a Department of Energy laboratory, has designed and built a Seismic Fragility Testing System. This paper describes several fragility tests on representative piping systems recently concluded at ETEC. These tests, all resulting in piping failure, include programs sponsored by the US Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI). The results of the dynamic load testing of representative piping systems has generated valuable data which can provide the basis for ASME Code changes to current piping design criteria.

INTRODUCTION

The Energy Technology Engineering Center (ETEC), a Department of Energy (DOE) laboratory operated by Rockwell International near Los Angeles, California has designed a facility to meet seismic fragility testing needs. ETEC's Seismic Fragility Test System (SFTS) was designed and built for destructive testing of nuclear power plant components and structures. Its large displacement and high velocity capability can generate large acceleration loadings in the low frequency range generally associated with seismic events (3-10 Hz), and the multi-table support capability enables testing of large, complex, structural shapes at these same high levels.

To date, five piping systems have been tested. The first test article was a 3-in. unpressurized pipe loop. This test was sponsored by DOE to demonstrate that ETEC had an operational facility capable of producing dynamic pipe failures and to provide insight into the seismic design margins. The second, and by far the most thoroughly documented test, was a 6-in. pressurized pipe loop sponsored by the USNRC. The third test, also a 6-in. pressurized pipe loop sponsored by the USNRC and EPRI, was supported by a prototypic spring hanger and contained an actual motor operated valve, in addition to simulated valve weights. The fourth test, a 6-in. pressurized pipe loop of stainless steel also sponsored by the USNRC/EPRI was driven by three tables and a snubber. The snubber and strut were also under evaluation for this program. The last test was a re-test of the third piping system.

TEST FACILITY

ETEC's SFTS has four major subsystems: 1) shaker tables/seismic mass; 2) energy storage; 3) hydraulic power supply; and 4) digital computer control. The system is built around existing facilities and equipment, which included a 20- by 40-ft load reaction floor (seismic mass) and a gaseous nitrogen storage system.

The SFTS has four uniaxial (horizontal), independently controlled shaker tables that are mounted on a 20- by 40-ft seismic floor. Non-synchronous inputs were applied to piping to simulate required operating conditions.

The energy storage system consists of 12 30-gal piston accumulators that are manifolded to deliver hydraulic fluid to the tables, and a 3200 psi 1100 ft^3 gaseous nitrogen (GN_2) supply system to pressurize the accumulators.

The hydraulic power supply provides pressurized oil to the 24 table bearings (six pairs per table) from a 75 hp motor/pump assembly.

The microcomputer-based control system provides table control and real-time data acquisition for dynamic testing. Tables were controlled independently or synchronously with defined time history displacement functions.

The SFTS digital data acquisition system (DDAS) supplements data recorded by the digital computer control system. Up to 96 additional channels of test data can be recorded at sample rates of 400 samples/second.

TEST ARTICLES AND TEST RESULTS

3-in. Diameter Piping System Demonstration Test

The initial checkout of the test facility was performed using a 3-in. diameter, Schedule 40, unpressurized piping system.

The piping system (test article) consisted of 51 ft of 3-in. diameter (Schedule 40) carbon steel (A-106 Gr B) piping and components. Materials of construction and fabrication of the test article were in accordance with ASME Code, Section III, Class 1 requirements. Instrumentation included 8 accelerometers and 6 strain gages (3 locations).

The unpressurized pipe system was filled with oil to simulate fluid inertial effects. The test article was subjected to the following three levels of seismic input.

Low level seismic load - 5 g nominal ZPA
Intermediate level seismic load - 14 g nominal ZPA
High level seismic load - 30 g nominal ZPA

Following the successful completion of seismic test series, (no structural failure) three low-level, limited cycle (constant displacement) harmonic inputs were applied. Following the successful completion (no structural failure) of the low level input series, the following harmonic input load was applied:

6.0 Hz, ± 7.5 inches, 4-6 cycles

Failure occurred in the tee during this 6.0 Hz sine burst input. A preliminary examination of the failed component indicated a fatigue failure in the crotch area accompanied by local structural collapse. The exact sequence of events leading to failure (which came first, collapse or fatigue?) was not determined.

The test demonstrated the ability of the piping system to withstand a seismic input greater than that predicted to cause failure. ETEC pre-test analysis predicted failure would occur at 20 g - the test article did not fail at a 35 g ZPA input level. The 35 g maximum test level (30 g nominal) corresponds to 6 times the calculated elastically ASME Code Section III level D allowable value. Test results also indicated strain controlled failure rather than load controlled failure as assumed for pretest failure predictions and by ASME design criteria.

6-in. Diameter Piping System Feasibility Test

This test has been comprehensively documented in Ref. [1]. The following discussion is taken from a summary in that report.

The piping system utilized in the test (test article) consisted of some 48 ft of 6-in. diameter and 17 ft of 3-in. diameter carbon steel (A-106 Gr B) Schedule 40 piping and piping components and included a simulated valve assembly. The construction, including support locations, of the test article, was in accordance with both the NRC requirement and ASME Code Section III Class 1. Instrumentation included 6 accelerometers, 30 strain gauges at 18 locations and 1 pressure transducer and provisions to measure test article permanent set.

During testing, the test article was internally pressurized at 1000 psi and was to have been subjected to the following three levels of dynamic seismic loads:

Low level seismic Load:	5 g nominal ZPA
Intermediate level seismic load:	14 g nominal ZPA
High level seismic load:	25 g nominal ZPA

The load levels were selected on the basis of the 17.1 g ZPA level predicted by ETEC (and later corroborated by Hanford Engineering Development Laboratory (HEDL), Ref. [2], to cause failure of the test article and previous ETEC experience gained during prior similar testing of the 3-in. diameter piping system. Provisions were also made to conduct the following sequence of three sine burst tests following seismic testing if failure of the test article did not occur during the seismic tests:

Sine burst - 4 Hz: 8 cycles of ± 7 in max. displ.
Sine burst - 5 Hz: 11 cycles of ± 7 in max. displ.
Sine burst - 6 Hz: 7 cycles of ± 6 in max. displ.

The number of cycles were programmed and were designed to provide a minimum of 2 seconds of maximum displacement at 4 Hz and 5 Hz and a minimum of 1 second of maximum displacement for 6 Hz.

Three sine burst tests were to be repeated sequentially as necessary to cause failure of the test article if failure did not occur during the seismic tests.

Failure (i.e., rupture) of the test article did not occur during seismic testing. However, a 1-in. wide circumferential bulge indicative of ratchetting was observed following the high level (30 g actual ZPA) seismic test in a vertical leg of the test article. The bulge was located in a straight pipe section some 2 to 3 in above a welding neck flange at an anchor location. Subsequently, failure occurred during the second sine burst test. Rupture occurred in the previously observed circumferential bulge during the 6th of the planned 11 cycles of maximum displacement of the 5 Hz harmonic input. Failure resulted from a 300° circumferential break in the bulge; a double-ended guillotine break was avoided with prompt termination of testing. Fig. 1 shows the failure location.

Subsequent to failure of the test article, post-test examinations were conducted. These examinations included visual, metallographic and scanning electron microscope techniques.

Test Conclusions

Based on test results as presented in Ref. [1], conclusions regarding the previously stated objectives are as follows:

Although the 6-in. piping system did not fail during seismic testing at loading levels in excess of that predicted to cause failure, the test demonstrated the feasibility of testing to failure using sine burst tests. However, in retrospect, it was felt that failure under seismic loadings could have been achieved by subjecting the piping system to either: (1) an increased level of seismic loading with ZPA of approximately 50 g, or (2) repeated application of the 25 g ZPA seismic loading.

The tests demonstrated the increasing resistance of the piping system to respond to increasing levels of seismic loadings. This characteristic was exhibited by the peak acceleration or amplification observed during testing. Strain gauge data indicated that inelastic straining occurred in the highly stressed elbows and straight pipe in the failure zone during high level seismic testing. Based on test results, estimated system equivalent viscous damping for the seismic tests were between 1-6%, 3-12% and 13-22% for the low, intermediate and high level seismic tests, respectively, and 19% for the 4 Hz sine burst test.

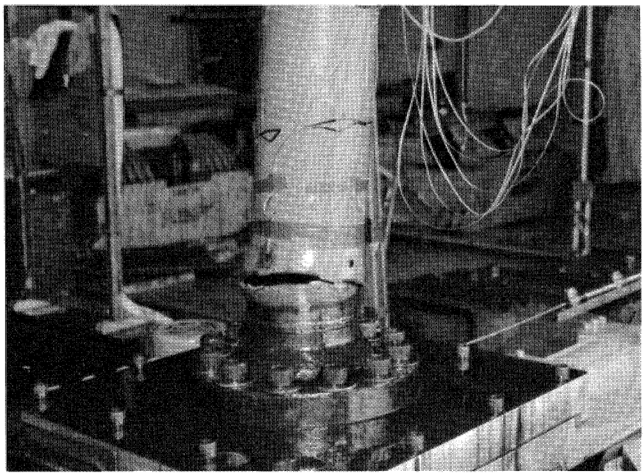

Figure 1. Failure Location, 6-In. Pipe Test

Failure of the test article was attributed to incremental ratchetting due to the internal pressure in the piping system resulting in wall thinning and bulging and subsequent fracture due to tensile overloading. Although fatigue contributed to the failure, the cumulative fatigue usage factor (not considering ratchet effects) for the test series was estimated to be between 0.13 and 0.27. The failure mode was not predicted by any of the current nonlinear failure analyses which are based on the collapse failure mode. Furthermore, failure did not occur in any of the locations of high stresses considered critical by the ASME Code.

Prototypic 6-in. Diameter Piping System Fragility Test (System #1)

This test was completed in June 1987 in compliance with Task 3 of the EPRI/NRC Piping and Fitting Dynamic Reliability Program (PFDRP). Results are presented in detail in Ref. [3].

The piping system used in this test is also A106B carbon steel constructed in accordance with the requirements of the ASME Code, Section III, Class 1. It consists primarily of 6-in. Schedule 40 piping except for a 3-in. Schedule 40 cross-over piece and short sections of Schedule 160 piping near the three actuator tables. The piping was supported by the connections to the three tables and by a spring hanger attached near the piping center. One actual motor operated valve was installed in the 3-in. cross-over section and three heavy sections simulating other valve weights were installed in the 6-in. piping. The system was instrumented with 59 strain gauges, 15 accelerometers, 5 displacement sensors and various pressure and temperature sensors.

As in the previous 6-in. piping test, this piping system was oil filled and pressurized to 1000 psi. The nominal load levels were "OBE", "SSE", "Half Table Capacity", and "Full Table Capacity". The response spectrum had an amplitude peak at 7 Hz and the ZPA was 0.4 g's at the SSE level. The "Half Table Capacity" load level corresponded to a ZPA of about 16 g's.

During the "Half Table Capacity" test, the spring hanger failed and the dynamic response increased. The connecting bolts on the motor operated valve's actuator broke and the actuator disengaged from the valve assembly. There was measurable permanent deformation of the piping system, increased swelling at the elbows, but no leakage in the piping system or valve.

The "Full Table Capacity" test was next run without repairs to the piping system, valve or supports. The short radius elbow near Table #4 ruptured about 10 seconds into the test. The piping system response resulted in primarily torsional loading on this elbow.

Test Conclusions

Unlike the previous tests, failure of this test article occurred during a seismic response spectrum test rather than during a sine burst test. This permits direct comparison of actual failure levels with allowable seismic loads as determined from the ASME Code analysis. For the nominal SSE input, the piping system was loaded to about 80% of the allowable loading for a Class 1 Level D event. For the "Half Table Capacity" level input, the corresponding stress levels were about 27 times the Level D allowable. Thus there was a factor of conservatism of at least 34 (i.e., 27/0.8) between the actual failure and the allowable loading.

It is further significant that the failure was localized, the piping system as a whole did not leak or collapse prior to failure, and flow through the piping system would not have been compromised prior to failure.

6-in. Diameter Piping System Fragility Test (System #2)

The system consists of 6-in. diameter Schedule 40 piping, 4-in. diameter Schedule 40 bypass line and a 12-in. diameter Schedule 40 pressure vessel. All elbows were long radius elbows and all piping and components were of 316L stainless steel per ASTM A312 and A403 with the exception that all materials were selected to have a minimum tensile strength of 75K psi and a minimum yield strength of 30K psi. The material, welding and inspection requirements for the system met the standards specified by ASME Code Section III, Class 1.

The piping was supported by pipe flange connections to three tables. A fourth table supported a stiff member that reached the level of the highest elevation of the piping system. The piping system was excited by four tables, three of which included the pipe flange connections. The piping system was also driven by attaching a snubber between the stiff member and the elevated piping system.

At full table level, approximately 9.0g peak, the crack propagated through and the pressure boundary was violated ending the test series. In addition to the failed weld joint, visual deformation in the form of bulge was observed on the 6" Schedule 40 pipe located above Table #4.

Test Conclusions

As was predicted by most analysts, the failure occured at the transition of the 4-in. nozzle to 12-in. vessel weld. It was evident from viewing video covereage and strain gage data, during the signature burst at 30 Hz and the low level sine sweep, that this transition weld was undergoing significant strain loadings. The transition was probably in a weakened condition prior to the imposition of the planned full table seismic load levels. Although the test snubbers experienced bent clevis' during the planned test sequence, the snubbers would have provided the necessary support to the piping had this level been imposed in an actual plant.

Prototypic 6-in. Diameter Piping System Fragility Test (Re-Test of System #1)

The carbon steel piping system previously discussed in this report and identified as System #1 was re-tested following removal of all three short radius (SR) elbows. The elbows were replaced with new SR elbows. The yield strength of the new elbows were approximately 30% greater than those used in the original test. A new spring hanger was provided. The 3-in. valve actuator was re-installed.

The testing sequence was abbreviated and only included the sine sweep, SSE, 5 SSE and one-half and full-table tests. The test results were nearly identical. The elbow that failed was located in the same position in the piping system that previously failed. The elbow failed approximately 10 seconds into the full table test, which was the failure time for the original failure. However, one significant difference was the propagation of the pipe rupture. The original elbow failure generated a circumferential rupture path while the second test generated an axial propogation path.

Test Conclusion

The repeat test demonstrated the credibility of the results from the original test. The repeated results included the failure of pipe hanger, the yielding and dimensional changes in the elbow following the half-table test, and the failure of the elbow at approximately the same time in the test signature time history. Essentially the only difference was the direction of the propogated rupture - circumferential in the first test, but axial in the re-test.

SUMMARY

Recent piping system tests at the ETEC Seismic Fragility Test System have demonstrated that piping systems can withstand much greater seismic loads than permitted by current design practice. The initial, unpressurized 3-in. pipe demonstration system withstood a 35 g ZPA response spectrum input without failure and was ultimately failed by a sine burst test. The next, 6-in. pressurized piping system test withstood loads 20 to 30 times larger than usually specified for SSE's of contemporary nuclear power plants. Again, a sine burst test was required to develop a failure. The third test, also a pressurized piping system, primarily 6-in. pipe, ultimately failed at full table capacity with a seismic response spectrum input. A spring hanger broke at a 16 g ZPA input, and a valve actuator separated from its valve. However, the piping system did not leak and collapse did not occur until a load level about a factor of 34 greater than that permitted by the ASME Code Class 1 Level D design criteria was reached.

REFERENCES

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