Piping and fitting dynamic reliability program

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ABSTRACT

There is a general concern about the over-conservatism in the treatment of infrequent dynamic loads in the design of nuclear power plant piping. To address this concern, in 1985 the Electric Power Research Institute (EPRI) in conjunction with the U. S. Nuclear Regulatory Commission (NRC) initiated the Piping and Fitting Dynamic Reliability (PFDR) Program with General Electric Company as the prime contractor and ANCO Engineers as the subcontractor for component testing. The ultimate objective of this program is to introduce new, improved, realistic and defensible ASME Code design rules which take advantage of the inherent dynamic margin in piping and which result in a more balanced piping design between infrequent dynamic loads and daily operating loads.

The basis for the proposed changes in design criteria will be derived from an extensive testing program together with supporting analyses. The first of three testing programs is focusing on the behavior of typical piping components when subjected to dynamic loading introduced through hydraulically operated sleds. A second testing program is investigating the behavior of piping systems under dynamic loading and the third program is focusing on development of a laboratory type specimen which can be used to quantitatively evaluate low cycle fatigue in the presence of ratcheting.

This paper represents a status report of results of the component tests to date. The tests have demonstrated that the mode of component failure is fatigue ratcheting and not plastic collapse. No appreciable loss of flow area has been observed even for inertia loads many times (15-27) the safe shutdown earthquake (SSE). System tests are expected to corroborate these findings.

1 INTRODUCTION

The EPRI/NRC sponsored Piping and Fitting Dynamic Reliability (PFDR) Program, which began in the Spring of 1985, was motivated by the belief that current design rules for nuclear piping produce piping systems with excessive conservatism for dynamic loading effects.

Although conservatism is prudent in the design of any components or systems in a nuclear power plant, in the case of nuclear piping,

excessive conservatism often produces a system with a large number of snubbers which can lead to both unnecessary costs and less reliable systems than could be obtained with a more optimized approach.

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code developed rules for the design of nuclear piping which took no credit for this difference between dynamic and static loading. Evidence has been accumulating over the years to suggest that pipes and pipe components are capable of resisting much larger dynamic loads than when those same peak loadings are applied statically. Several nonlinear phenomena occur as a piping system is loaded dynamically toward failure:

1. the apparent damping increases,
2. the stiffness of the piping decreases, causing a detuning effect, and
3. dynamic loads may be redistributed to other cross sections due to redundancy.

The main technical objective of the PFDR Program is to demonstrate once and for all that one of the several failure modes assumed by the ASME Code, that of plastic collapse, simply does not occur in piping under dynamic loading. In this program, dynamic loadings are categorized into three different frequency ranges. The lowest frequency dynamic loading of significant interest for piping design is that associated with seismic effects (1-30 Hz). The other two types that commonly occur in LWR plants are containment-related hydrodynamic effects (20-70 Hz) and waterhammer effects (50 Hz and higher). Therefore, any ASME Code rule changes for dynamic effects must address the entire range of loading frequencies that may be encountered.

2 EXPERIMENTAL PROGRAMS

To provide a necessary experimental data base in support of design rule changes, the component test program involves 40 tests, which include elbows, tees, nozzles, reducers, and attachments. Most test components are pressurized with water at room temperature and all are instrumented to measure the dynamic response. Two pipe materials, carbon steel (A106B) and stainless steel (316L), are being tested in 6-inch diameter nominal pipe sizes with wall thicknesses corresponding to schedule 10, 40, and 80. The component is mounted on a specially designed shake table and a 20 second time history record which represents a scaled-up building-filtered seismic input to the piping support system is applied to the table through the action of a high-powered hydraulic actuator device.

In addition to the component tests three 6-inch pipe system tests will be performed to provide an important data base to verify that the engineering understanding of the component tests can be accurately extrapolated to pipe systems.

The system tests will allow us to properly extrapolate our understanding of pipe component behavior to pipe systems, and a third type of experiment, a materials test, will help us understand the details of the failure process itself. At the present time there is no satisfactory engineering theory to accurately forecast a fatigue-ratchet-type failure, which is the dominant failure mode when pressurized piping is dynamically overloaded to failure.

Approximately 110 materials specimen tests have been planned using four different pipe materials so as to provide the basic data for a new theory.

3 RESULTS OF PIPE COMPONENT TESTS

Seventeen of the 40 planned component tests have been completed. Figure 1 shows the test set up for all in-plane elbow tests. The sled input motion simulates a building filtered Taft earthquake time history at the main steam nozzle of a typical BWR reactor pressure vessel. The response spectrum of the earthquake time history is shown in Figure 2. The seismic input time history was chosen such that its dominant frequency was slightly lower than the natural frequency of the component system. During the high amplitude input, the system frequency shifted down into the peak of the input as the elbow became plastic and the equivalent stiffness was reduced.

Table 1 provides a summary of the 17 component test results. Included in the table are the test configuration, material, the ratio of dynamic moment to limit moment, the maximum peak-to-peak strain, and the input level in multiples of Level D stress allowable (for a linear response spectrum analysis with 2% damping, and a $\pm$15% peak broadened response spectrum).

Test results continue to show that piping components do not experience plastic collapse under dynamic loading up to 27 times the load required to achieve Service Level D stress limits. This multiple becomes 13 instead of 27 if ASME Code Case N-411 damping is used in the analysis.

A plot of maximum measured strain versus sled input acceleration obtained from Test 3 is shown in Figure 3. The curve indicates that the incremental increase in cyclic strain is reduced when strain amplitude is above 1.5%.

4 CRITICAL DAMPING RATIO EVALUATIONS

Two methods were used to determine the damping ratio. They are described as follows:

- o Equivalent damping ratio

The equivalent damping ratios were obtained by performing a linear elastic response spectrum analysis using the response spectrum of the actual sled input time history with $\pm$15% peak broadening and adjusting the damping until the calculated moment in the test component was equal to the measured moment. Equivalent damping has been observed up to 40-50% in the component tests. This is an order of magnitude higher than the currently acceptable design value of 5%.

- o True damping ratio

The true damping ratios were obtained by using the Fourier Transformation of the sled input time history and the output time history at the top mass of the test assembly to obtain power spectral densities (PSD) and transfer functions.

Table 2 summarizes the PSD and Transfer Function calculational results. The damping ratio for each transfer function is also tabulated. From this table it can be seen that, for the low level tests, the damping ratios are about 1.8%. For high level tests, the damping ratios range from 17% to 23%.

5 FATIGUE ANALYSIS OF TEST COMPONENTS

An investigation was made of variations of the ASME Code rules for fatigue analysis with corrections applied for mean stress effects. A computer program was written which uses the ASME Code fatigue equations for carbon steel and stainless steel and the moment/strain time histories measured during the tests to obtain an indication of the cumulative fatigue usage. Every cycle of time history loading was accounted for in the evaluation of fatigue usage.

Three fatigue relationships were used for the fatigue evaluations: Markl's equation, ASME Section III Appendix I-9.0 Design Fatigue Curves, and the fatigue equation in the Criteria for the ASME Section III document. The usage factor obtained from the Design Fatigue Curve and the Criteria document are close. Markl's equation slightly underestimates the usage factor at high level inputs.

Three methods were used to obtain the alternating stress ranges. They were as follows:

1. Measured Strain
2. Measured moment and calculated strain
3. Measured moment and NB-3600 equations

The results of the fatigue evaluations for these tests showed that Method 3 measured moment together with ASME NB-3600 equations (with or without correction for mean stress) provided a reasonable prediction of fatigue ratchet failure for the elbow. The summary of fatigue evaluations by Method 3, as presented in Table 3, shows that the evaluation procedure results in a conservative prediction when compared to test results.

6 CONCLUSIONS

The primary focus of this program has been to demonstrate that fatigue and/or fatigue ratcheting is the most likely cause of piping system failure under dynamic loading--rather than by ductile collapse. While this paper represents only a status report, the evidence to date suggests that piping components do not experience ductile collapse or hinge formation under dynamic moment loading of more than twice the static limit moment. When these components are pressurized with internal pressure and subjected to a large, seismic-like inertia loading which causes significant plastic deformation, the components develop cracks and leak. They do not collapse.

The damping that has been measured during the component tests is well in excess of that permitted by Regulatory Guide 1.61 or by ASME Code Case N-411. This suggests that present codes and standards are much too conservative for use in predicting the plastic response of components to large dynamic loads.

If current observations concerning the behavior of piping under dynamic loading continue to be confirmed by subsequent component and system tests, the ASME Code rules for the design of nuclear piping systems will need to be modified to account for fatigue ratcheting and to more realistically address those loading conditions which can lead to collapse (i.e., static loads).

Table 1. Component test summary

No.	Type	Mat	Sch	Press	Load Dir	Dyn Mom Lim Mom	PP Cyc Strain ID	PP Cyc Strain OD	Input X Level D	No TH	Fail Mode	Residual Strain
1	Elbow	CS	80	1500	I-P	1.21	2.3%(1)(3)	1.5%	15	5	NF	No Data
(Retest)			80	2600	I-P	1.21	2.3%(1)	1.5%	15	0.5	FR	No Data
2	Elbow	CS	80	1500	O-P	1.04	2.1%(1)(3)	1.4%	15	5	NF	No Data
(Retest)			80	2600	O-P	1.04	2.1%(1)	1.4%	15	4.5	FR	No Data
3	Elbow	SS	10	400	I-P	2.36	3.6%(1)(3)	2.4%	21	3.5	FR	7.0%(1)
4	Elbow	CS	40	1000	I-P	1.83	3.0%(1)(3)	2.0%	18	2.5	FR	No Data
5	Elbow	CS	40	1700	I-P	2.06	3.0%(1)(2)	2.0%	21	3.5	FR	27%(1)
6	Elbow	SS	40	1700	I-P	2.00	3.0%(1)(2)	2.0%	19	3.5	FR	32%(1)
7	Elbow	SS	40	1000	I-P	1.80	3.0%(1)(2)	2.0%	23	4.5	FR	18%(1)
8	Elbow	SS	40	0	I-P	1.80	3.0%(1)(2)	2.0%	24	5	NF	3%
9	Tee Fix-2	SS	40	1700	O-P	2.50	*	2.2%	21	1.5	FR	8%
10	Tee Fix-2	SS	40	1000	O-P	2.40	*	2.2%	21	2.5	FR	6.5%
11	Tee Fix-2	SS	10	400	O-P	1.00	*	1.9%	16	0.5	FR	5%
12	Tee Fix-2	SS	40	1700	I-P	2.30	*	2.2%	27	2.5	FR	11%
14	Tee Fix-2	CS	40	1700	O-P	2.46	*	2.2%(2)	18	1.5	FR	*
15	Reducer	SS	40	1700	N/A	1.18	*	1.29%(3)	13	5	FR	*
35	Elb High Wt	CS	40	1700	I-P	1.63	3.42%	2.28(1)	18	5	FR	*
38	Tee Fix-1	CS	40	1700	O-P	1.92	*	2.7%(3)	20	3.6	FR	*
39	Tee Fix-1	SS	40	0	O-P	1.84	*	3.4%(3)	21	4	NF	*

OBSERVATIONS:

- Collapse did not occur for any load input
- Failure mode was fatigue ratchet with leakage
- Cracks detected, growth monitored before failure
- Eqv. Damping much greater than RG 1.61 (2%)
- Seismic inputs much greater than reality
- Elbow behavior more like secondary than primary

SYMBOLS:

I-P = In-Plane
O-P = Out-of-Plane

* Later

NO TH = Number of high level input test runs to cause failure
FR = Fatigue ratcheting failure
NF = No failure
Residual strain = measured by 2 inch scratch marks
Input X Level D = calculated stress using linear response spectrum analysis, 2% damping, ±15% broadening and actual sled input. Use the calculated stress, (B_2M/Z), divided by Level D allowable, $3S_m$ to determine multiple of Level D allowable.

NOTES:

(1) The measured strains are on the outside of the pipe, a factor of 1.5 has been applied because;
The inside surface is 1.388 times of the outside, principal strain is 1.072 time of circumferential strain and the circumferential strain is 1.01 time of average strain over gage length 1/16".
1.388 x 1.072 x 1.01 = 1.50. For 2" scratch mark, the factor 1.01 is increased to 1.52 and the multiplication is,
1.388 x 1.072 x 1.52 = 2.26. (Use 2.0 for conservative estimates)

(2) Gage failed too early, there is almost no data, use previous similar test run data.

(3) Gage failed too early, it is not known if peak values have been obtained.

Table 2. Summary of transfer function calculations

Test No. (T) Run No. (R)	PSD Peak Freq (Hz) Input	Output	Transfer Functions Freq	Transmissibility (TR)	Damping Ratio %	Input Level ZPA(g)	Measurement B2 M/Z (KSI)
T7R5	6.6	6.6	7.1	33.8	1.8	1.14	52.2
T7R6	6.3	6.3	4.92 5.45 5.98	3.8 3.0 3.8	17 23 17	23.1 23.1 23.1	152.0 152.0 152.0
T7R8	5.8	5.8	4.04 4.92 5.45 5.98	3.11 3.95 3.13 3.91	22 17 22 17	23.4 23.4 23.4 23.4	164.5 164.5 164.5 164.5

Table 3. Results of fatigue analysis

	Mean Stress psi (Long.)	ASME Appen. I-9.0 Usage/Run	Runs to Fail	Tested Runs to Fail
Stainless Steel	(P=0) 0	0.230	4.3	5
	(P=1000) 6,000	0.339	2.9	4.5
	(P=1700) 10,000	0.458	2.2	3.5
Carbon Steel	(P=0) 0	0.680	1.5	No Data
	(P=1000) 6,000	0.908	1.1	2.5
	(P=1700) 10,000	1.131	0.88	3.5

Note: Using Markl's equation calculated 6.4 runs to failure.

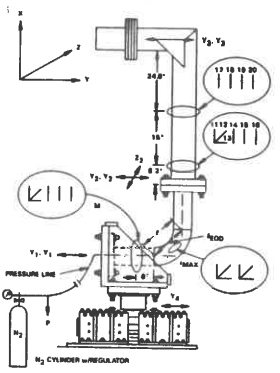

Figure 1. Elbow test set-up

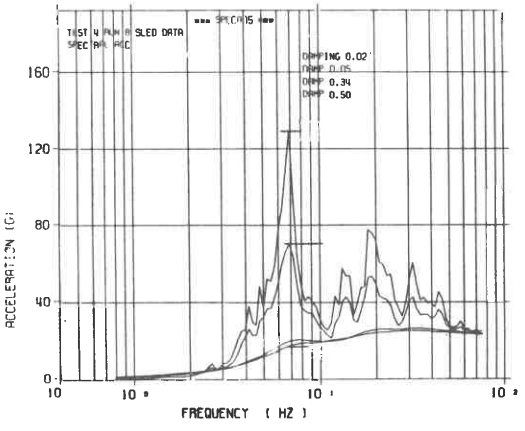

Figure 2. Response spectrum of input

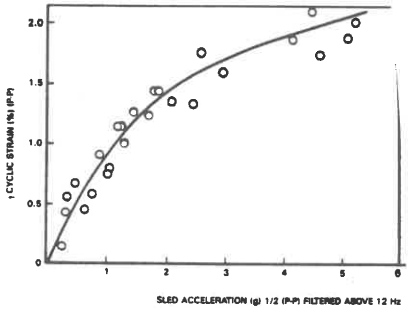

Figure 3. Measured elbow strain vs. input acceleration (test 3)