Response Analysis of In Situ Pipe Tests

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SUMMARY

An in situ pipe test program, sponsored by the Electric Power Research Institute, was performed to provide a basis for evaluating piping analysis methodologies. Some of the items which were addressed by the program are: the level of conservatism existing in current piping practice; the piping system damping values, particularly at higher load levels; the significance of non-linearities in the piping response related to support nonlinearities; and the effect of different support types on the piping response.

A three-phase test and analysis program was designed to address the issues listed above. In the first phase, Phase I, a piping system at Consolidated Edison's Indian Point Unit 1, a boiler feedwater line, was evaluated and dynamically tested in its original configuration, including the piping insulation. These tests were performed to study relatively flexible piping system designs employed in the early 1960's. Linear and nonlinear simulation analyses were then performed to correlate with the test data. In the second phase, Phase II, the original piping system, excluding the insulation, was studied to determine the effect relatively stiff insulation has on the piping damping. In the final phase, Phase III, the piping system was refitted with "modern" support types (i.e., struts and snubbers) and tested with four different support configurations. These tests were then simulated by analyses to evaluate current piping analysis methodologies and to study the characteristics of relatively stiff piping systems.

The linear analyses performed in the evaluation study of the original piping system used the SUPERPIPE code. In these analyses, the pipe supports were assumed to be either rigid or linear springs. The ANSYS code was used in the nonlinear study where the lift-off gapping effect of the hanger supports was modeled. Results obtained indicate that there is no significant overall difference in piping response between linear and nonlinear analyses. For the modern piping system, which was relatively stiff, the effective stiffness of the pipe support backup steel and building structural steel had to be included with the pipe support stiffness to accurately compute the piping system dynamic characteristics. In addition, test data for the modern system was studied to determine the system damping. It was found that the damping values were generally greater than the damping values specified in Regulatory Guide 1.61.

1. Introduction

An important subject within the nuclear industry is the qualification of piping systems and equipment. In general, the evolution of regulatory criteria and guidelines has placed increasingly conservative requirements on assumptions and procedures used for design. This ultimately results in increased hardware costs, and has also raised questions concerning design criteria for older plants. These concerns have given rise to the need for a program which would provide basic data useful in evaluating the level of accuracy and conservatism in analyses of both "old" and "modern" designs (i.e., piping systems designed using flexible and stiff-based design philosophies). Thus, a program was established by Electric Power Research Institute to obtain experimental data, and analytical comparisons with this data, on the dynamic response of actual nuclear plant piping systems.

Consolidated Edison's Indian Point Unit 1 facility was selected as the site for performing the in situ tests. A boiler feedwater line was selected as a representative piping system with sufficient length and accessibility for making all support scheme modifications and for testing. A series of tests were performed and studied in three phases. In the first test phase, Phase I, the pipe was tested in its original configuration, including the piping insulation. This test phase was performed to study "old" piping system designs (i.e., relatively flexible piping systems having hanger supports) employed in the early 1960's. In the second test phase, Phase II, the original piping system, excluding the insulation, was studied to determine the effect of insulation. In the final phase of testing, Phase III, the piping system was refitted with "modern" support types (i.e., strut and snubber supports) and was studied to evaluate current analytical piping analysis procedures for relatively stiff piping systems. The pipe insulation was also excluded in this test phase.

2. Pipe Tests

2.1 Original Piping System

The segment of pipe (length of 110 ft. including 14 elbows) chosen for testing is part of a boiler feedwater system. One end of the pipe was anchored near the upper drum of a steam generator, while the lower end was anchored to a biological shield wall. The piping is 8" schedule 80 piping from the biological shield wall to the upper anchor. The piping had a 1.5"-thick insulation, with a 0.016"-thick aluminum jacket along its entire length for Phase I tests. The pipe support locations are shown in Figure 1. A more detailed description of the system is provided in Reference [1].

2.2 Modern Piping Systems

One of the objectives of the pipe test program was to evaluate piping analysis procedures with respect to pipe test data for pipes supported with modern support types (i.e., struts and snubbers). The modern support schemes were designed using production computer analysis techniques and standard pipe design criteria. These criteria resulted in the selection of four different restraint schemes, with each scheme using the same support configuration. This then allowed the use of removable supports for changing support types between tests. The first scheme included removable rigid struts at various locations on the pipe. Then the three other support schemes were implemented by replacing any of the rigid struts with either a mechanical snubber or a hydraulic snubber. The four support configurations tested are described in Reference [2]. The location and the orientation of the supports is shown in Figure 2.

2.3 Test Descriptions

Snapback and forced vibration tests were performed in the test program. In testing of the original system, acceleration and strain data were recorded, along the entire length of the pipe. In testing of the modern system, load cells at the supports and displacement gages were used in addition to the accelerometers and strain gages. In each test, the loads were applied in a horizontal direction in the region near the midpoint of the pipe. The measured data was used to determine the system natural frequencies, mode shapes, damping, and response levels. In addition, the measured data was used in comparison studies with analysis results.

3. Piping Analyses

A number of linear piping analyses were performed for correlation studies of the original and the modern piping systems using the SUPERPIPE computer program, an EDS proprietary code. Nonlinear piping analyses of the original piping systems were performed using the ANSYS computer program. These analyses were performed to study the effect of support gaps on the piping response.

3.1 Original Piping System

The linear elastic piping analyses performed for the original piping system were done to determine the piping system's dynamic characteristics, set limits for the test loads, and perform simulation analyses. Reference [1] provides additional detail on this subject.

Certain aspects of the original system which are normally not included in standard piping analysis procedures were also evaluated. The three aspects studied were: isolation of the line from any external influences, effects of the nonlinear guide, and "lift-off". All of the parametric studies performed indicated that the effects from these sources except for lift-off were negligible and could be ignored.

The linear analysis results did not compare as well as expected to test results for the original piping system. In an effort to resolve this discrepancy between test and analysis results, a nonlinear piping analysis was performed to explicitly verify that the nonlinear effects were negligible. Only the nonlinearities associated with lift-off at the pipe supports were included in the model since the nonlinearities associated with the pipe material and the pipe cross-section distortion were considered to be higher-order with negligible effect on the piping global response. Two snapback simulation analyses were performed and compared to the linear SUPERPIPE results. As expected, based on the previous parametric studies performed, the differences between the SUPERPIPE and ANSYS results were very small, indicating that the effects of the nonlinearities were negligible.

3.2 Modern Piping System

A mathematical model of the boiler feedwater line with modern restraints was developed with the SUPERPIPE code using the standard piping assumptions. The model of the modern system is similar to the model of the original system model, but has new supports and several new nodes added to accommodate these supports. It was found necessary to include the effective stiffness of the backup structures in the pipe support representation to accurately determine the piping system dynamic characteristics. It was found that the nonlinear effects of the snubber restraints were of second-order importance in determining the piping system frequencies and mode shapes for the lower modes which dominated the response. It was also found that there was little difference in the pipe frequencies between the cases where the pipe was supported by struts, hydraulic snubbers, or mechanical snubbers. Thus, it could be concluded that production-type piping analysis techniques are sufficiently accurate for determining the dynamic characteristics of the boiler feedwater line, provided the finite support stiffnesses were adequately accounted for.

4. Test Analysis Comparisons

Test results were compared to analysis results for both the original and the modern piping systems. Comparisons of frequencies, mode shapes, and snapback responses were made. In general, it was found that the comparison between the test and analysis results for the modern system were very good while, for the original system, the comparison was not as good.

A comparison of the analytically obtained frequencies and the measured frequencies is given in Table 1. The quality of the comparison between the analytically obtained mode shapes and the test mode shapes was comparable to the quality of the frequency comparison. A comparison between the computed and measured mode shapes for the first two modes of the modern system is shown in Figure 3.

A comparison of the peak acceleration response, from the snapback tests and simulation analyses, is provided for two locations on the pipe in Figure 4. In general, the good comparison between the results demonstrated the adaquacy of the analyses. It is also noted that the piping system response increased fairly linearly with the applied load level, indicating that the nonlinearities in the system were not significant in terms of the piping global response.

5. Modern System Damping

A detailed review of the test data was performed to develop a basis for evaluating analysis results. One of the issues studied was the pipe system damping. Figure 5 shows damping as a function of load level and peak strain for two test configurations of the modern system. The damping was computed using the logarithmic decrement procedure to avoid the uncertainties associated with the half-power bandwidth procedure described in References [2] and [3].

No specific conclusions could be made on the effect of strain level on damping. It is seen that the damping nearly always decreased slightly with increasing load level, in agreement with the findings reported in Reference [4]. In some cases, however, the damping increased with load level after decreasing to a minimum damping level. This behavior in damping is thought to be due to two factors: material damping, which is relatively low, and frictional damping, which is irregular due to the different behavior of the pinned connections in the pipe supports (i.e., stick-slip phenomenon and impact).

Two different evaluations of the damping data were performed to assess the technical quality of the damping data. The first, shown in Figure 5 for configuration 4, is a plot of maximum and minimum damping values obtained by at least four evaluations of damping from each response time history. It was found that the level of damping did not correlate to the range of time or the location of the range of the response time history in the sample data. Hence it is felt that the confidence limits are simply a measure of the scatter in the damping data and not directly related to the applied load level.

The second evaluation of the technical quality of the damping data was obtained by comparing damping data for different locations along the pipe obtained from one test in a given time interval. It was found that although the pipe response levels were different at the various locations, the damping was nearly constant for the entire system. Therefore, it was concluded that the energy at any location of the pipe was being dissipated through damping and was not being transferred to other locations of the pipe.

6. Conclusions

Two sets of analyses were performed for a segment of the boiler feedwater line. The first set was used to evaluate the original line, which was supported by spring and rod hangers. The second set of analyses was used to evaluate the piping system with various configurations of modern supports (i.e., struts and snubbers).

Linear and nonlinear analyses were performed for the original system. These analysis results were compared to each other and to snapback test data. The results of the study on the original boiler feedwater line are:

1. The dynamic characteristics of the piping system with "old" support types (i.e., spring and rod hangers) can be adequately predicted using standard production piping analysis techniques.
2. Nonlinearity effects were insignificant in influencing the piping frequencies for the load levels employed in the snapback tests.
3. The piping insulation had little effect on the pipe response.

The results of the study on the modern boiler feedwater line are:

1. The dynamic characteristics of the piping system with modern supports (i.e., struts or snubbers) were accurately predicted using linear piping analysis techniques, provided the effective stiffness of the pipe supports was used in the analyses.
2. The system damping is generally greater than the damping specified in Nuclear Regulatory Guide 1.61.

Based on these findings, it is recommended that for stiff piping systems consideration should be given to the actual support stiffnesses, including the back structure, in modeling the piping system. It is also recommended that further industry evaluation of pipe damping data be performed to determine representative pipe system damping values.

REFERENCES

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[3] CHITTY, D.E., HOWARD, G.E., AND WALTON, W.B., "Damping in Nonlinear Piping Systems", 82-WA/PVP-10, Presented at ASME Winter Meeting, Phoenix, Arizona, 1982.

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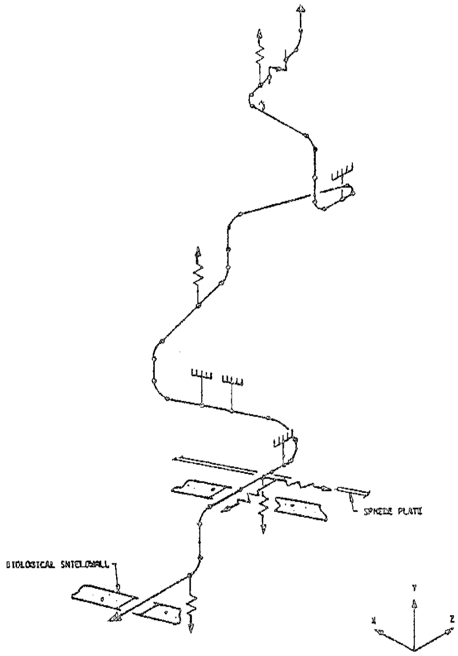


FIGURE 1

Boiler Feed Line with Original Supports

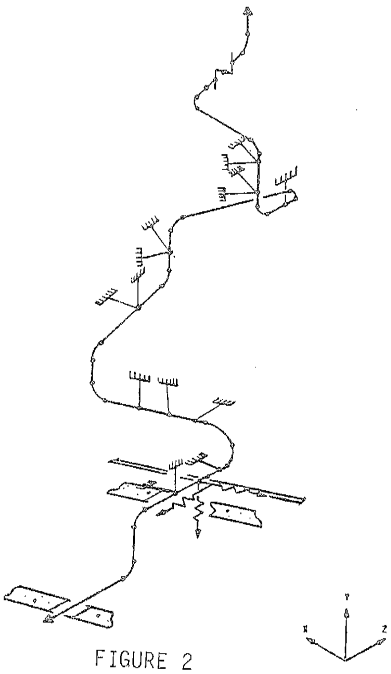
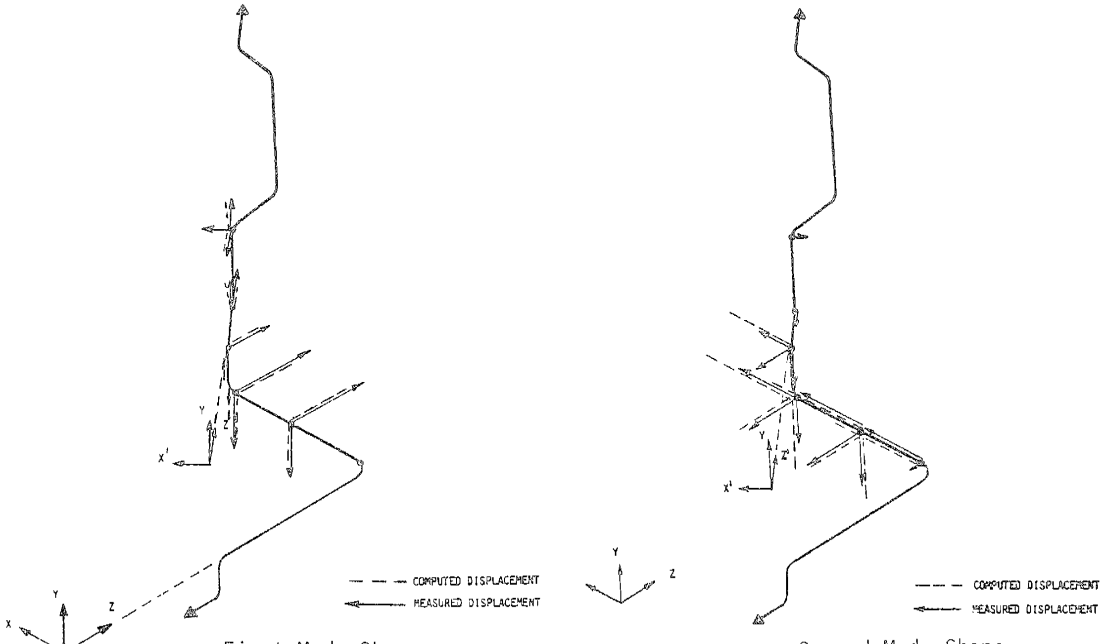


FIGURE 2

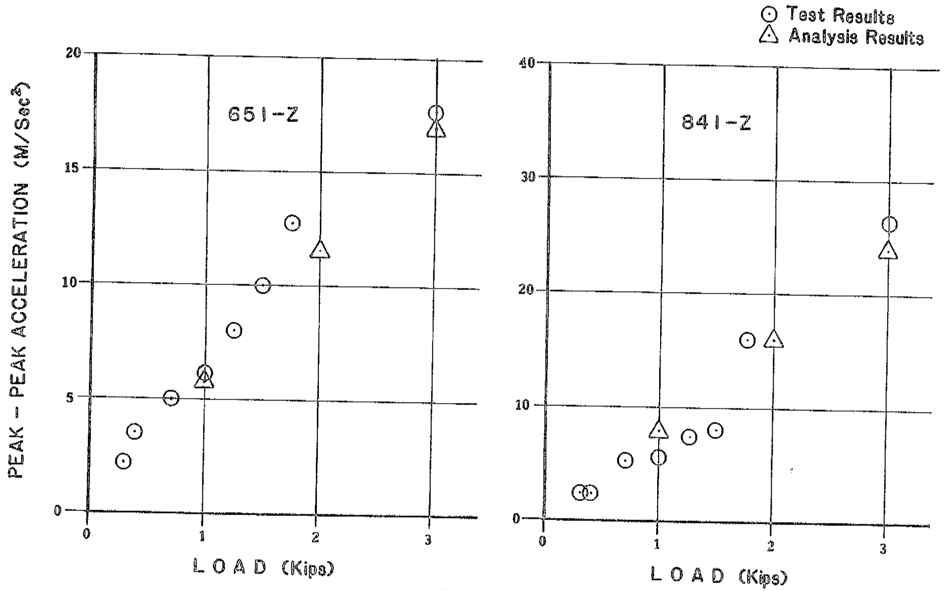
Boiler Feed Line with Modern Supports



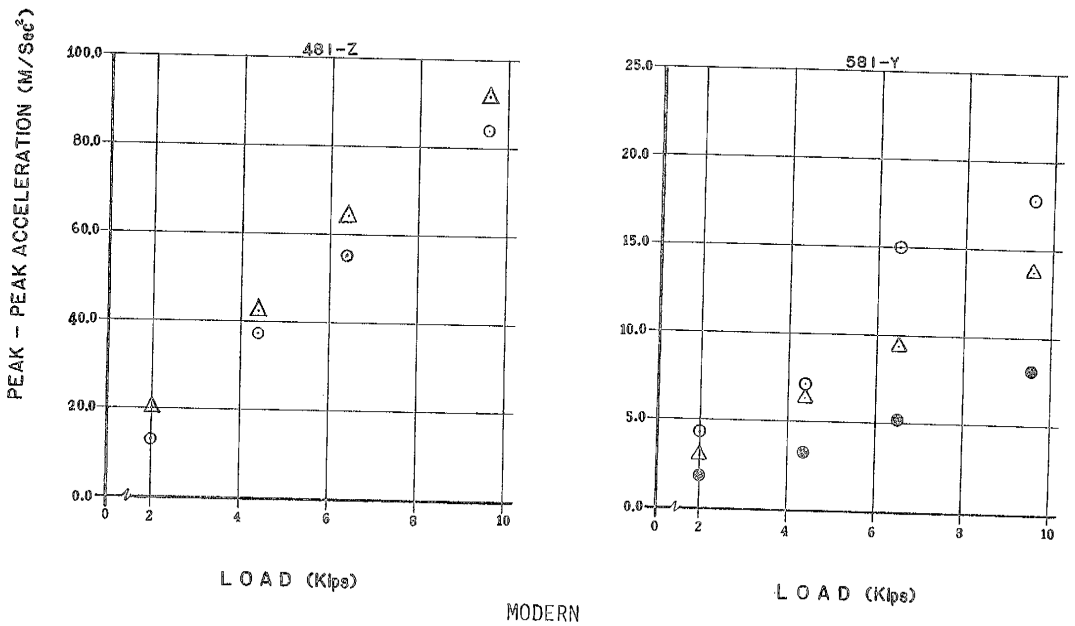
First Mode Shape

Second Mode Shape

FIGURE 3 Modes Shapes of Boiler Feed Line with Modern Support Configuration

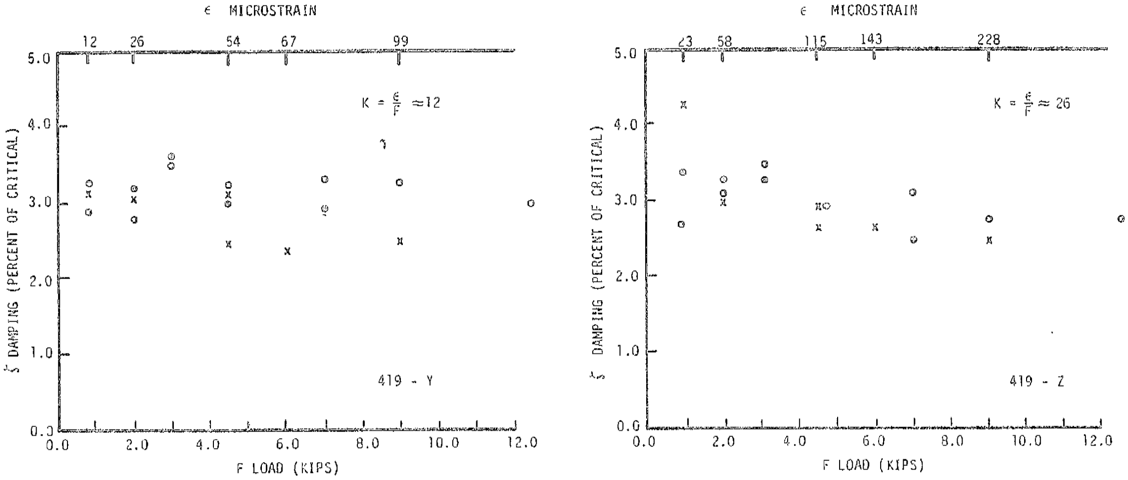


ORIGINAL

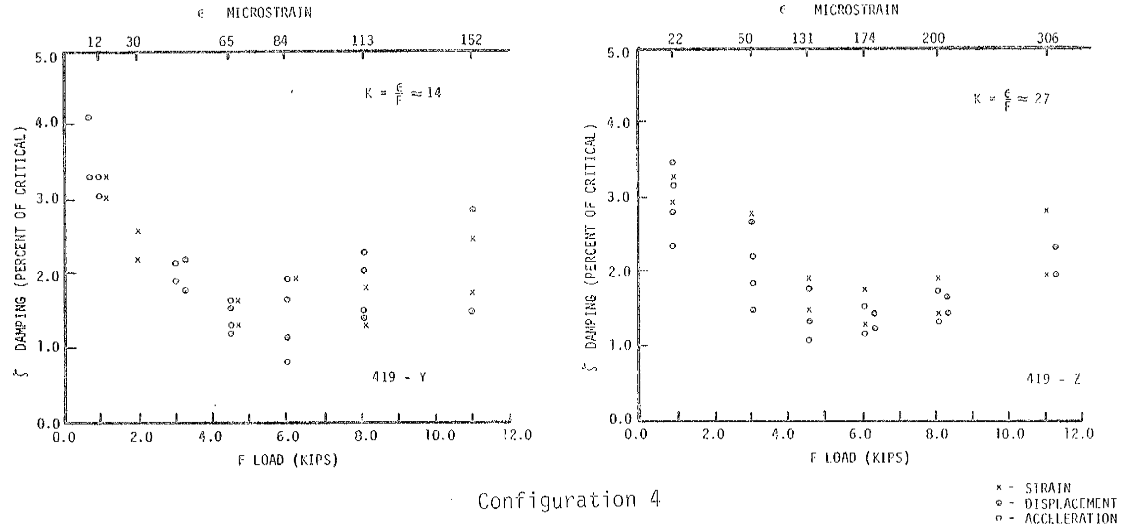


MODERN

FIGURE 4 Pipe Accelerations From Snapback Tests and Analysis



Configuration 1



Configuration 4

FIGURE 5: Logarithmic Decrement Damping from Snapback Test Data

TABLE 1

Comparison of Test and Analysis Frequencies (Hz)

MODE NO.	ORIGINAL		MODERN	
	TEST	ANALYSIS	TEST	ANALYSIS
1	1.2	.8	4.3	4.5
2	1.6	1.5	6.8	6.4
3	2.4 3.1	2.7	8.8	9.8
4	3.7	3.4	10.6	12.1
5	4.6	4.7	12.1	12.7
6		7.1	12.0	13.4