Test Correlation and Analytical Investigation of Piping Dynamic Response Including Support Failure

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Abstract

This paper presents the correlation analysis of a simple Z-bend piping system tested with support failure. The analytical simulation was conducted using the ABAQUS-EPGEN computer code. Parametric studies were also performed to investigate piping response behavior during and after the support failure. Results show that good correlation can be achieved through proper analytical modeling. For the simple case investigated, it was found that piping dynamic response is sensitive to system damping assumed. However, the support failure appeared to have a lesser effect on piping response.

1. Introduction

Nuclear safety-class piping systems need to be designed not only to support its deadweight and normal operating loads but also to withstand those low-probability occasional extreme loads such as those due to earthquakes and postulated thermal-hydraulic transients. To meet the design requirement, a significant amount of support restraints are installed. This, coupled with many conservative engineering design/analysis assumptions, often leads to relatively stiff piping systems. However, since a stiff piping system will induce undesirable high thermal stress, supports such as snubbers are utilized. The main function of a snubber is to insure free movement during normal operation and serve as a rigid strut support during an earthquake event. In recent years, it has been recognized that such design practices may in fact make the piping system less reliable and more susceptible to risk [1] because of the complexity and the required maintenance of the system. Past experience indeed has shown [2] that the malfunctioning of snubbers, either for mechanical ones or hydraulic ones, is quite probable in operating plants.

Before one can remove snubbers to solve the problem altogether, one question to ask is what is the effect of a snubber failure on piping response, be it a complete failure to lock up or be it a sudden loss of function during the earthquake. In a broader sense, if there is a sudden failure of any kind of support (e.g., pull out of base plate), what is its effect on piping response. In 1981 EPRI initiated a high-amplitude piping dynamic test project [3]. In the initial phase of the program, a simple Z-bend piping system was dynamically excited beyond its design allowable limit. Test results showed that a large margin existed in current piping and support design practice [4]. The data which included support failure serve as a base for the present study to provide some insights into the above-raised questions.

An analytical model was first qualified by correlating with the test data and then parametric studies were performed to evaluate various effects of support failure conditions.

2. Test Description

The high-amplitude piping test was conducted in a laboratory [5]. The piping layout was of a simple Z-bend shape consisting of three straight run segments and two 90° elbows (Figure 1). The pipe was constructed of 4-inch Schedule 40, ASTM A-106 carbon steel and was supported on three one-dimensional mini-shake tables (i.e., linear bearing sleds attached by servo-controlled hydraulic actuators). The two ends of the pipe were attached to the sleds through pin connections, allowing rotation about a vertical axis. At the mid-support location, the pipe was attached to the sled through a variety of support hardware, including struts, snubbers, and box frame. During the tests, the pipe was filled with water at room temperature and was pressurized to 1500 psig. Heavy weights were attached to the pipe near the elbows to simulate pipe-mounted equipment.

Synchronized support movements were applied along the Z-direction through the base sleds. Various levels of earthquake-like excitations were used to drive the piping system beyond its design limit and to induce support failure conditions. More detailed descriptions of the test program and its findings are documented in [5].

3. Analysis Approaches

Analyses presented in this paper were performed using the ABAQUS-EPGEN computer code [6], which is a general purpose finite element nonlinear structural and piping analysis code. One main reason for selecting ABAQUS-EPGEN was that the code has the "model change" capability which allows one to remove an element in the middle of analysis to simulate support failure at any given time.

A finite element model consisting of 24 nodes and 19 elements was constructed. Two-node straight beam element with linear interpolation (element B31) was chosen to represent straight pipe segments, and three-node curved beam element with quadratic interpolation and proper flexibility factor (element B32) was used for elbows. Eigenvalue analysis was first performed for model validation. Good agreement was reached. The first two computed frequencies were 6.9 Hz and 15.3 Hz, while the test measurements were around 7.2 Hz and 16.0 Hz.

ABAQUS-EPGEN was initially developed to be an inelastic analysis code. The only dynamic energy dissipation possible was through material hysteresis. At the time of analysis being performed, the code did not permit the direct use of conventional viscous damping coefficient at the element level.* To properly take into account the energy dissipation observed during the tests, special dashpot elements with proper damping constant (dashpot constant C) were attached to each node. In order to establish the relationship between dashpot constant C and the equivalent system damping, a snapback analysis was performed and a log-decrement method was used to derive damping. It was found that a C-value of 0.16 lbs-sec/inch would match system damping of 2%.

A correlation analysis was performed on test case T4R5, where a one-inch diameter strut was installed at mid-support but was broken into two parts during a high-amplitude earthquake

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*The code now has the conventional linear capability with viscous damping to account for system energy dissipation.

excitation. The test-correlated model was then used to carry out parametric studies. Eight cases were studied as shown in Table 1. The parameters studied include system damping, support failure time, and failure duration. A reference case was also analyzed assuming no mid-support.

4. Analysis Results

(a) Test Correlation

Two percent system damping was first used on the ABAQUS-EPGEN model for test correlation (Case 1 in Table 1). This selection was based on the log-decrement damping measurement from snapback test of strut-supported Z-bend system. A typical computed displacement response near the lower elbow is plotted in Figure 2(c). It can be seen that, comparing with Figure 2(a), the analysis overpredicted the test measurement by a factor of two before the support failure and more than a factor of two after the failure. It was obvious that a 2% system damping assumed in the analysis was too low for earthquake-type excitation input. Subsequently, system damping was increased to 6% of critical and the analysis results (Case 4 in Table 1) shown in Figure 2(b) matched well with the test measurement. With this, it may be concluded that the actual energy-dissipation of the system when subject to strong broadband-spectra ground motion could be much higher than the measured value obtained from the conventional snapback test.

It also should be noted that the purpose of this analytical effort was to study piping response behavior during and after the support failure. Therefore, no attempt was made to analytically predict the time of the support failure. In this correlation analysis, the strut was forced to fail by way of the model change feature of ABAQUS-EPGEN (removal of support element) at a chosen time based on the test results.

(b) Response Affected by Support Failure Time

As mentioned above, the support failure time was chosen based on the measured time-history result. Analyses were performed to study the sensitivity of the failure time by shifting the time instance a ±0.04 second (Cases 2 and 3 in Table 1). Comparison of results between Cases 1, 2 and 3 shows that the effects of small failure time shifting were significant.

(c) Response Affected by Support Failure Duration

It was suspected that the sudden support failure might impart more dynamic energy to the system than the case of a progressive support failure. Comparison of results between Case 4 (a sudden failure case) and Case 5 (support failed through a time duration of 0.024 sec) indicates that there is no higher response amplification for a sudden failure case. The only difference is a 0.024 second time lag in response between the two cases after the support failure.

(d) Response Amplification Comparison Among Cases With Mid-Support Failure and With No Mid-Support

A study was also performed to investigate whether the sudden support failure, which would release energy to the system, would dynamically amplify the piping responses more as compared against cases without the mid-support. Two groups of analyses were performed which are Cases 1 and 8 for 2% damping and Cases 5 and 6 for 6% damping. Figure 3 shows a typical displacement response comparison near the top elbow location. It was observed that the post-failure response with support failure (Cases 1 and 5) was not noticeably amplified more than that with no support cases (Cases 8 and 6). It can be seen that a very slight amplification increase exists for only a couple of cycles right after the support failure. The reason that the response difference is so small may be because of the energy released from the support failure being small in comparison to the total earthquake energy inserted to the system.

5. Concluding Remarks

The limited study presented in this paper has (1) demonstrated the analytical capability in simulating piping response with support failure, and (2) provided some understanding of piping dynamic behavior during and after a support failure. Some important findings are

(a) Damping value higher than measured by snapback test appears existing in the piping system when subject to strong broadband-spectra earthquake excitation. More study may be needed to further confirm this finding.

(b) The influence of the support failure does not appear to be significant enough to impact the piping response during and after the failure in comparison with the case of no such support. This may be due to the fact that the energy released from the failed support is small in comparison with the total energy imparted to the system by seismic excitation. It should be noted, however, that the response after the support failure is significantly higher than that before the failure.

References

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Table 1. Summary of Analysis Cases

CASE NUMBER	INPUT RECORD	DAMPING (%)	MID-SUPPORT* CONDITION	TIME OF FAILURE (SEC)	DURATION OF THE FAILURE (SEC/INC)
1	T4R5	2	F	9.288	0.
2	T4R5	2	F	9.248	0.
3	T4R5	2	F	9.328	0.
4	T4R5	6	F	9.288	0.
5	T4R5	6	F	9.264	0.024/3
6	T4R5	6	NO	---	---
7	T4R5	6	F	9.264	0.024/3
8	T4R5	2	NO	---	---

*F = failure at mid-support
NO = mid-support not installed

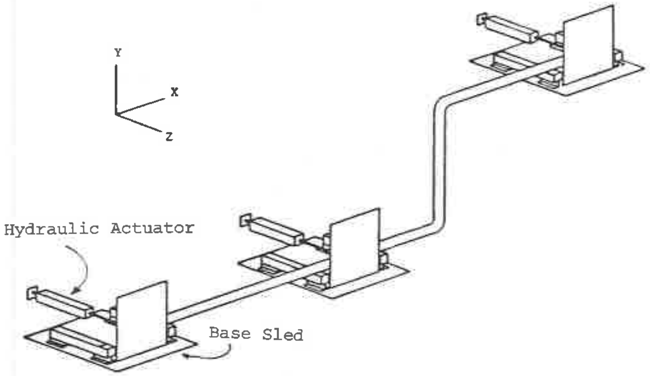
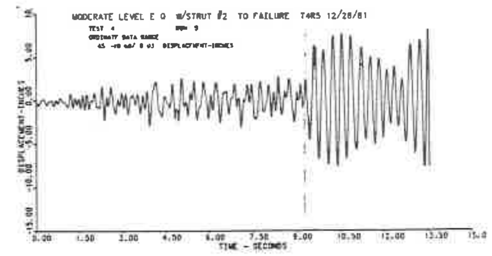
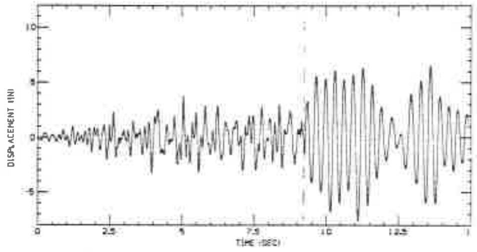


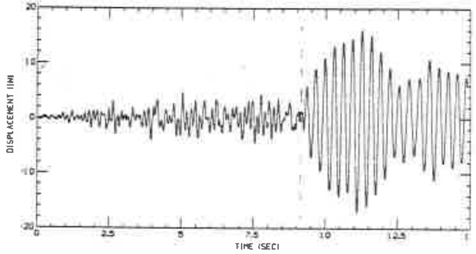
Figure 1. Schematic of Z-Bend Pipe Test Setup



(a) Z-bend T4R5 Test Measurement

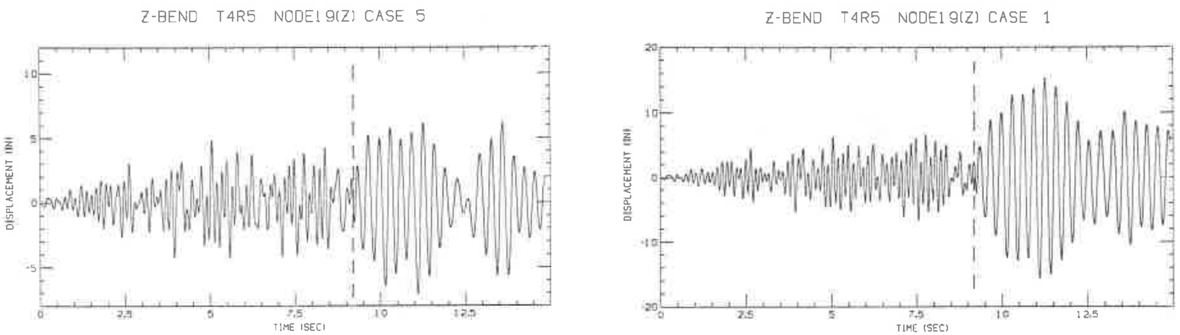


(b) Z-Bend T4R5 Case 4



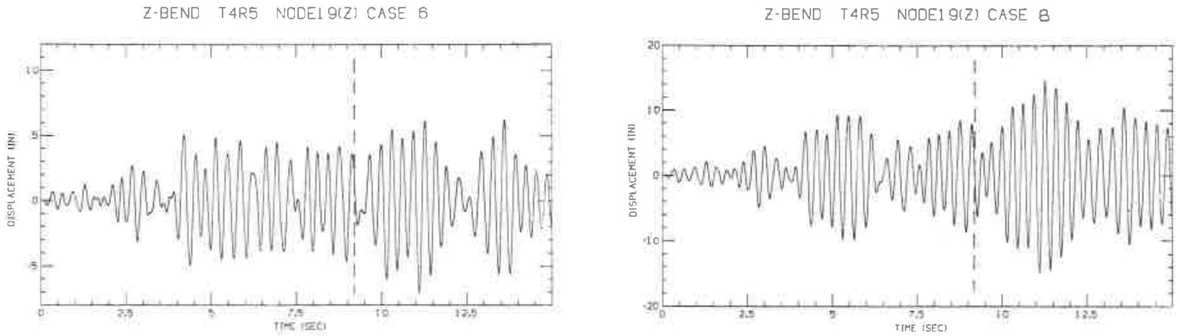
(c) Z-Bend T4R5 Case 1

Figure 2. Test vs. Analysis Response Comparison



(a) Failed support (6% damping)

(c) Failed support (2% damping)



(b) No support (6% damping)

(d) No support (2% damping)

Figure 3. Pipe Response Comparison on Support Failure