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ABSTRACT

The specification of damping for nuclear piping systems subject to seismic-induced motions has been the subject of many studies and much controversy. Damping estimation based on test data can be influenced by numerous factors, consequently leading to considerable scatter in damping estimates in the literature. At present, nuclear industry recommendations and nuclear regulatory guidance are not consistent on the treatment of damping for analysis of nuclear piping systems. Therefore, there is still a need to develop a more complete and consistent technical basis for specification of appropriate damping values for use in design and analysis. This paper summarizes the results of recent damping studies conducted at Brookhaven National Laboratory.

INTRODUCTION

The specification of damping for nuclear piping systems subject to seismic-induced motions has been the subject of many studies and much controversy. Damping represents the system's ability to dissipate the input energy, and is a significant factor in appropriately determining the dynamic response of the piping system. For mathematical simplicity, damping is often modeled as equivalent viscous damping, proportional to velocity. In reality, vibration energy is dissipated through numerous mechanisms, and determining an appropriate equivalent viscous damping for analysis of a nuclear piping system is not straightforward. Damping estimation based on test data can be influenced by the specific estimation method, the physical details of the test specimens, and the level of dynamic excitation. Consequently, there is considerable scatter in damping estimates in the literature. At present, nuclear industry recommendations and nuclear regulatory guidance are not consistent on the treatment of damping for analysis of nuclear piping systems.

NRC Regulatory Guide 1.61, Rev. 1 [1] prescribes constant damping ratios of 4% for safe shutdown earthquakes (SSE) and 3% for operating basis earthquake (OBE). These constant damping ratios are allowed to be used in time history analysis, response spectrum analysis, and equivalent static analysis. Regulatory Guide 1.61, Rev. 1 also allows the use of a frequency-dependent damping model in response spectrum analysis. The ASME Boiler and Pressure Vessel Code [2] currently recommends a frequency-independent damping ratio of 5% for both OBE and SSE in its Non-Mandatory Appendix N. Both the ASME code and Regulatory Guide 1.61, Rev. 1 are common in allowing constant damping ratio(s) over all frequencies and diameters but are different in the recommended damping values.

Therefore, even though much effort has been expended over many years, there is still a need to develop a more complete and consistent technical basis for specification of appropriate damping values for use in design and analysis. An appropriate (or correct) damping ratio (or model) for the seismic analysis of piping systems may require more than just regression analysis of the damping test data. Ideally, a calibration of any proposed damping value should be carried out using the reliability (or the traditional safety factor) of

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designed piping systems to determine whether the desired level of safety can be achieved economically.

Some recent studies performed at Brookhaven National Laboratory (BNL) involved damping assessment and estimation based on test data and may provide insights that can be useful for seismic analysis of piping systems in nuclear power plants (NPPs). As part of collaborative efforts between the United States and Japan on seismic issues, the U.S. Nuclear Regulatory Commission (NRC) and BNL evaluated the large scale piping system test data and the degraded piping test data, which were provided to NRC/BNL by the Japan Nuclear Energy Safety Organization (JNES). This evaluation included nonlinear time history analyses and response spectrum analyses of the test piping systems. Most of the results of this evaluation have been documented in two NUREG/CR reports [3,4]. Damping assessment was one of the important areas during the evaluation process. This paper summarizes the results of the relevant analyses with an emphasis on the damping study. The goal of this paper is to provide more data and insights to the seismic piping design and analysis community.

More specifically, this paper presents (1) an assessment of the sensitivity of response predictions to small variations in the damping ratio; (2) estimation of damping ratios from test data based on a simple procedure; and (3) a comparison of time history and response spectrum analysis results to test data, using the estimated damping ratios from the test.

SENSITIVITY OF SMALL DAMPING VARIATION

The purpose of this sensitivity analysis was to determine how much impact using a 4% versus 5% damping ratio has on the dynamic response of a typical large-scale piping system.

JNES carried out design method confirmation tests (DM tests) and ultimate strength tests (US tests), as shown in Figure 1 and Figure 2, respectively [3]. The two specimens were very similar except that the US specimen removed one horizontal support and added one concentrated mass, as shown in Figure 2. Figure 3 shows the ANSYS linear model for the DM tests; the model for the US tests was similarly developed. These piping system models were used for the study of the differences in dynamic response due to 4% versus 5% damping ratios. Each model also had two variations: one with nominal dimensions for the straight pipe segments and the elbows, and the other with nominal dimensions for the straight pipe segments but as-built dimensions for elbows.

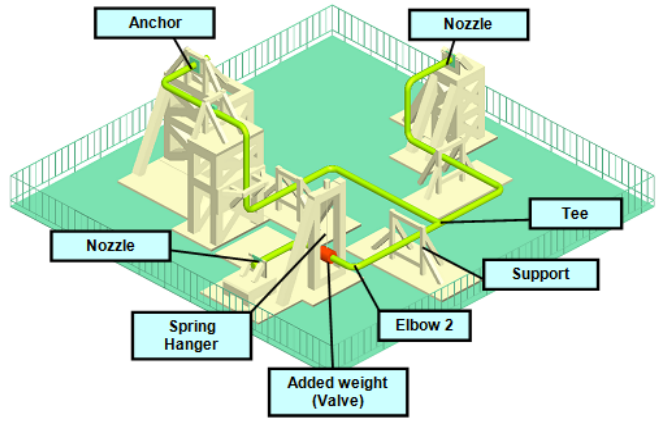

FIGURE 1 DESIGN METHOD CONFIRMATION TEST SETUP

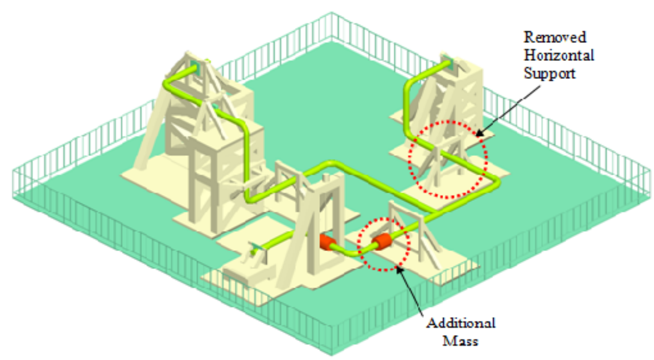

FIGURE 2 ULTIMATE STRENGTH (US) TEST PIPING SYSTEM SETUP SHOWING DIFFERENCES FROM DM TEST SETUP

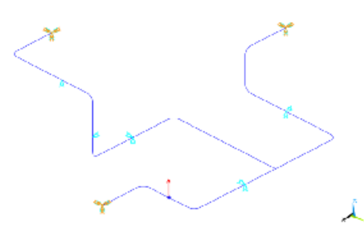

FIGURE 3 DESIGN METHOD CONFIRMATION TEST LINEAR ANSYS MODEL

Response spectrum analyses were performed on these models. The analyses considered only the seismic loads in individual directions, without combination of internal pressure, gravity load, and seismic loads in different directions. For each of the four model variations, five seismic load cases were used for this study, including DM2-2 horizontal and vertical seismic loads, DM4-2(2) horizontal and vertical seismic loads, and US2-1 horizontal seismic loads. Figure 4 shows the 2%, 4%, and 5% response spectra for the US2-1 horizontal seismic motion. Each of these five load cases included the unbroadened and broadened input spectra (see Figure 5 for an example). The spectrum-broadening algorithm was developed following the simplified approach in the Regulatory Guide 1.122 [5], which utilizes a ±15% broadening factor at each peak.

Using the response spectrum method, a complete solution was found for each of the 40 analyses using the Combination Method B in Regulatory Guide 1.92, Revision 2 [6], which is a combination of the static ZPA method and the Lindley-Yow method. The complete quadratic combination (CQC) method with the Der Kiureghian correlation coefficient, designated as the CQC combination method in ANSYS, is used to combine the periodic modal responses. For a few cases where the first natural frequency is lower than the frequency of the lowest-frequency spectral acceleration peak (peak frequency), the rigid response coefficient is set to zero (conservatively) in accordance with the Regulatory Guide 1.92 requirement. This modification indicates that the beginning part of the input spectrum with frequencies below the peak frequency is considered to generate purely periodic response.

The piping system support reactions are utilized to evaluate the impact of the damping ratio. For the DM model, there are 17 reaction forces and 9 reaction moments. For the US2-1 model, there are 16 reaction forces and 9 reaction moments. The comparison was made by either considering all reactions or considering only the significant ones, which are defined as the top half of the reactions when ranked by magnitude.

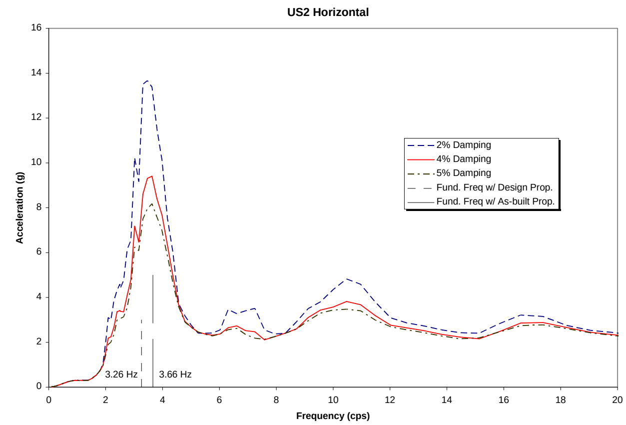

FIGURE 4 US2-1 HORIZONTAL RESPONSE SPECTRA (2%, 4%, AND 5% DAMPING)

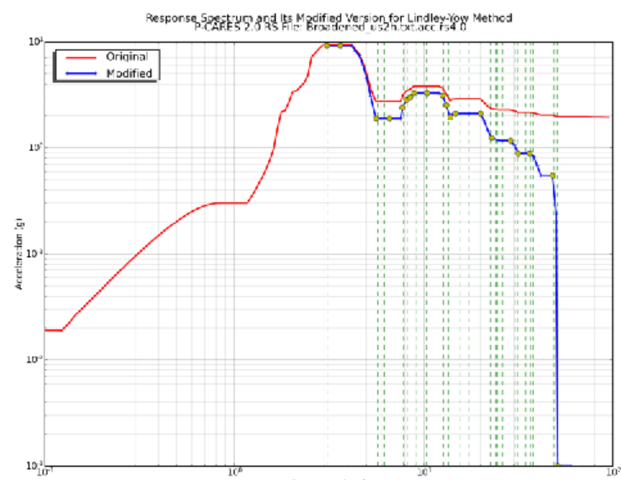

FIGURE 5 BROADENED ORIGINAL AND MODIFIED RESPONSE SPECTRA FOR LINDLEY-YOW METHOD FOR US2-1 NOMINAL DIMENSION AND 4% DAMPING

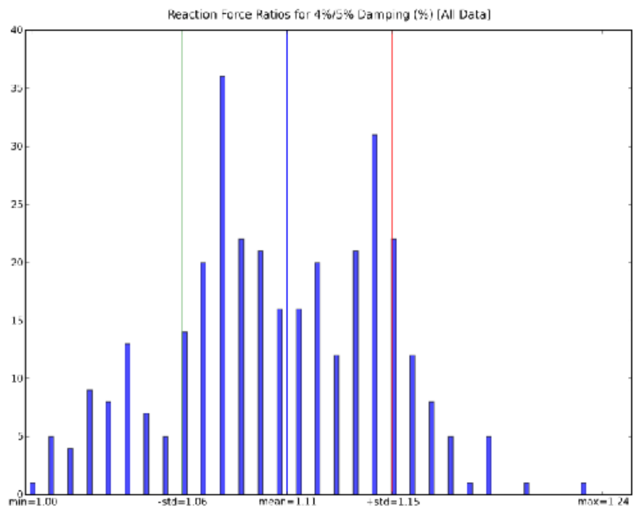

FIGURE 6 RATIO OF REACTION FORCES USING ALL DATA

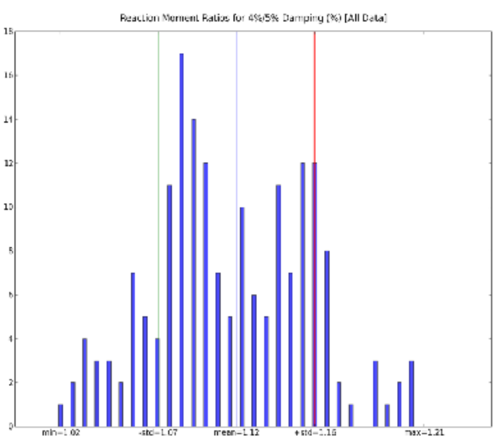

FIGURE 7 RATIO OF REACTION MOMENTS USING ALL DATA

Figure 6 and Figure 7 show histograms for the ratio of the reaction forces and the ratio of the reaction moments using all data. The mean and the standard deviation of the percentage increase in response (PIR) using 4% damping versus 5% damping are about 11~12% and 4~5%, respectively. Using the top half significant reactions (ranked by magnitude), the mean of the same PIR decreases slightly to 10~11% while the standard deviation remains about the same. The four comparisons also showed that the maximum PIR is about 20%.

The effect of spectrum broadening was also investigated. By using broadened input spectra instead of the unbroadened input spectra, the mean of the PIR uniformly increases by 3% for all cases, the standard deviation of the PIR slightly decreases, and the maximum of the PIR increase in various degrees but remains close to 20%. Therefore, using the broadened spectra as in the current design practice is unambiguously conservative in assessing the difference in dynamic responses due to 4% damping versus 5% damping.

In summary, compared to 5% damping, the seismic reactions of piping systems calculated using 4% damping can be 10~16% (mean ~ mean + standard deviation) higher, while the maximum increase in reactions can be 20%. The PIR could be slightly lower if other loads, such as dead weight and internal pressure, were also combined. Broadening of the input spectra can add an additional 3% percentage increase in reactions, compared to using unbroadened input spectra.

DAMPING ESTIMATION FROM TEST DATA

Test data from the JNES degraded piping system tests were used to estimate the equivalent viscous damping values [4]. The purpose of this effort was to obtain realistic damping estimates directly from the test data and then to use these damping estimates in analytical prediction of the dynamic response of the subject degraded piping system.

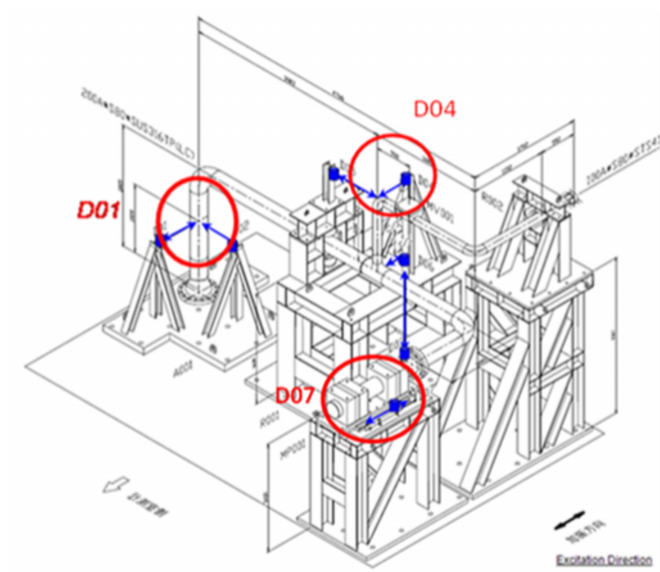

FIGURE 8 JNES DEGRADED PIPING TEST SETUP (FTP-04)

Figure 8 shows the configuration of one of the JNES degraded piping systems, designated as FTP-04. Detailed information on the test and the analytical effort can be found in references 4 and 7.

A method referred to as the "partial fraction model – least squares SDOF method" [8] was used to estimate the damping and fundamental frequency. This method is briefly described in the following. The frequency response function (FRF) in terms of input/output accelerations *H* can be defined as:

$$H(\omega_i) = \frac{\ddot{X}_{\text{out}}(\omega_i)}{\ddot{X}_{\text{in}}(\omega_i)} \approx \frac{A}{j\omega_i - \lambda_r} \tag{1}$$

where ω_i is angular frequency (rad/sec) near the damped natural frequency ω_r, λ_r is the modal frequency, and A is the residual. The modal frequency is defined as

$$\begin{gathered} \lambda_r = \sigma_r + j\omega_r \\ \Omega_r = |\lambda_r| \\ \zeta_r = -\frac{\sigma_r}{\Omega_r} \end{gathered} \qquad (2)$$

where σ_r is the damping coefficient (rad/sec), Ω_r is the resonant (undamped) natural frequency (rad/sec), and ζ_r is the damping ratio (percent of critical damping). Equation (1) can be rewritten as,

$$H(\omega_i)\lambda_r + A \approx (j\omega_i)H(\omega_i)\epsilon \qquad (3)$$

If a FRF function determined from test data has many points around a mode, Equation (3) can be repeated for a number of frequencies near the damped natural frequency, leading to a least-square SDOF method:

$$\begin{bmatrix} H(\omega_1) & 1 \\ \vdots & \vdots \\ H(\omega_i) & 1 \\ \vdots & \vdots \end{bmatrix} \begin{Bmatrix} \lambda_r \\ A \end{Bmatrix} \approx \begin{Bmatrix} (j\omega_1)H(\omega_1) \\ \vdots \\ (j\omega_i)H(\omega_i) \\ \vdots \end{Bmatrix} \qquad (4)$$

Solution to this least square equation automatically removes the high frequency noise as shown in Figure 9. This method is fast and suitable for lightly damped modes that are well separated from each other.

FTP-04 was excited at various levels of input acceleration time histories. Simulated seismic input waves up to run C029 were low-level inputs that did not induce plasticity. Six runs with high level input excitations, designated as C030 to C035, basically had the same wave applied for six times. The magnitude of these high level waves was generally more than 1.5 times the Japanese S2 level (the original plan was 1.5 × S2 ≈ 1.5 g, while the actual measurement at the shaking table top was about 2 g). Natural frequencies and damping ratios were estimated for seismic inputs C029 to C035 based on recorded output accelerations at a location close to D07 as shown in Figure 8.

Using interactive figures as shown in Figure 9 and Figure 10, the fundamental frequencies for runs C029 to C035 were estimated to be 4.96 Hz, 4.89 Hz, 4.94 Hz, 4.93 Hz, 4.91 Hz, 4.89 Hz, and 4.89 Hz, respectively. These estimates agree very well with the calculated fundamental frequency based on the JNES NASTRAN model, an ANSYS model, and an ABAQUS model of the FTP-04 piping system. It is interesting to note that the JNES tests showed that the dynamic characteristics of the piping system were not affected much by the three artificial cracks in the FTP-04 piping system. The estimated damping ratios for runs C029 to C035 were 2.03%, 2.40%, 2.53%, 2.57%, 2.71%, 2.71%, and 2.77%, respectively. These damping estimates should be treated as *equivalent* viscous damping because they include the effect of plasticity and support friction.

In general, as the seismic input level increased from C029 to C030, and the piping system was repeatedly excited at the C030 level five additional times, the fundamental frequency decreased and the damping ratio increased. The fundamental frequency estimated from the elastic run C029 is slightly higher than the other estimates, as expected. The damping ratio increases from runs C029 to C035, as also expected. From this series of damping ratio estimates, it is reasonable to conclude that increase in damping ratio is primarily due to the increased level of plasticity. Based on these results, for a linear elastic analysis, 2% damping would be appropriate, because the estimate from the elastic test run C029 is 2.03%. In the dynamic analyses of runs C030 to C035 using ABAQUS, 2% damping at 5 Hz and 50 Hz was used in the Rayleigh damping model, while the entire piping system was allowed to behave plastically in order to account for the increase in damping due to plasticity (e.g. 0.4% for C030) [4,7].

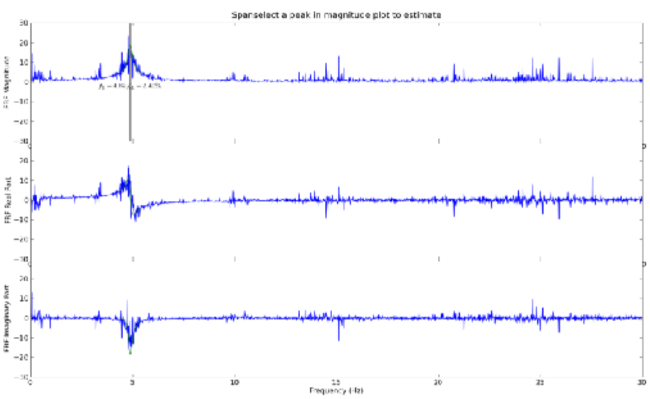

FIGURE 9 1ST NATURAL FREQUENCY AND DAMPING RATIO – C030 (F_1= 4.89 HZ, ζ_1=2.4%)

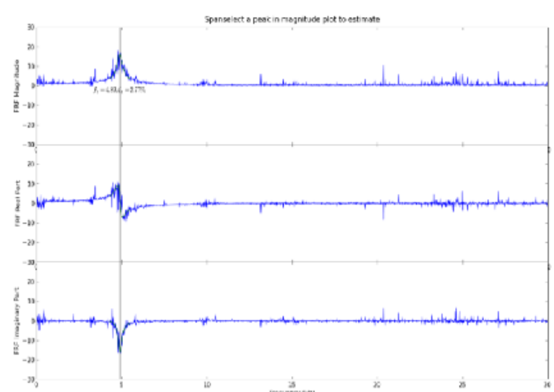

FIGURE 10 1ST NATURAL FREQUENCY AND DAMPING RATIO – C035 (F_1= 4.89 HZ, ζ_1=2.77%)

DAMPING AND SEISMIC ANALYSIS METHOD

A nonlinear time history analysis of C030 was also conducted in ANSYS, which produced comparable results at the ABAQUS analyses, as described in references 4 and 7. From the test data, it appears that inelastic behavior in the elbows accounts for the 0.4% increase in damping for C030 (slightly higher for C031 to C035). As shown in Figure 11 and Figure 12 where blue curves are from the test, comparison of displacement D07 and acceleration A05X (at a location very close to D07) showed slight over-prediction of about +3.6% and +4.3%, respectively. The estimated displacement D07 from the analysis was about 87.45 mm. The peak spectral response was over-predicted by only 2%, as shown in Figure 11. The moment at the crack location near the reducer was predicted to be about 105 kN-m.

A parametric study using an elastic viscous damping of 3% while keeping other model parameters the same under-predicted D07 and A05X by -7.2% and -7.3%, respectively. The peak spectral response of A05X was under-predicted by-11.3%. This shows that a damping ratio of 3% was somewhat too large for this test model. The moment at the crack location near the reducer was predicted as 93 kN-m. The response difference between 2% and 3% damping cases are about 8-10%.

A response spectrum analysis of the same model was conducted using a damping ratio of 2.4% (an equivalent level of damping to the nonlinear time history analysis). The predicted maximum displacement D07 is about 104 mm, which is 22.6% higher than the test value of 84.86 mm and about 19% higher than the nonlinear time history analysis. The corresponding maximum moment at the crack location near the reducer was predicted to be 127.8 kN-m, which is about 22% higher than the nonlinear time history analysis.

Another response spectrum analysis using 4% damping, which was used by in the JNES response spectrum analysis of the same model, predicted a maximum D07 of 85.4 mm, which is +0.6% higher than the test result. The corresponding maximum moment at the crack location near the reducer was predicted to be 104.7 kN-m, which agrees very well to what was predicted in the JNES response spectrum analysis. It can be concluded that the response spectrum analysis using 4% damping is better than the one using 2.4% damping.

It appears that 4% damping in the response spectra analysis is equivalent to 2% viscous damping in the nonlinear time history analysis, based on comparisons of the displacement D07 and the maximum moment at the crack location near the reducer. Both the damping ratios estimated from the test data and the excellent predictions using the nonlinear time history analysis clearly indicate that an equivalent viscous damping ratio of 2.4% might be appropriate for test run C030. However, response spectrum analysis generally is conservative compared to a time history analysis. NUREG/CR-6645 showed that the response spectrum analysis predicted on average 20% higher than the time history analysis [9]. A similar level of over-prediction has been observed in this current study, when compared to the nonlinear time history analysis.

From the above discussion, it appears that the choice of analytical method for seismic response prediction has a significant impact on how the equivalent viscous damping should be specified.

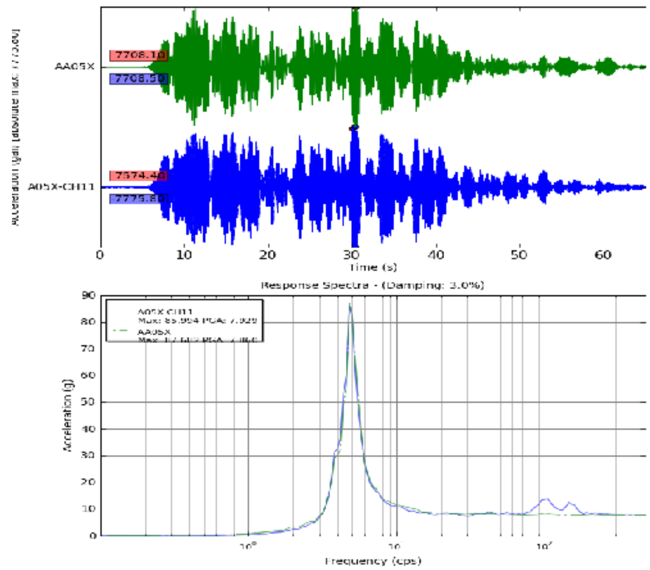

FIGURE 11 COMPARISON OF A05X FOR C030

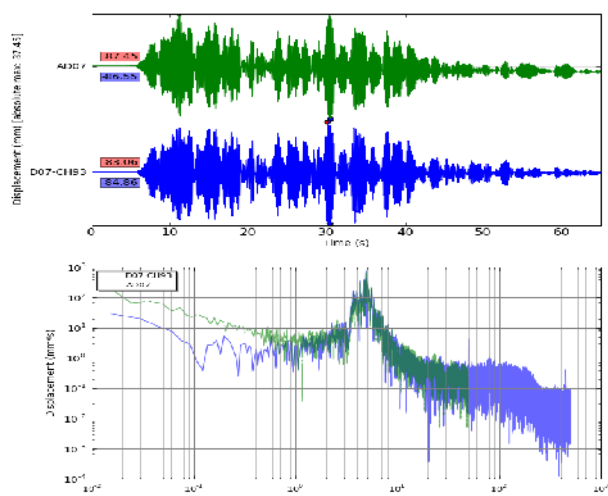

FIGURE 12 COMPARISON OF D07 FOR C030

CONCLUSIONS

This paper presents the results of three studies related to equivalent viscous damping for seismic analysis of piping systems: (1) the impact of 4% versus 5% damping on seismic responses obtained by response spectrum analysis; (2) damping estimation from test data; and (3) the effect of the seismic analysis method on selection of appropriate damping. The common goal of these studies was to provide relevant technical information, useful in the effort to resolve the differences between the nuclear industry recommendations and the nuclear regulatory guidance related to damping specification for seismic analysis and design of piping systems in nuclear power plants. While significantly more effort will likely be required to achieve this overall goal, the specific studies presented in this paper provide several important insights:

(1) The reaction responses predicted by response spectrum analysis using 4% damping are about 10% on average, and about 20% at maximum, higher than the 5% damping responses

(2) The equivalent viscous damping ratios estimated from the JNES degraded piping test data were between 2.03% and 2.77%. The excitation level in the test was up to about a ZPA of 2g.

(3) It was confirmed from the series of estimated damping ratios that damping increases as excitation level increases, as commonly recognized.

(4) Nonlinear time history analysis was in excellent agreement to the test results when 2% equivalent viscous damping was used in conjunction with plasticity specification in the piping system model.

(5) A higher level of damping was required for response spectrum analysis (4% versus 2%), to predict the same level of response as the nonlinear time history analysis.

(6) Appropriate damping specification for design may need to consider the dependency of the appropriate damping ratio on the seismic analysis method.

ACKNOWLEDGEMENT

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All of the test results and/or information about the test models used in this paper were provided by JNES and are greatly appreciated.

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