APPLICATIONS OF EQUIVALENT LINEARIZATION APPROACHES TO NONLINEAR PIPING SYSTEMS

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ABSTRACT

The application of equivalent linearization approaches (ELA) to seismic analyses of nonlinear piping systems is presented. Two types of ELA's are studied; i.e., one based on the response spectrum method and the other based on the linear random vibration theory. The test results of main steam and feedwater piping systems supported by snubbers and energy absorbers are used to evaluate the numerical accuracy and limitations.

1 INTRODUCTION

The piping systems in nuclear power plants, even with conventional snubber supports, are highly complex nonlinear structures under severe earthquake loadings mainly due to various mechanical gaps in support structures. Some type of nonlinear analysis is necessary to accurately predict the piping responses under earthquake loadings. In recent years, various energy absorbing (E.A.) devices have been proposed as alternatives for conventional snubbers not only for a new plant design but also for redesign efforts of snubber reduction. The equivalent linearization approach (ELA) has been used in the past as a practical analysis tool in seismic analyses to account for the nonlinearities of pipe support structures, e.g., for the gap nonlinearity of the seismic stop supports (Ref. 1), snubber supports (Ref. 2), as well as various E.A. supports (Refs. 3 and 4). Past studies are mostly based on iterative response spectrum approaches. The analysis errors and limitations in ELA have also been discussed (e.g., Ref. 5). However, few studies have been performed in the past on the applicability of ELA's to nonlinear piping systems based on large-scale vibration tests.

The MS Proving Test Program (Ref. 6) has provided a unique opportunity to perform such studies. Scaled models (1/2.5) of a main steam piping system for a typical PWR plant and a feedwater piping system for a BWR plant were fabricated and subjected to a large number of earthquake motions at the Tadotsu Engineering Laboratory of Nuclear Power Engineering Corporation (NUPEC) of Japan. The pipes were supported by conventional snubbers, then in the second phase of testing, most of the snubbers were replaced by E.A. devices. This paper describes the application of ELA's to the piping systems supported by E.A. devices.

2 EQUIVALENT LINEARIZATION APPROACHES

Two different ELA's have been developed; i.e., one based on the response spectrum method (ELA/RS), and the other based on linear random vibration theories (ELA/LRV). Both the methods use classical eigenvalue solutions of linearized structural systems. The detailed mathematical formulations of the methods have been described before (Ref. 7). Therefore, this paper briefly outlines the two ELA's.

ELA/RS Method. . .According to the classical study by Caughey (1963), the equivalent stiffness, k_{eq}, of a hysteretic system is obtained based on the slowly-varying assumption on the nonlinear oscillation, as

$$K_{eq} = \frac{1}{\pi U} \int_0^{2\pi} F(u) \cdot \cos \theta \, d\theta, \qquad u = U \cdot \cos \theta \qquad (1)$$

in which, U is the peak displacement amplitude; F(u) is the nonlinear restoring force for the largest hysteresis loop as a function of displacement, u.

For the gap nonlinearity in Figure 1, the equivalent stiffness is expressed as,

$$k_{eq} = \alpha K + \frac{2K}{\pi} (1-\alpha) \left\{ \cos^{-1}\left(\frac{1}{\mu}\right) - \left(\frac{1}{\mu}\right)\sqrt{1 - \frac{1}{\mu^2}} \right\} \qquad (2)$$
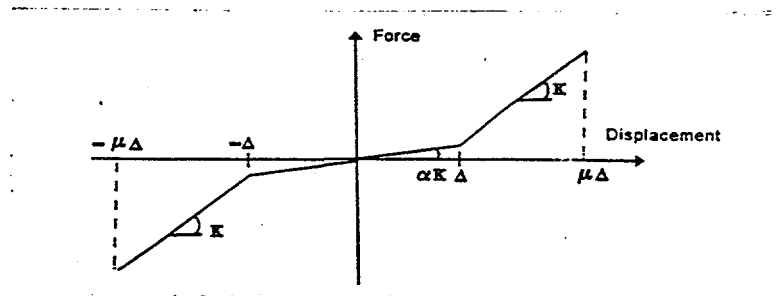

Figure 1 Modeling of Nonlinearity of Snubbers

For the equivalent modal damping, h_{eq}, the formulation proposed by Tansirikongkol and Pecknold (1980) is used in this study,

$$h_{eq,r} = h_{o,r} \frac{\omega_r}{\omega_{eq,r}} + \frac{\sum_i \epsilon_{ir}^2 \cdot S_i}{2M_r \cdot \omega_{eq,r}^2} \qquad (3)$$

in which, $h_{o,r}$ = elastic modal damping; ω_r = frequency for r-th mode; $\omega_{eq,r}$ = equivalent frequency;

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M_r = modal mass; ϵ_{ir}= modal strain of component-I; and S_i = normalized hysteresis area of component-I.

The SRSS approximation is used in the iterative solution scheme, in which the above k_{eq} and h_{eq} are updated, followed by a new eigenvalue analysis of the equivalent linear system.

ELA/LRV. . . . .The method is based on the linear random vibration theory and a modified Kryloff-Bogoliubov equivalent linearization approach. A displacement component, u_i, in a piping system is expressed as,

$$u_i = \sum_r \phi_{ir} q_r + \sum_m \phi_{im} X_m \tag{4}$$

in which, q_r is the r-th normal mode response; ϕ_{ir} is the eigenvector of the fixed-based system; X_m is the differential displacement at the m-th fixed degree of freedom; and ϕ_{im} is the displacement mode due to the m-th differential displacement. Assuming stationality of responses, the covariance for a pair of displacements, u_i, and u_j, are obtained as,

$$R_{u_i u_j}(o) = \sum_r \sum_s \phi_{ir}\phi_{is} R_{rs} + \sum_m \sum_n \phi_{im}\phi_{jm} \cdot \bar{R}_{mn} \tag{5}$$

in which, R_{rs} is the covariance for the r-th and s-th normal mode responses; and $\bar{R}_{mn}$ is the covariance for the m-th and n-th differential displacements.

$$R_{rs} = \sum_k \sum_l C_{kl} \cdot \beta_{rk} \beta_{sl} \int_{-\infty}^{\infty} H_r(\omega) \cdot H_s(\omega) \sqrt{S_k(\omega) \cdot S_l(\omega)} d\omega \tag{6}$$

$$\bar{R}_{mn} = C_{mn} \int_{-\infty}^{\infty} \frac{1}{\omega_4} \sqrt{S_m(\omega) \cdot S_n(\omega)} d\omega \tag{7}$$

In which, C_{kl} is the correlation coefficient for the k-th and l-th excitations; β_{rk} is the r-th participation factor for the k-th excitation; $H_r(\omega)$ is the transfer function for the r-th function for the r-th mode; and $S_k(\omega)$ is the k-th PSD function.

The equivalent component stiffness k_{eq}, and modal damping, h_{eq}, can be defined using the peak distribution functions, $p_1(u, \sigma_\epsilon)$ and $p_2(u, \sigma_\epsilon)$, as,

$$K_{eq} = \int_0^{\infty} K_{eq}(u) \cdot p_1(u,\sigma_\epsilon)du, \qquad h_{eq} = \int_0^{\infty} h_{eq}(u) \cdot p_2(u, \sigma_\epsilon)du \tag{8}$$

in which, σ_ϵ is the standard deviation of the strain response.

For the peak distribution function, the Gumble type I distribution for p_1 and the Rayleigh distribution for p_2 were used (Ref. 7). The selection of the above peak distribution functions is purely empirical and based on the past simulation studies on hysteretic systems. Although the above method requires power spectral density (PSD) functions for the input excitations, a simple approach is available to directly convert from a PSD to an equivalent response spectrum (Ref. 9).

3 MODELING OF MAIN STEAM AND FEEDWATER PIPING

Figure 2 shows the finite element model (FEM) for the main steam piping system. In the test series used in this study, the node-10, which is the joint to the steam generator, was fixed to the support structure. Three E.A. supports, called lead extrusion dampers (LED), were used for the main pipe supports, and designated as LED-1, LED-2 and LED-3 in Figure 2.
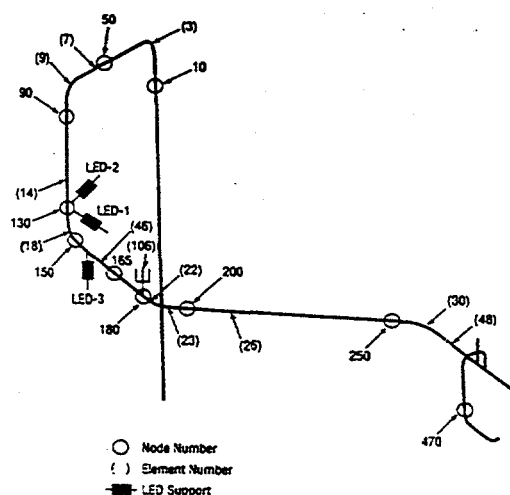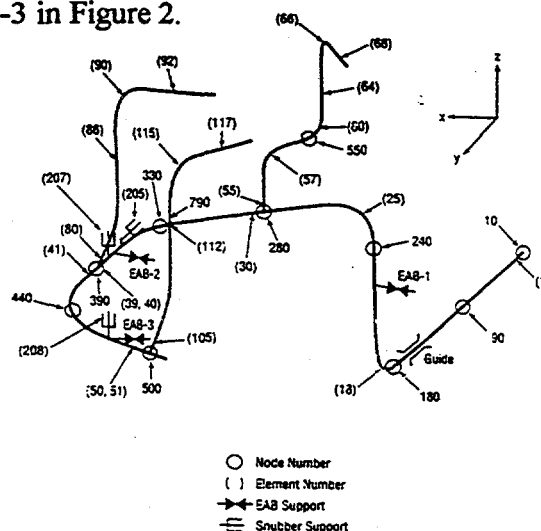

Figure 2 Main Steam Piping

Figure 3 Feedwater Piping Model

Figure 3 shows the FEM for the feedwater piping system. In the model, the node-10 as well as the ends of all three branch lines are fixed. The pipe was supported by three mechanical snubbers and three E.A. supports, called energy absorbers (EAB), and designated as EAB-1, EAB-2 and EAB-3 in Figure 3. More details of the tested piping systems can be found in the accompanying paper (Ref. 6).

To model the hysteretic behavior of the E.A. supports, the so-called Bouc-Wen model was used (Ref. 10). According to Wen (1980), the nonlinear restoring force, q, is expressed as,

$$q = \alpha \, k \, u + (1 - \alpha) \, kZ \tag{9}$$

$$\dot{Z} = \dot{u} - \beta \cdot \dot{u}|Z|^n - \gamma \, |\dot{u}|Z|Z|^{n-1} \tag{10}$$

in which, u and $\dot{u}$ = the relative displacement and velocity; K = the initial stiffness; α = the postyield stiffness ratio; and Z = hysteretic component with the unit of displacement; and n = a parameter to characterize hysteresis loops.

The above hysteretic parameters, K, α, β, γ and n, were determined by curve-fitting the available component test data for the EAB supports and the MS test results for the LED supports. The results are shown in Figure 4 for the EAB supports.
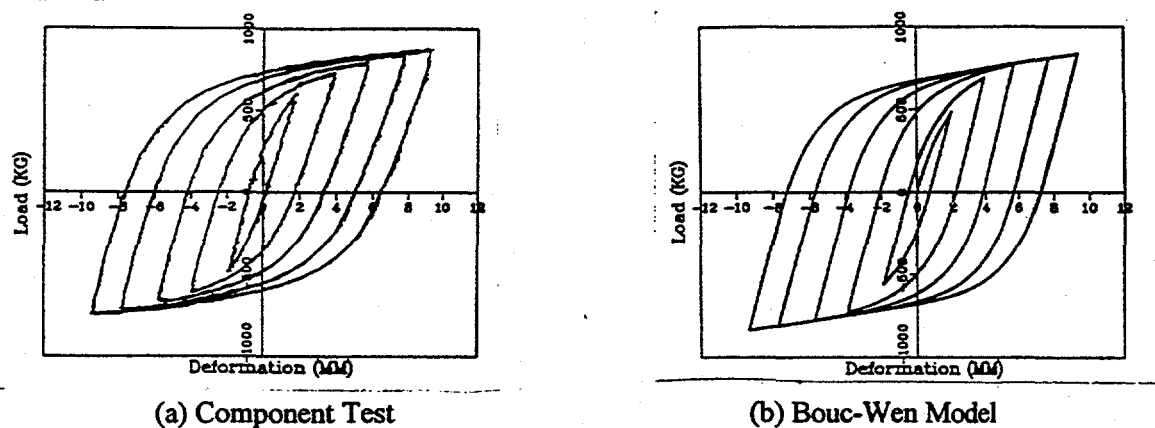

(a) Component Test   (b) Bouc-Wen Model

Figure 4 Hysteretic Behavior of EAB Support

4 COMPARISON STUDY

Figure 5 shows the recorded table motion in the X-direction. This motion is a calculated floor response of a typical reactor building, and characterized by a sharp spectral peak at around 14 Hz. The recorded table motions in the Y- and Z- (vertical) directions were much lower, i.e., 0.13g and 0.39g, respectively. This table motion is referred to as the S2A wave, and was used for vibration tests for both the main steam and feedwater lines at various excitation levels up to 2.5 times the motion shown in Figure 5.
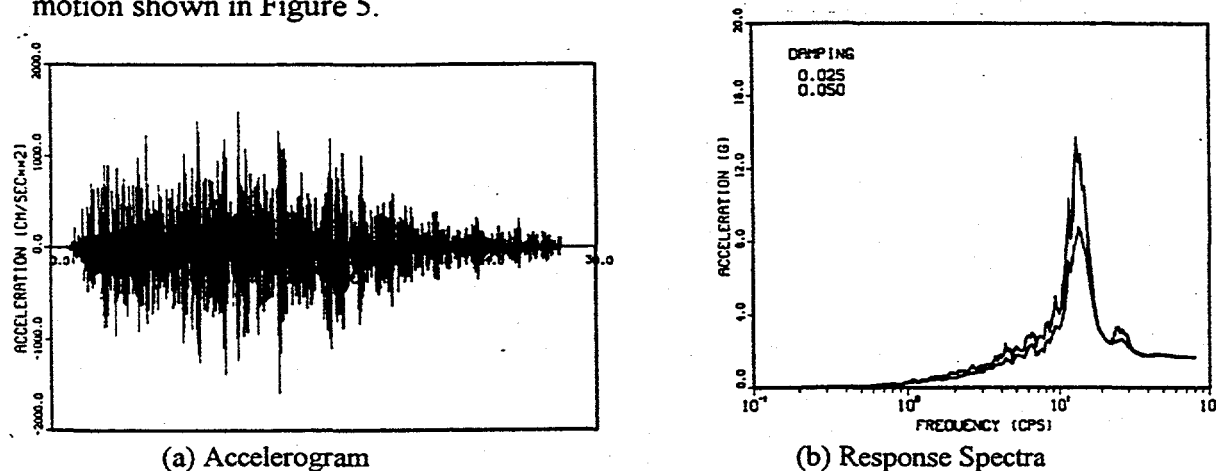

(a) Accelerogram   (b) Response Spectra

Figure 5 Recorded Shaking Table Motion, S2(A) Wave in X-Direction

Figure 6 compares the peak responses of the main steam line from three types of analyses; i.e., nonlinear time history (NTH), ELA/RS and ELA/LRV, with those of the measured test results. The X-direction acceleration at Node-90 and the displacements of the LED-2 are compared at three (3) excitation levels; i.e., 1/3, 1.0, and 2.5 times the S2A motion. The comparisons in Figure 6 indicate that the ELA analysis results correlate well with the NTH analysis results as well as the measured peak values, particularly at lower excitation levels. At a higher excitation level, the results from the

ELA/RS tends to deviate from the measured responses. Tables 1 and 2 list the calculated vibration frequencies and the equivalent damping values from both the ELA/RS and ELA/LRV. In general, the detuning of vibration frequencies is more prominent in the ELA/LRV than in the ELA/RS.

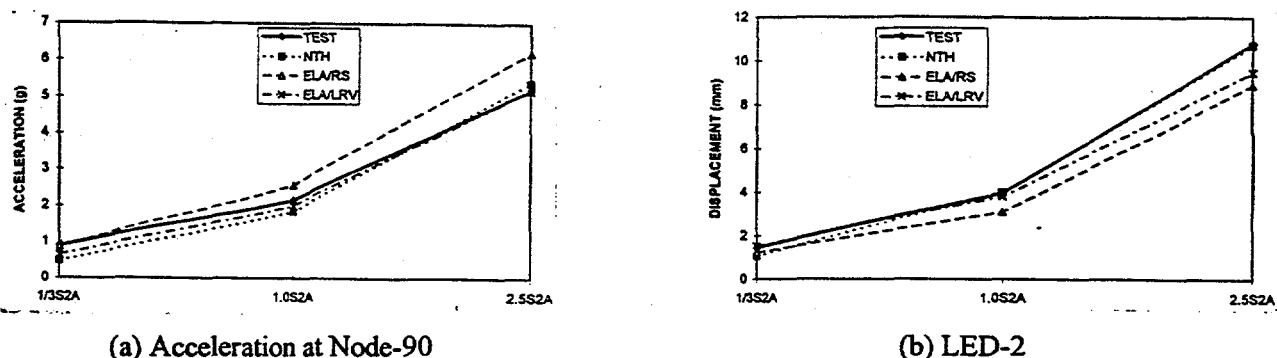(a) Acceleration at Node-90   (b) LED-2

Figure 6 Comparison of Responses for Main Steam Line

Table 1 Comparison of Vibration Frequencies of Main Steam Pipe
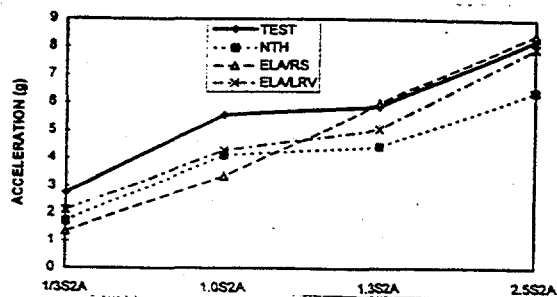Obtained From Equivalent Linearization Analyses

Mode	Linear	1/3 S2(A)		1.0 S2(A)		2.5 S2(A)	
		RS	LRV	RS	LRV	RS	LRV
1	8.27Hz	8.27	8.02	7.21	6.83	5.60	5.53
2	9.38	9.12	8.88	8.43	8.54	8.42	8.51
3	9.60	9.52	9.92	9.28	9.78	9.21	9.23
4	15.24	14.41	13.51	12.31	11.96	10.69	10.85
5	16.64	15.91	15.50	14.51	13.86	12.68	12.88

Table 2 Comparison of Equivalent Modal Dampings of Main Steam Pipe
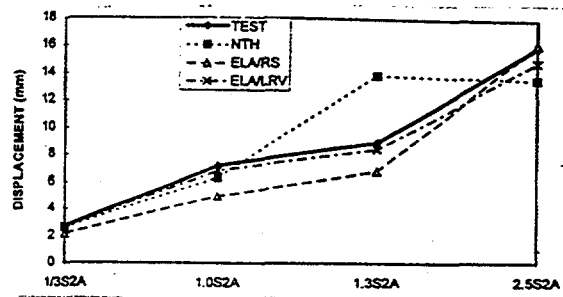Obtained From Equivalent Linearization Analyses

Mode	Linear	1/3 S2(A)		1.0 S2(A)		2.5 S2(A)	
		RS	LRV	RS	LRV	RS	LRV
1	1.0%	2.7	3.3	15	14.9	23.4	36.6
2	1.0%	3.4	2.5	4.1	2.7	3.5	3.8
3	1.0%	2.1	1.3	1.8	1.7	4.3	4.9
4	1.0%	6.4	4.9	12.5	10.7	11.6	15.8
5	1.0%	5	3.4	10.2	8.4	9	11.2

Figure 7 shows the similar comparison for the feedwater line. Due to complex nonlinearities in snubbers and other support structures due to mechanical gaps (Ref. 6), the observed analysis errors are larger than those of the above main steam line case. However, the analysis errors in the ELA results are not significantly worse than those in the NTH results.
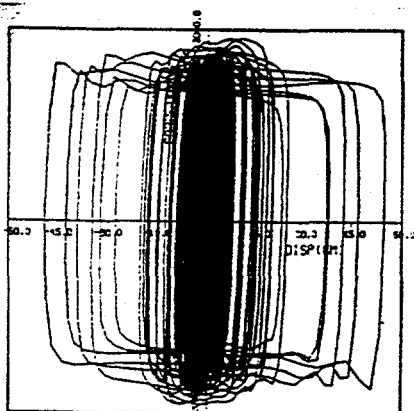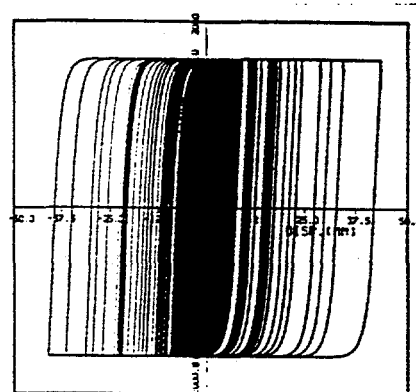
(a) Acceleration at Node-550

(b) EAB-2

Figure 7 Comparison of Responses for Feedwater Line

To illustrate the limitations in the ELA, the most damaging test run for the main steam line was analyzed. Figure 8 shows the hysteretic responses of LED-2 from the test and NTH results. During the test, the LED-2 deformed 54.9 mm., which in terms of ductility factor is more than $\mu = 38$. Table 3 compares the peak displacement responses. For this extremely large plastic test case, the ELA responses largely overshoot or undershoot the measured responses.

(a) Recorded (Peak = 54.9 mm.)   (b) Time History Analysis (Peak = 43.4 mm)

Figure 8 Response of LED-2 During Maximum Excitation Test Run

Table 3 Comparison of Peak Displacement Response
for Maximum Excitation Test Run

INSTRUMENT/ELEMENT NUM.		TEST	NTH	ELA	
				RS	LRV
Node-90	(X)	17.3	16.4	40.4	10.4
	(Y)	10.2	3.9	29.9	3.4
LED-1		4.7	4.5	11.8	2.9
LED-2		54.9	43.4	92.9	25.3
LED-3		15.3	13.0	29.2	6.5
Node-150	(X)	50.9	43.9	89.7	25.3
	(Y)	36.0	30.2	70.1	18.9
	(Z)	15.3	13.3	30.0	6.6

5 CONCLUSIONS

Two different equivalent linearization approaches were applied to nonlinear piping systems supported by energy absorbing devices, that were tested at NUPEC's Tadotsu Engineering Laboratory. The

applicability and reliability of the analysis methods were demonstrated based on the comparison study using both the measured responses and conventional time history analysis results. The limitations of the ELA's were also studied by an additional comparison study on a test result involving extremely large plastic deformations.

6 ACKNOWLEDGMENTS

7 DISCLAIMER

This work was performed under the auspices of the U.S. Nuclear Regulatory Commission. The findings and opinions expressed in this paper are those of the authors, and do not necessarily reflect the views of the U.S. Nuclear Regulatory Commission or Brookhaven National Laboratory.

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