Simplified piping analysis methods for piping with inelastic supports

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1 INTRODUCTION

The use of an energy absorbing supports (EAS) such as the x-plate (1) has been demonstrated to reduce piping response loadings significantly. However, due to yielding nature of the device, response behavior of the piping system is non-linear. A response spectrum analysis, as normally would apply to a typical piping system, may no longer be conservative. A time history analysis may be necessary, which can be very costly in terms of computer time and data handling. In order to reduce the computation effort to enhance the merit of considering inelastic supports in piping design and analysis, a simplified analysis method needs to be developed. This method has to be able to predict the inelastic system response conservatively and within reasonable bounds.

Simplified inelastic analysis has been proposed by Newmark & Hall (2) to be treated in the form of an inelastic response spectrum. But the proposed inelastic response spectrum deals only with the development approach for a ground response spectrum; and there is no discussion of the method of applying the inelastic response spectrum.

In this paper, a method is presented which would provide a realistic prediction of the inelastic response for piping systems with energy absorbing type of supports.

2 SIMPLIFIED INELASTIC ANALYSIS PROCEDURE

Before discussing the procedure for conducting simplified inelastic analysis, it is important to review the parameters which contribute to the response determination. First, there is the probable maximum displacement of the inelastic support. This is the displacement where the motion will occur at the lowest possible system frequency. It is also the greatest amount of damping the support will dissipate. Associated with this displacement, there is the lowest possible stiffness for the inelastic support.

In contrast with the lowest possible displacement and stiffness for each inelastic support, there will also be the highest possible stiffness and smallest displacement correspond to when the support is at the onset of plasticity.

The response behavior of the piping at the inelastic support will be bounded by these two sets of displacements and stiffnesses. One may use the lowest displacement obtained at the elastic range of the support to calculate damping associated with the EAS. Using this damping value, a lower magnitude response spectrum can be conservatively constructed.

Next, inelastic response of the system could occur at any frequency in between the frequencies defined by the elastic displacement and the probable maximum inelastic displacement. For conservatism, it is necessary to assume that the system frequency be actually coincide with the spectra peak frequencies defined by the reduced response spectrum at the higher damping. The support stiffness is then set at this frequency value. System analysis can now be carried out using the reduced response spectrum (support specific) at each support and using the multiple support response spectra technique.

Finally, it should be noted that because the multiple support response spectra analysis is a linear elastic analysis, the loads obtained at the inelastic support will most likely exceed the yield loads. Thus, a load redistribution will have to be performed to redistribute the excess loads to other supports.

3 DEVELOPMENT OF INELASTIC RESPONSE SPECTRUM

As pointed out in the earlier section, the first step of the simplified inelastic analysis method is to conduct a uniform response spectrum analysis, using the elastic EAS support stiffness and the existing piping damping spectrum as input. The response obtained is used to determine the EAS deflection which is then used to determine the potential lower bound inelastic stiffness, using an energy balance approach. The EAS deflection is also used to compute the additional damping associated with the energy dissipation due to inelasticity, based on the calculated ductility.

4 MULTIPLE SUPPORT INELASTIC SPECTRA ANALYSIS

Because each EAS support has a different response spectrum due to different levels of ductilities reached, final analysis of the piping system can best be accomplished using the grouping approach (3,4) of the multiple support response spectra analysis. In this approach, the support spectra which are similar are grouped in the same group.

In the present method of conducting piping response analysis consisting of inelastic supports, the motions at inelastic supports are quite different from the elastic supports, and each inelastic support will undergo different patterns of inelastic motion. Hence, each inelastic support motion should be considered as a group by itself. After filtering through the inelastic support, the motions can be represented by a response spectrum with higher damping computed from an estimated inelasticity (ductility) of the support. In conjunction with the inelastic response spectrum, an equivalent (linear) support stiffness is also obtained for the inelastic support. As a result of the process, the non-linear problem has been transformed into a linear analysis problem. The response of such an equivalent linear system can be obtained directly from a multiple support response spectra analysis.

5 SUPPORT LOAD REDISTRIBUTION

The support loads obtained at the inelastic support from the multiple support spectra analysis are anticipated to be above yield. This is based on the fact that inputs at the inelastic supports are at least equal to but are most likely to be higher than the loads determined from the uniform spectrum analysis. As a result, the excess loads of the portion above yield need to be redistributed to other supports of the system. This redistribution is simply illustrated in Figure 1. The redistribution is accomplished by applying the excess portion of the support load at the support point but with the support removed from the model. The final result is a combination of the redistributed loads and the loads after redistribution. With this process, all inelastic supports will have loads at yield.

6 NUMERICAL EXAMPLES

6.1 Example 1

Three numerical examples are presented herein to illustrate the entire simplified inelastic analysis procedure. Two examples use the two span beam shown in Figure 2. The center support is inelastic, while the two end supports are assumed to be hinged (and is, therefore, rigid). The total length of the beam is 20 feet, and has an outside diameter of 6.625". These two models have been created using the basic configuration by changing the pipe weight. The intent is to create models with two distinct fundamental modes (8.45 and 6.54 Hz, respectively), one at the higher frequency side (above the peak of the spectrum shown in Figure 5) and one at the lower frequency side. In addition to the pipe weight which includes water and insulation, a valve weight was added at the inelastic support point.

Figure 2 shows the load deflection curve, which also shows that the elastic stiffness of the support is 7000 lb/in.

First, time history analyses were conducted using the initial five-second portion of the input shown in Figure 4. The reason for using such a short duration time history is mainly to reduce cost. A corresponding response spectrum for the five-second portion of the input is shown in Figure 5. This is the spectrum that was used as input at the two end supports for all steps. It is also used for the inelastic support during the first step to establish the upper bound frequency of the model.

Figures 6 and 7 show the two highly damped response spectra for the two models, respectively. These spectra were developed using the damping value from the ductility factor calculated for the uniformed response spectrum analysis (i.e., all supports were assumed to be elastic).

Figure 8 shows a typical force displacement motion computed from the time history solution, which is highly hysteritic in nature.

Tables 1 and 2 present the comparison of the results from the present simplified inelastic analysis with the time history solution for the two models with the same geometry but different valve mass and therefore different fundamental frequencies.

The higher frequency model (Table 1) has a fundamental elastic frequency of 8.45 Hz. By using the energy balance approach, it was determined that the support inelasticity could reduce the controlling motion to below the peak spectral frequency of 7.5 Hz. Therefore, the analysis was conducted by forcing the inelastic support to have an equivalent stiffness which is capable of producing the controlling frequency at 7.5 Hz.

On the other hand, the lower frequency model (Table 2) has a fundamental, elastic frequency of 6.54 Hz. By using the energy balance approach, it was concluded that the support inelasticity could reduce the controlling motion to lower than 6 Hz, but not enough to be at the other side of the response spectra spike (lower than 4 Hz). Therefore, the simplified inelastic analysis was conducted by forcing the equivalent stiffness to be unchanged from the elastic frequency of 6.54 Hz.

The solution in both Tables 1 and 2 illustrates that the procedures adopted are indeed more conservative than the time history solution. But the conservatisms are all less than 30 percent in both cases.

6.2 Example 2

The two examples discussed in the previous section are all for simple two-span beams with EAS in the middle support. As an illustration for the use of the present method to more complex problems, Figure 2 shows a piping model which was analyzed using the same procedure as outlined earlier. The piping is a 6 inch residual removal line which was heavily supported by snubbers. These snubbers were replaced by the EAS' with dynamic characteristics shown in Table 3.

Originally, the system was analyzed with the 2% damping response spectrum (Figure 5) using the elastic EAS stiffness. The controlling natural frequency of each EAS is shown in Table 3.

Using the elastic displacements calculated from the 2% damping response spectrum input, higher damping of about 5% was obtained for these supports. The lower bound frequencies calculated using the energy balance approach indicate that the equivalent controlling natural frequencies of the system are not low enough to increase the elastic response spectrum input computed at the upper bound frequencies. Hence, the equivalent inelastic analysis was conducted using the same elastic stiffness for the EAS'. As a result of the difference in damping values, the response spectra input at the supports are different. Therefore, the multiple support response spectra grouping technique (Ref. 3) was used in the analysis.

Table 4 shows the result of the piping analysis after load redistribution. It shows that except for two non-EAS supports, the response loads are all more conservative than the time history solution. For the two non-EAS supports where the simplified method is under the time history solution, the under prediction is less than 20%. Also, since only Z direction input is applied, additional load redistribution is possible when other directional input is present which would improve the ratio. Finally, except for the two EAS supports where displacements are small, majority of the ratios are less than two. This indicates that the simplified method is quite close to the exact time history solution.

7 SUMMARY

A simplified procedure is presented to analyze piping systems supported by energy absorbing type of inelastic supports.

The procedure bounds the system solution conservatively by first identifying the upper bound frequency which controls the inelastic support motion. This solution is used, with the help of an energy balance approach, to obtain the potential inelastic displacement. Associated with it, the higher damping value and the lower bound support stiffness are obtained. This information is then applied to determine the bounding support stiffness and the higher damping response spectrum.

Finally, a load redistribution is conducted by distributing the loads in excess of yield to other supports in the system; and the solutions combined to provide the final results.

Comparison of the time history solution with the solution obtained for the two simple and one actual piping models illustrates that the procedure is conservative. Further, the solution procedure is straight forward, and the computer cost is less than 10 percent of the elastic-plastic time history analysis.

REFERENCES

Schneider, S., Lee, H. M., and Godden, W. G., Piping Seismic Test with Energy-Absorbing Devices, EPRI NP-2902, March 1983.

Newmark, N. M. and W. J. Hall, "Procedures and Criteria for Earthquake Resistant Design," Proceeding of the Workshop on Building Practices for Disaster Mitigation, National Bureau of Standards Building Science Series 46, Aug. 28 - Sept 1, 1972 (issued Feb. 1973), Boulder, Colorado.

Lin, C. W. and Loceff, F., "A New Approach to Compute System Response with Multiple Support Excitation," Journal of Nuclear Engineering and Design 60 (1980) 347-352.

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TABLE 1
COMPARISON OF RESULTS FOR MODEL 1

Parameter		Uniform Response Spectrum Solution	Multiple Support Response Spectra Solution	Time History Solution
Fundamental (Controlling) Frequency		8.5 Hz	7.5 Hz	--
Damping		5 percent	12 percent	--
Support Displacement	Before Load Redistribution	1.37"	1.25"	--
	After Load Redistribution	3.45"	3.12"	2.44"
EAS	Before Load Redistribution	6.75 Kip	6.134 Kip	--
Load	After Load Redistribution	0.844 Kip	0.844 Kip	0.844 Kip
END REACTION	Before Load Redistribution	2.32 Kip	3.404 Kip	--
Load	After Load Redistribution	5.27 Kip	4.680 Kip	3.71 Kip

TABLE 2
COMPARISON OF RESULTS FOR MODEL 2

Parameter		Uniform Response Spectrum Solution	Multiple Support Response Spectra Solution	Time History Solution
Fundamental (Controlling) Frequency		6.54	6.54	--
Damping		5 percent	12.4 percent	--
Support Displacement	Before Load Redistribution	2.49"	1.47"	--
	After Load Redistribution	8.34"	4.80"	4.53"
EAS	Before Load Redistribution	17.41 Kip	10.27 Kip	--
Load	After Load Redistribution	0.844 Kip	0.844 Kip	0.844 Kip
END REACTION	Before Load Redistribution	3.92 Kip	2.31 Kip	--
Load	After Load Redistribution	12.21 Kip	7.03 Kip	6.69 Kip

TABLE 3
EAS CHARACTERISTICS FOR PIPING OF EXAMPLE 3
(From Initial Analysis)

EAS Node	Frequency (Hz) Elastic	Frequency (Hz) Inelastic	Damping (%) Elastic	Damping (%) Total	Displacement (in) Yield	Displacement (in) Total	Yield Force (Kip)
20	6.45	4.0	2	4.6	.12	.22	1.4
41	5.8	4.5	2	4.5	.12	.18	1.1
61	6.45	4.7	2	4.9	.12	.20	3.3
120	6.45	5.1	2	5.3	.12	.22	3.05

TABLE 4
RATIOS OF SIMPLIFIED ANALYSIS RESULTS VS. TIME HISTORY

(in.)

EAS	Dx	Dy	Dz
6070	6.18*		1.17
6120		1.89	
6180	2.70**		1.23
8000	1.55		1.92

(Kips)

NON-EAS	Fx	Fy	Fz	Mx	My	Mz
9624	1.97	1.50	1.66			
6280	.83	1.30	.81			
6350		.99				
6420	1.25		1.25			
6440		1.07				
6490	1.45	1.38	1.54	.96	2.24	1.46

Note:

Z-Direction input only

* Actual Difference is .105"-.017" = .09"
** Actual Difference is .19"

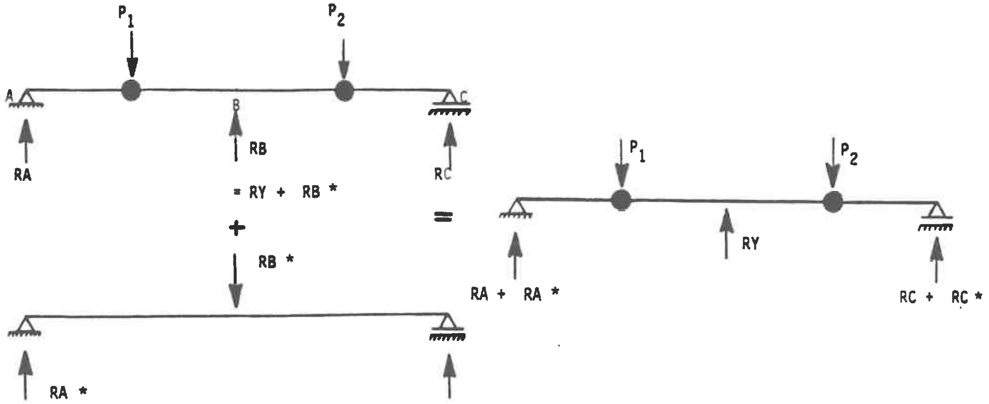

FIG. 1 SUPPORT LOAD REDISTRIBUTION

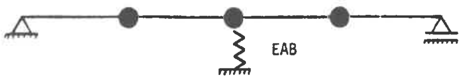

FIG. 2 SIMPLE BEAM MODELS

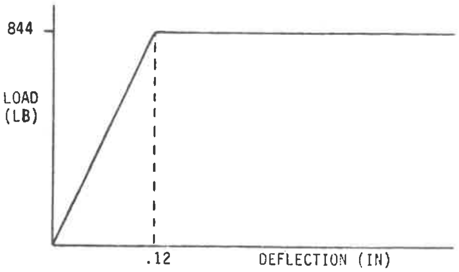

FIG. 3 EAB LOAD VS. DEFLECTION CURVE

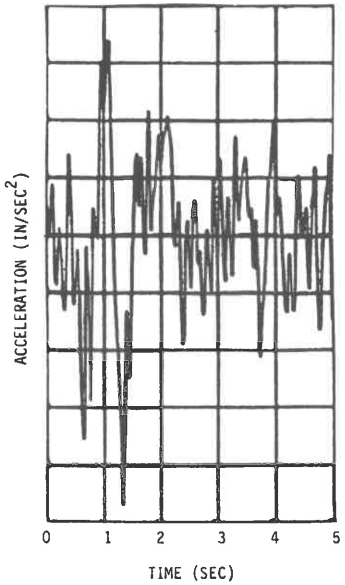

Figure 4 - EAS Earthquake Time-History Forcing Function

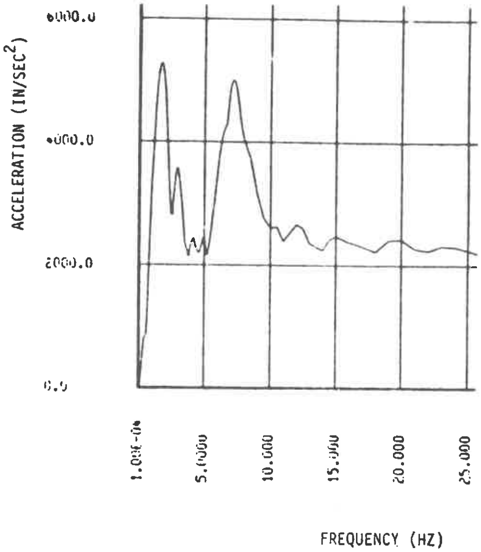

Figure 5 - Response Spectra Curves

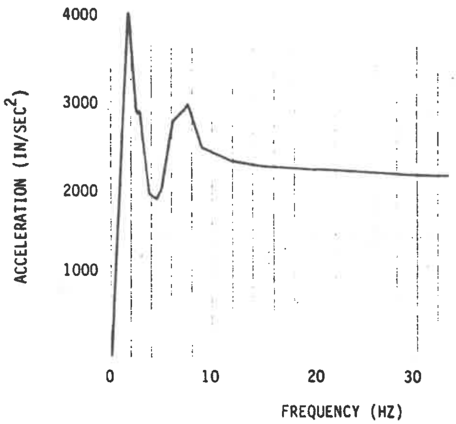

Figure 6 - Modified Response Spectrum for Model 1 with 12% Damping

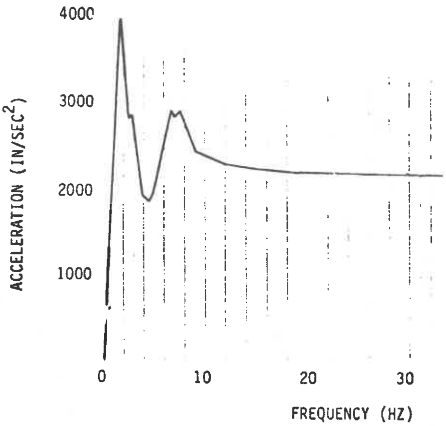

Figure 7 - Modified Response Spectrum for Model 2 with 12.4% Damping

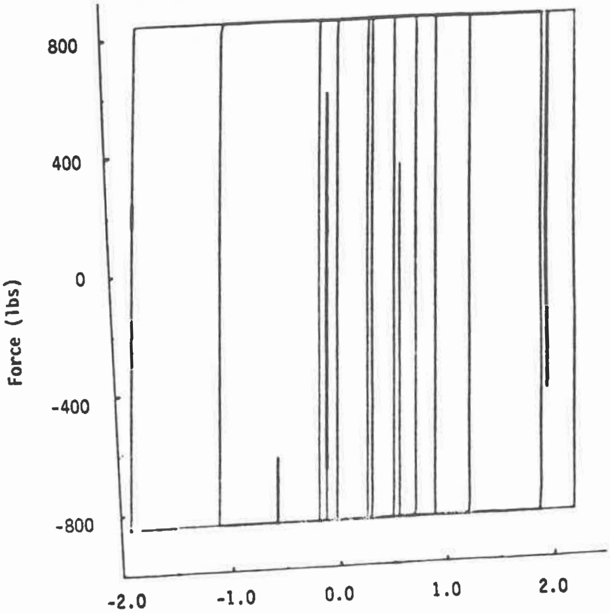

Figure 8 - A Typical Force Displacement Time History Motion

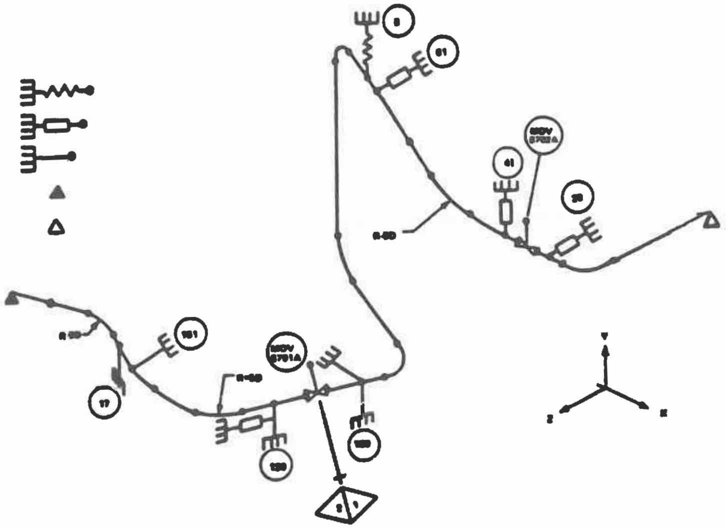

FIGURE 9: PIPING MODEL FOR EXAMPLE 3