

## EFFECT OF ENERGY ABSORBING SUPPORTS ON SEISMIC PIPE STRESSES

G. H. POWELL, D. G. ROW

*Department of Civil Engineering, University of California,  
Berkeley, California 94720, U.S.A.*

A research program to explore the effects of energy absorbing restrainers is being conducted in the Earthquake Engineering Research Center at the University of California, Berkeley, under sponsorship of the U. S. Department of Energy. Within the program, research is being carried out in several areas. In this paper, preliminary results of the research in one of these areas are presented.

The study is being carried out in several phases. In Phase I, very simple systems were analyzed, to investigate the influence of such parameters as pipe configuration, pipe size, ground motion, restrainer strength, and restrainer location. In Phase II, a somewhat more complex piping configuration was analyzed, and the influence of the same parameters was studied. Only the Phase II analyses are described in this paper. In later phases, progressively more complex systems will be studied, and greater emphasis will be placed on design concepts.

Analyses were first carried out assuming that the restrainers were elastic and essentially rigid. The peak restrainer loads were thus found, and the restrainer strengths for subsequent inelastic analyses were based on these peak loads. Analyses with restrainer strengths equal to (a) 0.7 and (b) 0.3 of the peak load were carried out for each configuration, assuming elastic-perfectly-plastic restrainer behavior. Three-dimensional earthquake excitations were applied, using design records for actual power plants.

Although the analyses to date have considered only small systems, a number of trends have emerged. For piping systems with moderate amounts of restraint, the analyses show a consistent trend of reduction in pipe stress as the restrainers are allowed to yield. For piping systems which are heavily restrained, the analyses show a consistent trend of increases in pipe stress as the restrainers are allowed to yield. However, the stresses with elastic restrainers are small for such systems, and the stresses remain small as the restrainers yield. There is an overall trend for stresses to be lower with energy absorbing restrainers than with elastic restrainers.

With elastic restrainers, the restrainer loads vary substantially with restrainer location and orientation; and there is no correlation between the load on a restrainer when it is assumed to be elastic and the deformation of the same restrainer when it is allowed to yield. The maximum deformations of yielding restrainers do not appear to be excessive. The number of inelastic cyclic excursions to which a restrainer is subjected increases as the restrainer is made weaker.

## 1. Introduction

In the design of structures for seismic resistance, it has long been recognized that earthquake-induced forces are different from static loads. If a structure is to remain elastic under a design load, whether static or dynamic, the strengths required in the structural members can be determined by elastic structural analyses. For elastic-perfectly-plastic behavior and static loading, if the actual strengths of the members are all less than those required for elastic behavior, the structure will collapse. If, however, the loading is dynamic, then collapse will not necessarily occur. Rather, the structure will yield, and provided the members have sufficient ability to sustain the inelastic deformations (i.e., sufficient ductility), collapse need not result. As a general rule, the stronger the structure the less will be the ductility "demand" produced by seismic loading. Also, the ductility demand will generally decrease as the ability of the structural members to absorb inelastic energy increases.

Over the years, a great deal of effort has been devoted to the development of piping design criteria, in particular Section III of the ASME Boiler and Pressure Vessel Code. A correspondingly large effort has been devoted to the development of guidelines, procedures, and computer programs to analyze pipes and piping components for compliance with the design criteria. The compliance checking procedures are based on linear elastic analyses, with allowance for small amounts of inelastic behavior. If substantial yielding were to be allowed in pipes and piping components during seismic events, this would represent a change in design philosophy and could require major changes in the design criteria. Because these criteria are complex and have taken years to develop, it would be unrealistic to propose any changes at the present time. Nevertheless, it may be possible to improve piping system design by allowing significant yield to occur only in the piping restrainers, while retaining the existing design philosophy and criteria for the piping itself.

A research program to explore the effects of energy absorbing restrainers is being conducted in the Earthquake Engineering Research Center at the University of California, Berkeley, under sponsorship of the U. S. Department of Energy. Within the program, research is being carried out in several areas.

In this paper, preliminary results of the research in one of these areas are presented. A more detailed report describing work completed in all areas has been published [1], and further reports will be published as the work progresses.

## 2. Objective and Scope

The ultimate objectives of the studies described in this paper are as follows (these objectives have only partially been realized to date):

- (1) Perform dynamic analyses of piping systems with energy absorbing restrainers, considering not only seismic but also water hammer loadings.
- (2) From the results of these analyses, assess whether or not the use of energy absorbing restrainers leads to improved dynamic response.
- (3) From the results of the analyses, develop guidelines or principles to assist support designers in selecting and positioning energy absorbing restrainers.

It has not been an objective to develop new analytical techniques. The existing computer program ANSR-I, with only minor modifications, is being used in the study.

It is ultimately intended to perform analyses of large piping systems. However, as the scope of the study was planned, it became clear that more would be learned initially if parameter studies, involving changes in piping configuration, pipe size, restrainer location, restrainer strength and earthquake motion, were carried out. Because of the large number of parameters which might be varied, it then became evident that the initial study would have to be limited to small systems. The analyses described herein are therefore for simple configurations only. However, several parameters have been varied, in the hope of identifying trends in the dynamic response.

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### 3. Systems Analyzed

#### 3.1 Pipe Configuration

Simple configurations with the dimensions shown in Fig. 1 have been analyzed. Four different restrainer patterns were considered, identified as A1, A2, A3, and A4, with restrainers located as shown. Configuration A1 is restrained both longitudinally and laterally at the end of each straight leg. Configuration A2 has restrainers located so that only the longitudinal motion of each leg is restrained. Configuration A3 has restrainers positioned to restrain only the transverse (out of plane) motion at each bend. Configuration A4 has a combination of longitudinal and transverse restrainers, and is classified as a "typical" restraint pattern. The unrestrained system is identified as Configuration A.

Two different pipe sizes were considered, namely 4-inch Schedule 80 and 10-inch Schedule 80, assumed to be filled with water but having no insulation. The pipe was modelled with straight and curved elastic pipe elements with mass points as shown in Fig. 1. The restrainers were assumed to be elastic-perfectly-plastic, and the pipe was assumed to be rigidly restrained in translation and rotation at the end anchors. The first mode natural frequencies of the systems with rigid elastic restrainers ranged from 1.93 Hz to 44.64 Hz. The piping was assumed to be undamped, so that energy absorption occurred only through yielding of the restrainers.

#### 3.2 Earthquake Motions

Three-dimensional earthquake excitation was used in the analyses, using acceleration records supplied by Duke Power Co. (through EDS Nuclear Inc.) and by Bechtel Corp. The cooperation of these companies is gratefully acknowledged. For the analyses reported herein, the excitations are identified as Motion 1 (using the Duke records) and Motion 2 (using the Bechtel records). These records represented ground motions, without filtering by the power plant structure. Filtered records are also being used, but the results for these records are not presented here. Space does not permit the accelerograms or response spectra to be shown.

Each motion consisted of three records (one each for the X, Y, and Z directions), each of 10 seconds duration and each scaled to a peak acceleration of 0.35 g. The support points (anchors and restrainers) were all assumed to move in phase. Analyses with out-of-phase motions and relative displacements between support points will be carried out in later phases.

### 3.3 Restrainer Strengths

Analyses were first carried out assuming that the restrainers were elastic and essentially rigid. The peak restrainer loads were thus found, and the restrainer strengths for subsequent inelastic analyses were based on these peak loads. Analyses with restrainer strengths equal to (a) 0.7 and (b) 0.3 of the peak load were carried out for each configuration.

For each configuration, different restrainer strengths were used for each of the earthquake motions, based on the peak restrainer loads for each motion. For some configurations the two motions produced similar peak loads, whereas in others these loads were substantially different. The peak loads also varied substantially from restrainer to restrainer. For practical design, it probably would not be realistic to select the restrainer strengths individually in this way. In later studies, restrainer strengths will also be selected on the basis of average elastic load for a group of restrainers, with all restrainers in the group being assigned the same inelastic strength.

In all cases, the inelastic restrainers were assumed to have stiffnesses of 100 k/in up to yield, with yielding at constant force and unloading around an elastic-perfectly-plastic hysteresis loop. The analyses were all carried out using step-by-step integration with time steps of 0.005 sec. for the elastic cases and 0.001 sec. for the inelastic cases.

## 4. Results: Pipe Stresses

### 4.1 Maximum Stress

An important measure of the effectiveness of a restrainer is its ability to reduce stresses in the piping. For each analysis, peak pipe stresses were calculated as  $S = M_{\max}/Z$ , where  $S$  = stress;  $M_{\max}$  = maximum resultant moment on cross section; and  $Z$  = pipe section modulus. The resultant moment at any time is given by

$$M = \left( M_x^2 + M_y^2 + M_z^2 \right)^{1/2}$$

Note that stress intensification factors have been ignored.

### 4.2 Typical Results

For four different restrainer configurations, three different strengths, two pipe sizes, and two earthquake motions, a total of 48 analyses were carried out, plus two analyses for the unrestrained case. In all cases the stresses were largest at the end anchor points, and substantially lower in the body of the piping system. Although such a stress distribution might not be desirable in a practical design, it does not invalidate the conclusions reached in the study.

The stresses for each case can be summarized by two values, the first being the average of the stresses at the two end anchors, and the second the average in the body of the

piping system. These average stress values are shown in Table 1 for three cases, namely configurations A, A1, and A2 with 4S80 pipe and earthquake motion 2. The results for the other cases showed similar trends, as considered in the following section.

#### 4.3 Trend of Results

It can be seen from Table 1 that for configuration A1, restrainer yielding causes an increase in the pipe stresses, whereas for configuration A2 it causes a decrease. It is important to recognize, however, that configuration A1 is very heavily restrained. For this configuration with elastic restrainers, stresses are produced only by transverse vibration of the pipe between restrainers, because longitudinal and transverse motions of the pipe legs are both prevented at each elbow. As a result, the stresses are very low. When the restrainers yield, longitudinal and transverse motions of the pipe legs are permitted, with the result that the stresses increase. These increased stresses, however, are still small (for the "0.3" restrainers, approximately one-sixth of those in the unrestrained pipe).

In Configuration A2 with elastic restrainers, longitudinal motions of the pipe legs are prevented, but out-of-plane displacements at the elbows are permitted. The stresses are therefore substantially larger than for Configuration A1 with elastic restrainers (approximately one-half of the stresses in the unrestrained pipe). When the restrainers yield, longitudinal motions of the pipe legs are permitted, which must lead to an increase in the stresses associated with these motions. The overall effect, however, is a reduction of stress (for the "0.3" restrainers, to approximately one-third of those in the unrestrained pipe). This reduction must be brought about by a decrease in the out-of-plane motions of the piping. That is, yielding of the restrainers increases movement of one type (longitudinal) but decreases movement of another type (out-of-plane), with a net decrease in peak stresses. The decrease results from the damping and isolating effects of the restrainers. Because the piping changes direction in space, individual restrainers are not affected purely by longitudinal or out-of-plane vibrations, but by combinations of the two. For example, restrainer number 4 is affected by out-of-plane vibrations at its elbow. If this restrainer yields, then it can act to damp out such vibrations, or, because of its limited strength, it can act to limit the amount of load exerted on the piping system, and hence partially isolate the system from the earthquake.

In all of the analyses carried out to date, a trend of the type shown in Table 1 has emerged. That is, for heavily restrained systems energy absorbing restrainers tend to increase the stresses, whereas for less heavily restrained systems they tend to decrease the stresses. In some cases without full restraint, the natural mode frequencies of the elastically restrained system may be such that the stresses are small (this happened for Configuration A4 with 10S80 pipe and earthquake motion 2). In such a case, yielding of the restrainers increased the stresses, as though the system were heavily restrained.

In all cases the stresses with energy absorbing restrainers were much lower than for the unrestrained pipe. In cases with reasonable amounts of restraint from a practical point of view (i.e., not including Configuration A1) the trend was for the stresses to be lower with energy absorbing restrainers than with elastic ones.

## 5. Results: Restrainer Deformations

### 5.1 Maximum Deformations

The maximum loads on elastic restrainers and the corresponding maximum deformations of inelastic restrainers were computed and compared. The results showed no correlation between elastic restrainer force and inelastic restrainer deformation. The maximum computed deformation was 0.64 inches, which should not be excessive for practical purposes.

### 5.2 Accumulated Inelastic Deformations

The maximum computed deformation for a restrainer indicates the stroke for which the restrainer must be designed. However, this value does not indicate the extent to which the restrainer deformations undergo cyclic yielding in tension and compression. For a given maximum deformation, the demands on the ductility of a restrainer will increase as the amount of inelastic cycling increases. A measure of the inelastic cycling is the accumulated inelastic deformation, which is the absolute sum of all positive and negative inelastic deformations during the earthquake. This accumulated deformation is conveniently expressed as a multiple of the maximum deformation. A multiple of 1.0 indicates either a single inelastic excursion or several excursions in the same direction with no inelastic reversal. A multiple larger than 1.0 indicates that inelastic reversal occurred.

The ratios of accumulated inelastic deformations to maximum deformations are shown for typical cases in Table 2. There was a clear trend for a greater amount of inelastic cycling to occur as the restrainers are made weaker. Restrainers must be designed to accommodate cycling of this amount without showing distress.

## 6. Conclusion

### 6.1 General

Although the analyses to date have considered only small systems, a number of trends have emerged. It must be emphasized, however, that more cases must be studied before these conclusions can be confirmed. The trends are listed in this section. The limitations of the studies completed to date, and the aspects to be explored in future studies, are also listed.

### 6.2 Pipe Stresses

(1) For piping systems with moderate amounts of restraint, the analyses show a consistent trend of reduction in pipe stress as the restrainers are allowed to yield.

(2) For piping systems which are heavily restrained, the analyses show a consistent trend of increases in pipe stress as the restrainers are allowed to yield. However, the stresses with elastic restrainers are small for such systems, and the stresses remain relatively small as the restrainers yield.

(3) Some systems with apparently moderate amounts of restraint may have low stresses with elastic restrainers, because the modes of vibration are not excited substantially by the particular earthquake motion. In such cases, the stresses will increase as the restrainers are allowed to yield. As for heavily restrained systems, however, the stresses remain relatively small.

(4) There is an overall trend for stresses to be lower with energy absorbing restrainers than with elastic restrainers.

### 6.3 Restrainer Behavior

(1) With elastic restrainers, the restrainer loads vary substantially with restrainer location and orientation. This is to be expected.

(2) There is no correlation between the load on a restrainer when it is assumed to be elastic and the deformation of the same restrainer when it is allowed to yield.

(3) The maximum deformations of yielding restrainers do not appear to be excessive.

(4) The number of inelastic cyclic excursions to which a restrainer is subjected increases as the restrainer is made weaker.

### 6.4 Limitations

The studies which have been carried out to date have the following limitations:

(1) The systems with elastic restrainers have been assumed to be undamped. This may unduly favor energy absorbing restrainers.

(2) Only small piping systems have been studied.

(3) Only two different strength ratios (0.7 and 0.3) have been considered for yielding restrainers.

(4) Only elastic-perfectly-plastic force-deformation characteristics have been considered for restrainers.

(5) In all cases, the strength of a yielding restrainer has been based on the maximum elastic load for that restrainer. It is unlikely in practice that restrainer strengths can be tailored in this way.

(6) Only a limited number of earthquake motions has been used. In particular, few analyses have been carried out for motions filtered by the reactor structure (none has been reported in this paper).

(7) Only in-phase shaking has been considered, with no relative anchor movements.

(8) It has been assumed that energy absorbing restrainers are active for dynamic loads only. Hence, analyses for dynamic loads can be carried out independently of analyses for static loads. This is a serious limitation, because it implies that restrainers are connected to the piping through viscous or mechanical snubbers.

### Future Studies

Future studies will explore the following aspects: (1) Larger piping systems. (2) The influence of viscous damping. (3) Out-of-phase support excitation. (4) Sensitivity of response to restrainer strength and location. (5) Procedures for designing inelastic restrainers. (6) Water hammer effects.

### References

- [1] "The Design of Steel Energy Absorbing Restrainers and their Incorporation into Nuclear Power Plants for Enhanced Safety", Earthquake Engineering Research Center, University of California, Berkeley, Report in press (3 volumes).

TABLE 1. APPROXIMATE AVERAGE STRESSES (PSI) FOR TYPICAL CASES

Config.	Restrainer Strength	Stress at Anchors	Stress in Body of System
A	N.A.	30000	13000
A1	Elastic	500	500
	0.7	1200	700
	0.3	5000	2000
A2	Elastic	15000	8000
	0.7	14000	8000
	0.3	10000	5000

TABLE 2. ACCUMULATED INELASTIC DEFORMATIONS

$R_e$  = Maximum Load for Elastic Restrainer (kips);  $\Delta$  = Maximum Deformation for Inelastic Restrainer (inches);  $r$  = (Accumulated Deformation)/(Maximum Deformation).

Conf. No.	Pipe Size	E.Q. No.	Restr. No.	$R_e$	"0.7 Ry" Restr.		"0.3 Ry" Restr.	
					$\Delta$	$r$	$\Delta$	$r$
A2	4880	1	2	.414	.045	3.8	.135	10.7
			5	.450	.048	2.1	.165	7.1
			7	.397	.024	5.2	.065	16.1
A3	4880	1	1	1.135	.620	4.0	.635	9.8
			3	.890	.008	2.9	.012	3.7
			4	.698	.073	5.3	.396	9.8
			6	.237	.043	3.6	.243	13.4
A2	10880	1	2	.543	.108	48.9	.140	71.3
			5	1.924	.014	2.2	.129	16.8
			7	.914	.065	5.9	.136	20.5

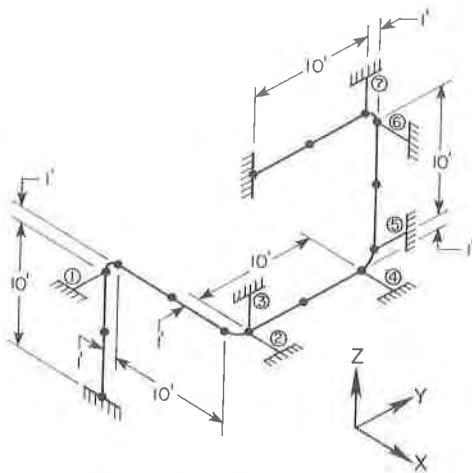


FIG. 1 PIPING CONFIGURATION

CONFIGURATION	RESTRAINERS
A	—
A1	1, 2, 3, 4, 5, 6, 7
A2	2, 5, 7
A3	1, 3, 4, 6
A4	3, 4, 5, 7