BEHAVIOR OF A PIPING SYSTEM SUBJECTED TO SEISMIC AND THERMAL LOADING

by

S. Schneider, H.M. Lee, W.G. Godden
University of California, Berkeley

ABSTRACT

This report presents the results of an investigation into the behavior of a complex spatial piping system under simulated seismic and thermal loading. The control of seismic response by steel energy absorbing devices is studied and compared with equivalent response controlled by shock arrestors.

The specimen selected for study was a half-scale model of a piping system from a nuclear reactor power plant. This was tested in its original design configuration using mechanical shock arrestors (snubbers), and subsequently in a revised configuration using ductile steel energy absorber.

The influence of the snubbers and of different energy absorbers on the dynamic response of the pipe system is discussed in this report. A direct one-to-one replacement of the snubbers by energy absorbers allows a direct comparison of the results.

The response of the structure was studied under all three direction components of ground motions, though a maximum of two components (one horizontal and the vertical) was applied simultaniously.

In the case of the energy absorbers, the effect of a thermal loading was simulated by deforming the system at the restrainers, and the seismic loading was superimposed on this biased configuration.

Over a hundred test runs were recorded using four different artificial earthquakes as well as sinusoidal input. A study of damping behavior, frequency spectra and hysteresis loops for both shock arrestors and energy absorbers facilitates an extensive interpretation of the experimental data.

1. Introduction

In designing nuclear power plants for seismic zones, it is necessary to study the behavior of the piping system under both thermal and seismic loading. Current design procedures use either hydraulic or mechanical shock arrestors (snubbers) to limit the pipe deformations, strains and accelerations. As these devices are relatively expensive, may require frequent inspection and possibly maintenance, and in certain cases are bulky, new design procedures which are based on replacing the snubbers with small ductile steel devices have been under consideration for some time (1,2,3). These so-called 'energy absorbers' are attached to the piping at appropriate locations to control the dynamic response by inelastic action. They have potential advantages over snubbers in being simple, inexpensive, having consistent properties over long periods without the need for inspection or maintenance, and being easy to replace or to upgrade if required.

To study the feasibility of using these ductile steel devices in a real design situation, a spatial piping system from an actual nuclear power plant was selected. The selection was made on the basis of the size and frequency characteristics of the shaking table at the Earthquake Engineering Research Center, University of California, and on the possibility of scaling the system down with available pipe sizes. The piping system includes three fixed boundaries, six mechanical snubbers, five fixed hangers or restraints, two spring hangers, and two valves each with an eccentric operator. The specimen tested on the shaking table was a half-scale model (Fig. 1) of this system. To induce equal strains in model and prototype (and hence scaled deflections) requires velocity and acceleration scales of 1.0 and 2.0 respectively. All of these values were retained as far as possible in the design of the model, and in places where exact scaling was not possible, as in certain pipe thicknesses, snubbers and spring hangers, the values used were close enough to retain the validity of the study.

Although the data presented in this report demonstrates the feasibility of using ductile restrainers in one design example of a spatial piping system, additional investigations would clearly be necessary before their use could be proposed as a general design procedure.

2. Shock Arrestor

Currently in nuclear power plants, thermal and seismic loading are handled by hydraulic or mechanical snubbers. The shock arrestors used in this test series were mechanical devices that as specified by the manufacturer "operate on the principle of limiting the acceleration of any pipe movement to a threshold level of 0.02g". At the same time, thermal expansion, which takes place slowly, is not restricted.

3. Energy Absorber (Restrainer)

3.1. Shape and Material

The ductile restrainers used in these test series all have the basic X-type geometry (Fig. 2) with rotational fixity at both ends. This design has the advantage over a single triangle design that no hinged bearings are required and consequently no maintenance is necessary. The devices have a slight flare at both boundaries to avoid stress concentrations and a rounded transition at the center instead of going to a theoretical point. The X-shape was chosen to obtain yielding over the largest possible area at the same load and with the simplest design. The influence of the type of steel on the fatigue behavior, energy absorption characteristics and temperature sensitivity of the devices has received some attention (1,3,4). It is desirable to use a steel with high ductility, i.e. the force-displacement graph (hysteresis loop) should indicate a large area as this is a measure of the energy extracted from the system. Furthermore, a good fatigue life is also required. The amount of energy absorption as well as the fatigue life and the work hardening characteristics vary significantly from steel to steel. For these test series, energy absorbers were made from hot-rolled 10-20 mild steel plates. The material with a yield stress of $36x10^3$ psi was found to have satisfactory ductile and fatigue characteristics in previous tests (1,2).

3.2. Theoretical Considerations

As the device is symmetrical about its mid-point (Fig. 2), one half will be considered in the following discussion. Considering an ideal triangle, the stress distribution within the elastic limit at any cross section associated with the bending moment M is given by:

$$\sigma = \frac{My}{I}$$

The moment at a distance s from the mid-point is given by M = Fs, where F is the shear force across the absorber. $I = sbt^3/12a$, hence the stress σ at the outside fiber ($y = t/2$) can be written as

$$\sigma = \frac{6F}{t^2}\frac{a}{b}$$

Consequently the yield force can be calculated to

$$F_y = \frac{1}{6}\sigma_y t^2 \frac{b}{a} \qquad (1)$$

The yield displacement is

$$d = \frac{6Fa^2}{Et^3}\frac{a}{b} = \sigma\frac{a^2}{Et} \qquad (2)$$

In terms of stiffness this equation can be written as

$$\frac{F}{d} = \frac{Et^3}{6a^2}\frac{b}{a} \qquad (3)$$

In the case where the energy absorber is strained beyond the yield point the ratio of applied force F to the yield force F_y is given for an ideal elastic-plastic material by

$$\frac{F}{F_y} = \frac{3}{2} - \frac{1}{2(\varepsilon/\varepsilon_y)^2}$$

This means that the ultimate load F_u approaches 1.5 times the yield load (Figs. 3,4,5).

Secondary effects such as work hardening, bending in the transverse direction, stress distribution near the rigid boundary, etc. will be neglected in this paper as they are of minor importance to the function of the devices. A study of the simple relationships given in eqs. 1 to 3, which take into account only bending forces, is necessary for designing an effective restrainer. The significant characteristics are as follows:

- The yield load F_y and ultimate load F_u are proportional to t^2 and b/a, but independent of length (for a given ratio b/a).
- The stiffness K is proportional to t^3, to $1/a^2$ and to b/a.
- The yield displacement d_y is proportional to a^2 and to 1/t.

In other words:

- Varying the thickness t of the restrainer alters the stiffness K, the yield force F_y, the ultimate load F_u, and the yield displacement d_y (Fig. 3).
- Varying the length, l=2a, only affects the stiffness and yield displacement. The yield load and ultimate load remain constant (Fig. 4).
- Varying the device angle b/a influences stiffness, yield load and ultimate load (Fig. 5).

3.3. Design of Energy Absorbers

From the above considerations certain general rules can be given for the design of the restrainers, but a thorough study would require a more complete analysis in the plastic range and comprehensive data on low cycle fatigue.

Preliminary recommendations based on the simple relationships derived above and on a limited test program can be summarized as follows:

- The material should have high ductility as this produces high system damping with a consequent reduction of pipe stresses and accelerations. It should also have an adequate fatigue life. If the range of application makes it necessary, temperature and radiation effects may have to be taken into account in evaluating both ductility and fatigue.
- To accomplish high stiffness with maximum energy absorption for a given displacement, clearly for any given plate thickness and device angle, the shorter the restrainer the better. In practice the lower limit of length will be determined by such factors as the thermal displacements, predicted seismic displacements, and fatigue life. Fatigue life is shorter for given displacements as the device is made shorter.
- The maximum thickness and angle of the device are limited by the thermal strains in the piping. The restrainer yield forces create a set of maximum self-limiting thermal forces applied to the piping, and in any design these will have maximum allowable values.

The design of the piping system as a whole with the ductile devices presumes an adequate knowledge of the structural stiffness and mass distribution and of the interaction between the energy absorbers and structure.

4. Test Model

The piping system used for this shaking table test (Fig. 1) is a half scale model of a section of piping from an actual nuclear power plant. It is assembled with 3" and 2" pipes. Additional weights simulated the mass of valves and valve operators. Extensive instrumentation recorded table motions, accelerations, strains and relative displacements of the piping as well as the forces in all restraints and the energy absorber deformations. The sampling rate for all instruments was 100/s.

5. Test and Results

To investigate the response of the pipe system to all three components of ground motion the structure had had to be turned through 90 degrees as the shaking table used can only be excited in the vertical and one horizontal direction. Separate tests were conducted with mechanical shock arrestors and with energy absorbers. Different sets of restrainers were tested both without and with initial strain, the latter to simulate thermal bias. The devices varied in length (from 2" to 6") and in thickness (1/8" for all lengths, 1/4" for 6" long devices).

5.1. Pipe Response under Increasing Intensity of Excitation

In Fig. 6 the maximum pipe strains and valve operator accelerations are plotted for snubber restraints and for both 4" and 2" long energy absorbers under increasing earthquake intensities (50% to 200% of a scaled safe shutdown earthquake). It can be seen that the intensities of dynamic responses with snubbers and with 2" long restrainers are about equal. A distinct nonlinear pipe response for increasing intensity can be recognized. This behavior was expected as for small excitation the restrainers remain almost completely elastic and operate as spring supports with minimal damping whereas for large movements the plastic deformation of the devices causes significant energy absorption, high damping and some decoupling from input excitation.

5.2. Pipe Response with Different Energy Absorbers and with Snubbers

The influence of restrainer length on the dynamic response of the pipe system can be seen in Fig. 7 for a one-component excitation. The long thin devices are both too flexible and have too large an elastic range for this system, and allow relative pipe-to-ground displacements which are not acceptable. These movements cause high stresses near the rigid boundaries. As the yield displacement in the energy absorber is proportional to the square of its length, significant plastic deformation will occure only for large deflections hence energy absorption was small and acceleration large. Decrease of the energy absorber length significantly reduces stresses and accelerations in the pipe. With the 2" long devices in position the strain in the pipe and the acceleration of the valve operator are of the same order as for the snubber case.

Doubling the restrainer thickness to 1/4" (length=6") produces an 8-times increase in its elastic stiffness. As could be expected, this caused a significant reduction in pipe stresses and accelerations. It also results in smaller restrainer displacements and hence prevented any significant restrainer yielding. However, this response reduction has to be weighed against the possibility of larger forces in the restrainers due to thermal changes in the piping, and hence larger self-straining stresses in the piping.

5.3. Energy Absorber and Snubber Characteristics

The shock arrestor induces a larger amount of high frequency energy in the piping than does the energy absorber (Fig. 8), due presumably to the multiple impact effect of locking and unlocking or of slack in the system (Fig. 9). On the other hand the ductile restrainer, both by its damping action and by some decoupling, reduces the high frequency (as well as in certain cases, low frequency) response. The energy absorbers have a well defined hysteretic behavior (Fig. 9). The discontinuities are fewer, the displacements are larger, and the forces smaller compared to a shock arrestor.

5.4. Thermally Biased Energy Absorber

In order to simulate the effect of the pipe displacements and resulting self-straining forces due to thermal expansion of the piping, the restrainers were prestrained after installation. By applying large differential displacements at the restrainers it was possible to study the superimposed effects of thermal and seismic loadings.

Fig. 10, which shows pipe displacements and forces for the same table motion both with and without initial bias, indicates clearly that the thermal and seismic effects are not additive. These test runs confirm results of tests with similar ductile steel absorbers conducted on a simple plane piping system (1). During the first few seconds of intense excitation the prestrain disappears as the initial force in the restrainers are released. The pipe response thereafter is the same as for the unbiased case.

In studying the graphs of Fig. 10 it is important to note that the zero displacement line in the biased time history graphs are found from the end value of each record and not from its apparent initial zero position. The values of prestrain and initial restrainer forces are given by the difference between the beginning and end values (the terminal values are not shown in Fig. 10). If the thermal effect should be reversed after the seismic excitations, similar internal forces will be produced with signs opposite to those obtained for the original bias.

5.5. Damping

The small-displacement damping was measured for the piping without restraint, with the snubbers in position, and with both the 5" and the 2" long energy absorbers. In all cases the system was excited by a sine wave motion with a period corresponding to the first natural frequency. The damping was evaluated from the free decay response. For the unrestrained system the damping coefficient was 1.2%; with snubbers in position 5.7%; and with the 5" and 2" long energy absorbers 5.6% and 7.9%, respectively.

5.6. Repeatability

Several test runs with snubbers as well as with energy absorbers were repeated to confirm the reliability and repeatability of the shaking table test results.

The table motions (displacements and accelerations) could be reproduced with an acceptable tolerance. The pipe behavior showed a good degree of repeatability, though the extreme values (some single peaks) showed some variation. These observations apply to both the snubber and restrainer test runs. The response of the energy absorbing devices themselves showed a high consistency in the measured values.

6. Conclusions

A comprehensive study of all of the data for this test series leads to the following general conclusions. Included in these conclusions is the confirmation that the results of earlier studies conducted on a simple planar piping system (1) apply to the much more complex case of a representative spatial piping system from an actual nuclear power plant.

- In the spatial piping system tested, snubbers can be replaced by suitably designed ductile steel energy absorbers (a one-to-one retrofit) without increasing the seismic response of the piping. The possible generality of this observation will require further study.
- For high intensity seismic excitation, energy absorbers provide better response control than snubbers as they provide high damping and some degree of local uncoupling between ground and pipe motion at the onset of yielding.
- The energy absorbing devices retained their behavior even after a large number (in some instances as many as 30) of repeated high intensity shaking test runs. Hence, in many situations, it is likely that the devices would outlast the operating life of a nuclear power plant without replacement.
- The devices are virtually maintenance-free, which gives them a considerable advantage over conventional snubbers.
- They permit thermal expansion, and the induced self-straining forces have limiting values given by the restrainer yield forces. The amount of thermal bias and the resulting strains induced in the piping is one of the design criteria of the devices.
- For given values of thickness 't' and base-width to mid-height ratio b/a, the shorter the restrainers the more effective they are in reducing dynamic response. The limitation on this will depend largely on the possible strain increase in the devices and a consequent reduction in fatigue life.
- Seismic loading superimposed on the thermally biased system does not produce additive effects due to the shakedown that occures during the first few seconds of seismic excitation. In fact, the combined effect of thermal and seismic loading in the examples tested was no greater than for seismic loading without

thermal bias.

- Due to the reduced dynamic forces at the points of restraint, and the fact that upper bound values can be specified directly from the restrainer design, the design of the total system (including that of the building frame) is greatly simplified.

7. REFERENCES

(1) S.F. Stiemer, W.G. Godden
Shaking Table Tests of Piping Systems with Energy Absorbing Restrainers
UCB/EERC-80/34, September 1980

(2) S.F. Stiemer, W.G. Godden, J.M. Kelly
Experimental Behavior of a Spatial Piping System with Steel Energy Absorbers Subjected to a Simulated Differential Seismic Input
UCB/EERC-81/09, July 1981

(3) V.F. Zackay, W.S. Owen, S.J. Hartman
The Design of Steel Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety, Volume 3, Evaluation of Commercial Steels.
College of Engineering, University of California, Berkeley, California
UCB/EERC-79/09, February 1979

(4) V.F Zackay, J.M. Kelley, J. Penzien, G. Powell, E.L. Wilson, S.H. Bush, I. Finnie, S.F. Stiemer The Design of Steel Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety
Prepared for the Department of Energy under Contract DE-AS03-76SF00035 PA DE-AT03-ER70296
College of Engineering, University of California, Berkeley, California Progress Report, March 1980

Fig. 1: Pipe with Instrumentation. Snubbers Subsequently Replaced with Energy Absorbers.

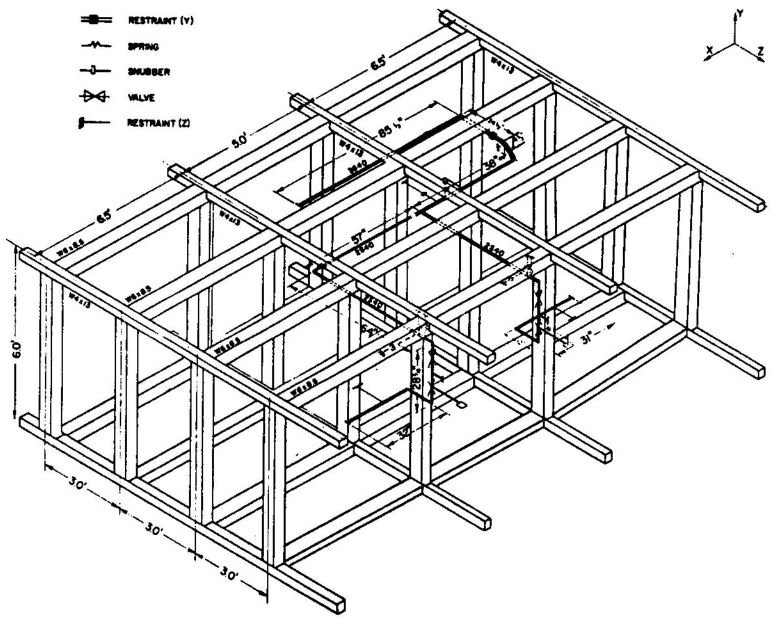

Fig. 2: The X-Configuration Energy Absorber

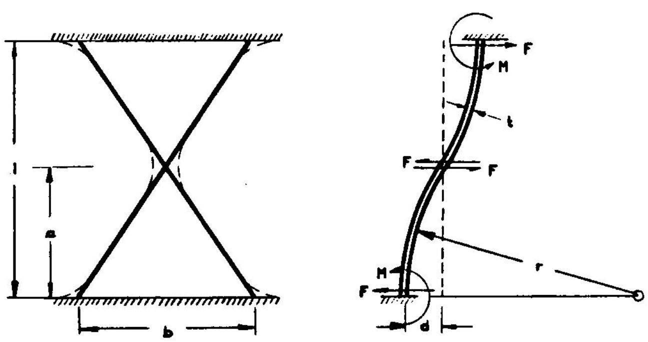

Fig. 3: Influence of the Restrainer Thickness t to Yield Force, Yield Displ. and Stiffness

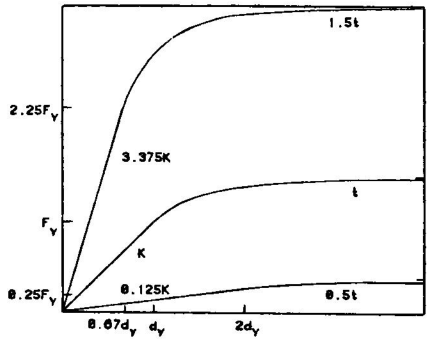

Fig. 4: Influence of the Restrainer Length a to Yield Force, Yield Displ. and Stiffness

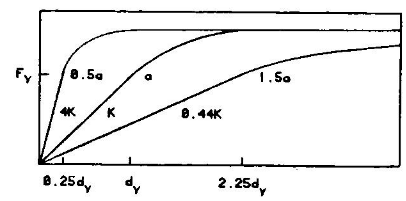

Fig. 5: Influence of the Restrainer Angle (b/a) to Yield Force, Yield Displ. and Stiffness

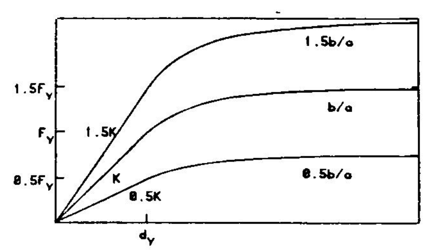

Fig. 6: Extreme Pipe Response vs. Increasing Earthquake Intensities

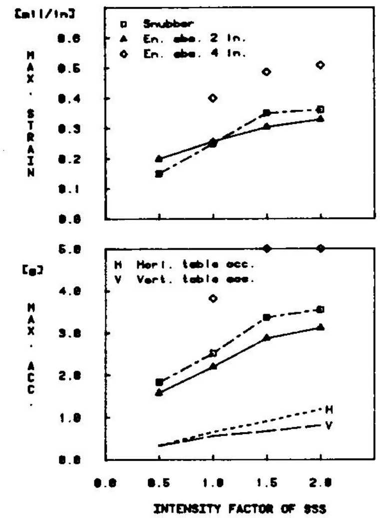

Fig. 7: Extreme Pipe Response vs. Restrainer Lengths

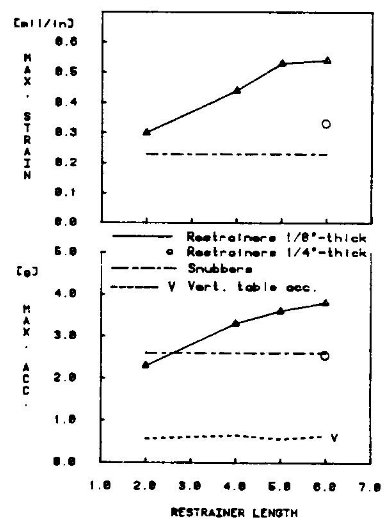

Fig. 8: Fourier Spectra; Separate Tests Using Snubbers (left) and Energy Absorbers (right)

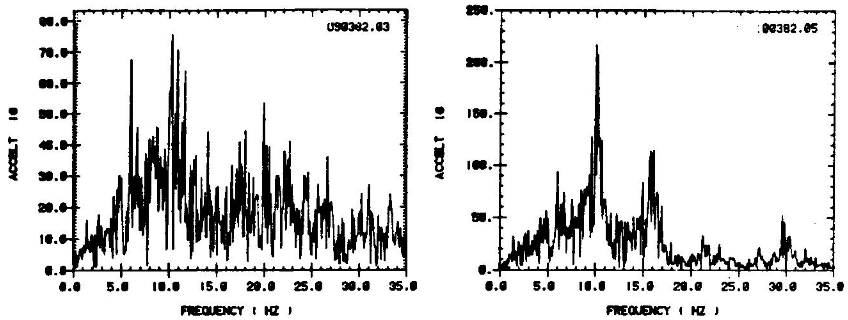

Fig. 9: Force - Displacement Behavior of a Snubber and a 2" Long Energy Absorber

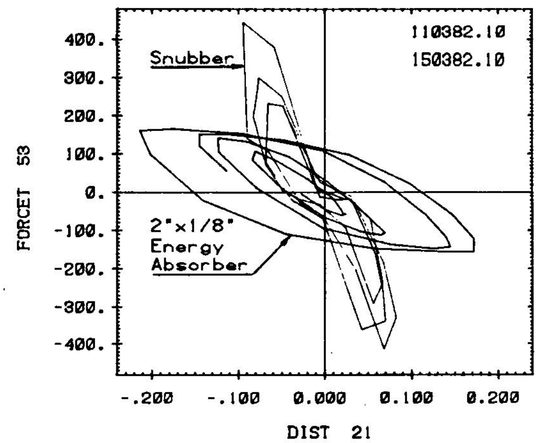

Fig. 10: Time Histories for Unbiased (left) and Biased (right) Energy Absorbers