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SEISMIC RESPONSE OF PIPING SYSTEMS WITH ISOLATION DEVICES

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SUMMARY

In this paper, effectiveness of sliding friction damper is studied for reducing the seismic response of piping system. A 3D piping system with sliding friction damper as piping support is chosen for the present study. PiSA\NL – a computer program is developed by the authors to analyze large sized 3D piping systems equipped with friction dampers. Time history analysis of a model piping system with friction damper is carried out using the PiSA\NL program. Wen's hysteretic model is used to represent the analytical force-deformation characteristics in the friction damper. A simplified method is also proposed for spectrum analysis of the piping system involving linearization of the hysteretic Wen's Model. The results obtained analytically are compared with the experimental results and found to be comparable. It is found that the friction damper when used as piping support is very effective in reducing the seismic response of the piping system. Comparison of results also shows the analytical results are in close agreement with the experimental results of piping system with friction support.

INTRODUCTION

Widespread destruction in the recent earthquakes in India like earthquake of Bhuj as discussed in the report prepared by a team from Department of Civil Engineering, IIT Bombay and Earthquake Disaster Mitigation Research Centre, Japan [1], has underlined the urgent need of upgradation of the existing seismic safety measures for piping system in Industrial and Nuclear power plants. On the other hand, snubbers, the largely used seismic supports in the piping system are found to be not behaving as designed. Also, they are found to be associated with oil leakage problems requiring frequent inspection that result in loss of production and increased costs.

Variety of passive devices have been proposed by Kuneida [2], Namita [3], Parulekar [4], Aiken[5] and Mualla [6] in the past including visco-elastic damper, elasto-plastic damper, metallic dampers, compact dynamic absorber, shape-memory devices and friction dampers. Based on the past studies on friction dampers by Aiken [5], Mualla [6], Reddy [7] and Anderson [8], it is evident that friction dampers can be effectively used in reducing the seismic response of piping systems. Friction dampers like Teflon coated steel plates, finds its application in the upgradation of the existing piping systems because of their simple working and fabrication. However, analysis of the piping systems with friction damper is tedious and time

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consuming. The accuracy of results also depends on the precise analytical modeling of the friction damper. Moreover, for developing countries like India, there is an urgent need of widening the existing infrastructure, which demands development of simplified methods like those proposed by Leung [9] and Lin [10]. Simplified methods unlike time history analysis method is designer's method, which takes less time for analysis and design of piping system with nonlinear dampers.

In the present study, the hysteretic Wen's model is proposed to predict the force in friction damper. Response history analysis is performed in PiSA\NL, programme developed to analyze large 3D piping systems equipped with friction dampers. Hysteresis loops for the friction damper obtained analytically are compared with the experimental hysteresis loops. A simplified method for response spectrum analysis of piping systems with friction damper is also proposed. Simple energy method is used for linearization of Wen's model for non-linear force of friction damper.

FRICTION DAMPER

Friction dampers are adopted because of their simple design, working and suitability for incorporation in the existing piping system. Friction damper chosen for the present study consists of slider being attached to a piping system and is supported on a Teflon coated mild steel plate having high friction coefficient, as shown in Figure 1. During a seismic event pipe deformations results in sliding of the slider on the Teflon. The sliding motion results in inelastic behavior of the damper, thereby dissipating the input seismic energy. Another obvious advantage of friction damper is that it offers no resistance to the thermal expansion of the piping system. Figure 2 shows photograph of the friction damper developed for the test setup.

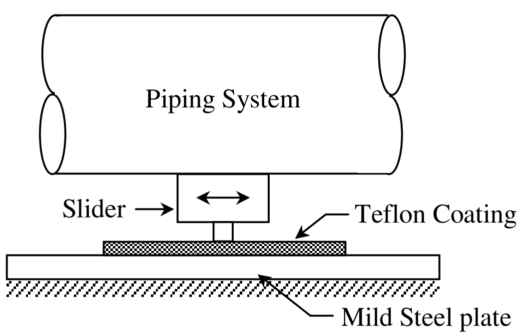


Figure 1. Friction damper for piping system

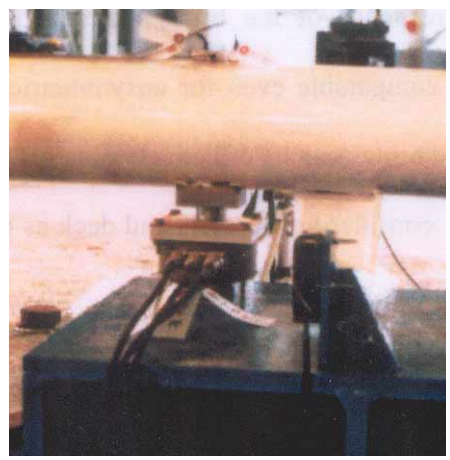


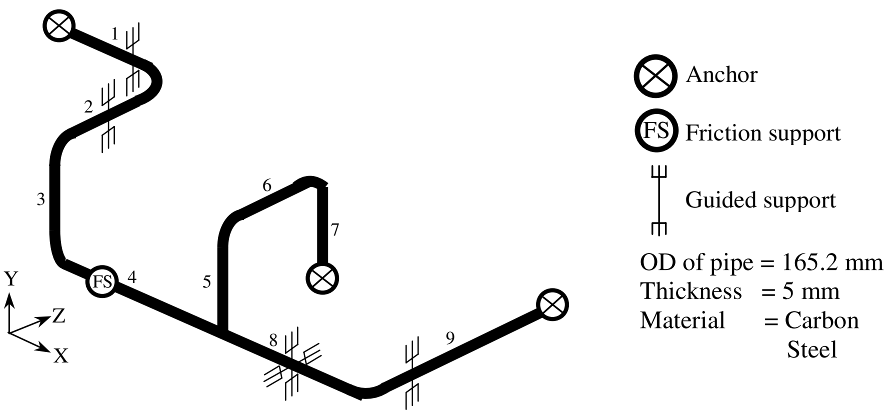
Figure 2. Photograph of the friction damper

TEST SETUP

Shake table test was performed on full-scale industrial piping system at the facilities of the National research Institute for Earth Disaster prevention (NIED), Tsukuba, Japan in year 1995. The shake table is of 15m × 15m. Piping system was subject to both narrow and wide-band random waves. Photograph of the tested piping system is shown in Figure 3. The material of the pipe is carbon steel with Young's modulus (E) of 192.2 GN/m^2 and poisons ratio = 0.214. All the bends are 90° with bend radius of 225 mm. The piping is supported on rod restraints and friction support. Figure 4 shows schematic diagram of the piping system. The friction support is shown by 'FS'. The element lengths of the piping system are also denoted.

Responses were measured for the peak table accelerations of 0.21g, 0.28g and 0.35g for uncontrolled piping system. For piping system with friction damper the peak table acceleration were 0.2g, 0.27g, 0.35g, 0.53g and 0.82g in X-direction and 0.22g, 0.29g, 0.35g, 0.56g and 0.85g in Z-direction, respectively. Also measured were the forces at the friction support with a 3-direction load cell.

Figure 3. Test setup of the piping system with friction damper



Element	Length (m)
1	2.741
2	2.538
3	1.235
4	2.420
5	0.833
6	3.045
7	1.545
8	3.123
9	4.100

Figure 4. Schematic diagram of the piping system with friction damper

ANALYTICAL MODELING OF FRICTION DAMPER

Behavior of piping system with friction support is non-linear. This non-linearity developed because of the stick-slip i.e. hysteretic behavior depends on the friction coefficient of the damper and the vertical force at the friction support. The best way to calculate the piping response for a piping system with nonlinear friction damper is by using time history analysis method. Hence, the damper element should also be capable to support all such dynamic analysis methods. Another requirement is representation of the damper as a finite element that can be easily accommodated in a FE package for solving large size real 3D piping systems with friction dampers. The empirical equation suggested by Wen [11] is found to be versatile in predicting accurately different hysteretic behavior of nonlinear bodies. Moreover, recent studies by Jangid [12] show good results of Wen's model for hysteretic systems and hence proposed to predict the damper force. The force in the damper, F, is given by the relation

$$F\ (x,\dot{x}) = \alpha kx + (1-\alpha)F_y Z \tag{1}$$

where $x, \dot{x}$ are the displacement and velocity in the friction damper at the point of load applied, respectively; αk is slope of hysteresis curve in slip condition; F_y is the sliding force and Z is Signum function (–1 to +1) satisfying the following nonlinear differential equation:

$$q\frac{d\dot{Z}}{dt} = A\dot{x} - \beta|\dot{x}||Z|^{n-1}Z - \gamma\ \dot{x}|Z|^n \tag{2}$$

where A, β, γ and n are dimensionless Wen's model parameters and q is the yield displacement which is zero in case of a friction damper. The force-deformation behavior of the friction damper can be modeled by properly selecting the parameters F_y, q, A, β, γ and n. A typical hysteresis loop generated using Wen's model is shown in Figure 5.

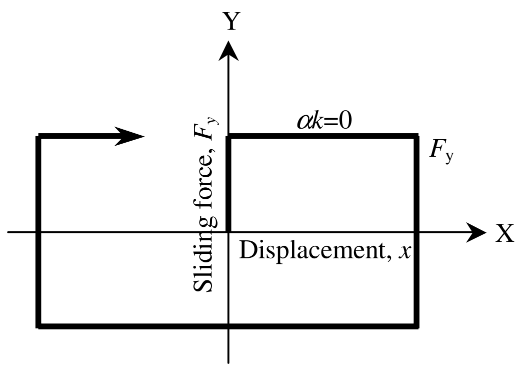


Figure 5. Hysteresis for friction damper represented by Wen's model

Methods have been proposed on Wen's model parameter identification by many researchers in the past. Among them methods proposed by Eliopoulous [13] and Sues [14] are simple to implement and accurate. Recently for predicting the various possible behavior of friction damper using Wen's model, a study has been carried out by Moreshi [15]. Thus the derived parameters are: A=1.0, β=γ=0.5, and n=1.

Parameter k is the initial slope of the hysteresis curve, which is a straight vertical line along y-axis, a large numerical value for k suffices the requirement. Moreover, for a very high value of parameter k, the value of q tends to zero. αk denotes the slip condition and is the slope of the hysteresis curve, after the limiting value of sliding force is attained. The nature of the hysteresis loop in this zone is a horizontal straight line, hence the value of α becomes zero. Analytically, the limiting value of sliding force can be computed using following relation:

$$F_y = \mu\,\overline{N} \tag{3}$$

where μ is the coefficient of friction and $\overline{N}$ is the normal force at the friction support. Value of μ as measured in the laboratory is 0.15. The limiting value of sliding force hence computed analytically based on the normal force at the friction support is 289.12N.

PiSA\NL PROGRAM

Piping system in Industrial and Nuclear power plant piping system can be very large with thousands of degrees of freedom. To solve large and realistic piping system with friction dampers, a FE based computer programme, PiSA\NL (Nonlinear Piping System Analysis) has been developed in MATLAB 6.0 (R12) [16]. Element library of the programme consists of 4 elements namely, Pipe, Elbow, Damper and Mass element. Pipe element is based on formulation of a 3D elastic beam. Elbow element is based on the formulation of a 3D curved beam whose moment of inertia is modified by using the flexibility factors as mentioned in the ASME code. Only the Damper element behaves nonlinearly as per the Wen's model.

ANALYTICAL RESULTS

Using PiSA\NL, the tested piping system is analyzed for the time histories recorded on the shake table. It is assumed in the analysis that the piping system behaves linearly and only the damper element behaves nonlinearly as per the Wen's model. Thus for a piping system equipped with nonlinear friction damper, the equation of motion is given as:

$$\overline{\mathbf{M}}\,\ddot{\mathbf{x}} + \mathbf{C}\,\dot{\mathbf{x}} + \overline{\mathbf{K}}\,\mathbf{x} + \mathbf{F} = -\overline{\mathbf{M}}\,\mathbf{r}\,\ddot{x}_g \tag{4}$$

$$\mathbf{F} = [F_1, F_2, .., F_m, .., F_p]^T \tag{5}$$

$$F_m = \{\alpha_m\, k_m\, x_m\} + \{(1 - \alpha_m)\, F_{ym}\, Z_m\} \tag{6}$$

$$q_m \frac{d\dot{Z}_m}{dt} = A\dot{x}_m - \beta|\dot{x}_m||Z_m|^{n-1} Z_m - \gamma\, \dot{x}_m |Z_m|^n \tag{7}$$

where,

$\overline{\mathbf{K}}$	= System stiffness matrix including nonlinear support's stiffness
$\overline{\mathbf{M}}$	= System mass matrix including nonlinear support's mass
$\mathbf{F}$	= Friction support force vector as per Wen's Model
F_m	= Force at m^{th} friction support
p	= Total degrees of freedom
$\alpha_m k_m$	= Slope in the slip condition at nonlinear support *m*
F_{ym}	= are yield force and at nonlinear support *m*
q_m	= yield displacement at nonlinear support *m*
x_m	= Displacement at nonlinear support *m*
Z_m	= Signum function (–1 to +1), in nonlinear support *m*
$\mathbf{Z}$	= Signum function vector for nonlinear support
A, β, γ, n	= Parameters in Wen's model varies with respect to the shape of Hysteresis loop

In above equations $\mathbf{x}$ and $\dot{\mathbf{x}}$ are the displacement and velocity vectors, respectively. Eq. (4) represents the nonlinear equation of motion for the piping system while Eq. (6) and (7) describes the hysteretic force in each nonlinear support. The two equations are coupled by the vector $\mathbf{Z} = [Z_1, .., Z_m, .., Z_p]^T$. Above equations are subject to initial conditions $\mathbf{x}(0) = x_0$ and $\dot{\mathbf{x}}(0) = \dot{x}_0$. Dynamic response of piping with or without energy dissipating devices can be obtained by numerically integrating these equations. Newmark's time-stepping method is used to evaluate the dynamic response of the piping system with or without energy dissipating devices.

Pipe responses are obtained for the peak table accelerations same as discussed in section for experimental tests performed on the friction damper. Figures 6 and 7 show responses obtained for both controlled and uncontrolled piping system in X and Z-direction of the piping system, respectively. Figures 8 to 12 and Figures 13 to 17 show analytical and experimental hysteresis loops for all the excitation levels in X and Z-direction of piping system, respectively.

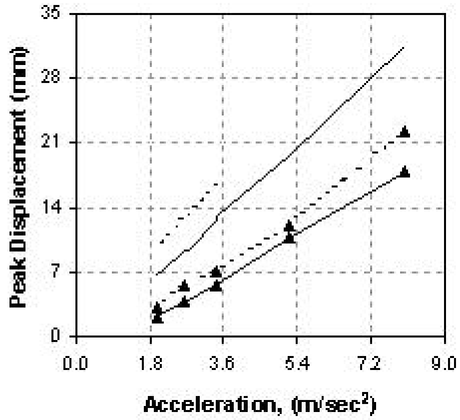


Figure 6. Seismic response in X-direction of piping system with friction damper

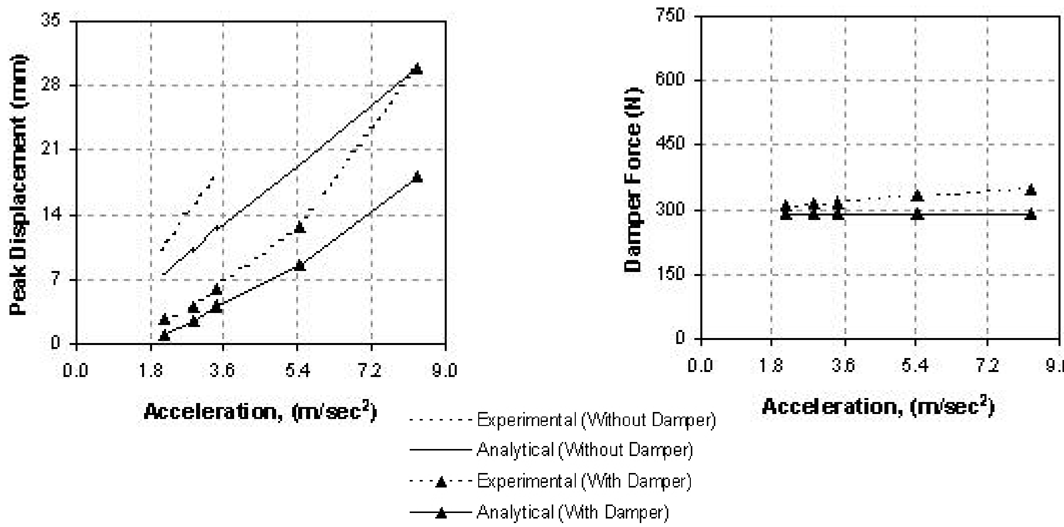


Figure 7. Seismic response in Z-direction of piping system with friction damper

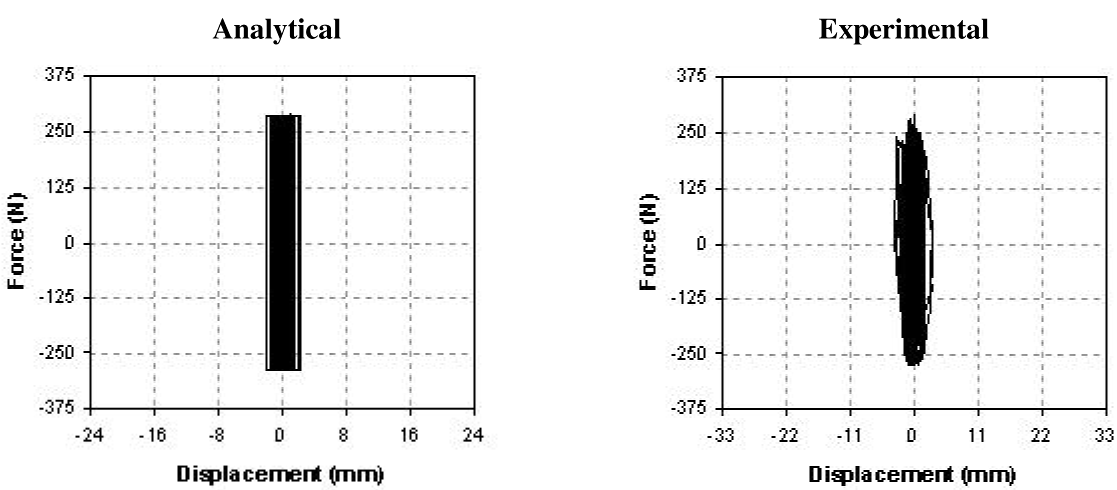


Figure 8. Hystereses for peak table acceleration of 0.2*g* in X-direction of the piping system

Analytical **Experimental**

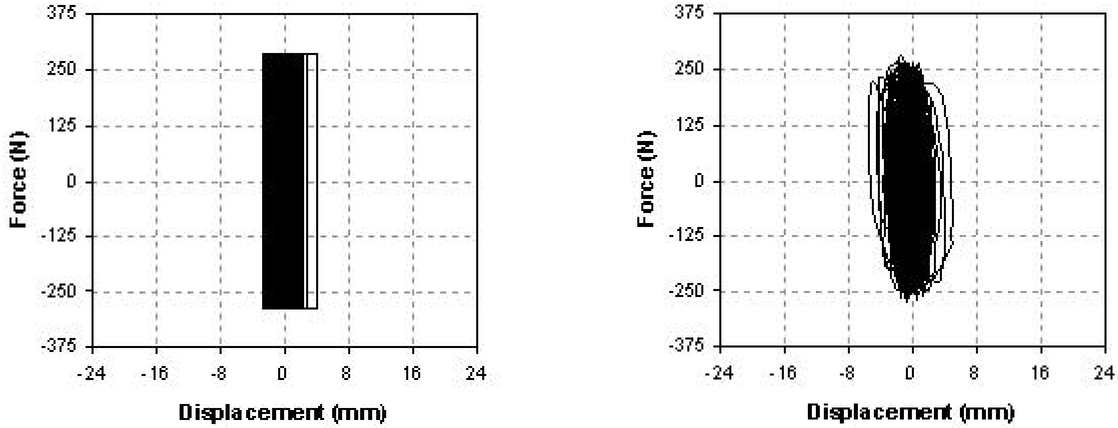


Figure 9. Hystereses for peak table acceleration of 0.27*g* in X-direction of the piping system

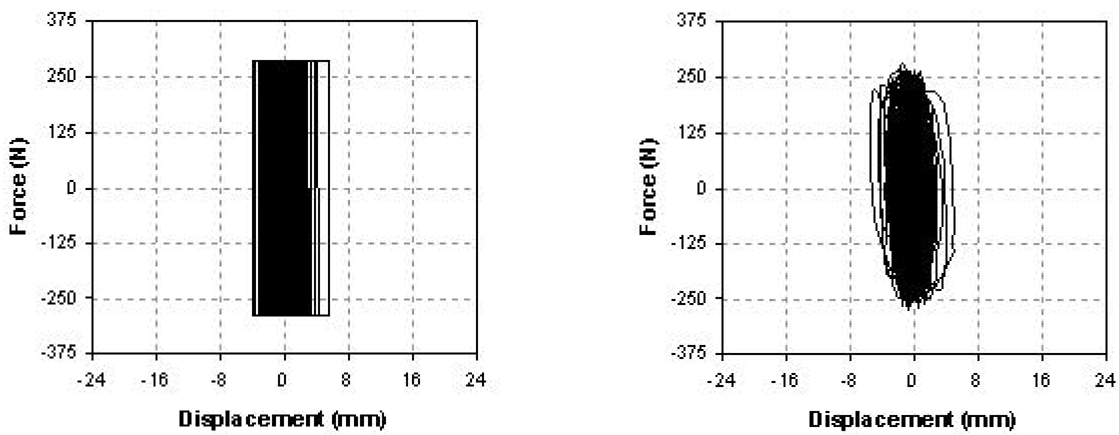


Figure 10. Hystereses for peak table acceleration of 0.35*g* in X-direction of the piping system

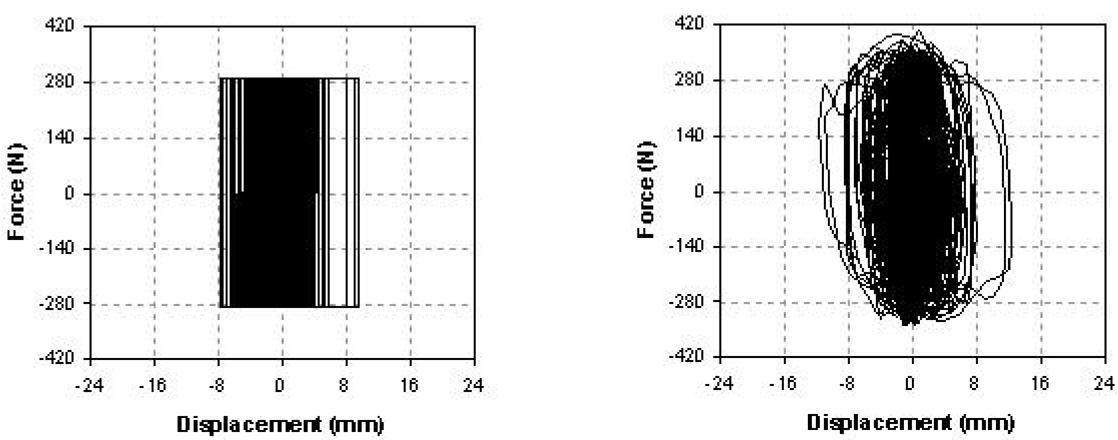


Figure 11. Hystereses for peak table acceleration of 0.53*g* in X-direction of the piping system

Analytical **Experimental**

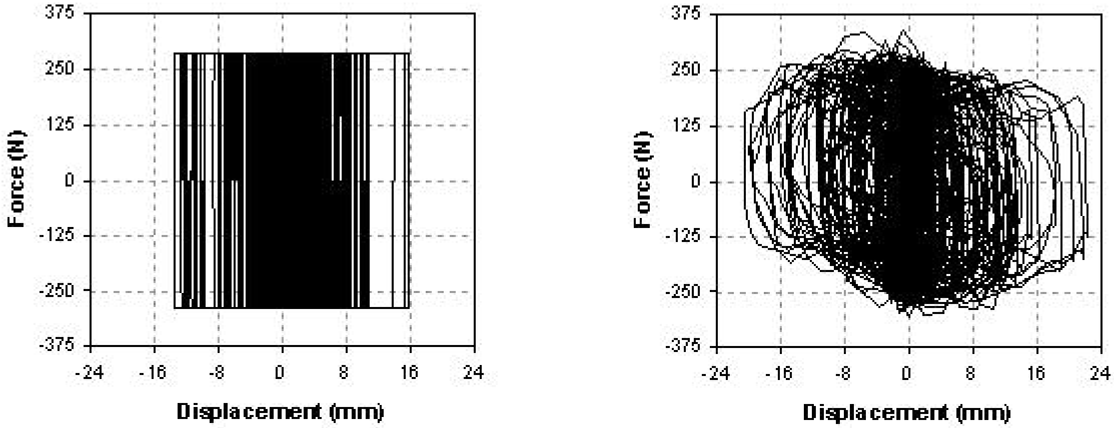


Figure 12. Hystereses for peak table acceleration of 0.82g in X-direction of the piping system

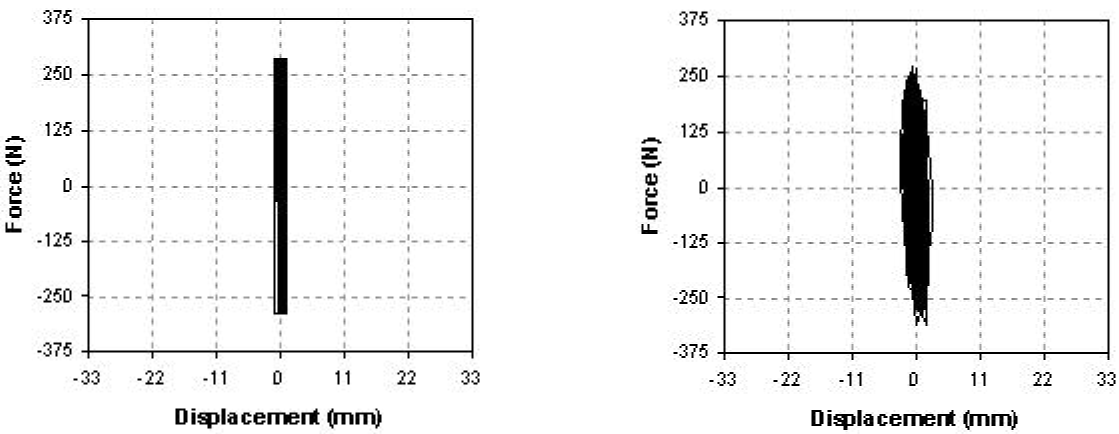


Figure 13. Hystereses for peak table acceleration of 0.22g in Z-direction of the piping system

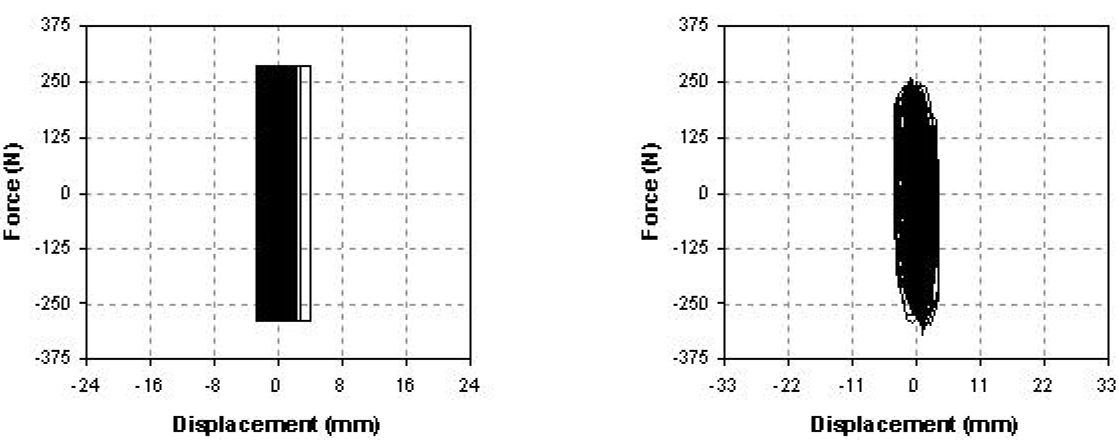


Figure 14. Hystereses for peak table acceleration 0.29g in Z-direction of the piping system

Analytical **Experimental**

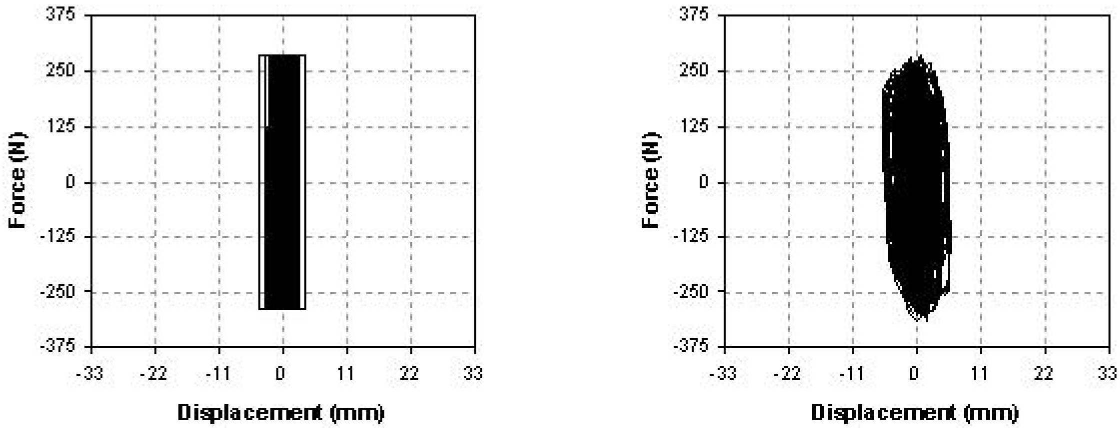


Figure 15. Hystereses for peak table acceleration of 0.35*g* in Z-direction of the piping system

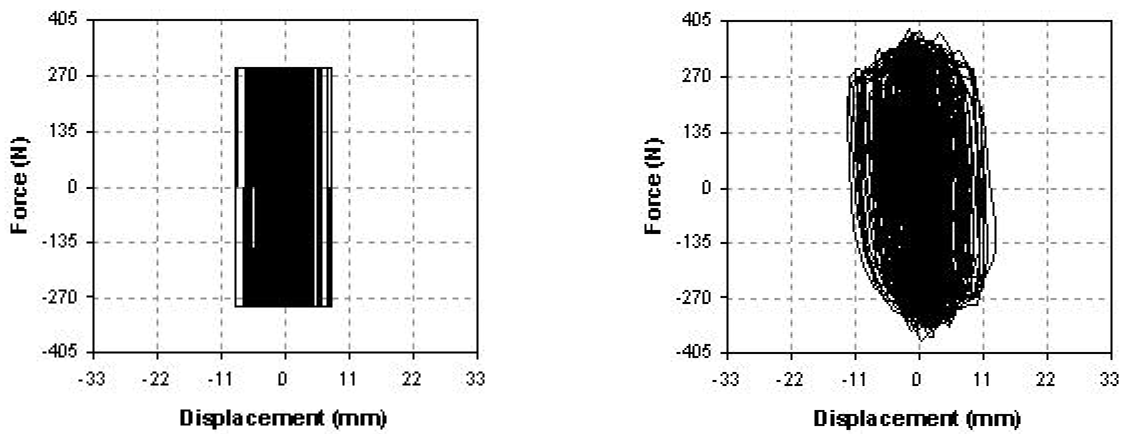


Figure 16. Hystereses for peak table acceleration of 0.56*g* in Z-direction of the piping system

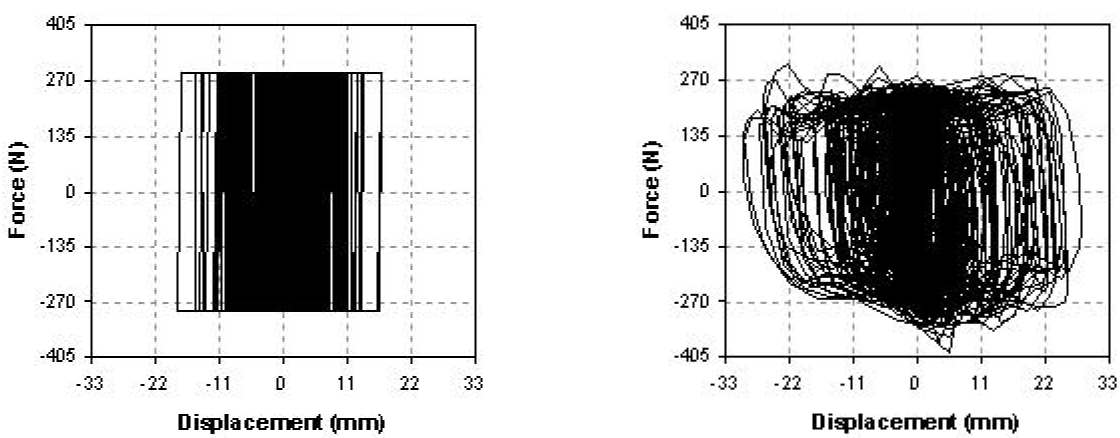


Figure 17. Hystereses for peak table acceleration of 0.85*g* in Z-direction of the piping system

LINEARIZATION OF WEN'S MODEL

Many researchers have proposed simplified methods for analysis of piping system with friction dampers based on random analysis approach. Few of them are Park [17], Igusa [18] and Park [19]. It is observed that this approach involves lots of complexities. Methods very simple in implementation and yet enough accurate have also been proposed by Suzuki [20], Yokoi [21], Shimuzu [22], John [23] and Reddy [24]. Linearization of the Wen's model discussed in this paper is also based on the methods proposed by above researchers.

The friction force obtained by Wen's model remains constant with respect to the response displacement of the piping system. This makes the energy calculations easier. Thus, the dissipated energy ΔE in one cycle can be computed by the following relation:

$$\Delta E = 4F_y x \tag{8}$$

where F_y is the limiting friction force and x is the slip displacement of the pipe or the friction support. The vibration energy E in the piping system can be computed using following relation:

$$E_T = \frac{1}{2}Kx^2 \tag{9}$$

where K is the modal stiffness and x is the displacement of the pipe at friction support. Now, using the energy dissipated ΔE and the vibration energy E, the damping ratio ζ_f of the friction support can be calculated using the following equation:

$$\zeta_f = \frac{\Delta E}{4\pi E_T} \tag{10}$$

Substituting Eqs.(8) and (9) in Eq.(10), the damping of the friction support is given as:

$$\zeta_f = \frac{2F_y}{\pi K x} \tag{11}$$

Now, the total damping ζ of the piping system with friction damper can be computed using following relation:

$$\zeta = \zeta_p + \frac{2F_y}{\pi K x} \tag{12}$$

Using the damping evaluated by the foregoing two approaches, the response of the piping system in any mode can be calculated using iterative response spectrum method discussed in forthcoming.

RESPONSE SPECTRUM ANALYSIS

The procedure proposed by Reddy [24] is adopted here for analyzing a piping system with friction damper by Iterative Response Spectrum (IRS) method. Flowchart for the IRS method is shown in Figure 18. The procedure applicable when the pipe is "Slipping" on the friction support consists of determining the piping displacement x_1 for the first iteration using the response spectrum method for the piping damping alone. This value is taken as the starting value for the next iterations with damping of the combined system. With this value of the displacement, viscous damping of the friction damper can be computed using the Eq.11 and hence the total damping of the system by using the Eq.12. New spectrum is evaluated for this damping value and hence the piping displacement. This process is repeated until the difference of the displacement in the successive iterations is less than or equal to 1%.

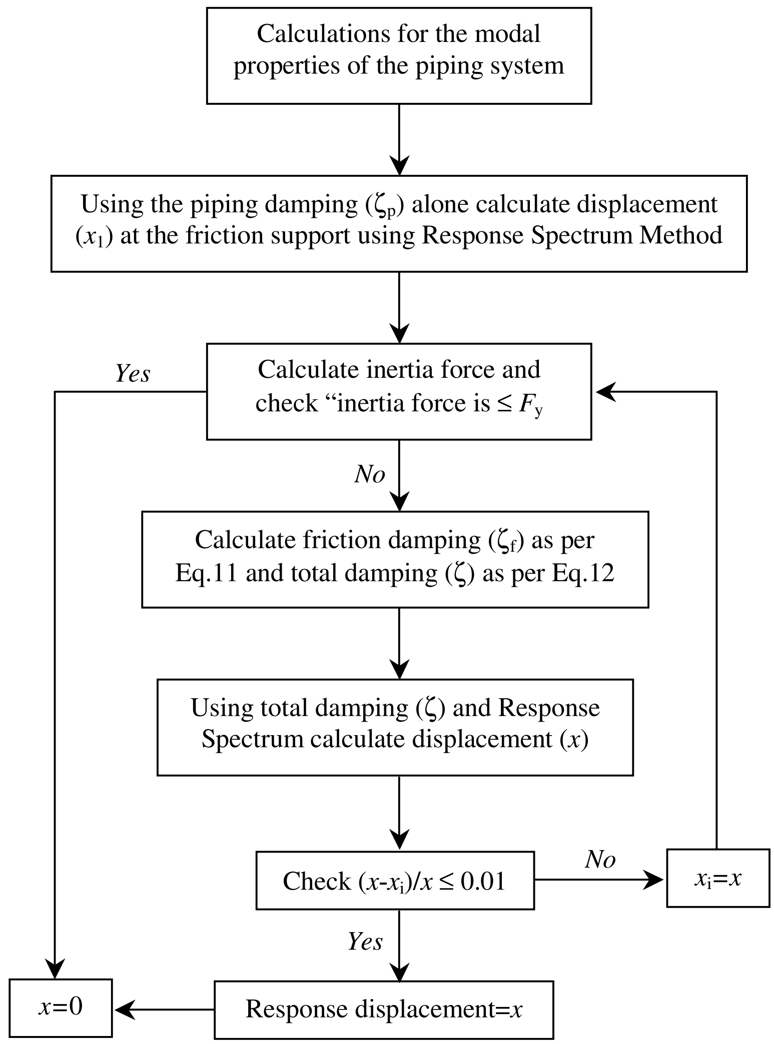


Figure 18. Flow chart of the Iterative Response Spectrum method

In the "Sticking" phenomenon of the pipe to the support the process is established based on the pseudo-inertia force, as shown in the flowchart. Here, inertia force is used for checking the stick or slip condition of the piping system on the friction support. If the inertia force is less than the limiting force, then the iterations will be stopped and the displacement at the friction support is set to zero.

Entire process is repeated for all the modes of the piping and the modal response is combined using the SRSS combination method. After studying various methods the modal combination method is chosen as Hure [25] found the method suitable and accurate for this purpose. Figure 19 show the piping response obtained by this method for X and Z-direction of the piping system, respectively.

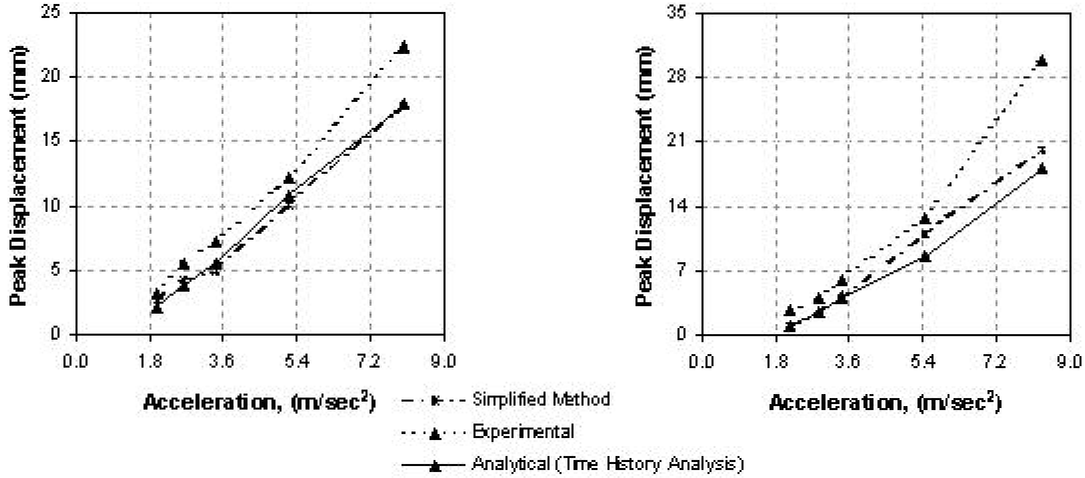


Figure 19. Seismic responses in X and Z-direction of the piping computed by simplified method

RESULTS AND DISCUSSION

The effectiveness of friction damper for seismic control of piping system is demonstrated numerically. A simplified method for analysis of piping system with friction dampers is also presented. The analytical values of the fundamental frequencies are 4.152Hz and 7.75Hz which are in good agreement with corresponding experimental values of 4.74Hz and 7.48Hz, respectively.

Significant reduction in the piping response is noted in case of piping system with damper as shown in Figures 6 and 7. Comparisons of analytical responses are also noted to be in good agreement with the experimental values. It is also noted that the damper forces predicted analytically are in good agreement with the experimentally measured forces. The analytical value of the limiting frictional force in the damper is seen to be constant for all the excitation levels, whereas, the corresponding experimental values are seen to be increasing with increase in the magnitude of the damper displacement. This is happening because of the fact that the coefficient of friction does not remain constant practically unlike assumed analytically. Comparison of the analytical and experimental hystereses also shows a good agreement.

Piping displacements computed by using the simplified method are seen to be in good comparison with the analytical and experimental results obtained from time history analysis, as shown in Figure 19.

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