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Reduction of Large Seismic Deformations using Elasto-plastic Passive Energy Dissipaters

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ABSTRACT

The design of supporting systems for pipelines carrying highly toxic or radioactive liquids at very high temperature, is an important issue in the safety aspect for a nuclear power installation. These pipeline systems are normally designed to be held rigid by conventional snubber supports for protection from earthquake. The pipeline system design must balance the seismic deformations and other deformations due to thermal effect. A rigid pipeline system using conventional snubber supports always leads to an increase in thermal stresses, hence a rational seismic design for pipeline supporting systems becomes essential. Contrary to this rigid design, it is possible to design a flexible pipeline system and to decrease the seismic response by increasing the damping using passive energy absorbing (PEA) element, which dissipates vibration energy. An X-shaped or a hourglass-shaped metal element is a classic example of elasto-plastic passive energy absorber of metallic yielding-type. The inherent ductile property of metals like steel, which undergoes stable energy dissipation in the plastic region, is made use of in achieving energy loss. This paper presents the experimental and analytical studies carried out on yielding-type elasto-plastic PEA elements to be used in a passive energy dissipating device for the control of large seismic deformations of pipelines subjected to earthquake loading.

Keywords: Passive energy dissipation, passive energy absorber, X-plate device, metallic yielding devices, large seismic deformations, seismic response control

NOMENCLATURE

a	Height of triangular portion of PEA element
b	Breadth of triangular portion of PEA element
d	Displacement of PEA element
d_y	Yield displacement of PEA element
E	Elastic modulus of PEA element
F_y	Yield force of PEA element
H	Hardening rate of PEA element
h	Hysteric energy dissipation ratio
K	Equivalent stiffness of PEA element
n	Number of PEA element
r	Ramberg-Osgood exponent
t	Thickness of PEA element

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y_0	Elastic depth
α	Jennings constant
ΔE	Energy dissipated per cycle by PEA element
σ_y	Yield strength of PEA element

1. INTRODUCTION

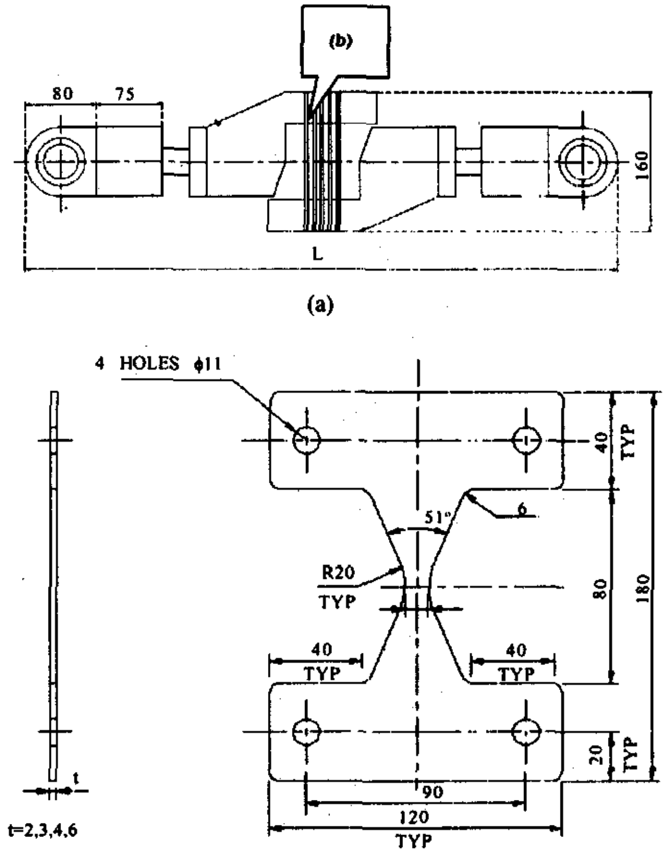
Presently, seismic design of pipeline systems in a nuclear plant is conducted under the rigid design philosophy, where large size rigid supports like snubbers are used as seismic supports. In the seismic support design, it is necessary to consider the thermal load in addition to the seismic load and the snubbers are used as devices to resist seismic load and allow thermal movement in piping. As these devices are relatively expensive and involve complex mechanisms, more inexpensive and reliable devices are desirable as alternative to snubbers. Recently, many studies[1-3] have been performed to find more reliable and economical support concepts, with various kinds of high damping supports of elasto-plastic, visco-elastic, friction, and lead extrusion types, aiming to reduce seismic response.

To evaluate an alternative seismic support for pipeline systems, a study[4-6] has been performed on yielding-type elasto-plastic passive energy absorbing (PEA) elements/devices applied to pipeline systems. An X-shaped metal PEA is one considered for the study, because it greatly increases the system damping and there is no fatigue problem in the damper structure. In this paper, an experimental study on X-shaped metal PEA elements having different plate thickness, subjected to tests of static, dynamic, fatigue, and seismic types is presented. The test results were correlated with the theoretical results obtained from a standard Ramberg-Osgood (R-O) model using the experimentally evaluated auxiliary parameters. The validity of the R-O model in predicting the force-displacement hysteretic characteristics of X-shaped metal PEA elements is studied.

2. TESTING METHODOLOGY

2.1 Passive Energy Absorbing Elements/ Device

PEA elements made of mild steel having three different thickness values of 3 mm, 4 mm and 6 mm were employed in the present study. Figure 1 shows the construction details of the yielding-type elasto-plastic PEA device and the individual PEA element used inside. The PEA element is basically made of mild steel plate having an X-shape. The energy dissipation is achieved by deforming the X-plate to plastic region. The force-displacement curve shows nonlinear hysteretic characteristics and the seismic response of the pipeline system is greatly reduced by the energy dissipation of the hysteresis loop. Since mild steel is used in the plastic region, this region must prevent plastic hinges from developing. Hence, a strong uniformly thick X-shaped plate is



t	L
2	664
3	669
4	674
6	684

(b)

Figure 1. Yielding-type (a) elasto-plastic PEA device and (b) X-plate PEA element. (All dimensions in mm).

used as a plate spring. When this X-shaped plate has large deformation, the plastic domain progresses in the thickness direction of the plate, leading to simultaneous yielding over the triangular region. In the present study, the height and base of the triangle portion in an individual X-shaped plate were kept as 40 mm and 40 mm, respectively. The overall height and width of the single element were kept as 160 mm and 160 mm, respectively. The properties like yield stress, elastic modulus, and hardening rate for the element material were evaluated as 235 MPa, 1.94×10^5 MPa and 5.00×10^3 MPa, respectively.

2.2 Tests Conducted on Passive Energy Absorbing Element

The PEA elements were initially tested (using the facility created) using a displacement-controlled 50 kN actuator as shown in Fig. 2 under static conditions for evaluating the yield and post-yield behaviour. Then, using the same facility, dynamic, fatigue, and seismic loading tests were carried out on similar devices up to failure, for evaluating the performance in a seismic environment. For the dynamic and fatigue loadings, the rate of loading was kept as 3 Hz and with different increasing peak displacement amplitudes of say 5 mm, 10 mm, and 15 mm. From the force-displacement hysteretic loops, the dynamic stiffness and damping of the elements were evaluated. For the seismic loading tests, a spectrum-compatible displacement time history for a specific site was generated and applied to the elements in succession to evaluate their design life.

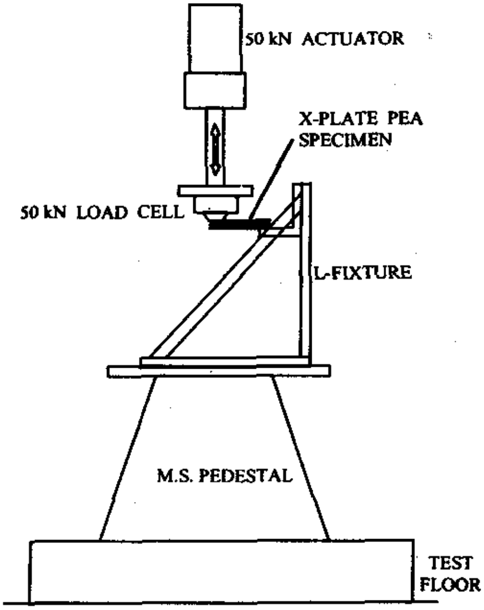


Figure 2. Test facility for evaluation of PEA elements

3. RESULTS

Figure 3 shows the dynamic/fatigue test results conducted on different PEA elements at constant peak-displacement amplitude of 15 mm at 3 Hz.

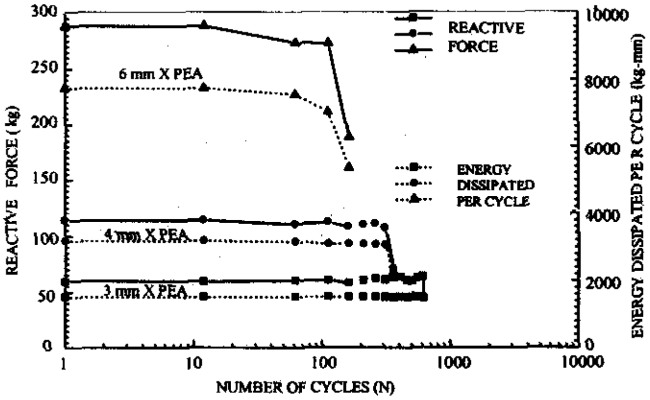


Figure 3. Dynamic test results on different PEA elements at constant peak displacement amplitude of 15 mm at 3 Hz.

From the reactive forces and force-displacement (hysteresis) curves obtained from the PEA elements, the design stiffness and damping of the individual PEA elements were evaluated.

Similarly, Fig. 4 shows the dynamic/fatigue test results conducted on 6 mm thick PEA elements at different peak-displacement amplitudes at the fixed loading rate of 3 Hz. Based on these results, the design life of different PEA elements were arrived at. A typical force-displacement response obtained on a 4 mm thick X-plate PEA elements under seismic loading is shown in Fig. 5.

4. ANALYTICAL STUDY

4.1 Static Loading

The material characteristics of the X-shaped plate [Fig. 6(a)], the elastic modulus, and the stress used as a plate spring. When this X-shaped plate has large deformation, the plastic domain progresses in the thickness direction of the plate, leading to simultaneous yielding over the triangular region. In the present study, the height and base of the triangle portion in an individual X-shaped plate were kept as 40 mm and 40 mm, respectively. The overall height and width of the single element were kept as 160 mm and 160 mm, respectively. The properties like yield stress, elastic modulus, and hardening rate for the element material were evaluated as 235 MPa, 1.94×10^5 MPa and 5.00×10^3 MPa, respectively.

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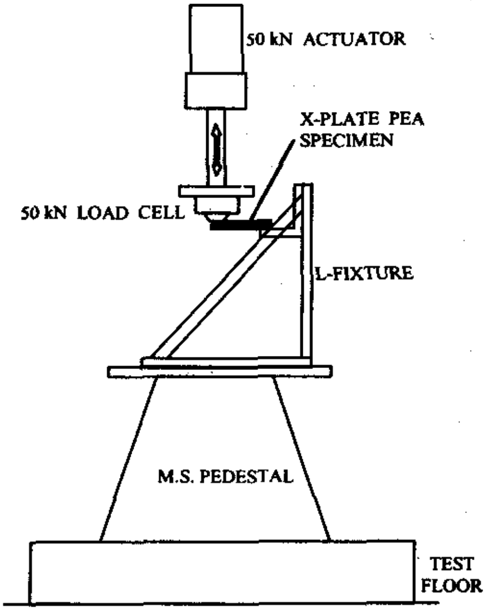

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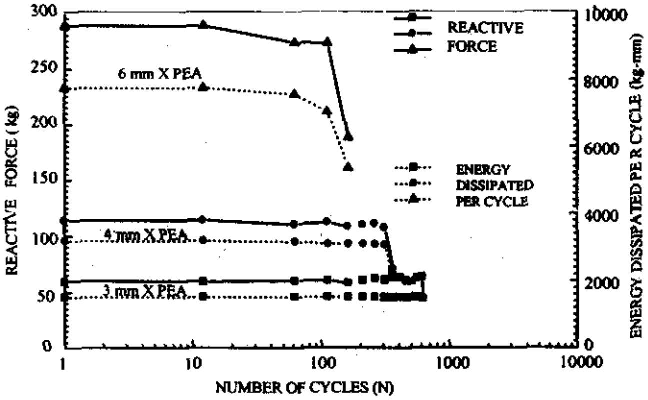

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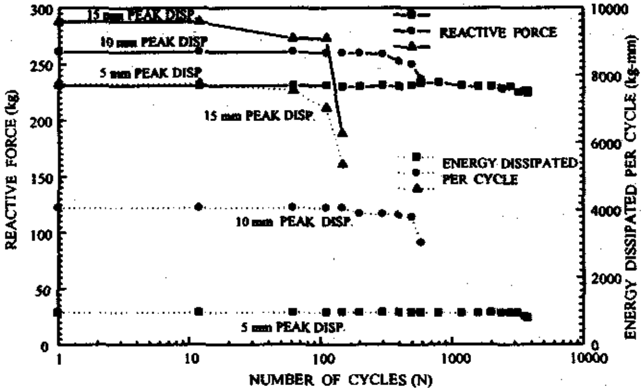
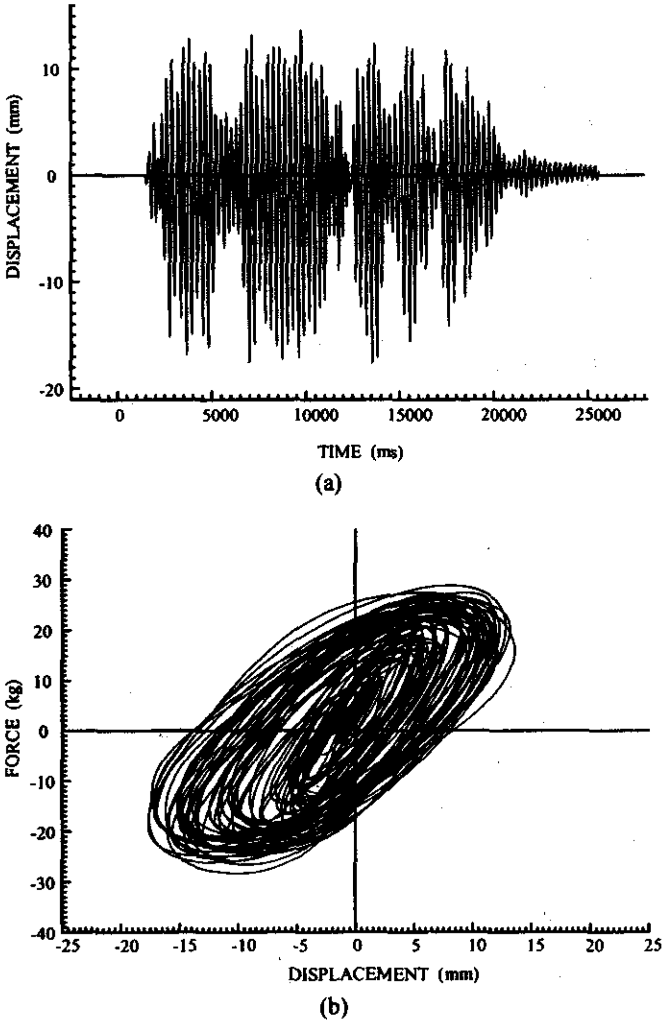


Figure 4. Dynamic test results on 6 mm thickness PEA elements at different displacement amplitudes at 3Hz.



(a)

(b)

Figure 5. Typical seismic responses measured on a 4 mm thick X-plate PEA element under earthquake loading: (a) displacement-time history and (b) force-displacement curve.

hardening rate, are expressed by the bi-linear model. The skeleton curve of the force-displacement curve [Fig. 6(b)] of the X-shaped plate for each stress level was investigated by beam theory.

In the elastic domain, the relationship between the force (F) and the displacement (d) is given as

$$F = \frac{Ebt^3 n}{12a^3} d$$

and the equivalent stiffness of the X-plate (K) is given as

$$K = \frac{Ebt^3 n}{12a^3} \quad (1)$$

where, a is the height, b is the maximum breadth, t is the thickness, and n is the number of the PEA elements,respectively of the triangular X-plate.

In the plastic domain at the yield point, the X-shaped plate surface is plastic and the plate surface stress is σ_y. The yield force (F_y) and corresponding yield displacement (d_y) are given as

$$F_y = \frac{\sigma_y t^2}{6} \frac{b}{a} n; \qquad d_y = \frac{2\sigma_y a^2}{Et} \quad (2)$$

Similarly in the plastic region [Fig. 6(c)], considering the effect due to strain hardening rate, the force-displacement relation is given as

$$F = \frac{nb\sigma_y}{12Ea}\left\{\left(4y_o{}^2 - 3t^2\right)\left(H - E\right) + H\frac{t^3}{y_o}\right\} \quad (3)$$

the elastic depth y_o can be evaluated using

$$y_o = \frac{\sigma_y a^2}{Ed} \quad (4)$$

The hysteresis loop can be obtained by giving the stress-strain characteristics of the very small part as bi-linear in each stress condition. The equivalent stiffness and the element damping ratio can show the dynamic characteristics of passive energy dissipation. The former is obtained from the

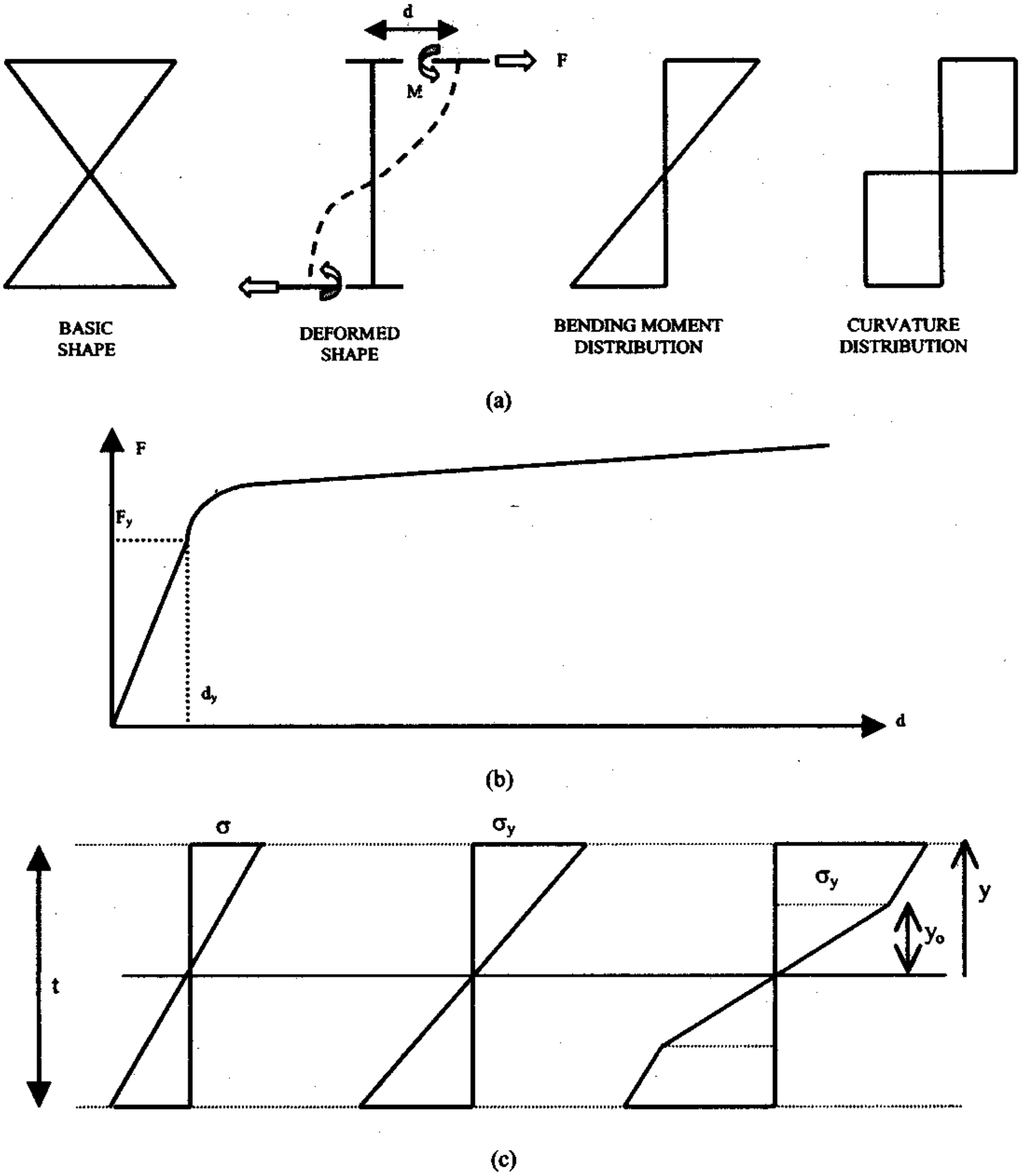


Figure 6. Analytical modelling of X-plate PEA element under static loading: (a) X-plate PEA element, (b) static force-displacement curve, and (c) variation of stress across thickness at various stages of loading.

tangential stiffness at the reversal point of the skeleton curve. The latter is obtained as the ratio between the element strain energy and the dissipating energy per cycle (ΔE).

$$\Delta E = 3F_y(d + d_1) + \frac{d_y{}^2 F_y}{(d + d_1)} - (3d_y F_y) - \left[Ft^2 / K\right] \quad (5)$$

$$h = \frac{\Delta E}{2\pi K d^2} \quad (6)$$

4.2 Dynamic/Cyclic Loading

In the elasto-plastic analysis of these X-plate PEA elements under dynamic or cyclic loadings, standard hysteretic models[1,4], such as ideal elasto-plastic, bi-linear, Bauschinger, Ramberg-Osgood, Takeda, Wen and Polygonal model, etc. are usually used. The basic form of the force-displacement model is selected, which is usually based upon an analogy with plasticity theory, and then the model parameters are determined via a curve-fitting procedure. Of all the hysteretic models stated, the Ramberg-Osgood model[1,4] developed by Jennings suits closely to such X-shaped PEA elements. The Ramberg-Osgood model essentially establishes a power law relationship between the force and the inelastic displacement, and consequently is effective in modelling the response of a variety of metals under cyclic/dynamic loadings. This model approximates the shape of the force-displacement curve ($F(t) - d(t)$) by appropriate selection of the auxiliary parameters called Ramberg-Osgood exponent and Jennings constant, according to the shape of the actual hysteretic curve (Fig. 7).

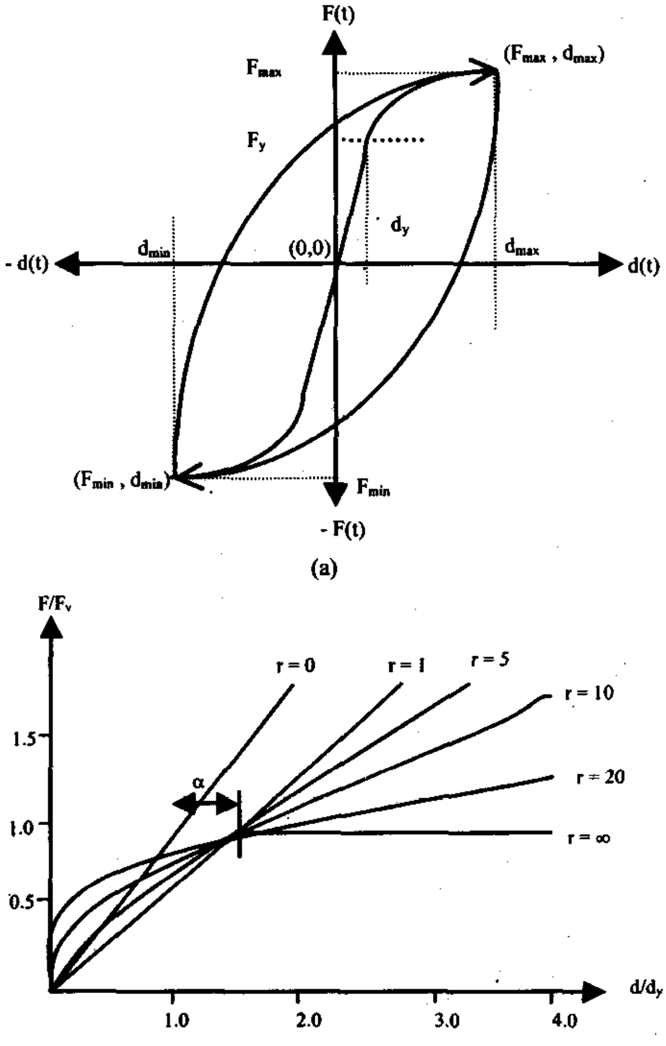


Figure 7. Ramberg-Osgood model employed for modelling X-plate PEA elements under dynamic loading: (a) hysteresis loop, and (b) Ramberg-Osgood function.

In the present study, the values of these auxiliary parameters were realistically evaluated from the static test results using curve-fitting procedure. The force-displacement relations at various stages in the hysteresis loop were obtained using the following expressions.

- For the basic loading branch of the hysteresis loop between the coordinates (0, 0) and (F_{max}, d_{max})

$$\frac{d(t)}{d_y} = \frac{F(t)}{F_y}\left(1 + \alpha\left(abs\frac{F(t)}{F_y}\right)^{r-1}\right) \tag{7}$$

- For the unloading branch of the hysteresis loop between the coordinates (F_{max}, d_{max}) and (F_{min}, d_{min})

$$\frac{d(t) - d_{max}}{d_y} = \frac{F(t) - F_{max}}{F_y} \times \left(1 + \alpha\left(abs\left(\frac{F(t) - F_{max}}{2F_y}\right)\right)^{r-1}\right) \tag{8}$$

- For the reloading branch of the hysteresis loop between the coordinates (F_{min}, d_{min}) and (F_{max}, d_{max})

$$\frac{d(t) - d_{min}}{d_y} = \frac{F(t) - F_{min}}{F_y} \times \left(1 + \alpha\left(abs\left(\frac{F(t) - F_{min}}{2F_y}\right)\right)^{r-1}\right) \tag{9}$$

The hysteretic energy dissipation index (h) of the X-plate PEA element using the Ramberg-Osgood model is expressed as

$$h = \frac{2}{\pi}\left(1 - \frac{2\alpha}{r+1}\right)\left(1 - \frac{d_y F_{max}}{F_y d_{max}}\right) \tag{10}$$

Figure 8 shows the comparison between the theoretical and the experimental results under static loading on a 4 mm thick X-plate PEA elements.

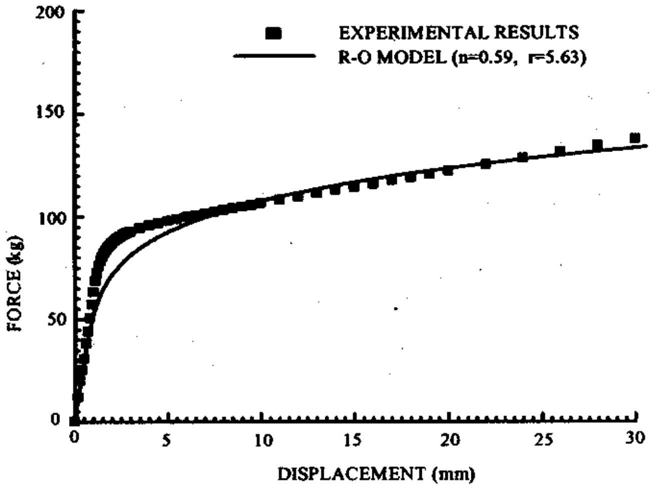


Figure 8. Comparison between theoretical and experimental results under static loading for a 4 mm thick X-plate PEA element.

Similarly, Fig. 9 shows the comparison between the theoretical and the experimental results on a 4 mm thick X-plate PEA elements under dynamic loading of sinusoidal nature at a loading rate of 3 Hz and 15 mm peak displacement amplitude, with an initial ramping-up enveloping function for the first ten cycles.

5. OBSERVATIONS & CONCLUSIONS

A close match is found between the analytical and the experimental responses of X-plate PEA elements both under static and dynamic loadings, thus proving the validity of Ramberg-Osgood model in predicting the design parameters required for designing PEA elements of yielding-type. The large and stable energy dissipation per cycle observed from the stable force-displacement hysteretic curves up to failure obtained from the dynamic/fatigue tests showed the suitability of X-plate PEA elements for designing a passive energy dissipating device for controlling the large seismic deformations of pipeline systems subjected to earthquake loading.

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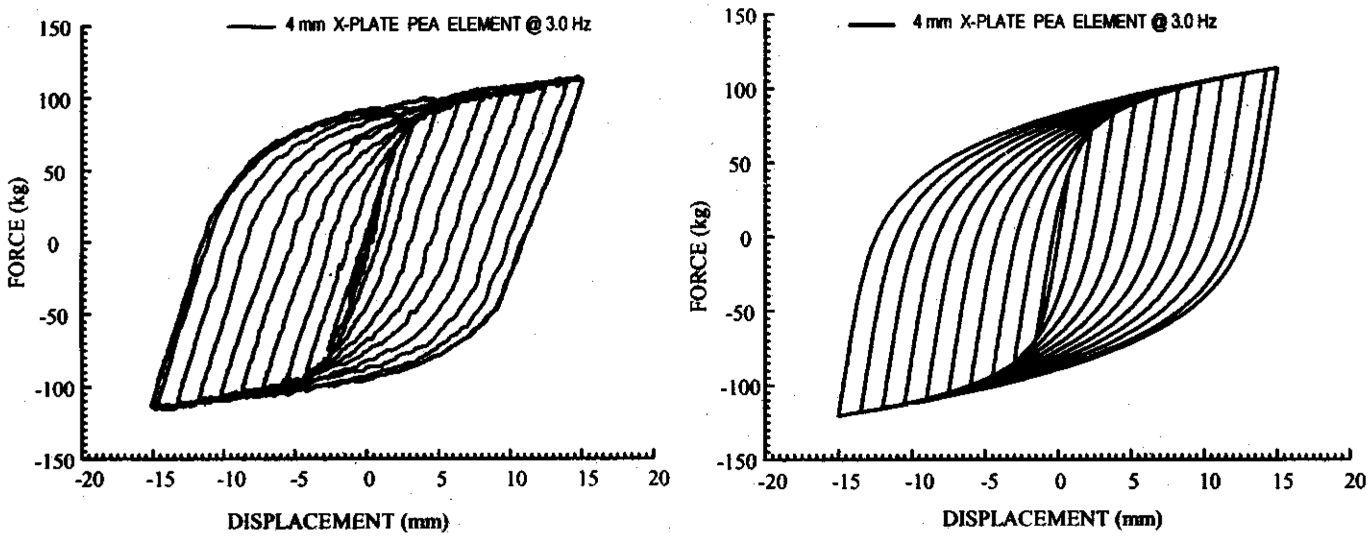

(a)

(b)

Figure 9. Comparison between theoretical and experimental results under dynamic loading at 3 Hz for a 4 mm thick X-plate PEA element: (a) Experimental curve and (b) theoretical curve.

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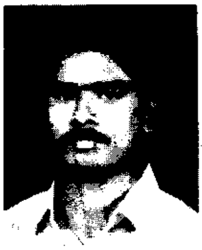
Contributors



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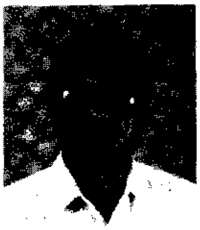

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