Performance of X-Plate Elasto-plastic Dampers, a Passive Seismic Support for Nuclear Piping Under Cyclic Loading

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1 ABSTRACT

In the nuclear power plant (NPP) piping design, major loads considered are pressure, dead weight, seismic and loads due to restraint to thermal expansion. The thermal stresses and seismic stresses are contradictory to each other, as to reduce the former, piping should be flexible enough to allow gradual and slow thermal expansion and for the later it should be rigid to resist the seismic forces caused by sudden and fast motion. Therefore it is very tedious to include these two mutual contradictory characteristics in same piping using conventional supports. In this condition snubbers are used, which allow the gradual thermal expansion and arrest the sudden motion due to earthquake. From the past experiences snubbers have proved to be very costly, expensive and need frequent maintenance, leakage problem in hydraulic snubbers and they also congest the space because of more space requirement for installation. Sometimes it is also observed that the mechanical snubbers lock during normal operation and cause undue thermal stresses in the piping and nozzles. Due to inherent drawbacks and high initial and maintenance cost involved with snubbers, recently a trend has been started to use dampers in place of snubbers. In the present paper testing of 6 mm thick X-plate Elasto-plastic Dampers made of SS316L material has been performed for evaluation their performance under cyclic loads at different frequencies and tip displacements. By testing it was found that they can sustain many cycles of stable yielding deformation, resulting in high levels of energy dissipation.

2 INTRODUCTION

In nuclear power plants large numbers of piping are used ranging from low pressure, temperature to high pressure and temperature to meet the different processes requirements. To safeguard the environment and personnel working, from the long lasting, undue radiation hazard is prime importance under normal operation and accidental loads due to external events like earthquake. Major loads on piping during normal and occasional loadings conditions are pressure, dead weight, earthquake and loads due resistance to thermal expansion. Piping requires flexibility to allow gradual slow thermal expansion whereas earthquake load requires the rigidity in the piping. These two requirements are contrary to each other and it is very tedious to include both contrary characteristics in the same piping using conventional supports, some times large number of bends and supports needs to be incorporated at appropriate locations. Large numbers of elbows require more number of weld joints which eventually increase in-service inspection cost and radiation dose during in-service inspection in addition to drop in line flow pressure. Some times for high temperature pipeline it is very difficult to qualify for thermal and seismic loads together using conventional supports, in that situation snubbers are used, which allow gradual thermal expansion during normal operation and arrest the sudden motion caused by earthquake. Hella Schuarkopf (1991) and Cloud, RL et. al (1988) found from past experiences snubbers have proved to be very costly, expensive and need frequent maintenance, hydraulic snubbers have been subjected to loss of fluid, degradation of hydraulic fluid in radioactive environment, and premature locking due to corrosion (or even painting, though this is not confined to hydraulic snubbers) and they also congest the space because of more space requirement for installation. Sometimes it is also observed that mechanical snubbers locked-up inadvertently, leading to additional stresses that could be detrimental to the system. Hella Schuarkopf (1991), Cloud, RL, Anderson et al (1988) and R Baltus and A Billinton (1996) investigated that for single snubber maintenance cost is too high. Due to inherent drawbacks involved with snubbers, recently a trend has been started to use other seismic response controlling devices in place of snubbers. Active and passive control devices may be used to control the seismic response of piping systems and equipments. In nuclear industry the use of passive control devices is encouraged because there are
already numbers of active devices to control the different reactor parameters and addition of more active controls, reduces the over all system reliability. Passive response controlling devices do not need power supply, rather they work on principles such as friction sliding, yielding of metals, phase transformation in metals, deformation of visco-elastic solids or fluids, and fluid orificing, etc. Friction supports, visco-elastic supports, tuned mass friction dampers (TMFD), elastomeric base isolators, lead extrusion dampers (LED), elasto-plastic dampers (EPD), Houde dampers, are few common types of passive response controlling devices. Among all, EPD is mostly preferred or piping due to its simple design, easy installation, lower cost, less maintenance and high reliability.

3 X-PLATE ELASTO-PLASTIC DAMPERS

Normally X- shaped plates as shown in Fig.1, are chosen as elasto-plastic energy absorbers such that the strain is constant over the height of the device, thus ensuring that yielding occurs simultaneously and uniformly over the full height of the damper. X-plates are preferred because of their high seismic energy absorbing capacity, simple design, low cost and maintenance free operation. EPDs are based on plastically deforming steel components or layered laminated plate in flexure, shear, torsion or a combination thereof. For critical applications like in NPPs, where safety of public and environment from undue risk of radiation hazards is prime concern, it is necessary to evaluate the performance of supports under seismic loads by testing before implementation. In the present paper testing of 6 mm thick X-plate EPDs made of SS 316L material has been performed for evaluation of its performance under cyclic loads at different frequencies and tip displacements. From tests it was found that they can withstand substantial number of cycles of stable yielding deformation, resulting in high levels of energy dissipation (damping).

![Figure 1. X-plate Elasto-plastic damper](image)

4 DESIGN AND CHARACTERISATION OF EPD

From last few years the research and experiments are being performed on different possible configurations of EPD, to develop EPDs as an extensive tool for seismic response control of the piping in nuclear industry for future. Experiments carried out on EPDs have reflected very promising results for absorbing the vibration energy during earthquakes. The design and test characteristics of EPDs have been explained under following headings.

4.1 Force displacement characteristics of X-plate

The force displacement characteristics were obtained by analytical formulations and also by conducting static tests and cyclic tests on X plates of different thickness. The force displacement curve for an X- shaped plate was obtained using the beam theory. The expressions are derived for three cases as follows:

Case-1: Considering bending stress in X- plate is elastic

The X-shaped plate connects the top of two triangular plates. Thus considering only triangular plate

$$EI \frac{d^2 y}{dx^2} = -F_x$$  \hspace{1cm} (1)
\[ F = \frac{Ebt^3d}{6a^3} \]  \hspace{1cm} (2)

For X- plate,
\[ K = \frac{F}{2d} = \frac{Ebt^3}{12a^3} \]  \hspace{1cm} (3)

Where ‘d’ is the displacement, ‘b’ is the width, ‘t’ is the thickness, ‘a’ is the height of the triangular plate and ‘E’ is the Modulus of Elasticity.

Case-2: Considering bending stress in X-plate just reaching yield stress,

For triangular plate, \[ M_y = \frac{\sigma_y bt^2}{6} \]  \hspace{1cm} (4)
\[ F_y = \frac{\sigma_y bt^2}{6a} \]  \hspace{1cm} (5)

Substituting eqn (5) in eqn (2) it is found
\[ d_y = 2 \frac{\sigma_y a^2}{Et} \]  \hspace{1cm} (6)

For X-plate yield displacement,
\[ d_y = \frac{\sigma_y a^2}{Et} \]

Case-3: Considering the bending stress in which elastic depth of the X-plate reaches 2\(y_0\). The stress of the triangular plate before yield as shown in Fig.2, for 0<\(y<y_0\) is given as follows
\[ \sigma_1 = \frac{y\sigma_y}{y_0} \]  \hspace{1cm} (7)

The stress of the triangular plate after yield, using the strain-hardening rate ‘H’ is given by eqn (8).
\[ \sigma_2 = H\varepsilon + \frac{\sigma_y (E - H)}{E} \]  \hspace{1cm} (8)

Using the balance of the moment at the fix point of the triangular plate:
\[ Fa = 2b \int_0^{y_0} \alpha_1 y dy + \int_{y_0}^{t/2} \alpha_2 y dy \]  \hspace{1cm} (9)

Substituting values of \(\alpha_1\) from eqn (7) and \(\alpha_2\) from eqn (8) in eqn (9) we get,
\[ F = \frac{b\sigma_y}{12Ea} \left\{ (4y_0^2 - 3t^2)(E - H) + \frac{Ht^3}{y_0} \right\} \]  \hspace{1cm} (10)

The force in the X-plate is the same as that in the triangular plate,
5 EVALUATION OF STRESS-STRAIN CHARACTERISTICS OF SS 316L

In order to evaluate the mechanical properties of SS 316L, the material of X-plates, tensile tests were performed on rectangular tensile test specimens as shown in Fig. 3, by Universal Testing Machine (UTM), and obtained stress-strain characteristics is shown in Fig.4.

From the slope of linear portion in Fig. 4, the Young’s modulus (E) was found 1.93 X 10^5 N/mm² and yield strength calculated at 0.2% proof strain is 265 N/mm².

For X-plate,

\[ d = \frac{\sigma_s a^2}{2E_y} \]  

(11)

\[ d = \frac{\sigma_s a^2}{E_y} \]  

(12)

\[ E = 193 \text{ kN/mm}^2 \]

Figure 4. Stress-Strain curve for SS 316L

6 EVALUATION OF CYCLIC CHARACTERISTICS OF X-PLATES

In order to evaluate the cyclic characteristic of 6.0 mm X-plates made of SS 316L material, tests were performed. At a time, two X-plates were tested because of concentric load requirement of testing machine, a fixture was made as shown in Fig. 5, and cyclic tests were carried out on 6 mm thick X-plates made of
SS316L, at 10mm, 20mm and 30mm tip displacements of at one end of EPD plates and measuring the reaction forces by the load cell at the common end of the plates. Forces so measured will be on two plates and hence have been halved in order to plot the cyclic load-deflection curve of single EPD plate. The hysteresis curve at 10mm, 20mm and 30 mm tip displacements are shown in Figs. 6-8.

Fatigue tests were performed at 10 mm, 20 mm and 30 mm tip displacements till the failure of at least one EPD plate. From the tests it was also found that 6 mm thick X-plate EPDs can sustain 313 cycles, 52 cycles and 30 cycles of dynamic loading at 10 mm, 20 mm and 30 mm tip displacements respectively. It can be observed that as the tip displacement increases the fatigue life reduces. As observed in the work of Paruleker, Y. M. et. al. (2004) that 3 mm thick X-plates can withstand large number of fatigue cycles before failure, therefore for higher fatigue life combination of 3 mm thick X-plates can be used.
Using the eqn (10) the force displacement curve has been obtained for a 6 mm thick X-plate made of SS 316L with mechanical properties $E = 1.93 \times 10^5$ N/mm$^2$, $H$ (2.58% of $E$) = $4.98 \times 10^3$ N/mm$^2$ and $\sigma_y = 265$ N/mm$^2$ and shown in Fig. 9. For evaluating the cyclic characteristics of the 6 mm X-plates Ramberg Osgood model as given in eqn (13) has been adopted. The ‘$\alpha$’ and ‘$n$’ parameter of the R-O model are obtained using curve fitting technique. Cyclic characteristic curve has been obtained for a 6 mm X-plate EPD, by putting $n = 7.781$ and $\alpha = 0.0985$, in equations (13), (14 (a)) & (14 (b)) for different regions of curve shown in Fig. 10.

(i) For the basic branch of loading up to point ‘b’ following eqn. (13) has been used.

$$\frac{d_y}{d} = \frac{F_{y}}{F} \left(1 + \alpha \left( abs \left( \frac{F}{F_{y}} \right) \right)^{n-1} \right)$$ \hspace{1cm} (13)

(ii) For unloading branch, which starts from point ‘b’ following eqn 14(a) has been adopted.

$$\frac{d - d_{b}}{d_y} = \frac{F - F_{b}}{F_{y}} \left(1 + \alpha \left( abs \left( \frac{F - F_{b}}{2F_{y}} \right) \right)^{n-1} \right)$$ \hspace{1cm} 14 \,(a)
(iii) For reloading branch, which starts from point ‘d’ up to ‘b’ following eqn 14(b) has been adopted.

\[
\frac{d - d_b}{d_y} = \frac{F - F_d}{F_y} \left( 1 + \alpha \left( \frac{F - F_d}{2F_y} \right) \right)^n \quad 14(b)
\]

![Figure 9. Force deflection characteristic of 6mm X-plate EPD](image)

The experimental hysteresis curves shown in Figs 6-8, and theoretical the hysteresis curve shown in Fig. 10, for 6 mm thick X- plate at different tip displacement are matching. The force displacement characteristics can be best represented by R-O model but a bilinear approximation is also a very close to the actual curve.

![Figure 10. Theoretical hysteretic characteristics of 6 mm thick EPD plate](image)

The 6 mm X-plate was 3-D FE modelled as shown in the Fig. 11(a), and nonlinear analysis was carried out. Dimensions of 6mm X-plate EPD has been shown in Fig. 11(b). All degrees of freedom were restrained at
the common edge of EPD plates and nonlinear analysis was performed at 10 mm, 20 mm, and 30 mm peak tip displacements.

The non-linearity was assumed to follow Hill’s plasticity multi-linear curve. The stress-strain values after the yield point were input from stress-stain characteristic of the material as shown in Fig. 4, where Young’s modulus and Poisson ratio are taken as $1.93 \times 10^5$ N/mm$^2$ and 0.3 respectively. The force and displacement values thus obtained have been plotted at different tip displacements is shown in the Fig. 12. Comparing the hysteresis curves obtained from in theory shown in Fig. 10, and analysis hysteresis curves shown in Fig 12, it can be deduced that they are closely matching with respective tip displacements.

![Figure 11. 3-D FE model of EPD plate (b) Dimensions of EPD plate](image)

![Figure 12. Hysteresis characteristic X-plate EPD obtained from analysis](image)

## 9 CONCLUSION

It is observed that, theoretical and analysis results on EPD are matching with the test results. EPDs made of SS 316L, 6 mm thick X-plates were fabricated and static and fatigue tests were performed to understand the EPD characteristics viz. number of earthquake cycles which a damper can tolerate without failure during seismic event. It can be concluded from the tests and analysis that the characteristics of EPD can be estimated by beam theory also. Fatigue tests on 6 mm EPD plate shown that they can withstand 313 cycles, 52 cycles, 30 cycles at 10mm 20mm and 30mm tip displacements respectively. Dampers are very flexible and they allow almost free thermal expansion
and absorb the substantial amount of seismic energy by hysteretic deformation. Shift in the frequency of the piping with EPD support is less than 5%. EPD can be effectively used to reduce the seismic response of piping system as a better, reliable, maintenance free and economic substitute for unreliable and costly snubbers. EPDs are passive supports, so its functionality can be guaranteed in exigencies unlike active and semi active dampers.

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Symbols

$\alpha$  Ramberg Osgood coefficient  
$\sigma_y$  Yield strength of EPD material  
n/m$^2$  
$a$  Height of triangular EPD plate  
n/mm  
$b$  width of triangular EPD plate  
n/mm  
t  Thickness of triangular plate EPD  
n/mm  
d  Deformation  
n/mm  
d$_y$  Yield deflection  
n/mm  
$E$  Young's modulus  
n/m$^2$  
$F$  Force in the triangular plate  
n  
$F_y$  Force at yield point  
n  
$H$  Rate of strain hardening  
n/m$^2$  
$I$  Moment of inertia  
m$^4$  
$K$  Stiffness  
n/mm  
$n$  Ramberg Osgood parameter  

REFERENCES


water piping support by energy absorbing supports under very large seismic input. ASME, PVP, vol.345, Seismic Engineering, pp. 133-136.

