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Optimum X-plate dampers for seismic response control of piping systems

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Abstract

In a vibrating system, the most effective mechanism to dissipate energy is the inelastic strain of supplemental metallic elements with plastic deforming characteristics. An X-plate damper (XPD) is one device that is capable of sustaining many cycles of stable yielding deformation resulting in a high level of energy dissipation or damping. The present paper focuses on a numerical study to investigate the seismic effectiveness of an XPD for piping systems in industrial units (e.g. chemical and petrochemical industries) and utilities such as thermal and nuclear power plants. The seismic performance of piping systems is investigated under important parametric variations of the damper properties (i.e. height, width and thickness of the XPD) under arbitrary ground motions. Investigations are reported for an industrial piping system equipped with an XPD and the response quantities of interest are the relative displacements, absolute accelerations and support reactions of the piping system. The response quantities of the controlled (with XPD) piping system are compared with the corresponding uncontrolled (without XPD) piping systems, to establish the seismic effectiveness of the XPD. Seismic energy dissipation in the piping system, which is represented by the hysteretic energy of the XPD, is also evaluated and compared. It is observed that the XPDs are very effective in reducing the seismic response of piping systems. Moreover, for a given piping system and ground motion, it is difficult to arrive at the optimum properties of an XPD from the parametric variation of the properties of the XPD and by monitoring the responses of the piping system. Therefore, use of hysteretic energy dissipation by an XPD is proposed to obtain the optimum properties of the XPD. Furthermore, the effects of the properties of an XPD on the free vibration characteristics of the piping system are also presented, which is crucial for the design of piping systems with XPDs.

Keywords: Piping system; X-plate damper; Hysteretic; Seismic; Energy; Parametric; Optimum parameters

1. Introduction

Structural control using energy dissipating devices is an appealing alternative to the traditional earthquake-resistant design approaches. In this approach, a substantial portion of the vibration energy is absorbed or consumed at selected locations within a structure through protective devices especially designed for this purpose. In particular, passive control devices offer various advantages over functionally complex active and semi-active control devices. Devices in this class have the ability to dissipate the earthquake input energy by virtue of their nonlinear behavior. Since these protective devices are separated from the main structure, they act as structural 'fuses' that can be replaced, if damaged, after the occurrence of a severe seismic event. For piping systems, these devices should satisfy the basic requirement of thermal expansion without generation of undesired stresses. During strong earthquakes, it should be ensured that these devices dissipate most of the earthquake input energy and thereby reduce the forces transferred to the piping system. At present, snubbers are used in nuclear power plants to reduce the seismic forces in the piping system. However, snubbers are very expensive and are associated with problems of oil leakage (in the case of hydraulic snubbers) and locking (in the case of mechanical snubbers) and as a result, require frequent inspection. Hence, Olson and Tang [1] and Cloud

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Nomenclature

α	post-to-pre-yield stiffness ratio	E	modulus of elasticity
β	Wen's model parameter	E_{d}	percentage energy dissipated by an XPD
γ	Wen's model parameter	E_{h}	hysteretic energy in an XPD
τ	Wen's model parameter	E_{I}	input energy to the piping system
σ_{y}	yield stress of an XPD	F	force in an XPD
a	half the height of an XPD	F_{y}	yield force of an XPD
b	width of an XPD	H	rate of hardening
n	Wen's model parameter	K_{d}	initial stiffness of an XPD
t	thickness of an XPD	q	yield displacement of an XPD
A	Wen's model parameter	x_{p}	displacement of piping system
		$\ddot{x}_{\mathrm{p}}$	absolute acceleration of piping system
		$\dot{x}_{\mathrm{p}}$	relative velocity of piping system

et al. [2] proposed the reduced use of snubbers and proposed seismic stops instead. It is very difficult to frequently inspect snubbers in the high-radiation conditions that exist in nuclear power plants and there are huge costs required for yearly maintenance of snubbers. Moreover, malfunctioning of snubbers develops undesired loads [3] on the piping systems thus questioning their safe functioning.

A variety of passive devices have been proposed for the structural control of piping systems including the visco-elastic damper, the compact dynamic absorber, friction damper and X-plate damper (XPD) [4,5]. The XPD consists of an assembly that holds either single or multiple components of thin metallic or layered plates of 'X' or 'V' shape. It utilizes the plastic deformation characteristics of the steel components to damp the input seismic energy. The XPD can sustain many cycles of stable yielding deformation without fatigue thus dissipating the input seismic energy in the form of hysteretic deformation. Kelly et al. [6] were the first to propose the use of XPDs for seismic energy dissipation in structures, and this work was extended by Skinner et al. [7] and Tyler [8]. Proposals for the use of XPDs in piping systems was first presented, again by Kelly et al. [9]. Schneider et al. [10] performed a series of experimental tests on a complex spatial piping system equipped with XPDs. Kobayashi [4] reported studies on composite laminated plates for a triangular plate damper. Later, several experimental and analytical studies were reported on a piping system equipped with metallic energy absorbers [11–17]. More recently, Parulekar et al. [18] and Bakre and Jangid [19] performed several component tests on X-plate metallic damper and on piping systems with an XPD. In all the aforementioned studies, XPDs were found to be very effective in seismic control of structures. However, comparatively detailed studies are not yet available on parametric variations of the properties of XPD, which play an important role in the seismic analysis and design of piping systems equipped with XPD. Moreover, the stiffness being added to the piping structure in the form of an XPD significantly alters the vibration characteristics of the system. Hence, it is important to study the effect of the damper properties on the free vibration characteristics of the piping system.

The present preliminary research focuses on a numerical study to investigate the seismic effectiveness of an XPD as a seismic protective system for industrial piping systems. The seismic performance of a piping system is studied under important parametric variation of the damper properties for an industrial piping system under real earthquake ground motions. The damper parameters considered are height, width and thickness. It is observed that the optimal XPD properties are very difficult to obtain by simply monitoring the piping responses. Hence, use of hysteretic energy dissipation by the XPD is proposed to obtain the optimal properties of an XPD for a given piping system and ground motion. Lastly, the effect of the properties of an XPD on the free vibration characteristics of the piping system is also studied.

2. Mechanism of XPD

XPDs are made of thin metallic plates that dissipate energy through their flexural yielding deformation. They can sustain many cycles of stable yielding deformation [16,17], resulting in high levels of energy dissipation or damping. The 'X' shape of the damper is adopted so as to have a constant strain variation over its height, thus ensuring that yielding occurs simultaneously and uniformly over the full height of the damper. A typical XPD with the holding device used in the present work and its application to a piping system is shown in Fig. 1(a). A series of experimental tests was conducted at Bhabha Atomic Research Centre (BARC) [18] and IIT Bombay [19] to study the behavior of these dampers. The following observations are noted from the force–deformation characteristics of the XPD shown in Fig. 1(b): (i) it exhibits smoothly nonlinear hysteretic loops under plastic deformation, (ii) it can sustain a large number of yielding reversals, (iii) there is no significant stiffness or strength degradation and (iv) it can be accurately modeled by Wen's hysteretic model [20] or as a bilinear elasto-plastic material. A