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Piezoelectric sensing and non-parametric statistical signal processing for health monitoring of hysteretic dampers used in seismic-resistant structures

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ABSTRACT

The paper proposes a new application of non-parametric statistical processing of signals recorded from vibration tests for damage detection and evaluation on I-section steel segments. The steel segments investigated constitute the energy dissipating part of a new type of hysteretic damper that is used for passive control of buildings and civil engineering structures subjected to earthquake-type dynamic loadings. Two I-section steel segments with different levels of damage were instrumented with piezoceramic sensors and subjected to controlled white noise random vibrations. The signals recorded during the tests were processed using two non-parametric methods (the power spectral density method and the frequency response function method) that had never previously been applied to hysteretic dampers. The appropriateness of these methods for quantifying the level of damage on the I-shape steel segments is validated experimentally. Based on the results of the random vibrations, the paper proposes a new index that predicts the level of damage and the proximity of failure of the hysteretic damper.

1. Introduction

The traditional seismic design approach relies on the inelastic deformation of particular zones of the structure to dissipate most of the energy input by an earthquake (commonly, beam-ends and column-ends on moment-resisting frames). In contrast, in structural control systems, this energy is delivered to special devices that can be repaired or replaced after suffering damage. This is one of the reasons why structural control systems are installed on civil or building structures to improve their response under seismic events or wind loads and mitigate risks. In general terms, structural control systems can be classified into three categories: active, hybrid and passive. Active control systems consist of real-time processing sensors and force delivery devices that require an external source of power. Hybrid control systems use minimal power to change the control force opposed by certain elements of the structure. Although active and hybrid control are very powerful techniques, their application is normally restricted to large or very singular

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structures. In contrast, passive control systems consist of energy-dissipating devices (dampers) that do not require any external source of power.

Passive control systems afford many advantages: (i) the inelastic deformations are concentrated in the seismic dampers, and the damage in the parent structure can be drastically reduced or eliminated; (ii) the addition of damping reduces the lateral displacements of the structure, which also reduces damage to non-structural elements; (iii) by strategically locating the seismic dampers, their inspection, repair and/or replacement following an earthquake can be carried out with minimal cost and without interrupting occupancy. Overall, passive control systems are more affordable and can be more easily implemented in general purpose structures. These technologies have been increasingly taken into consideration in the USA after the Northridge earthquake (1994). Likewise, since the Kobe (1995) earthquake in Japan, more buildings have been designed to include dampers [1,2].

A structure with passive control comprises a main frame designed to predominantly sustain the gravity loads, and a series of special energy dissipating devices (EDD) also called dampers, which dissipate most of the energy input by the earthquake, as shown in Fig. 1.

Several mechanisms have been used for passive energy dissipation, including metal yielding, phase transformation of metals, friction sliding, fluid orificing, viscous dampers, deformation of viscoelastic solids or liquids [3–5] and hysteretic dampers [6]. Viscous (solid or liquid) and friction dampers dissipate the vibration energy through heat, while hysteretic dampers are based on the yielding or phase transformation of metals. The hysteretic damper is one of the most widely used EDDs due to its good balance between cost and efficiency. However, since both yield and phase transformation of metals involve inelastic strains in the material (i.e. damage), evaluating the health of the hysteretic damper after a seismic event is a matter of great concern.

The goal of passive control systems is to limit the damage on the main structure under different levels of ground motion hazard. In the modern framework of seismic design called performance based design, the level of damage allowed on the main structure for each level of seismic hazard must be determined by the designer. For minor or moderate earthquakes (i.e. those with a probability of exceedance of 50% and 20% in 50 years), the main frame of a structure with hysteretic EDDs must remain within the elastic range (i.e. undamaged) and most of the seismic input energy must be dissipated through plastic deformations on the EDDs. Wind storms can also induce plastic deformations on the dampers while the main frame remains within the elastic range. Minor to moderate earthquakes and wind storms can occur several times during the lifetime of structure and usually do not exhaust the energy dissipation capacity of the hysteretic EDD. That is, the EDDs would not need to be replaced after a minor or moderate earthquake or after a wind storm, provided that their health (i.e. level of damage) and their proximity to failure can be reliably evaluated. Simple visual inspection is not enough to determine the proximity to failure of a hysteretic EDD because the damage caused by the plastic deformation of the steel is not visible until the element is in its final stage, near collapse.

Non-destructive techniques (NDT) or structural health monitoring (SHM) strategies can be appropriate to determine whether the hysteretic EDDS need to be replaced after a seismic event or wind storm. SHM refers to systems embedded in the structure that may detect the occurrence of damage that represents a structural risk. This saves time and reduces maintenance costs because unnecessary inspections and replacements are avoided. In contrast to NDT, SHM strategies assume that sensors are permanently attached to the structure, working for its whole service life without operator intervention. Thus, data collected by the sensors that are distributed throughout the structure must be automatically processed and synthesized for warning signals when damage is detected.

In recent years, many SHM techniques have been improved and new sensor technologies have appeared in the area of damage detection in structures. The goal of these innovations is that the structures can be self-sensed and intelligent, to preserve their integrity, optimize their performance, and provide continuous safety for their users and operators. Most experiments are oriented toward aeronautical and civil areas, and are applied to composite materials, aircraft structures, aluminium plates, glass fiber panels and reinforced concrete columns and blocks.

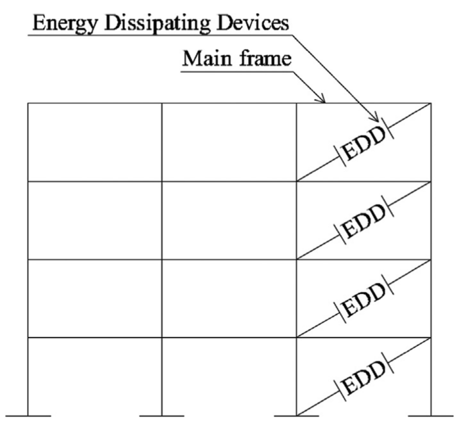

Fig. 1. Basic configuration of a frame with energy dissipating devices (EDD).