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Large-scale experimental evaluation and numerical simulation of a system of nonlinear energy sinks for seismic mitigation

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ABSTRACT

As a novel dynamic vibration absorber, the nonlinear energy sink has been studied for mitigating structural and mechanical vibration through the last decade. This paper presents a series of large-scale experimental evaluations and numerical simulations on a system of nonlinear energy sink (NES) devices for mitigating seismic structural responses. Two distinct types of NES devices were installed in the top two floors of a large-scale model building structure. In the device system, four Type I NESs employing smooth essentially nonlinear restoring forces were used in conjunction with two single-sided vibro-impact (SSVI) NESs employing non-smooth impact nonlinearities. These NES devices utilize the existing structural mass and space of the model building to realize an integrated design of building structure with non-parasitic control devices. Scaled historic earthquake ground motions were implemented by a large-scale shake table as the base excitation input into the system. Direct comparisons between mitigated and unmitigated structural responses, including story displacement, column strain and base shear force, demonstrate that rapid mitigation of structural responses was achieved by the system of devices. Reductions of both peak and average values of structural responses were clearly observed. The synergistic effects obtained by simultaneously using two types of NES devices were demonstrated. To computationally investigate the mitigation performance of the devices subjected to a wide variety of ground motions, a numerical model was developed for the structure-NES system and two suites of earthquake ground motions representing distinct earthquake intensities were employed. Simulation results demonstrate that mitigation of structural responses caused by diverse earthquake ground motions can be achieved by a system of NES devices.

1. Introduction

During the past several decades, a variety of passive energy dissipation devices have been proposed and developed for civil engineering applications [1,2]. By definition, passive devices are unpowered and utilize their intrinsic response to mitigate structural vibration. Based on different operating mechanisms, these devices can be subdivided into dissipative vibration dampers and dynamic vibration absorbers (DVAs). The dissipative vibration dampers include various metallic dampers, friction dampers and viscoelastic dampers [3–5]. These devices achieve their vibration mitigation by transforming vibration energy into heat. Devices in the other category, the DVAs, typically consist of a mass-spring system with damping properties. These devices can absorb vibration energy from the primary structure and locally dissipate it. The application of linear DVAs dates back to the first half of the twentieth century [6–8]. The natural frequency of the linear absorber is normally tuned to the vicinity of the most energetic structural mode so that it can resonantly suppress the vibration at this mode. Due to its fixed natural frequency, the suppression bandwidth of the linear absorber is relatively narrow. Distinct from the linear absorbers, nonlinear DVAs employing smooth nonlinear spring components were proposed and found to be capable of suppressing vibratory motions over a broader frequency band [9,10].

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Another type of nonlinear DVA is the impact absorber [11,12]. For these devices, the moving mass impacts the primary structure and the momentum transfer and energy dissipation caused by the inelastic impacts are utilized to mitigate the structural vibration.

Since the last decade, nonlinear energy sink (NES) devices have been studied as DVAs employing essentially nonlinear restoring forces. "Essential nonlinearity" means the absence (or near absence) of linear component in any portion of the entire load-displacement characteristic of the spring element providing the restoring force. The nonlinear dynamic response of structures with attached NESs has been studied through extensive analytical studies and numerical simulations as well as a number of bench-scale experiments [13–22]. It has been demonstrated that when attached to a primary structure, properly designed NES devices can rapidly absorb vibration energy from the structure and locally dissipate it, leading to effective mitigations of structural vibration responses. A favorable phenomenon exhibited by the NES is targeted energy transfer (TET) [19], denoting the nearly one-way, irreversible transfer of vibration energy from the primary structure to a set of a priori defined NESs, in which it is locally confined and rapidly dissipated without backscattering to the primary structure. Due to the nonlinear stiffness, the NES has no fixed natural frequency, and, hence, can resonantly interact with single or multiple structural modes through isolated resonance capture or resonance capture cascades, respectively [23]. These features enable the NES to act as local, passive boundary controllers, which can be regarded as nonlinear and broadband generalizations of the linear DVAs whose suppression band is relatively narrow [18,19]. Besides absorbing and dissipating energy, the NES can also redistribute the vibration energy from low-frequency modes to high-frequency modes. This may benefit the vibration mitigation of many civil structures that have much lower modal contributions to displacement responses from the high-frequency modes than those from the low-frequency modes.

These developments motivated further investigation of the NES devices for hazard mitigation of civil engineering structures. During a recent research project funded by the Defense Advanced Research Projects Agency, several types of NES devices were physically designed, numerically simulated and experimentally tested on model building structures with different scales. Type I NES, the simplest form of the device, consists of a single-degree-of-freedom (SDOF) moving mass coupled to the primary structure through essentially nonlinear spring and linear viscous damping elements. A two-DOF form of the NES, Type III NES, is composed of two Type I devices connected in series. Distinct from these two types employing smooth nonlinear restoring forces, a single-sided vibro-impact NES (SSVI NES) employs non-smooth impact nonlinearity between the device and the structure. These three types of NES were experimentally tested on a two-story small-scale model building using impulse-like base motions [24–26]. Based on these small-scale studies, an innovative Type III NES employing nonlinear restoring forces provided by specially designed elastomeric bumpers was developed and tested on a six-story medium-sized model building [27,28]. Finally, the research work culminated in a series of large-scale experiments of an approximately five-meter-high, nine-story steel frame equipped with four Type I and two SSVI NES devices using both impulsive and seismic base motions.

This paper presents the large-scale experimental evaluation of a model building equipped with multiple NES devices for mitigation of seismic response. Different from previous experimental studies in which a single type of NES device was tested on a small to medium-scale structure using impulsive base motions, in the presented study, a nine-story large-scale model building structure was constructed as the test bed. Furthermore, on this model building, six NES devices of two distinct types were installed and operated simultaneously in the experiments. Historic earthquake ground motions with reduced scales were input into the structure-NES system by a large-scale shake table. The main purpose of the experimental program is to explore the feasibility and effectiveness of applying the NES technology to the seismic protection of large civil structures. The NES devices in this study were originally designed to mitigate the structural vibration caused by a generic impulse-like base excitation. The general design procedure used is similar to that discussed in [28]. The first step was to develop a multi-degree-of-freedom (MDOF) numerical model of the structure equipped with the NES devices. This model was used to simulate the responses of the structure-NES system subjected to the given impulse-like base motion. To determine the design variables of the devices, mainly the stiffness parameters of the two types of NES, a multi-variable numerical optimization was performed using the system model in MATLAB [29]. The values of the design variables were iterated by the optimizer to achieve maximized first-mode effective damping. Finally, elastic cords and elastomeric springs were employed to approximately realize these numerically optimized design variables of the devices. The development of the numerical model and physical configurations of the devices will be further discussed in following sections.

The observed good performance in suppressing impulsively excited vibration motivated the evaluation of the devices for seismic mitigation. Through numerical simulations performed before the seismic testing, it was found that these NES devices designed for the impulsive loading can also provide significant response reduction for earthquake ground motions whose input energy levels are similar to that of the impulsive base motion. This is expected because the performance of the nonlinear device typically depends on the input energy level to a certain degree. According to a recent study [26], the SSVI NES can provide mitigation over a relatively broad range of input energies. Moreover, as one of the objectives of this work was to evaluate the robustness of the system to multi-hazard scenarios, the devices were not re-designed. However, the design procedure described in the last paragraph for impulse-like base motions is also applicable to designing the devices for any earthquake ground motion of interest.

For the seismic testing, three historic earthquake ground motions scaled at various levels were implemented as the base excitation. The performance of the multiple NESs was experimentally evaluated by direct comparisons of a variety of structural responses with and without the mitigation effect of the devices. The synergistic effects achieved by simultaneously using different types of NES were also discussed. Finally, a numerical model of the structure-NES system was developed and simulations were performed using a variety of earthquake ground motions with diverse characteristics to computationally evaluate the effectiveness and robustness of the devices.

2. Model building structure and nonlinear energy sink devices

2.1. Nine-story model building structure

As the test bed on which the NES devices were installed, a large-scale model building structure was constructed. This structure is a nine-story steel frame that has a height of 5.12 m and a mass of approximately 10,000 kg. The model building was designed to represent the dynamic properties of a prototype mid-rise building, so its fundamental period was designed to be around 0.6 s, which is a common value for mid-rise buildings. The structural system of the building is a typical "shear frame" whose deformation under horizontal base motions is dominated by the in-plane translational motion of the floors. Fig. 1(a) shows the structure fixed on the shake table. The floor system consists of nine steel floor plates