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Performance evaluation of existing isolated buildings with supplemental passive pseudo-negative stiffness devices

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ABSTRACT

A new configuration for passive pseudo-negative stiffness device (PPNSD) is proposed to work as a supplemental device for the seismic protection of existing isolated buildings. The proposed PPNSD reproduces the hysteretic behaviors of semi-active pseudo-negative stiffness devices (PNSD). Using the ratchet-pawl mechanism, a prototype was realized and tested under cyclic loading, validating the feasibility of the proposed PPNSD. Seismic reduction effect of the PPNSD on single-degree-of-freedom (SDOF) systems was verified through seismic response analysis. The PPNSD shows superiority in suppressing the peak acceleration response of long period structures, which is unlikely to be achieved even with large supplemental damping. Then, the performance of isolated buildings with PPNSD was evaluated in comparison to those of isolated buildings with traditional passive isolators under far-field (FF), near-fault pulse-like (NFP), and near-fault non-pulse-like (NFNP) ground motions. It is shown that the use of PPNSD not only simultaneously reduced the base drift and the acceleration of superstructures, but also was effective for all the FF, NFNP, and NFP motions.

1. Introduction

Suppressing structural displacement and acceleration responses concurrently under earthquakes is an important issue for isolated buildings. The maximal structural acceleration response determines the damage level of the superstructures, while the maximal base drift response determines the "seismic gap" required for utilities, connections to adjacent structures or sidewalks. The three passive isolation systems most commonly used today, i.e. elastomeric bearing systems, lead rubber bearings and friction pendulum systems, might suffer from excessive base drifts when subjected to near-fault ground motions, especially for near-fault pulse-like ground motions having pulse periods close to the isolation period [1,2]. That requires a careful selection of equivalent damping and effective stiffness of conventional passive isolator for new designed isolated buildings closing to the fault. For retrofitting existing isolated buildings, or further improving the performance of existing isolated buildings, one can also replace the former LRB with a new LRB which has lower effective period and higher equivalent damping ratio. From the point of view of practical application, this method costs too much for the need of uplifting the entire building. Therefore, the use of supplemental devices seems more practical for retrofitting existing isolated buildings. Generally, the most widely-used supplemental device is the viscous damper, which increases the equivalent damping ratio of the isolation system. Previous studies [3,4] showed the use of only high additional damping would effectively reduce such excessive base displacement, but at the expense of possible increase in inter-story drifts and floor accelerations, thus defeating much of the gain intentionally to be achieved by base isolation. It seems that only using supplemental viscous damper cannot further reduce the displacement and acceleration responses of isolated buildings simultaneously. Therefore, active and semi-active control strategies, which use sensors and actuators or devices with controllable force to provide optimal resisting force for structures [5], have attracted more attention in seismic isolation. It has been validated that active and semi-active strategies may be able to provide the reduction in base drift responses without the increase of superstructure motion seen for passive devices [6–8].

One major reason why active/semi-active strategies are more effective than passive strategies is that the former introduces apparent negative stiffness to the structures [9–11]. For example, active control using linear quadratic regulator (LQR) algorithm, which aims to minimize both the structural response and the device force, may produce a force-deformation relationship with an apparent negative stiffness feature that benefits the control effect [12]. As active/semi-active control strategies require feedback systems and energy supply, which cannot always be guaranteed during extremal disasters such as

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earthquakes, passive negative stiffness mechanisms or devices have become more appealing in civil engineering. In 2010, Nagarajaiah et al. [13] first published their pioneering work on the passive realization of negative stiffness devices (NSDs) for civil engineering application. This work was further then developed by Sarlis et al. [14] and Pasala et al. [15] in 2013. The NSD proposed by Nagarajaiah et al. [13–15] is made up of a pre-compressed spring, a pivot plate, a gap spring, a self-containing system, and viscous damping devices. The pre-compressed spring and the pivot plate can generate true negative stiffness bi-directionally. The gap spring is used to simulate a bilinear elastic behavior with an apparent-yield displacement, helping the primary structural system to suffer fewer base shear. Later, this NSD type was extensively studied through experiments and numerical analysis [16–18]. Application of this NSD in isolated buildings [19] and highway bridges [20–22] were also carried out. Meanwhile, further researches were extended to other passive NSD configurations such as the NSD using pre-compressed spring and ramps [23], the NSD using pre-compressed spring and templates [24,25], the NSD using pre-torqued torsional springs and gearwheels [26]. In 2015, Shi and Zhu et al. [27–30] proposed and tested a magnetic NSD which uses the attraction of the magnets to achieve negative stiffness. Later, this magnetic NSD is optimized and is applied to stay cables, achieving satisfactory effectiveness.

In comparison to the above NSD pursuing true negative stiffness mechanism which shows rare hysteresis in force-displacement curves, pseudo-negative stiffness device (PNSD) not only performs apparent negative stiffness properties in its hysteretic curves, but also provides energy dissipation capacity. In 2002, to improve the performance of an isolated cable-stayed bridge, Iemura and Pradono [11,31] proposed a semi-active PNSD (as shown in Fig. 1(a)), which generated a hysteresis curve similar to that of the friction bearing plus negative stiffness effect. Their proposed PNSD, combined with a positive stiffness curve of the deck-tower connections, achieved a very large damping ratio (53.4%), which was close to the 64% damping ratio of rigid-perfectly plastic force-deformation characteristics, without increasing the total structural force. Consequently, this PNSD reduced not only base displacement but also force transmission to the superstructure. In this regard, the effectiveness and application of this PNSD of base-isolated structures has been extensively studied in the past [32,33]. Moreover, Iemura et al. [12] also proposed a passive configuration for this type of PNSD, which works similarly to the friction pendulum sliding isolator but has a convex friction interface (as shown in Fig. 1(a)). Their device was validated by a shaking table test, showing that the PNSD has a large damping ratio while keeping the total force low.

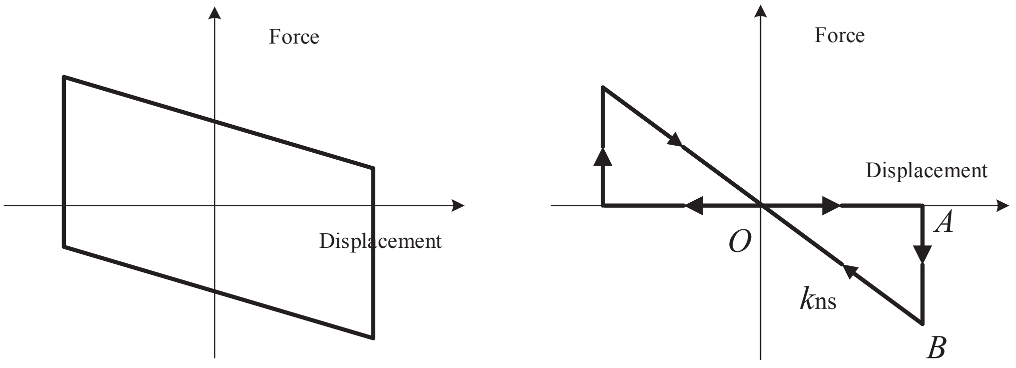
Nevertheless, in terms of isolated buildings, the control force of this conventional PNSD at the centered location is nonzero and quite large, which may potentially increase the response of superstructures [34]. Wu et al. [35] proposed a novel type of semi-active PNSD with zero centered force which exhibited triangular-shape hysteretic curves (as shown in Fig. 1(b)), where k_{ns} is the so-called pseudo-negative stiffness. This new PNSD type was demonstrated to perform better than the traditional PNSD in improving the structural functionality at low seismic intensity as well as improving the structural safety at extreme seismic intensity [34]. Later, Gong et al. further improved this kind of PNSD based on the ‘ideal isolation control principle [34], or based on filter to prevent isolated structures from experiencing significant jerks under earthquakes rich of high-frequency components [36]. Meanwhile, previous studies [34,35] about the isolation performance of this zero-centered-force semi-active PNSD were mainly limited to the case of far-field ground motions (source-to-site distance bigger than 10 km according to [37]), lacking evaluation in the case of near-fault motions. Last but not least, there is no passive configuration for this type PNSD, which limits its further application.

Therefore, this paper proposed a new configuration of passive pseudo-negative stiffness devices (PPNSD), which reproduces the hysteretic behaviors of the semi-active zero-centered-force PNSD [35]. Using the ratchet-pawl mechanism, a prototype was realized and tested under cyclic loading to validate the feasibility of the proposed PPNSD. The seismic reduction effect of the proposed PPNSD on SDOF systems was verified through the seismic response analysis. Then, the performances of isolated buildings with the proposed PPNSD were evaluated under different kinds of earthquake records, including far-field, near-fault pulse-like, and near-fault non-pulse-like ground motions.

2. Device description

2.1. Proposed configuration for the PPNSD

Unlike the force generated by positive stiffness devices, the control force of the true NSD is able to assist motion, rather than resist it at all time [23]. Particularly, for PNSD, the control force only hinders the structure from coming back to initial position (‘B-O’ in Fig. 1(b)) but not pushes the structure away from its equilibrium (‘O-A’ in Fig. 1(b)), performing apparent negative stiffness in the force-displacement diagram. In other words, the PNSD force suppresses the relative movement which is towards the initial position rather than the movement which is away from the initial position [34]. To passively achieve this feature, a new configuration for PPNSD is proposed in Fig. 2. The proposed PPNSD consisted of a unidirectional force device (UFD), two trolleys (Tx and Ty) and a rigid rod. The rod was connected to the trolleys using hinges. The trolley, Tx (Ty) shown in Fig. 2, can only move in X (Y) direction. The UFD is required to generate substantial force in one direction but rare force in the opposite direction (as shown in the red dashed box in Fig. 2). For simplicity, the UFD force is given as



(a) conventional PNSD (b) zero-centered-force PNSD

Fig. 1. Force-displacement diagrams of pseudo-negative stiffness devices (PNSDs).