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The Multangular-Pyramid Concave Friction System (MPCFS) for seismic isolation: A preliminary numerical study

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ABSTRACT

The Multangular Pyramid Concave Friction System (MPCFS) is introduced in this study. Different from the conventional Curved Surface Slider (CSS), the concavity of the MPCFS is designed as a multangular (mostly triangular or rectangular) pyramid, and the slider is removed from the isolator. While maintaining the virtues of the CFS, the MPCFS can provide greater vertical sustaining capacity with a more stable friction force. When combined with a cross uplift restraint, the MPCFS offers numerous virtues such as increased uplift stability, a greater initial yielding force, and resonance-dodge ability during near-fault earthquakes (variable frequency). Frequency-sweeping and acceleration time-history numerical investigations are conducted on a four-storey building model using the MPCFS. The revised State-Space Method (SSM) is expanded from two-degrees-of-freedom to multi-degrees-of-freedom as to accommodate more complex analysis such as dynamic analysis of high-rise, multi-storey structure installed with MPCFS. The simulation result verifies the merits of the MPCFS, indicating that the MPCFS, viewed as a beneficial complement to the existing well-established isolation techniques, may be a promising tool for the seismic isolation of high-rise, and super high-rise buildings in near-fault earthquake prone zones.

1. Introduction

1.1. Background

The recent devastating earthquakes on 16th April in Japan, 24th August in Italy in 2016, and 19th September in Mexico in 2017 have reminded us of the crucial importance of ensuring the structural safety of residential and commercial buildings during large earthquakes. These earthquakes caused extensive damage and resulted in numerous victims, even though they were not extremely severe (Mw = 7.0 and 6.2 in the Japanese Kyushu island, 6.0 in the Italian Amatrice area, and 7.1 in the Central Mexico) and that the structures in these nations are usually much better constructed than those elsewhere. This result was probably due to the "superficial" nature of these events (hypocentre depths about 10 km). This issue of securing seismic building safety has been addressed extensively and intensively by a multitude of structural engineers and seismological researchers worldwide in the past seven decades, with numerous effective and practical methods being innovated to achieve various seismic hazard mitigation goals.

Seismic isolation, among these anti-seismic achievements, is generally viewed as one of the most substantial fruits obtained by the earthquake engineering community up to now. By positioning a soft, sliding or rolling layer between the superstructure and the foundation, the transmission path of the ground excitation energy to the upper building is cut off, so that the structural seismic response is significantly reduced. Further, since the seismic isolators have a very low stiffness compared to the superstructure, the overall stiffness of the building is dominated by the isolation layer, if the isolators are sufficiently stiff in the vertical direction to prevent vertical rocking motion. The structural fundamental horizontal period, therefore, is shifted by the isolators to a longer value. When the earth shakes, this period elongation (usually over two seconds) can enable the structure to shun the energy-rich frequency range (less than one second) of the spectral ground acceleration, which is common for most far-field earthquakes.

Seismic isolation techniques can mainly be categorized into two different types, rubber bearing (RB) and sliding or rolling friction bearing. Each of these two isolation tools has its own advantages: RB is cost-effective, has good self-centring ability, and can better accommodate the concrete creeping of the structure and uneven settlement of the foundation [1]. The friction bearing, generally achieved using a curved surface slider (CSS) or a rolling isolator, can provide a greater vertical sustaining load [2,3]. Such isolation techniques, introduced by the world's leading academicians in earthquake engineering, have been widely applied in the U.S., Japan, China and other nations, saving

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thousands of precious lives plus millions of dollars from potential seismic hazards, which should be sincerely respected and kept in mind.

The existing well-established seismic isolation tools have successfully helped a multitude of buildings to withstand severe earthquakes, which are mostly far-field ground shakings. However, the situation may be different if the building is subjected to near-fault/field excitations. Compared to far-field shaking, the near-fault earthquake may have a greater vertical peak ground acceleration (PGA), which may increase the ground overturning moment to the structure. Moreover, the energy-rich frequency band of the near-fault earthquake may be concentrated over a period of two seconds, which could induce resonance in conventional isolated buildings. This resonance-like phenomenon has already been observed in a real case, in which the structural response of an isolated building was greatly magnified due to resonance with the local near-fault shaking in the 2011 Great East Japan (Tohoku) Earthquake [4]. These adverse effects may impede the overall performance of the conventional isolation systems when they are subjected to near-fault earthquakes.

1.2. Literature review

With the aim of providing a more robust, greater-performance solution than the conventional seismic isolation systems, a multitude of novel isolation tools have been introduced by researchers.

To control the displacement in conventional base isolators within a safe level during near-fault shakings, Saitoh [5] proposed a rotary friction technique with a wire wound on a shaft attached to a coil spring, which uses the "ratchet switch" mechanism. Computational results show that this tool effectively reduces the maximum lateral displacement of the isolators during near-fault and long-period ground motions. Ismail et al. [6–10] introduced the roll-in-cage isolator, which is very efficient in balancing isolator displacement demands and structural accelerations. This novel isolator also has a built-in energy-absorbing buffer and linear re-centring mechanism that can be very beneficial in protecting against near-fault earthquakes. A systematic parametric study was performed by Chen et al. [11] to illustrate the advantages of using abalone shells as an innovative bio-passive base isolation system. The proposed isolator is determined to have superior performance over conventional passive isolation systems, especially when subjected to near-fault earthquakes. A new roller seismic isolation tool was developed by Lee et al. [12] for use in highway bridges. This new isolation technique uses the rolling of cylindrical rollers on conical sloping surfaces to achieve seismic isolation. An experimental study on the prototype bearing was performed to verify its seismic isolation. A rolling isolation system with similar principles was studied by Harvey Jr. et al. [13,14]. The XY-FP sliding isolation system, introduced by Rouses and Constantinou [15,16], has been analytically and experimentally studied at the University of Buffalo. The results show that this isolator can appealingly be applied to near-fault strong ground motions and uplift-prone structural systems. The XY-FP bearing was also studied by Marin-Artieda et al. to test its performance on bridges [17,18]. Lu and Hsu [19] introduced variable-frequency rocking bearings (VFRB), which have variable mechanical properties. The variable-frequency mechanism enables this isolator to effectively suppress the excessive isolator displacement during a near-fault earthquake, while retaining good isolation. The Geotechnical Seismic Isolation (GSI) system, which uses rubber-sand mixtures as an energy-dissipating source, was introduced by Tsang [20]. This isolation technique is cost-effective and eco-friendly, making it especially suitable for financially distressed developing countries. The GSI was later studied numerically [21] and experimentally [22]. With the same aim of providing an effective and robust seismic isolation system for less developed regions, Yao et al. [23] introduced the steel-asphalt composite layer system. Experimental results show that this isolator can efficiently reduce the structural response and control the displacement limit. More researches can be found in the Refs. [24–28].

1.3. Multangular-Pyramid Concave Friction System (MPCFS)

In this research, the Multangular-Pyramid Concave Friction System (MPCFS) is presented. The design of the MPCFS is a further refinement of the Convex Friction System (CFS). While maintaining the features of the CFS, the MPCFS can offer a larger vertical sustaining load with a more constant friction coefficient. The authors have no intention to claim that this MPCFS will replace the existing well-established and matured isolation techniques. Rather, it is a beneficial complement to these excellent tools that make the structures much safer during earthquakes.

The MPCFS can offer numerous virtues such as increased uplift stability, a greater initial yielding force, and resonance-dodge ability during near-fault earthquakes (variable frequency). These virtues are qualified and quantified in the remainder of this paper. This research is fourfold:

(1) The design of the MPCFS is first presented, and its design enhancement over the CFS is illustrated, the design procedure of the MPCFS is also presented.
(2) The design of the MPCFS is then followed by the establishment of a numerical model for the acceleration time-history analysis of the MPCFS. The numerical model is expanded to multi-degrees-of-freedom for the consideration of more complex and high-rise buildings.
(3) Furthermore, an acceleration time-history analysis using the established numerical model is conducted to compare the initial yield force between the CSS and the MPCFS. A time-history numerical simulation is also performed for evaluating the seismic isolation of the CSS and the MPCFS.
(4) Next, the limitations of this study are discussed. Finally, conclusions on the feasibility and overall performance of the MPCFS are drawn.

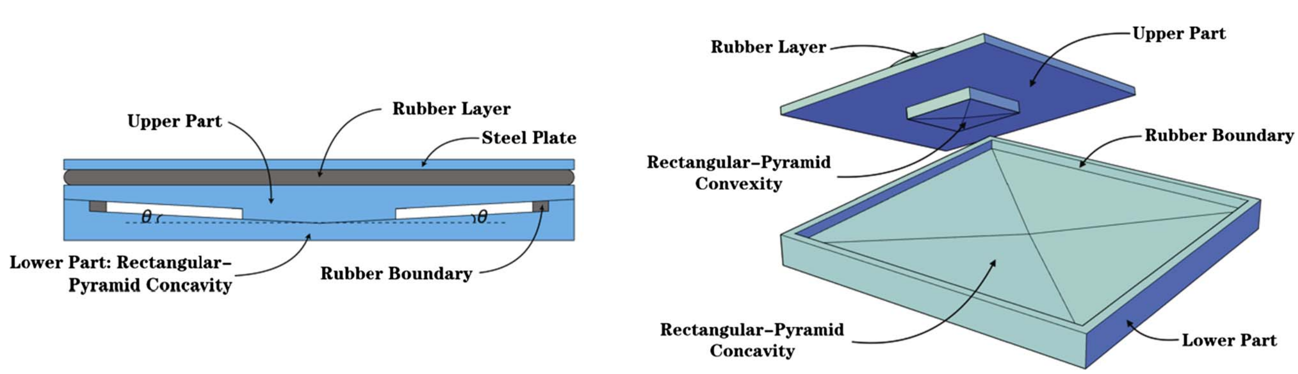

Fig. 1. Design of the MPCFS. (a) Cross-section view; (b) Perspective view.