Shake-table testing of resilient, low-cost seismic isolators based on rolling rubber spheres

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ABSTRACT

This study presents the results of a large-scale experimental investigation of sustainable and low-cost seismic isolators based on deformable rubber spheres, rolling of concrete surfaces. Three types of polyurethane spheres were tested, with varying diameter, with or without a steel core inside them. Both flat and spherical (concave) concrete plates were investigated. A potential application of the proposed isolator could be in low-rise masonry structures in the developing world. The spheres were first subjected to monotonic and sustained compression to investigate their response under vertical load. Subsequently, lateral cyclic tests were performed. Finally, a total of 1170 shake-table tests were performed in 1:2 scale, with various different isolators subjected to a large number of ground motion excitations. Results showed that the compressive strength of the spheres was substantially higher than the design load. The rolling friction coefficient ranged between 3.7% and 7.1%, with these values being suitable for seismic isolation applications. A higher vertical load leads to a slightly higher value of the rolling friction coefficient and increased energy dissipation. The spherical concrete plates increase the restoring force of the system. When tested in a shake table under 1170 ground motions, the isolators substantially reduced the acceleration transmitted to the superstructure (to less than 0.15 g) while maintaining reasonable peak displacements. Notably, the shake table tests were repeatable, and the isolators did not deteriorate even after being subjected to 65 ground motion excitations.

1 INTRODUCTION

Even though earthquakes are a global phenomenon, their impact, both in terms of fatalities and economic loss, is mainly concentrated in the developing world. This is due to the high vulnerability of the building stock in areas of the world where modern structural codes are too expensive to be followed. Hence, there is a pressing societal need for earthquake-resistant solutions that are applicable in low-income countries.

Seismic isolation is an effective method of seismic protection. The conventional implementation of seismic isolation includes the installation of bearings with low lateral resistance at the base of the structure to uncouple the superstructure from the ground motion. These bearings should have high bearing capacity under vertical loading to support the gravity load of the superstructure. Due to its high cost, seismic isolation is mainly applied in important projects in the developed world. The applications of the method in the developing world are much more limited. To address this problem, reduced-cost isolators have been proposed over the last decades. These isolators are distinguished into flexible rubber bearings, sliding bearings, and rolling bearings.

The replacement of steel shims (used in conventional steel-laminated bearings) with flexible fibre reinforcement reduces the cost and weight of the isolators, leading to the "Fiber reinforced Elastomeric Isolator (FREI)" (Das et al., 2016; De Domenico et al., 2023; Galano and Calabrese, 2023; Osgooei et al., 2014; Toopchi-Nezhad et al., 2009; Tran et al., 2020; Van Engelen et al., 2014, 2016). FREIs remain too stiff to isolate lightweight residential buildings. Conventional sliding-based seismic isolators (such as the Friction Pendulum System, FPS) require polished metals and Teflon surfaces from the sliding interfaces. This increases their cost and limits their applicability in the developing world. Jampole et al. (2016) studied high-density polyethylene sliders on galvanized steel as an alternative to these interfaces. Brito et al. (2019, 2020) used concrete-steel friction interfaces. In both previous systems restoring force is provided through the use of concave surfaces, similar to the FPS. Tsiavos et al. (2020, 2021) used sand grains enclosed in PVC sheets as isolation layers below the foundation slab. These sliding-based isolation systems act as a fuse, limiting the maximum transmitted acceleration at the values of the sliding friction coefficient. Such a solution lacks restoring force.

Rolling bearings have been extensively used, with the vast majority of the applications comprising steel bearings rolling on steel surfaces (Harvey et al., 2014; Harvey and Kelly, 2016). Hence, they may be too expensive to apply in low-income countries. The use of rubber at the contact interfaces was proposed to increase damping and reduce localized failure (Foti 2019; Katsamakas et al., 2021b, 2022c; Katsamakas and Vassiliou, 2022b; Zéhil and Gavin, 2014).

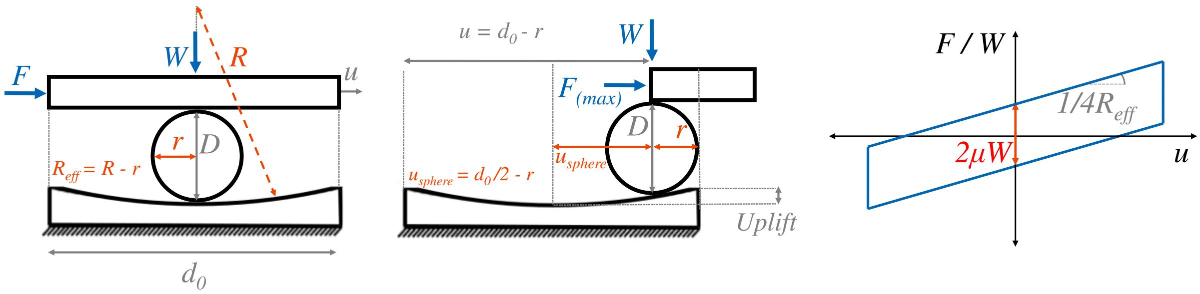

Figure 1. Rigid body model for rolling seismic isolators. Left, Isolator under compressive load and zero lateral displacement; Middle, Isolator under compressive load and maximum lateral displacement; Right, Bilinear force-displacement plot.

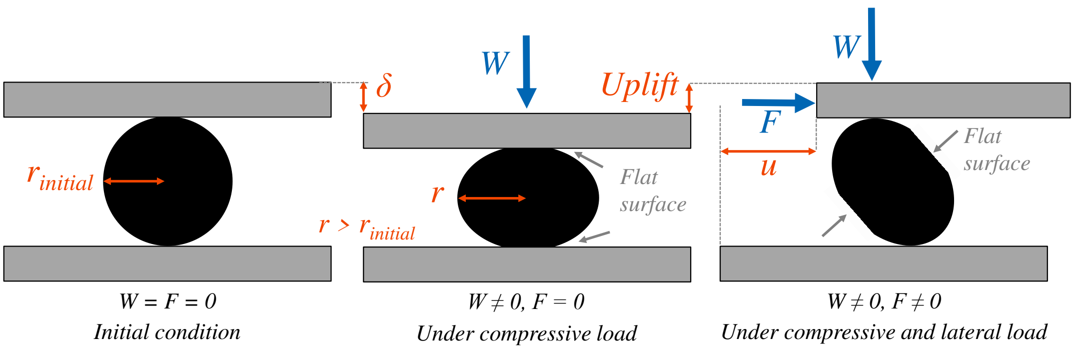

Figure 2. Left, Initial condition of the spherical isolator; Middle, Isolator under compressive load with evident compressive displacement; Right, Isolator under compressive and lateral load, with evident uplift.

2 DESCRIPTION AND POTENTIAL APPLICATION OF THE ISOLATOR

2.1 Description of the isolator

One of the most recent suggestions for seismic isolation of lightweight residential structures has been the Spherical Deformable Rolling Seismic Isolator (SDRSI) (Katsamakas and Vassiliou, 2023), initially proposed by Cilsalar and Constantinou (2019a, 2019b). The isolator is based on a deformable elastomeric sphere rolling on concrete surfaces (Fig. 2). It is noted that, in most cases, the deformability of the sphere cannot be neglected and that the response is significantly different from an idealized rigid-body model (Katsamakas et al., 2022a). This is due to residual "creep" deformation of the sphere under vertical compressive load that results in essentially rolling an oval-shaped sphere, rather than a perfect sphere (Fig. 2).

In a practical application, one of the concrete surfaces should be concave to provide restoring force to the system. Configurations with two flat plates are also tested in the present study to characterize the behaviour of the rolling sphere without the curvature of the concrete surface influencing the response.

2.2 Potential application of the isolator

A potential application of the proposed isolator could be in one- or two-story masonry houses, in countries where reinforced concrete is unavailable or unaffordable. In these regions, the construction of seismically-isolated masonry houses could be a viable solution for earthquake-resistant structures. Communication with practicing engineers from Cuba and Peru has unveiled that, in many low-income countries, seismic isolation cannot be financially viable for low-rise buildings because of the cost of the additional, heavily reinforced slab (diaphragm) that is typically constructed at the isolation level. Unless the cost of this slab is reduced, seismic isolation cannot be financially competitive, even if the isolation system is provided at zero cost.

We propose a combination of the systems of Cilsalar and Constantinou (2019a, 2019b) and of the one suggested by Tsiavos et al. (2020, 2021), for the isolation of 1-2 story masonry houses (Fig. 3). The walls are supported on concrete beams that serve as the upper rolling surface of the isolators. The ground floor slab will be continuously supported by two sheets of PVC (with sand in between). Such a continuous support allows for reducing the thickness of the slab and for providing minimal (if any) reinforcement, making its cost similar to the cost of a concrete slab-on-grade that is used in fixed base structures.

Because of the SDRSIs, a horizontal motion of the beams also causes a vertical one. Therefore, a PVC joint could be used to connect the slab to the beams. This would allow the vertical motion of the beams while the slab only moves horizontally (Fig. 3).

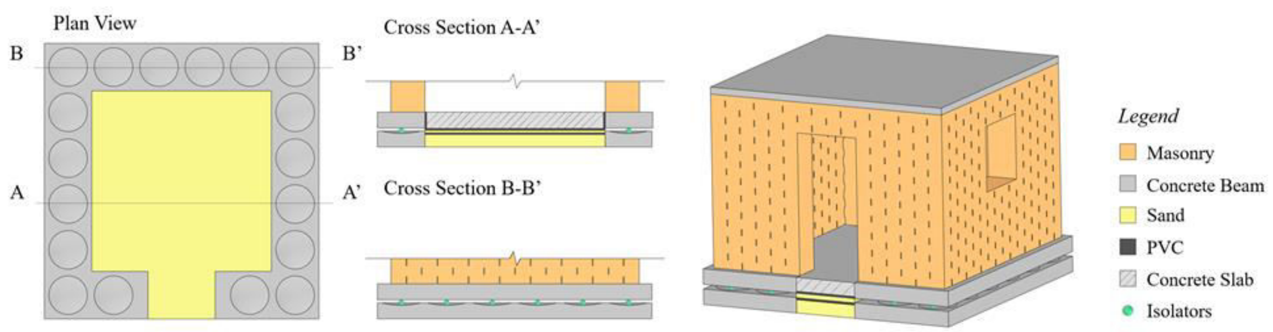

Figure 3. Representation of a potential application of deformable rolling isolators in low-rise masonry buildings.

3 EXPERIMENTAL SETUP

3.1 Testing equipment and instrumentation

Both the lateral cyclic and the shake-table tests were performed using the uniaxial shake table of ETH Zurich. The experimental setup comprises 4 isolators (Fig. 4). An isolator comprises a polyurethane (PU) sphere rolling between two concrete plates. In all tested configurations, the lower concrete plates were flat. The upper concrete plates were either flat ("flat configurations") or spherical/concave ("spherical configurations"). The lower concrete plates were fixed to the shake table platen, whereas the upper ones were mounted on a steel slab.

During the lateral cyclic tests, the motion of the top slab parallel to the x-axis (and the out-of-plane y axis) was restrained by two rigid struts fixed to a rigid column (Fig. 4). The shake table applied a sinusoidal motion to the bottom concrete plates, the top plates were kept in place by the rods, and shearing of the isolators was achieved. The vertical load (emulating the weight of the isolated superstructure) was applied by fixing masses on top of the steel slab. For the shake table tests, the steel rods were removed, and the steel slab was free to move along the x-axis.

Three-dimensional accelerometers were placed on top of the steel slab and the shake table platen. The struts that hold the steel diaphragm in place were equipped with load cells, measuring the reaction force of the isolators to the applied motion during the lateral cyclic tests. Another load cell was placed at the actuator that drives the shake table. The movement of the shake table and the superstructure was measured using an NDI Optotrak Certus camera, with an accuracy of 0.1 mm (Fig. 4).

3.2 Materials and geometry

Three types of spheres were tested: Solid spheres with a diameter of 100 mm, spheres with a diameter of 100 mm and a 50 mm steel core inside (spheres 100/50 mm), and spheres with a diameter of 80 mm and a 50 mm steel core inside (spheres 80/50 mm). The spheres were made of polyurethane (PU) with a shore hardness of 95A. The steel core was made of Gcr15 steel. The cost of 100 mm, 100/50 mm, and 80/50 mm spheres was $23, $30, and $25 per piece, respectively. For larger orders, the price per piece is expected to be significantly lower.

A commercial M15 concrete mix was used for the construction of the concrete plates. Figure 5 shows the dimensions of the spherical (concave) concrete plates. The mean compressive strength of the concrete mix was 27.6 MPa. The plates were unreinforced. The material cost of each plate was $6. In plan view, the diameter of the spherical concrete plate was 350 mm (Figure 5). The radius of curvature of the spherical concrete plates (R) was R = 750 mm.

3.3 Similitude laws and tested configurations

All tests were performed in 1:2 scale. To ensure similitude of stresses, the geometric, force and time scaling factors were S_L=0.5, S_F = 0.25 and S_T = 0.707, respectively. A modern unconfined masonry house in Cuba was considered (Katsamakas et al., 2021b) to calculate the expected vertical load, resulting in a gravity load of 11 kN (i.e. 2.75 kN in the model scale) per isolator. Four compressive loads (2.08 kN, 3.23 kN, 4.74 kN, or 8 kN per sphere - model scale) under 2 rolling surface curvatures (flat and concave) were planned for all 3 spheres. The actuator of the shake table had a stroke of 230 mm. To test the isolators under larger lateral displacements, two types of cyclic tests were performed: a) between -115 and +115 mm ("±115 mm") and b) between 0 and +230 mm and 0 and -230 mm ("±230 mm").

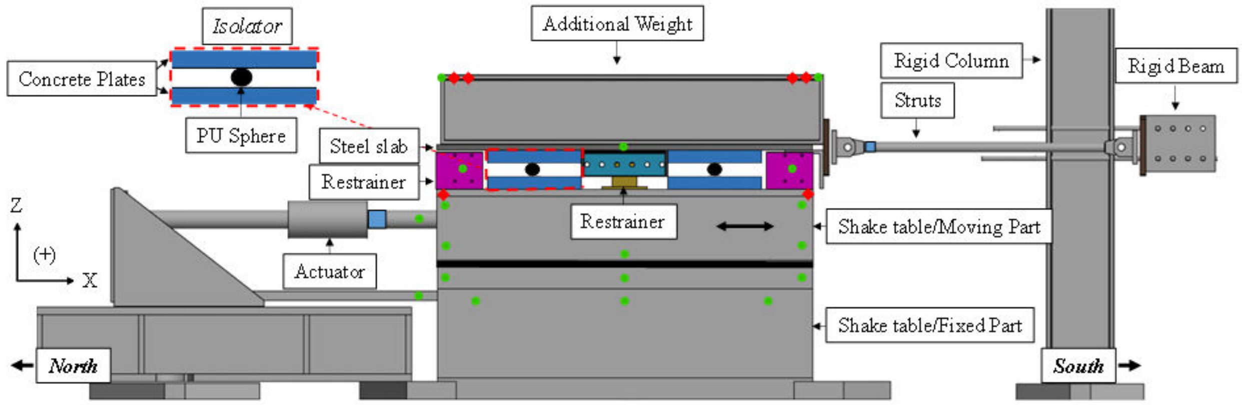

Figure 4. Representation of the experimental setup. Green circles, red diamonds, and blue squares show the location of the triaxial displacement sensors, the triaxial accelerometers, and the uniaxial load cells, respectively.

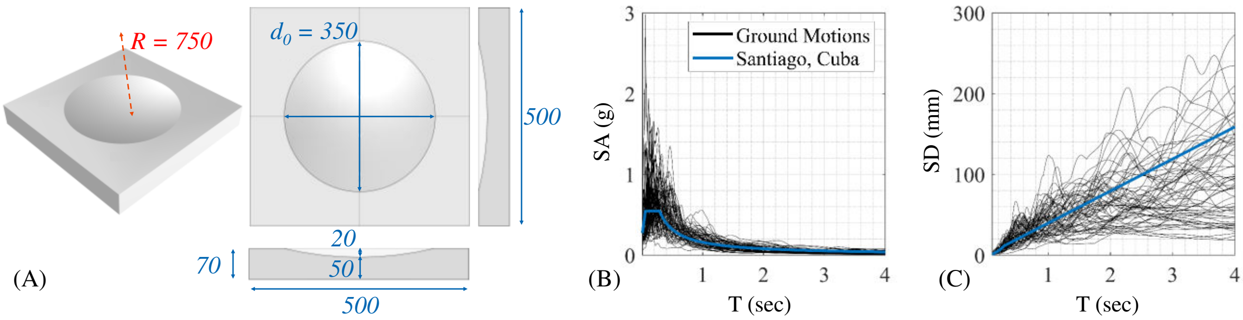

Figure 5. (A) Shape and dimensions of the utilized spherical concrete plates (in mm); Elastic response spectra of the applied ground motions and design spectrum of Santiago, Cuba (in model scale). (B), Pseudo-accelerations; (C) Displacements.

The shake table tests were performed under an ensemble of 61 different ground motions, selected from the three different categories of FEMA P695 (2009) (i.e., far-field, near-field pulse-like, and near-field non-pulse-like). All ground motions were scaled in the frequency domain since the tested model corresponds to a half-scale (S_L=0.5) representation of a prototype structure. Subsequently, all ground motions were acceleration-scaled to comply with the capacity of the shake table, with the acceleration scaling factor ranging from 0.7 to 1. Figure 5 (B,C) plots the elastic response spectra of the pseudo-accelerations and displacements of the ground motions used in the shake table tests, together with the design spectrum for a site in Santiago, Cuba (model scale), assuming soil type C, 5% damping and a return period of 475 years (Katsamakas et al., 2022b). The example of Santiago, Cuba is used in the present study since it is considered as representative of regions of high seismicity and low availability of construction materials. Similar (or higher) seismicity and analogous lack of recourses can be found in many countries in Latin America, in Asia, and Africa.

4 COMPRESSIVE AND LATERAL CYCLIC RESPONSE

4.1 Compressive response

The maximum load that the spheres sustained under monotonic uniaxial compression was 105.2 kN, 118.8 kN, and 102.5 kN for the 100 mm, 100/50 mm, and 80/50 mm spheres, respectively (Fig. 6). These load levels are substantially higher than the ones that the spheres would have to sustain in a practical application (Section 2). Therefore, the loss of vertical load-bearing capacity of the spheres is not the critical design parameter. Under design loads, the compressive displacement of the isolators is non-negligible, indicating the shape change of the spheres. A comparison of the 100 and 100/50 spheres shows that the presence of a steel core increases the stiffness of the sphere.

4.2 Lateral cyclic response

Before the lateral cyclic tests, the spheres were subjected to sustained compression for 7 days, so their "creep" displacement and shape change is concluded. The excitation frequency of all cyclic tests was $f = 0.2$ Hz. Figure 7 collectively offers the force deformation loops for all lateral cyclic tests. The first and most important observation is that the behaviour of the system is clearly not bilinear elastoplastic. In fact, since the sphere has deformed into an oval-shaped object, a vertical motion of the top plate was recorded both in the tests presented in this study and in (Katsamakas et al., 2021a; Katsamakas and Vassiliou, 2022a). This vertical motion influences the restoring force, which is positive for small displacements (up to 30 mm) but becomes negative for larger displacements, due to the rolling of the sphere. The use of concave concrete plates adds positive stiffness to the system.

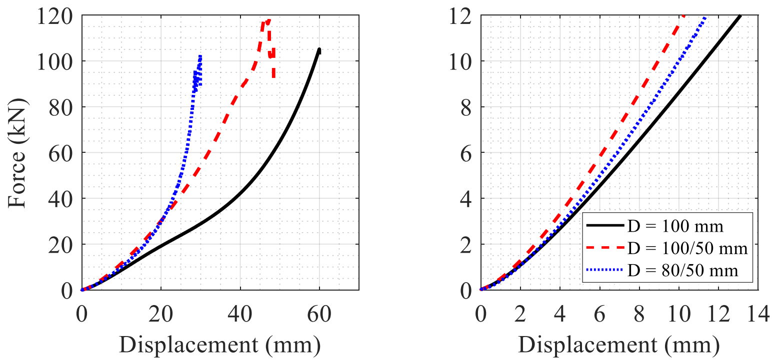

Figure 6. Compression testing results. Left: Force-displacement; Right: Force-displacement (detail).

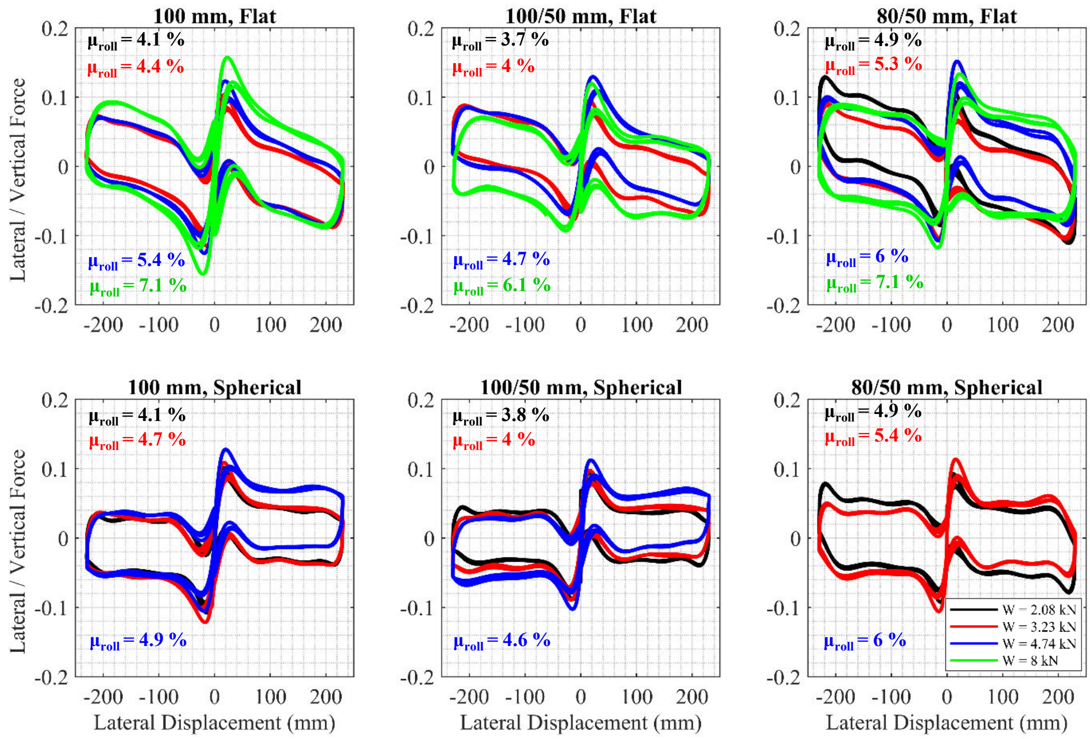

Figure 7. Influence of the vertical load (W) on the cyclic lateral response of the spherical isolator.

The rolling friction coefficient (μ_{roll}), is defined as the lateral-to-vertical force ratio at zero lateral displacement and describes the energy dissipation capacity of the isolator. In all following sections, the rolling friction coefficient was obtained by the "±115 mm" cyclic tests. The rolling friction coefficient, μ_{roll}, is noted in Figure 7. It is observed that as the vertical load (W) that each sphere supports increases, the rolling friction coefficient also increases. This is more pronounced in spheres without a steel core since they are more flexible. A detailed explanation of this phenomenon appears in (Katsamakas and Vassiliou, 2023).

5 SHAKE TABLE RESPONSE

Figures 8 and 9 show scatter plots between PGA and a) The acceleration of the top slab (Peak Superstructure Acceleration – PSA), b) the peak displacement of the isolators. Different categories of ground motions appear with different marks. Excitations with relatively small PGAs (smaller than 0.10-0.15) are not strong enough to start rolling the system (activate the isolators). Hence, the superstructure acceleration is roughly equal to the PGA (Fig. 8). However, for larger PGAs, the superstructure acceleration is capped at 0.15-0.2 g (Fig. 8). These values are slightly higher than the peak of the force deformation loops of the cyclic loops (Fig. 7). The isolators maintained moderate peak displacements during ground motion shaking, which were below 120 mm and 100 mm for the flat and the spherical plates, respectively (model scale). No systematic trend that could correlate the category of the ground motion (e.g., near-field pulse-like) to the response (e.g., maximum displacement) is apparent (Fig. 9). Some shake table tests were performed three times (using the same ground motion input) to examine the repeatability of the results. The response of the isolators was identical, confirming the repeatability of the tests. After the shake table tests, a set of cyclic tests was performed again to evaluate the deterioration of the spheres. The response was practically the same. Hence, no deterioration occurred.

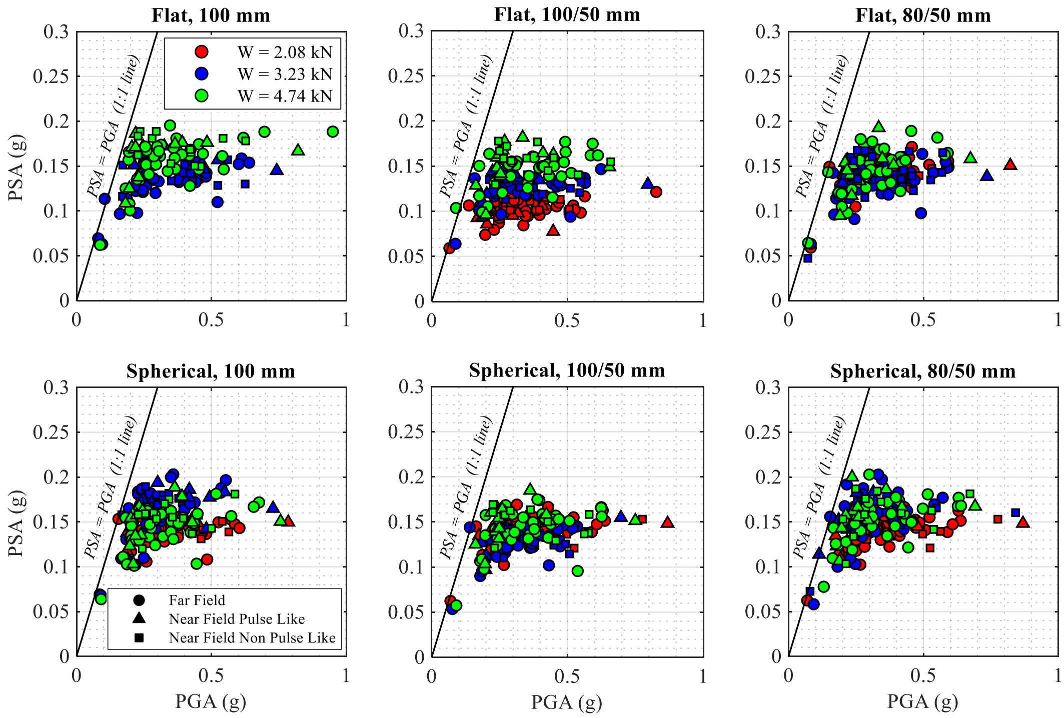

Figure 8. Correlation between the acceleration transmitted to the superstructure (PSA) and PGA for all tested configurations. Top, Flat concrete plates; Bottom, Spherical concrete plates.

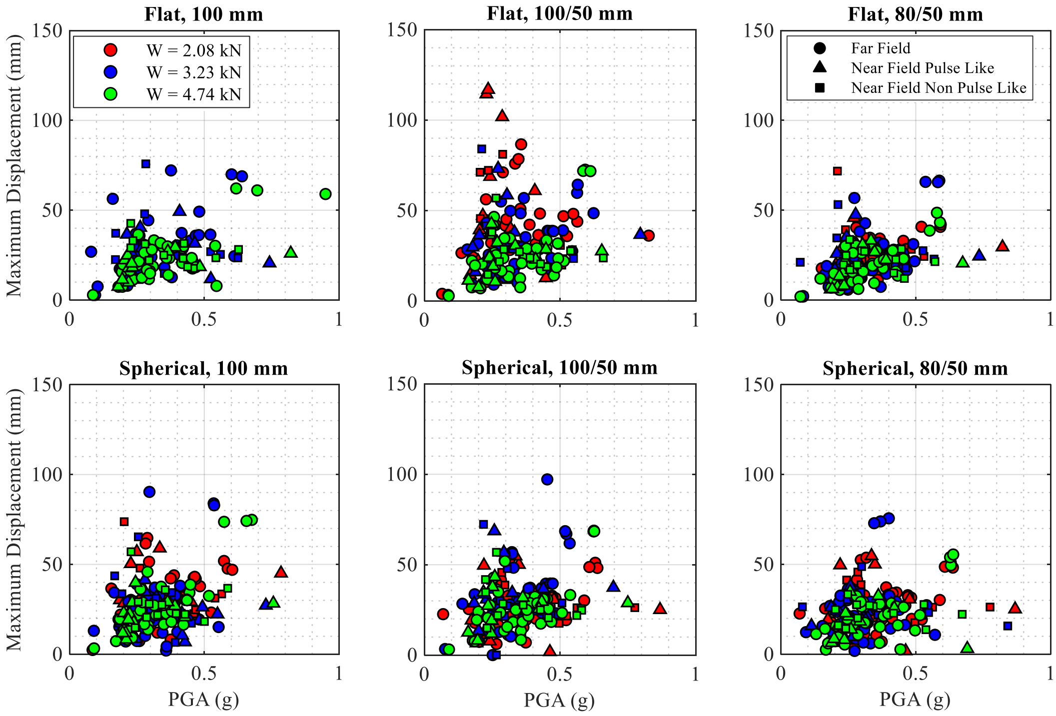

Figure 9. Correlation between the maximum displacement of the isolators and PGA for all tested configurations. Top, Flat concrete plates; Bottom, Spherical concrete plates.

6 CONCLUSIONS

The present study investigated the compressive, lateral cyclic, and shake-table response of an isolator based on rolling PU spheres (with and without steel core) rolling on concrete plates. Different levels of supported weight and curvatures of concrete plates were considered. A total of 21 different combinations of vertical load, sphere dimensions, and concrete plate curvature were tested under lateral cyclic loading. In the shake-table tests, 18 combinations were tested with 65 ground motions each, leading to a total of 1170 shake table tests. According to the experimental results, the following conclusions are drawn:

- The compressive strength of the spheres is substantially higher than the estimated design vertical load applied to the spheres, considering an application in a low-rise residential masonry structure in low-income countries.
- The lateral cyclic response differs substantially from the one that a rigid body model would suggest. This is due to the non-negligible deformability of the spheres that leads to both positive and negative stiffness branches.
- The lateral cyclic response is affected by the curvature of the concrete surface. When spherical plates are used, the stiffness of the system increases. The final stiffness of the isolators is affected by the deformed shape of the isolators (source of negative stiffness) and the curvature of the concrete plate (source of positive stiffness).
- During the uniaxial shake-table tests with excitations at the order of the seismicity of Santiago, Cuba, the isolators significantly reduced the accelerations transmitted to the superstructure (in the range of 0.15g), while maintaining displacements below 120 mm in the model scale (240 mm in the prototype scale).
- When the same isolators were subjected to 3 identical sequential uniaxial shake table excitations, the measured response, both in terms of accelerations and displacements, was practically the same. Therefore, the shake-table tests were repeatable.

- Even after subjected to 65 uniaxial ground motion excitations, the isolators do not deteriorate, and their cyclic lateral response remains practically unaffected by the loading history.

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