Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 3028-3040

ECCOMAS
Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

SHAKE-TABLE TESTING OF LOW-COST, HIGH-PERFORMANCE SEISMIC ISOLATORS BASED ON ROLLING RUBBER SPHERES

Antonios A. Katsamakas[1] **and Michalis F. Vassiliou**[2]

[1] Institute of Structural Engineering, ETH Zurich, Stefano Francini Platz 5, CH-8097, Switzerland
e-mail: katsamakas@ibk.baug.ethz.ch

[2] Institute of Structural Engineering, ETH Zurich, Stefano Francini Platz 5, CH-8097, Switzerland
e-mail: vassiliou@ibk.baug.ethz.ch

Abstract

This study presents the results of a large-scale experimental investigation of low-cost, high-performance seismic isolators based on deformable rolling rubber spheres. The spheres roll on flat or concave concrete surfaces. Different types of spheres and design scenarios were examined. A potential application of the proposed isolator could be in low-rise structures in regions where conventional seismic isolators are unaffordable.
The spheres were initially subjected to monotonic uniaxial compression and sustained compression under vertical load to examine their compressive behavior. Subsequently, lateral cyclic tests under large displacements 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 lateral cyclic response differs substantially from the one that a rigid body model would suggest due to the non-negligible deformability of the spheres. The rolling friction coefficient ranged between 3.7% and 7.1%. Hence, it is suitable for seismic isolation applications. 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 0.2 g) while maintaining reasonable peak and zero residual displacements. Notably, the shake table tests were repeatable, and the isolators did not deteriorate even after subjected to 65 ground motion excitations.

Keywords: Low-cost Seismic Isolation, Earthquake Engineering, Shake Table Testing, Rolling Isolators, Rubber Isolators.

Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10620.20718

1 INTRODUCTION

Earthquake-induced fatalities and economic loss are mainly concentrated in the developing world. This is due to the vulnerability of the building stock there, since modern structural codes are too expensive to be followed. Numerous recent examples prove that there is a pressing need to propose and implement earthquake-resistant solutions tailored to the needs and economic capabilities of the developing world.

Seismic isolation is a widely-acknowledged method of seismic protection. Its implementation includes the installation of devices (bearings) with low lateral resistance at the base of the structure. This allows for uncoupling the superstructure from the ground shaking. These bearings should have high bearing capacity under gravity loading to support the weight of the superstructure. Seismic isolation is mainly applied in important projects in the developed world, due to the associated high cost. The applications of the method in the developing world are much more limited. To this end, reduced-cost isolators have been proposed over the last decades. These isolators are distinguished into three main categories: flexible rubber bearings, sliding bearings, and rolling bearings.

Multiple studies [1-12] proposed the replacement of steel shims (used in conventional steel-laminated bearings) with flexible fiber reinforcement reduced the cost and weight of the isolators, leading to the “Fiber reinforced Elastomeric Isolator (FREI)”. However, FREIs remain too stiff to isolate lightweight residential buildings.

Conventional sliding-based seismic isolators (such as the Friction Pendulum System, FPS) [13] require polished metals and Teflon surfaces from the sliding interfaces. This increases their cost and, therefore, limits their applications in the developing world. Recent studies proposed alternative sliding surfaces to reduce the cost of the isolators. Jampole et al. [14-15] studied high-density polyethylene sliders on galvanized steel. Brito et al. [16-17] 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. [18-19] used sand grains enclosed in PVC sheets as isolation layers below the foundation slab. This system lacks restoring force.

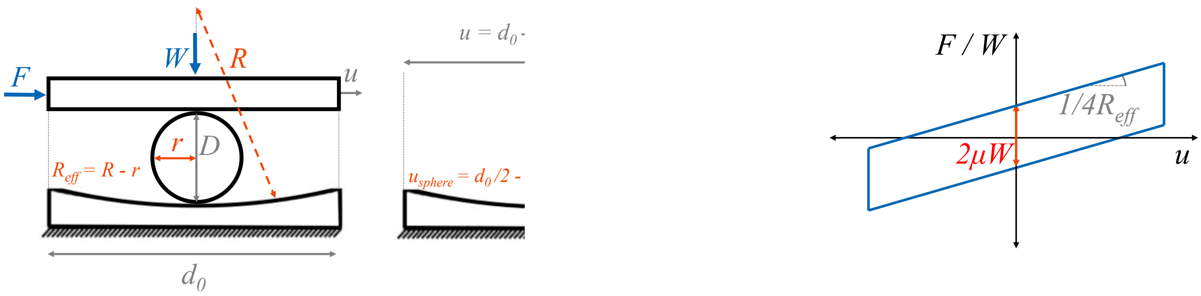


Figure 1: Rigid body model for rolling seismic isolators. Left, Isolator under compressive load and zero lateral displacement; Middle, Isolator under compressive load and maximum lateral displacement; Right, Bilinear force-displacement plot.

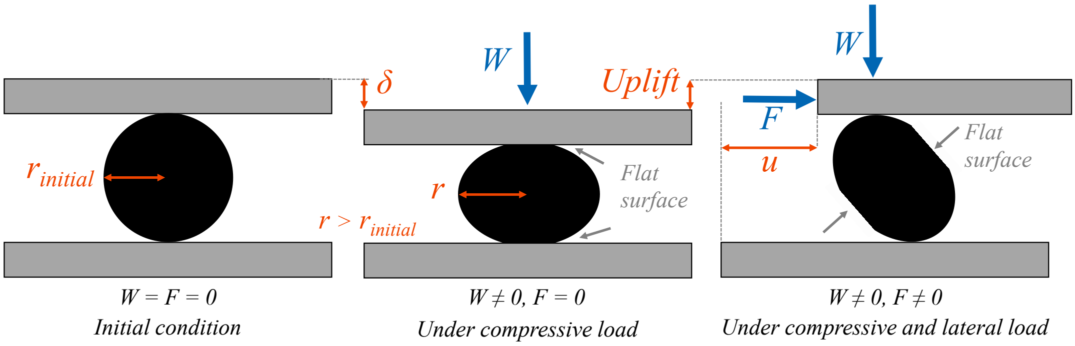


Figure 2: Left, Initial condition of the spherical isolator; Middle, Isolator under compressive load with evident compressive displacement; Right, Isolator under compressive and lateral load, with evident uplift.

2 DESCRIPTION AND POTENTIAL APPLICATION OF THE ISOLATOR

2.1 Description of the isolator and rigid-body equations

One of the most recent suggestions for seismic isolation of lightweight residential structures has been the Spherical Deformable Rolling Seismic Isolator (SDRSI) [27], initially proposed by Cilsalar and Constantinou [28-29]. Their work was based on the isolator proposed by Cui et al. [30]. The isolator comprises a deformable elastomeric sphere rolling on concrete surfaces (Figure 2). It is noted that the deformability of the sphere cannot be neglected and that the response is significantly different from an idealized rigid-body model [31]. 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 (Figure 2).

According to the rigid-body model, the force-displacement relation that describes the lateral response of the system is described by Equation (1) [28]:

$$F = \frac{W}{4R_{eff}}u + \mu_{roll}W sign(\dot{u}) \tag{1}$$

Where F is the horizontal force applied to the isolator, W is the vertical force (weight) applied to the isolator, u is the lateral displacement of the isolator, δ is the compressive displacement under load W, $R_{eff} = R - r$, R is the radius of curvature of the spherical concrete plate and $r = D/2$ is the radius of the rolling sphere (Figure 1). The quantity $\frac{W}{4R_{eff}}u$ is the restoring force of the system that originates from gravity and the use of concave concrete plates. The translational displacement of the sphere (u_{sphere}) is equal to half of the displacement of the isolator (u); hence, $u_{sphere} = u/2$. The isolation period of the system is equal to as $2\pi\sqrt{\frac{4R_{eff}}{g}}$. The μ_{roll} term is the rolling friction coefficient of the system and is equal to the lateral-to-vertical force ratio at zero lateral displacement. It is a macroscopic term that describes the initiation of rolling motion and the energy dissipation of the isolator.

It is recommended to use one concave concrete surface to guarantee restoring force to the system. Configurations with two flat plates are also tested in the present study to characterize the behavior 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 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. It is noted that the applications of the isolator are not limited to the aforementioned cases. The isolator could also be applicable in the developed world, in projects where conventional seismic isolation is too expensive to be applied.

We propose a combination of the systems of Cilsalar and Constantinou [28-29] and the one proposed by Tsiavos et al. [18-19], for the isolation of 1-2 story masonry houses (Figure 3). More specifically, the walls are supported on concrete beams that serve as the upper rolling surface of the isolators.

Two sheets of PVC (with sand in between) will continuously support the ground floor slab. This 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 the cleaning concrete layer that is used in fixed base structures.

When the deformable rubber sphere rolls, the horizontal motion of the isolator 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 (Figure 3).

3 EXPERIMENTAL SETUP

3.1 Testing equipment and instrumentation

The uniaxial shake table of ETH Zurich was used in both the lateral cyclic and the shake-table tests. The experimental setup comprises four isolators placed symmetrically on the shake table platen in a two-by-two configuration (Figure 4). An isolator comprises a PU sphere rolling between two concrete plates. In all tested cases, 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.

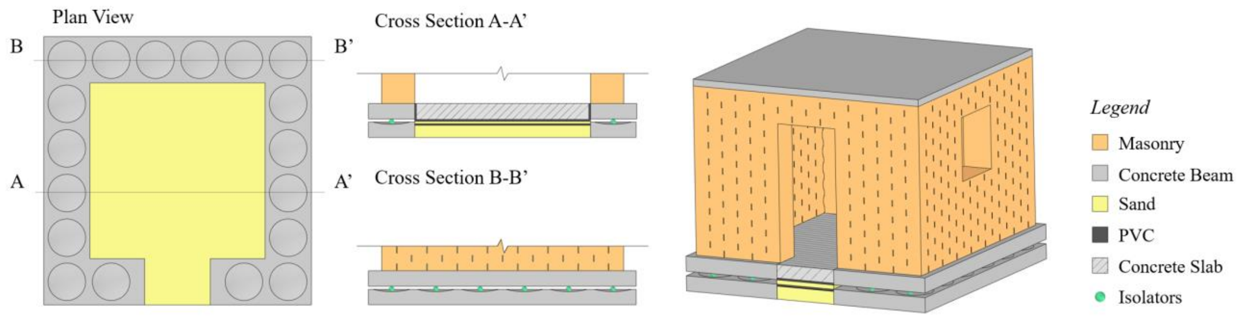


Figure 3: Representation of a potential application of deformable rolling isolators in low-rise masonry buildings.

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 (Figure 4). The shake table applied a sinusoidal motion by moving the bottom concrete plates, whereas the top plates were kept in place by the rods. Thus, shearing of the isolators was achieved. Large steel beams were placed on top of the steel slab to compress the isolators (emulating the weight of the isolated superstructure). 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 (Figure 4).

3.2 Materials and geometry

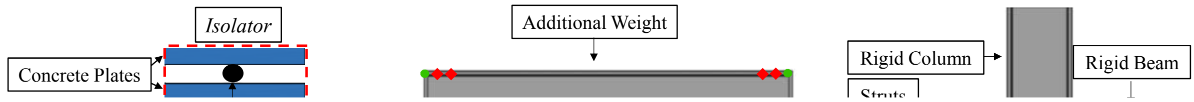
Three types of spheres were tested: Solid spheres with a diameter of 100 mm, spheres with a diameter of 100 mm and a 50 mm steel core inside (spheres 100/50 mm), and spheres with a diameter of 80 mm and a 50 mm steel core inside (spheres 80/50 mm). The spheres were made of polyurethane (PU) with a shore 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. In a practical application, the price per piece is expected to be significantly lower due to the increase in the total number of spheres ordered.

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 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 in model scale) under two rolling surface curvatures (flat and concave) were planned for all three 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").

The shake table tests were performed under an ensemble of 61 different ground motions, selected from the three different categories of FEMA P695 [32] (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. The example of Santiago, Cuba is used since it is considered representative of regions of high seismicity and low availability of construction materials. Similar (or higher) seismici-



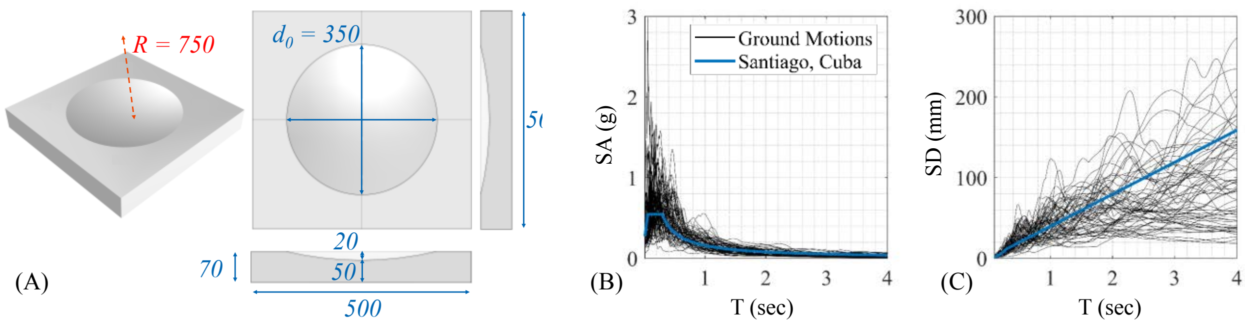


Figure 5: (A) Shape and dimensions of the utilized spherical concrete plates (in mm); Elastic response spectra of the applied ground motions and design spectrum of Santiago, Cuba (in model scale). (B), Pseudo-accelerations; (C) Displacements.

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 (Figure 6). These load levels are substantially higher than the ones that the spheres would have to sustain in a practical application (2.75 kN/sphere in model scale, 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 seven 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 behavior 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 [33-35]. 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.

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 and is noted in Figure 7. It is observed that as the vertical load (W) 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 [27].

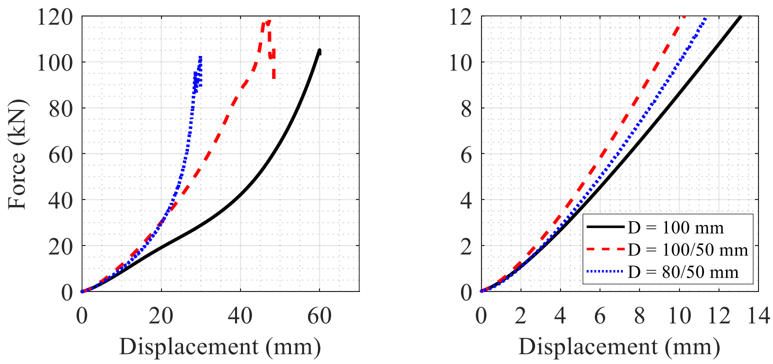


Figure 6: Compression testing results. Left: Force-displacement (overview); Right: Force-displacement (detail).

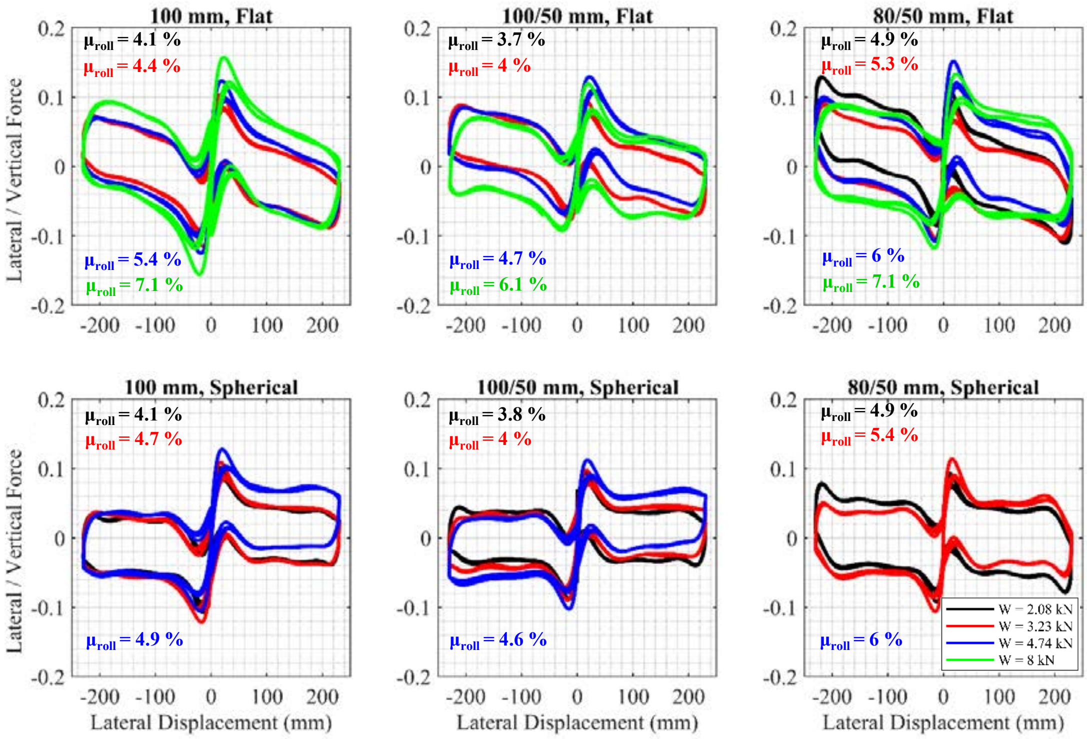


Figure 7: Influence of the vertical load (W) on the cyclic lateral response of the spherical isolator.

5 SHAKE-TABLE RESPONSE

Figures 8 and 9 show scatter plots between the Peak Ground Acceleration (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 (Figure 8). However, for larger PGAs, the superstructure acceleration is capped at 0.15-0.2 g (Figure 8). These values are slightly higher than the peak of the force deformation loops of the cyclic loops (Figure 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 (Figure 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 practically identical, both in terms of accelerations and displacements, confirming the repeatability of the tests (Figure 10). Figure 10 also shows a detail of the isolation effect that appears collectively in Figures 8 and 9. More specifically, we observe that the isolators cap the acceleration transmitted to the superstructure (limit of less than 0.20 g), regardless of the intensity of the applied ground motion (Figure 10, top). This comes at the expense of large displacements at the isolation level (Figure 10, bottom).

After the shake table tests, another set of lateral cyclic tests was performed to evaluate the deterioration of the spheres. The lateral cyclic response of the isolators was practically the same as before the shake table tests (Figure 11). Hence, even after 65 ground motions, the spheres did not deteriorate.

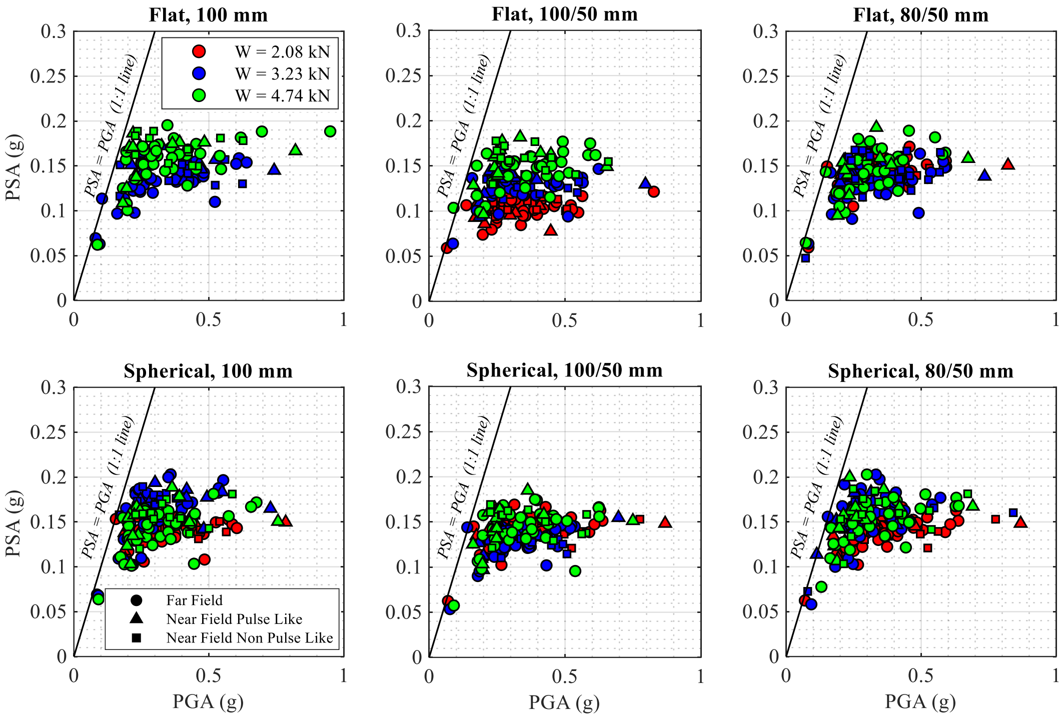


Figure 8: Correlation between the acceleration transmitted to the superstructure (PSA) and PGA for all tested configurations. Top, Flat concrete plates; Bottom, Spherical concrete plates.

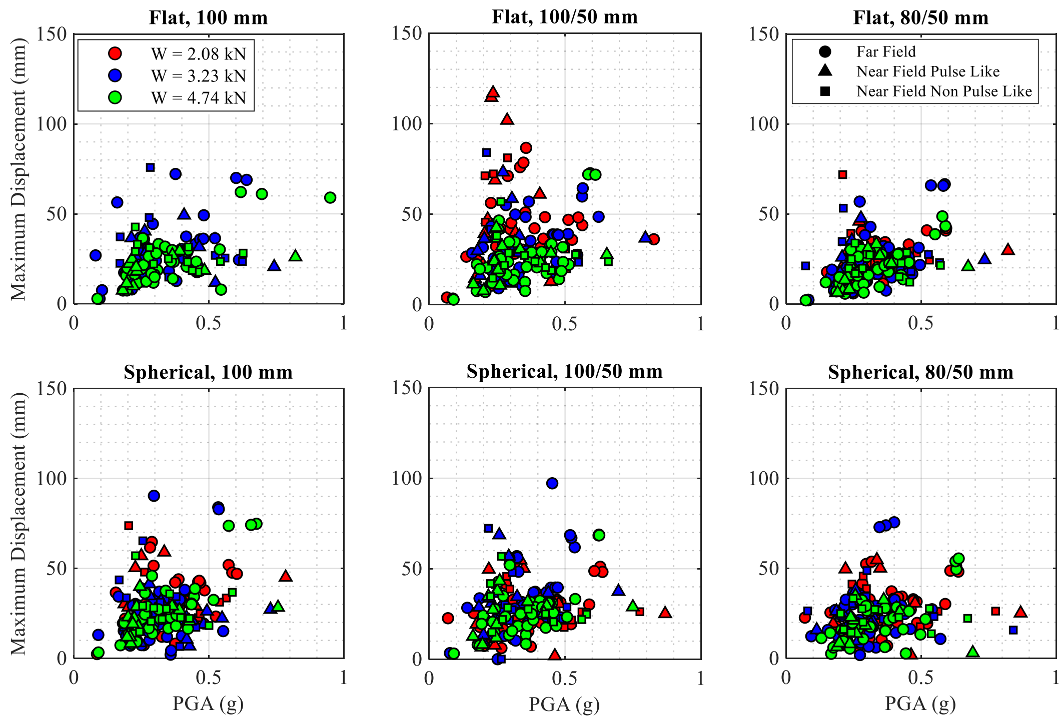


Figure 9: Correlation between the maximum displacement of the isolators and PGA for all tested configurations. Top, Flat concrete plates; Bottom, Spherical concrete plates.

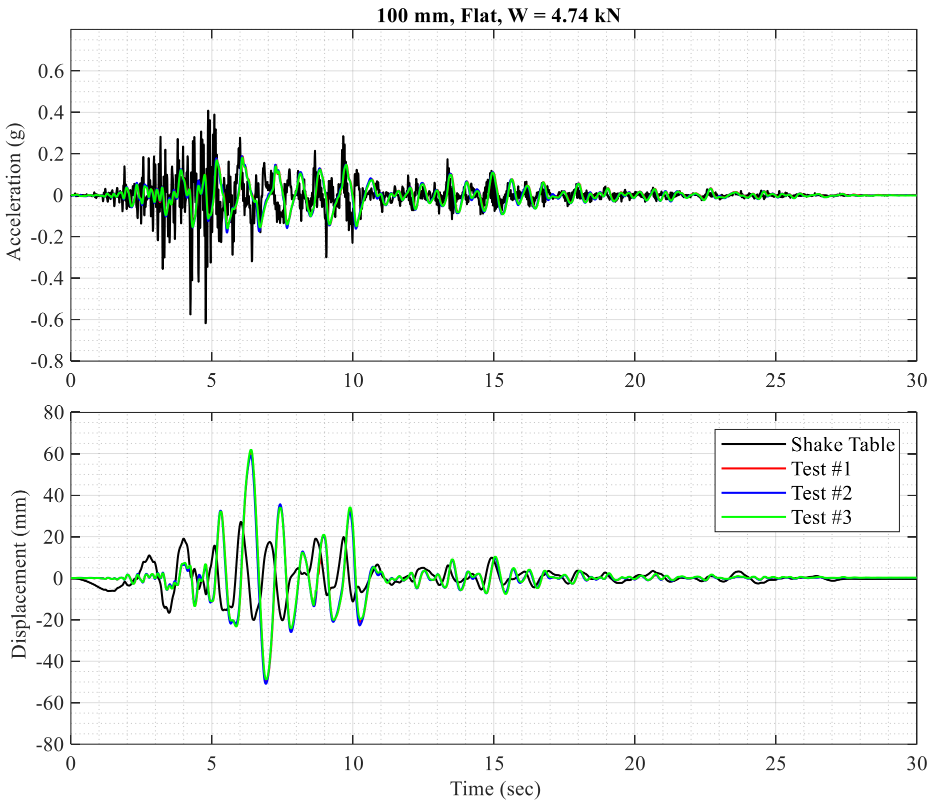


Figure 10: Repeatability of the shake table tests when using the same excitation in 3 sequential tests. Use of the 1989 Loma Prieta, USA, ground motion, component 0, as recorded at Capitola station.

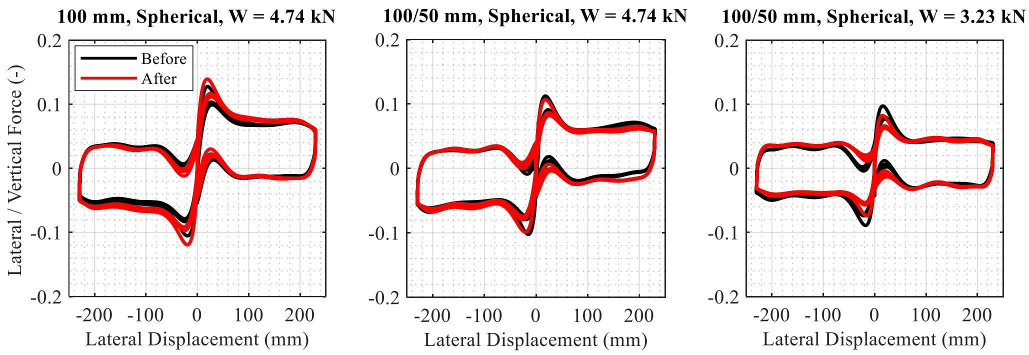


Figure 11: Lateral cyclic response of the isolators before and after being subjected to 65 ground motions. No deterioration was observed.

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 curvature of the concrete surface affects the lateral cyclic response. When spherical (concave) 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 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). This means that the proposed isolators cap the accelerations transmitted to the superstructure to less than 0.2 g, while they maintain reasonable displacements.
- When the same isolators were subjected to 3 identical sequential 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 ground motion excitations, the isolators do not deteriorate, and their cyclic lateral response remains unaffected by the loading history.

7 ACKNOWLEDGEMENTS

Financial support to the authors was provided by the European Research Council (ERC) under Starting Grant 803908. The methods, results, opinions, findings, and conclusions presented in this report are those of the authors and do not necessarily reflect the views of the funding agency.

REFERENCES

[1] A. Das, SK. Deb, A. Dutta, Shake table testing of un-reinforced brick masonry building test model isolated by U-FREI. *Earthquake Engng Struct Dyn*, 45(2), 253-272, 2016. https://doi.org/10.1002/eqe.2626

[2] D. De Domenico, D. Losanno, N. Vaiana, Experimental tests and numerical modeling of full-scale unbonded fiber reinforced elastomeric isolators (UFREIs) under bidirectional excitation. *Engineering Structures*. 274, 115118, 2023. https://doi.org/10.1016/j.engstruct.2022.115118

[3] D. Losanno, N. Ravichandran, F. Parisi, Seismic fragility models for base-isolated unreinforced masonry buildings with fibre-reinforced elastomeric isolators. *Earthquake Engng Struct Dyn*. 52:308–334, 2023. https://doi.org/10.1002/eqe.3761

[4] M. Spizzuoco, A. Calabrese, G. Serino, Innovative low-cost recycled rubber–fiber reinforced isolator: experimental tests and finite element analyses. *Engineering Structures.* 76: 99-111. 2014. https://doi.org/10.1016/j.engstruct.2014.07.001

[5] S. Galano, A. Calabrese, State of the Art of Seismic Protection Technologies for Non-Engineered Buildings (N-EBs) in Developing Regions of the World. *Journal of Earthquake Engineering*. 2023. https://doi.org/10.1080/13632469.2023.2165579

[6] P.M. Osgooei, M.J. Tait, D. Konstantinidis, Finite element analysis of unbonded square fiber-reinforced elastomeric isolators (FREIs) under lateral loading in different directions. *Composite Structures.* 113, 164-173, 2014. https://doi.org/10.1016/j.compstruct.2014.02.033

[7] H. Toopchi-Nezhad, M.J. Tait, R.G. Drysdale, Shake table study on an ordinary low-rise building seismically isolated with SU-FREIs (stable unbonded-fiber reinforced elastomeric isolators). *Earthquake Engineering & Structural Dynamics*. 38(11), 1335-1357, 2009. https://doi.org/10.1002/eqe.923 (2009).

[8] C. Tran, A. Calabrese, M.F. Vassiliou, S. Galano, A simple strategy to tune the lateral response of unbonded Fiber Reinforced Elastomeric Isolators (FREIs), 222, 111128, 2020. *Engineering Structures*

[9] N.C. Van Engelen, D. Konstantinidis, M.J. Tait, Structural and nonstructural performance of a seismically isolated building using stable unbonded fiber-reinforced elastomeric isolators. *Earthquake Engineering & Structural Dynamics,* 45(3), 421-439, 2016.

[10] N.C. Van Engelen, M.J. Tait, D. Konstantinidis, Model of the shear behavior of unbonded fiber-reinforced elastomeric isolators. Journal of Structural Engineering, 141(7), 04014169, 2014.

[11] G. Russo, M. Pauletta, A.A. Cortesia, A study on experimental shear behavior of fiber-reinforced elastomeric isolators with various fiber layouts, elastomers and aging conditions. *Engineering Structures,* 52, 422-433, 2013.

[12] D. Konstantinidis, J.M. Kelly, N. Makris, *Experimental investigations on the seismic response of bridge bearings*. Earthquake Engineering Research Center, Report No. EERC 2008-03, 2008.

[13] M.C. Constantinou, A.S. Mokha, A.M. Reinhorn, Teflon bearings in base isolation II: Modeling. *J. Struct. Eng.* 116(2), 455-474, 1990.

[14] E.A. Jampole, G. Deierlein, E. Miranda, B. Fell, S. Swensen, C. Acevedo, Full-scale dynamic testing of a sliding seismically isolated unibody house. *Earthquake Spectra.* 32(4), 2245-2270, 2016. https://doi.org/10.1193/010616EQS003

[15] E.A. Jampole, S.D Swensen, B. Fell, E. Miranda, G.G. Deierlein, Dynamic testing of a low-cost sliding isolation system for light-frame residential structures. 10NCEE. 2014.

[16] M.B. Brito, H. Ishibashi, M. Akiyama, Shaking table tests of a reinforced concrete bridge pier with a low-cost sliding pendulum system. *Earthquake Engng Struct Dyn*. 48: 366– 386, 2019.

[17] M.B. Brito, M. Akiyama, Y. Ichikawa, H. Yamaguchi, R. Honda, N. Ishigaki, Bidirectional shaking table tests of a low-cost friction sliding system with flat-inclined surfaces. *Earthquake Engng Struct Dyn.* 49: 817– 837, 2020 https://doi.org/10.1002/eqe.3266

[18] A. Tsiavos, A. Sextos, A. Stavridis, M. Dietz, L. Dihoru, N.A. Alexander, Large-scale experimental investigation of a low-cost PVC ‘sand-wich’(PVC-s) seismic isolation for developing countries. *Earthquake Spectra*. 36(4), 1886-1911, 2020.

[19] A. Tsiavos, A. Sextos, A. Stavridis, M. Dietz, L. Dihoru, F. Di Michele, N.A. Alexander, Low-cost hybrid design of masonry structures for developing countries: Shaking table tests. *Soil Dynamics and Earthquake Engineering*. 146, 106675, 2021.

[20] P.S. Harvey, K.C. Kelly, A review of rolling-type seismic isolation: Historical development and future directions. *Engineering Structures*. 125, pp. 521-531, 2016. https://doi.org/10.1016/j.engstruct.2016.07.031.

[21] P.S. Harvey, G.P. Zéhil, H.P. Gavin, Experimental validation of a simplified model for rolling isolation systems. *Earthquake Engineering and Structural Dynamics*. 43:1067–1088, 2014.

[22] D. Foti, Rolling devices for seismic isolation of lightweight structures and equipment. Design and realization of a prototype. *Structural Control and Health Monitoring*. 26(3), e2311, 2019.

[23] A.A. Katsamakas, M. Chollet, S. Eyyi, M.F. Vassiliou, Feasibility Study on Re-Using Tennis Balls as Seismic Isolation Bearings. *Frontiers in Built Environment*. 2021; 7, 768303. 2021. https://doi.org/10.3389/fbuil.2021.768303

[24] A.A. Katsamakas, M. Chollet, S. Eyyi, M.F. Vassiliou, Re-using tennis balls as low-cost seismic isolation devices: Experimental Investigation. *3rd International Conference on Natural Hazards & Infrastructure (ICONHIC2022)*, Athens, Greece, July 5-7, 2022.

[25] A.A. Katsamakas, M.F. Vassiliou, Low-cost and sustainable seismic isolation with re-used tennis balls: Lateral cyclic tests. *Third European Conference on Earthquake Engineering and Seismology (3ECEES)*, Bucharest, Romania, September 4-9, 2022.

[26] G.P. Zéhil, H.P. Gavin, Rolling resistance of a rigid sphere with viscoelastic coatings. *Int. J. Solids Struct.* 1;51(3-4):822-38, 2014.

[27] A.A. Katsamakas, M.F. Vassiliou, Experimental parametric study and phenomenological modeling of a deformable rolling seismic isolator. *Journal of Earthquake Engineering,* 2023. (under review)

[28] H. Cilsalar, M.C. Constantinou, Behavior of a spherical deformable rolling seismic isolator for lightweight residential construction. *Bull Earthquake Eng.* 17, 4321–4345, 2019. https://doi.org/10.1007/s10518-019-00626-z.

[29] H. Cilsalar, M.C. Constantinou, *Development and Validation of a Seismic Isolation System for Lightweight Residential Construction*. Technical Report MCEER, Report No.19-0001, University at Buffalo, USA, 2019.

[30] S. Cui, M. Bruneau, M.C. Constantinou, *Integrated Design Methodology for Isolated Floor Systems in Single-Degree-of-Freedom Structural Fuse Systems*. Technical Report MCEER, Report No. 12-0004, 2012.

[31] A.A. Katsamakas, G. Belser, M.F. Vassiliou, M. Blondet, Experimental investigation of a spherical rubber isolator for use in low income countries. *Engineering Structures*. 2022; 1; 250:113522, 2022. https://doi.org/10.1016/j.engstruct.2021.113522

[32] FEMA P695: *Quantification of Building Seismic Performance Factors*, Federal Emergency Management Agency, USA, 2009.

[33] A.A. Katsamakas, G. Belser, M.F. Vassiliou, M. Blondet, B. Stojadinovic, Experimental investigation of spherical rubber seismic isolation bearings. *8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2021),* Athens, Greece. June 27–30, 2021.

[34] A.A. Katsamakas, G. Belser, M.F. Vassiliou, B. Stojadinovic, M. Blondet, Shake-table testing of low-cost seismic isolation bearings based on rolling rubber spheres. *3rd International Conference on Natural Hazards & Infrastructure (ICONHIC2022)*, Athens, Greece, July 5-7, 2022.

[35] A.A. Katsamakas, M.F. Vassiliou, Lateral cyclic response of deformable rolling seismic isolators for low-income countries. *Third European Conference on Earthquake Engineering and Seismology (3ECEES)*, Bucharest, Romania, September 4-9, 2022.