

Performance of grout-filled tennis balls as seismic isolation bearings

Antonios A. Katsamakas

Assistant Professor, Polytechnique Montreal

Lorenzo Del Giudice

Structural Engineering Manager, Kanadevia Inova

Michalis F. Vassiliou

Assistant Professor, National Technical University of Athens

ABSTRACT

This paper investigates the behavior of a low-cost seismic isolator comprising a grout-filled tennis ball rolling on concrete plates. The isolator can be used in lightweight structures in resource-limited areas. The study first characterized the compressive response of the system. Subsequently, full-scale tests with combined compression and lateral cyclic loading were performed. The key parameters examined include the velocity (frequency) of lateral displacements, the compressive load on the isolator, potential degradation of the isolators under repeated loading, the influence of temperature on the response, and specimen-to-specimen variability when different grout-filled spheres from the same mix are used in nominally identical tests. Results show that the lateral cyclic response of the isolators is bilinear and can be approximated by rigid-body equations. The experimentally obtained rolling friction coefficient is suitable for seismic isolation applications. Specimen-to-specimen variability was minimal. Unlike sliding isolation systems, increased compressive load results in a higher rolling friction coefficient and analytical equations are provided to describe this effect. The rolling friction coefficient is independent of velocity (frequency) and temperature, and the isolators exhibited no deterioration under consecutive loading.

Keywords: seismic isolation, developing world, circular economy, experimental testing

INTRODUCTION

Seismic isolation is a highly effective method of seismic protection that uncouples the structure from ground motion and can lead to zero post-earthquake damage and minimal residual displacements. Despite its advantages, applications of the method in lightweight structures are extremely limited, largely due to the high cost of each seismic isolator, which makes applications in the developing world nearly impossible. Seismic isolators can be classified into three main categories: (i) flexible rubber bearings, (ii) sliding bearings, and (iii) rolling bearings. Several studies over the last decades have attempted to reduce isolator costs across all three categories.

Steel-reinforced flexible rubber bearings comprise layers of elastomer interleaved with steel shims and thick steel end plates. The use of steel increases their weight and cost. To address this, Fiber Reinforced Elastomeric Isolators (FREIs) (Russo et al, 2013; Losanno et al, 2022,2023; Das et al, 2016; De Domenico et al, 2023; Toopchi-Nezhad et al, 2009; Tran et al, 2020; Calabrese et al, 2019) replaced steel shims with flexible, lightweight fiber reinforcement and eliminated the steel end plates (unbonded FREIs) (Galano et al, 2022; Van Engelen et al, 2014, 2016; Osgooei et al, 2014,2015). However, the application of FREIs to lightweight

structures is challenging due to their high stiffness and potential instability under large horizontal displacements (Kelly & Konstantinidis, 2011). Modern sliding isolators, such as the Friction Pendulum System (FPS) (Fenz & Constantinou, 2006; Mosqueda et al, 2004; Becker & Mahin, 2012; Castaldo & Tubaldi, 2015), comprise stainless steel surfaces to provide recentering forces and polished steel-Teflon sliding interfaces to provide a low friction coefficient. Recent studies have proposed alternative sliding interfaces to reduce bearing costs. Messina and Miranda (2022) investigated polyethylene-galvanized steel interfaces. Jampole et al. (2016) tested a structure isolated on high-density polyethylene sliders on galvanized steel. Brito et al. (2020) studied bridge models isolated using bearings with concrete-steel interfaces. Tsiavos et al. (2020, 2022) studied timber-sand or PVC-sand sliding interfaces.

Existing rolling-based seismic isolators usually comprise steel spheres rolling on steel surfaces (Harvey & Kelly, 2016; Harvey et al, 2014; Menga et al, 2019; Zéhil & Gavin, 2013). Elastomeric materials at the rolling interfaces can increase energy dissipation and avoid localized damage (Reyes et al, 2023,2025). Cui et al. (2012), and more recently Cilsalar and Constantinou (2019), proposed an isolator comprising a deformable polyurethane (PU) sphere rolling between concrete plates. Following their findings, Katsamakas et al. (2021,2022,2023) and Katsamakas and Vassiliou (2022,2023,2025) performed shake table tests and large-displacement lateral cyclic tests of similar isolators, also proving the importance of sphere deformability.

This study investigates the reuse of grout-filled tennis balls as rolling seismic isolation bearings. The spheres roll between concrete plates. This paper examines the lateral cyclic response of the isolator through full-scale tests and assesses the influence of velocity (frequency) of lateral displacements, compressive load, potential degradation under repeated loading, temperature, and specimen-to-specimen variability.

DESCRIPTION, MODELING, AND MANUFACTURING OF THE ISOLATOR

The proposed isolator comprises a grout-filled tennis ball that rolls between two concrete plates. The grout core increases the bearing capacity and stiffness of the sphere. The rubber/wool shell of the tennis ball increases energy dissipation and distributes the stresses at the contact area. Concrete plates are used as rolling surfaces since they are more affordable than steel. The use of at least one spherical (concave) concrete plate is recommended to guarantee gravitational restoring force to the system. Isolators with two flat plates are also examined to better understand the sphere response. The isolator could be used in lightweight structures in resource-limited areas.

Assuming that the sphere and the concrete surfaces are rigid, the response of the system can be approximated by a rigid-body equation (Eq. (1)).

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

In Eq. (1) and Figure 1: F is the horizontal (rolling) force applied to the isolator, W is the weight applied to the isolator, u is the lateral displacement of the isolator, $R_{eff} = R - r$, where R_{eff} is the effective radius of the isolator, R is the radius of curvature of the spherical concrete plate and $r = D/2$ is the radius of the rolling sphere, and u_{yield} is the yield displacement. It is noted that the term “yield displacement” is only used to describe the stiffness reduction after the initial branch of the bilinear model (Figure 1, right). Rigid body approximation (i.e., Eq. (1)) assumes $u_{yield}=0$. The first part of the equation is gravitational restoring force of the system and originates from the spherical geometry of the concrete plate. The “4” factor in the denominator shows that the rolling isolator is 4 times more “flexible” than a sliding isolator with the same radius of curvature (R). The μ_{roll} term is the rolling friction coefficient of the system. It is a macroscopic term that controls the initiation of rolling motion and the energy dissipation of the system. The

isolation period of the system is equal to $T_{eff} = 2\pi\sqrt{\frac{4R_{eff}}{g}}$. The displacement capacity of the isolator is $\pm d_o - D$ (Figure 1). The response predicted by Eq. (1) is bilinear.

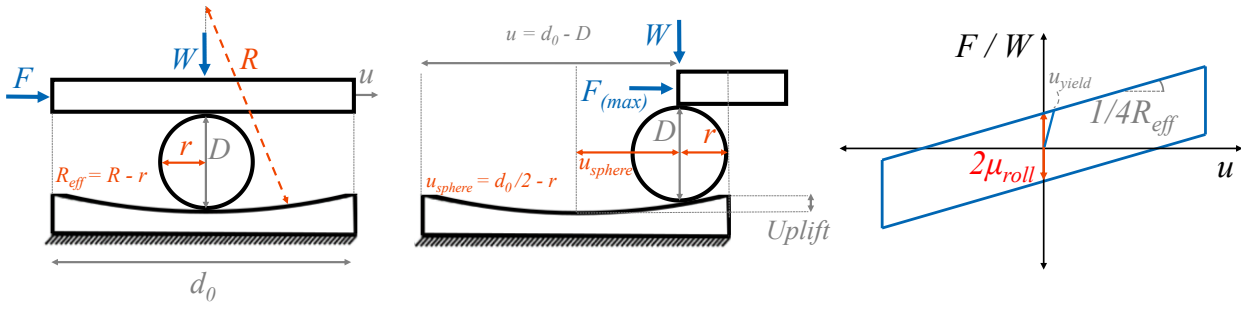


Figure 1. Rigid-body model of rolling seismic isolator. (A), Zero lateral displacement; (B), Maximum lateral displacement; (C) Bilinear force-displacement response.

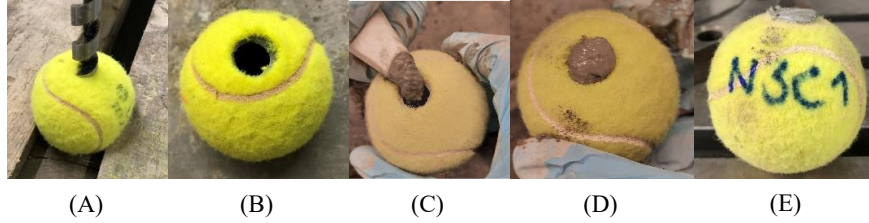


Figure 2. Manufacturing of the grout-filled tennis ball.

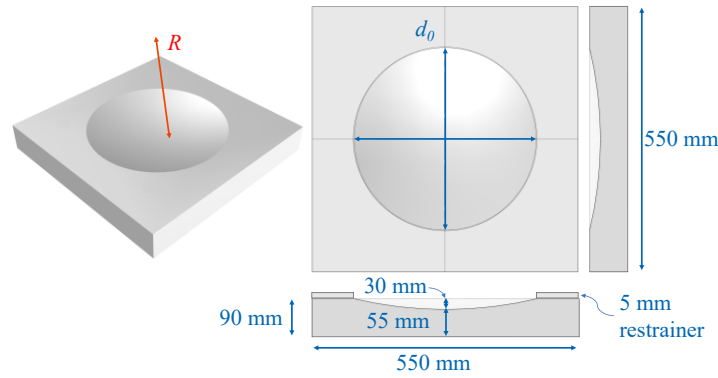


Figure 3. Sketch of the spherical concrete plates.

Tennis balls for official games have an approximate diameter of 67 mm. Their shell has a total thickness of 6 mm and is made of natural rubber (thickness of 3.5 mm) and wool/nylon (thickness of 2.5 mm). To manufacture the isolator, used tennis balls were obtained from tennis clubs. In fact, tennis balls are used only for a very limited number of games; after that, they lose their bounce and are discarded. Hence, the proposed isolator offers a reuse solution for tennis balls, compatible with the concept of circular economy.

All spheres were filled with the same grout mix using conventional Portland cement (CEM I 42.5) with a water-to-cement weight ratio $w/c = 0.3$ and a polycarboxylate ether superplasticizer (BASF Masterease ACE-30) with a superplasticizer-to-cement weight ratio of $s/c = 0.0038$. The superplasticizer reduces the water ratio and increases strength. Initially, a 15 mm hole was drilled through the shell of the tennis balls (Figure 2(A,B)). The grout mix was poured into the tennis ball using a piping bag attached to a steel tip (Figure 2(C,D)). After casting, the spheres were wrapped with plastic sheets to control water evaporation. After grout hardening for 28 days, the spheres were ready to be tested (Figure 2(E)).

Three different types of concrete plates were manufactured: flat plates, spherical plates with a radius of curvature (R) of $R = 560$ mm ($T = 3$ sec), and spherical plates with a radius of curvature of $R = 250$ mm ($T = 2$ sec) (Figure 3). A commercial M15 cementitious mix, with a maximum aggregate size of 4 mm, was used for the construction of the concrete plates. The mean compressive and flexural strength of the concrete mix tested according to EN 1015-11 (1993) was 27.6 MPa and 4.6 MPa, respectively. The concrete plates were reinforced with a coarse grid

of smooth rebars. The diameter and spacing between two adjacent rebars were 3 mm and 50 mm, respectively ($\phi 3/50$). All tests performed in the present study are in full scale.

EXPERIMENTAL SETUP

The isolators were tested under combined compression and shear using the experimental setup of Figure 4. The setup comprises two vertical actuators (denoted as V_S and V_N) and one horizontal actuator (denoted as H). The displacement capacity, maximum velocity, and maximum force of each vertical actuator were ± 100 mm, 100 mm/s, and 20 kN, respectively. The corresponding values of the horizontal actuator were ± 500 mm, 300 mm/s, and 10 kN. To accurately measure the forces acting on the isolator, a multi-axial load cell (MALC) was placed below its bottom concrete plate. This load cell measures components in five degrees of freedom and has an axial, shear, and moment capacity of 182 kN, 23 kN, and 5 kNm, respectively. The motion of the isolator was measured using an NDI Optotrak Certus system and 10 infrared-emitting diode markers. The NDI system recorded the three-dimensional position of the markers with an accuracy of 0.1 mm. The sampling frequency of all systems was 100 Hz.

TESTING PROCEDURE

Initially, the spheres were subjected to monotonic uniaxial compression to evaluate their vertical bearing capacity. Moreover, the spheres were subjected to sustained compression under constant vertical load (W) for 100 minutes ("creep" tests). The creep displacements of the spheres were measured to quantify whether sustained load could lead to increasing displacements over time. The isolators are intended to support a single-story unconfined masonry building in the developing world. The gravity load (W_{design}) of the building's perimeter ring beam would be 11 kN/m (Katsamakas et al, 2023). Assuming that the distance between two adjacent spheres ranges between 30 cm and 60 cm, W_{design} ranges between 3.4 kN and 6.6 kN (mean value of 5 kN). Due to the vertical component of ground motion and the overturning moment of the superstructure, the vertical load on the isolators during earthquake shaking may vary. To account for these effects, the isolators were tested for loads $W = 2.8$ kN to $W = 12.5$ kN.

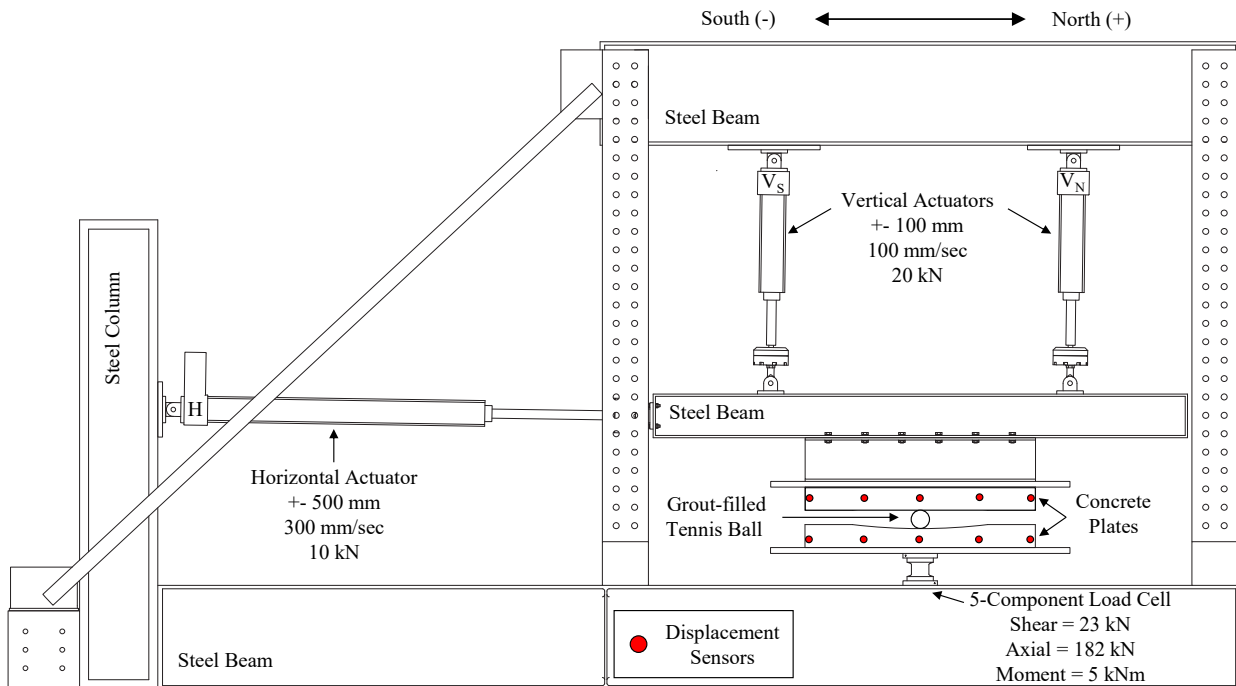


Figure 4. Experimental setup and instrumentation.

Hence, a wider range of compressive loads between $W = 2.8$ kN and $W = 12.5$ kN was tested. Before initiating the lateral cyclic tests, all spheres were subjected to sustained compression for

10 minutes ("creep" loading), with the "creep" load equal to the vertical load during the lateral cyclic test that followed. The following effects were investigated in the lateral cyclic tests:

- Repeatability among different specimens. Three different spheres were tested for each concrete plate geometry (flat, spherical ($T = 3$ sec), and spherical ($T = 2$ sec)), leading to a total of nine specimens. A compressive load of $W = 5$ kN and a low cyclic frequency ($f = 0.01$ Hz) were used.
- Deterioration (wear) of the spheres under multiple lateral cycles. The same specimen was subjected to 15 full cycles using flat concrete plates, $W = 5$ kN, $f = 0.01$ Hz, $A = \pm 300$ mm. These 15 cycles are above typical seismic demands (that would induce only a handful of cycles to the isolators). Performing 15 cycles is a reasonable simplification given that no code provisions exist for the deterioration testing of such isolators.
- Influence of the vertical load (weight) on the response. The tested loads ranged from $W = 2.8$ kN to $W = 12.5$ kN. Different frequencies (velocities), amplitudes (A), and types of concrete plates were used.
- Temperature dependency of the isolator. Three spheres were treated at room temperature. Three additional spheres were treated at 55°C for 24 hours, and three additional spheres were treated at -10°C for 24 hours. All spheres were tested at room temperature immediately after the temperature treatment.

RESULTS

Compression test results

Figure 5 (left) summarizes the results of 35 compression tests. The average compressive response can be approximated by a simple equation (Eq. (2)), where W is the compressive force in kN and δ is the compressive displacement (under load W) in mm. This equation also appears in Figure 5 (left) as a solid red line.

$$W = -0.14 + [0.14 \times \exp(0.62 \times \delta)] \quad (2)$$

Figure 5 (right) shows the creep response of the spheres. The initial abruptly ascending branch of the curves corresponds to the load application time interval (around 5 minutes). After this part, the vertical load remains constant, and the evolution of displacements is measured. The displacements of the spheres increase during the first 10–15 minutes of loading and remain practically constant after this time point (up to the total testing time of 100 minutes). The displacement increase due to creep is on the order of 0.3–0.4 mm, hence very low compared to the displacement due to monotonic compression, which ranges from 5.4–7.3 mm for the examined loads. These displacements are primarily due to the deformation of the rubber shell. Based on the above, the creep response of the shell can be neglected for practical applications.

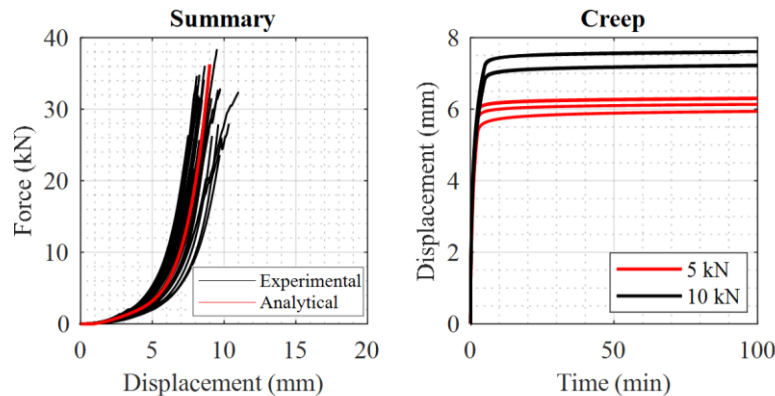


Figure 5. Compression (left) and creep (right) test results of grout-filled tennis balls.

Lateral cyclic test results

Figure 6 compares the experimental response of three tests to the analytical response of a fitted bilinear model. The first observation is that the experimental response is bilinear and closely matched by the bilinear model. The experimental response comprises an initial pre-yielding branch up to the yield displacement (u_{yield}). In all tests, the yield displacement was obtained by

inspection and ranged between $U_{yield} = 6$ mm and $U_{yield} = 9$ mm. After this point, the post-yield branch was either horizontal (flat plates) or ascending (spherical plates). The rolling friction coefficient (μ_{roll}) is approximately 5-6%, hence suitable for seismic isolation applications.

Figure 7 shows the lateral cyclic response of three different specimens of the same concrete mix. Results show that different specimens of the same mix have essentially the same lateral cyclic response. The range of the rolling friction coefficient is noted in Figure 7. This uniformity and repeatability of the response enhances confidence in the proposed isolator and in the adopted casting procedure. Figure 8 (left) shows the lateral cyclic response of a single isolator subjected to 15 consecutive cycles to investigate possible deterioration (wear). The bearing did not deteriorate, and the response remained stable.

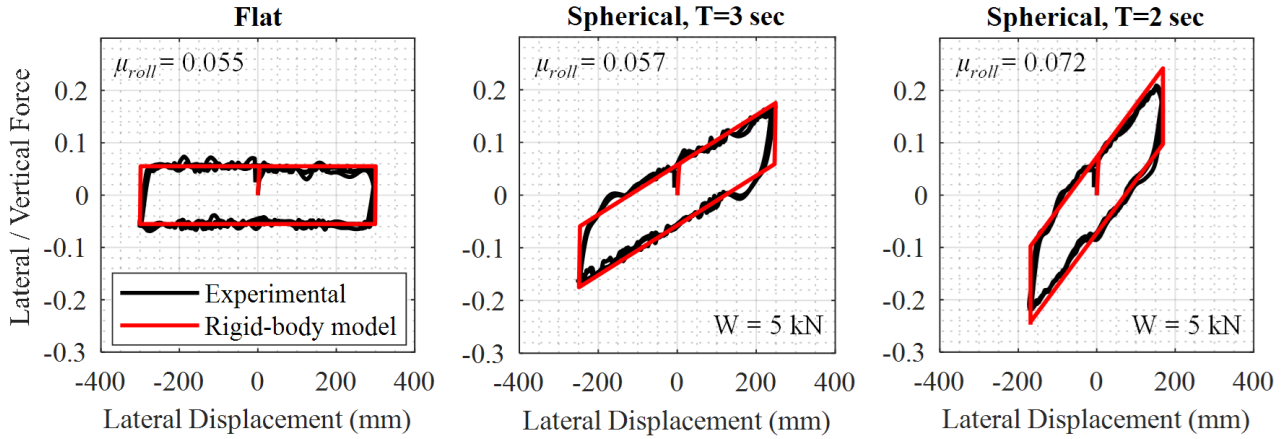


Figure 6. Comparison of the experimental response to the rigid-body model.

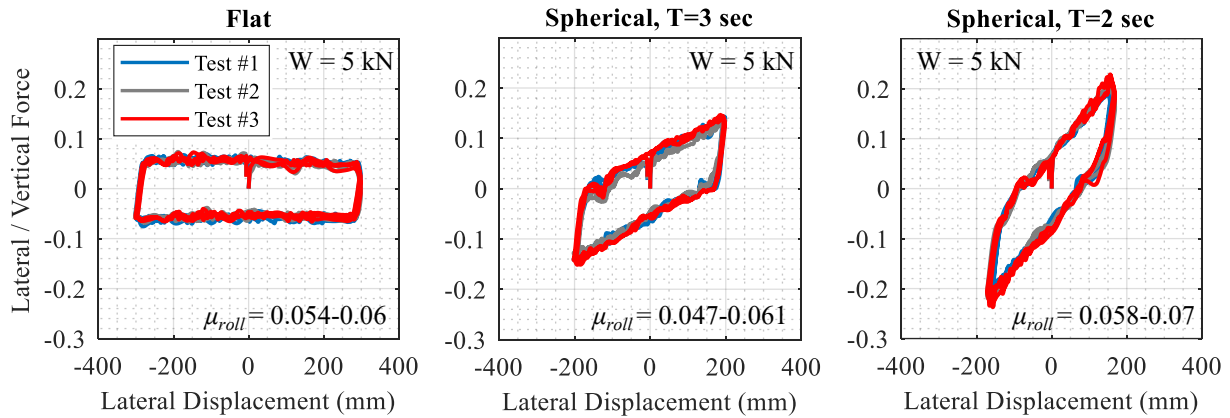


Figure 7. Repeatability of the lateral cyclic response among different spheres.

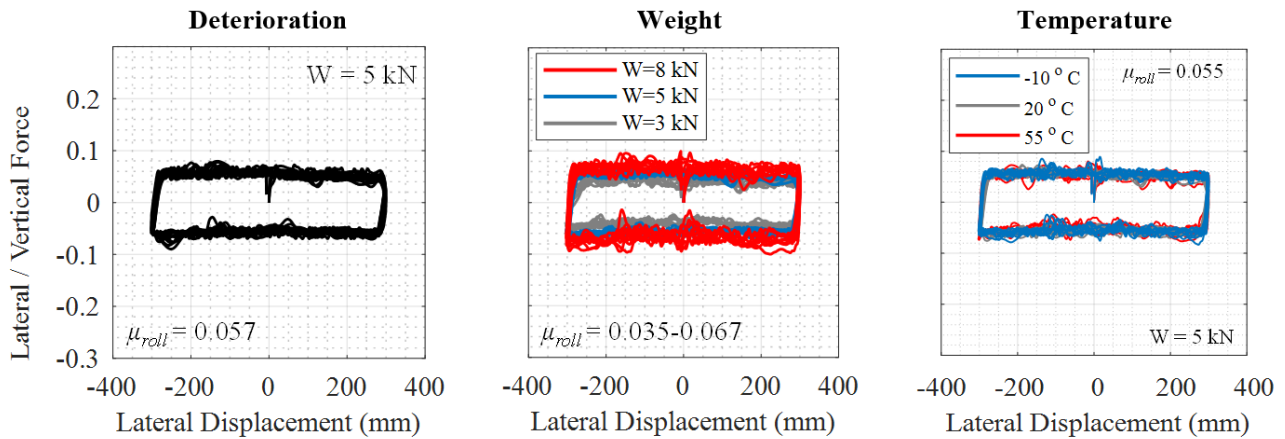


Figure 8. Lateral cyclic tests. (Left), Deterioration under consecutive loading; (Middle) Influence of weight (W); (Right) Influence of the temperature.

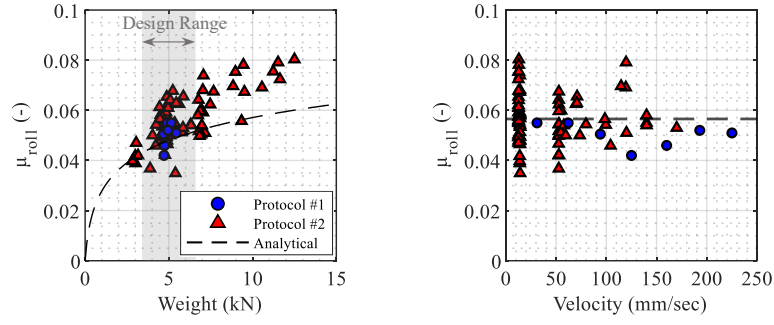


Figure 9. Variation of the rolling friction coefficient (μ_{roll}) with weight and velocity.

Figure 8 (middle) shows the response of the isolators under different vertical loads (W). Three spheres were tested per vertical load level (W). Results show that increasing W leads to a slightly increasing rolling friction coefficient (μ_{roll}). Figure 8 (Right) shows the influence of temperature on the lateral cyclic response. Neither the rolling friction coefficient nor the overall response is influenced by the prior temperature treatment of the sphere, at least for the range of temperatures tested.

The isolators were tested up to a maximum velocity of 225 mm/sec to investigate the dependency of μ_{roll} on the velocity of excitation. The overall response of the tested isolators was not influenced by velocity, as shown in Figure 9. Larger frequencies were not tested due to the limitations of the setup. Figure 9 summarizes the results of the 130 lateral cyclic tests performed in the present study, focusing on the variation of the rolling friction coefficient (μ_{roll}) with weight and velocity. As already discussed, the rolling friction coefficient depends on the vertical load but not on the rolling velocity. Eq. (2) correlates the compressive force (W) to the compressive displacement (δ). Dividing the compressive displacement by the sphere diameter (D) gives the non-dimensional compressive displacement (δ/D). Previous studies (Katsamakas et al, 2022) calibrated on tests of deformable rubber spheres with a steel core claimed that an approximate relation could associate δ/D to μ_{roll} (Eq. (3)).

$$\mu_{roll} = 0.829 \times (\delta / D) \quad (3)$$

The substitution of Eq. (2) in Eq. (3) gives a simple analytical equation to correlate μ_{roll} to W (Eq. (4)).

$$\mu_{roll} = 0.0134 \times \ln\left(\frac{W + 0.14}{0.14}\right) \quad (4)$$

In Eq. (4), μ_{roll} is non-dimensional, whereas W is in kN. Eq. (4) is plotted in Figure 9 as a dashed black line. It fits the experimental data points relatively well within the design range of interest and provides a reasonable and easy-to-use starting point for the design of the isolators. As shown in Figure 9, Eq. (4) tends to underestimate the value of μ_{roll} . The average value of μ_{roll} of the performed tests is 0.056 and is plotted with a dashed black line in Figure 9.

CONCLUSIONS

Seismic isolation is a mature technology that effectively protects structures from earthquakes. However, due to its perceived high cost, applications are limited to high-income countries. To reduce costs, this paper investigated the use of grout-filled, used tennis balls as seismic isolators in resource-limited areas.

The compressive strength of the isolator is on the order of 30 kN, significantly higher than the design compressive load of 3.4–6.6 kN. Creep displacements of the rubber shell are marginal and can be ignored.

The lateral behavior is bilinear and closely matches rigid-body model predictions. The isolator has sufficient damping due to a rolling friction coefficient on the order of 6%. Higher compressive loads lead to slightly higher rolling friction coefficients. The lateral cyclic response is independent of velocity and temperature treatment. Different isolators exhibit repeatable lateral cyclic response, which enhances confidence in the proposed casting process. The

isolator does not deteriorate under consecutive lateral loading. Overall, these results demonstrate that the proposed isolator can be highly effective in lightweight structures and pave the way for seismic isolation applications in the developing world.

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