EXPERIMENTAL INVESTIGATION OF A SUSTAINABLE SEISMIC ISOLATION SYSTEM BASED ON USED TENNIS BALLS

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Abstract

Seismic isolation is one of the most effective methods of reducing earthquake-induced damage to buildings. However, the associated high cost makes this technology non-applicable for residential structures, especially in the developing world.

This paper presents an experimental study of sustainable, low-cost spherical isolators, aiming to be used in low-rise buildings. Using a closely-spaced grid of such spheres could only require a thin, lightly-reinforced diaphragm slab above the isolation level, further reducing construction costs. Reducing or avoiding the cost of the extra slab is a prerequisite for the use of seismic isolation for low-rise buildings in low-income countries.

The examined systems are based on rolling, with grout-filled tennis balls rolling on concave or flat concrete surfaces. The experimental investigation comprised cyclic tests of these systems. Parameters of investigation are the geometry of the rolling surface (i.e., flat or concave) and the applied vertical load (i.e., supported structure's weight). Concave rolling surfaces provide restoring force to the system through gravity. In contrast, in the case of flat rolling surfaces, restoring force should be provided with a separate system, which is not studied in this work. Cyclic tests were performed to obtain the horizontal force-displacement curve of the various configurations under different vertical load levels and different rolling surfaces. Experimental results proved that the rolling friction coefficient (i.e., the ratio of vertical to horizontal load) has low values, suitable for seismic isolation applications. If placed in a grid, the tennis balls isolators could be able to support the vertical load of a low-rise building and limit the seismic forces transmitted to the superstructure.

Keywords: seismic isolation; rolling bearings; cyclic testing; low-cost isolation; sustainable seismic design

1. Introduction

Seismic isolation [1,2] is a seismic response modification technique, which uncouples the motion of the structure from the ground shaking. By placing a low-stiffness or slippery layer at the base of the structure, the dominant eigenperiod of the structure is elongated. This reduces the accelerations transmitted to the superstructure and, thus, the inertial forces. The main drawback is that it leads to increased displacements; however, these displacements are localized at the isolation level, with the interstory drifts maintaining low values. The three key concepts that a seismic isolation scheme should fulfill are: i) Sufficient bearing capacity under vertical (gravity) loads, ii) sufficient flexibility in the horizontal direction to uncouple the motion of the structure from the ground motion, iii) energy dissipation [3].

When seismic isolation is used, the superstructure should be designed to remain essentially elastic. Previous studies [4,5] proved that this is not a conservative design, but a necessity, emerging from the dynamics of base-isolated structures.

Modern applications of rolling seismic isolation systems focused on the isolation of precious equipment, where the supported mass is expected to be low. The rolling spheres were mainly made of steel or rubber, and the supporting plates were made of concrete or steel [6-10]. The geometry of the supporting plates was either conical or concave, providing restoring force through gravity.

Even though the efficiency of isolation devices is acknowledged, the implementation of these technologies is limited due to the associated high cost. The high cost originates from a) the cost of the isolation devices and b) the cost of the extra slab required at the isolation level. Moreover, the high weight of these devices (approximately 1 ton per device) demands the use of lifting equipment, further increasing the complexity of the construction [11].

There have been numerous attempts to reduce the cost of seismic isolation [12-30]. This work focuses on the recently published work by Cilsalar and Constantinou [28-30], who essentially suggested a Friction Pendulum System (FPS) based on rolling instead of sliding. It comprises two concrete surfaces (concrete plates) and a rubber sphere that rolls in between. The system is indeed low cost, as the rubber balls (with or without a steel core) can be obtained for a low price. However, it still requires an extra slab above the isolation devices – hence the overall cost still remains prohibitive for low-rise buildings in low-income countries.

This paper suggests the use of grout-filled tennis balls instead of rubber spheres. Then, the cost of the spheres becomes negligible as the volume of mortar needed for 100 balls is only 8 liters, thus allowing the use of even the most expensive cement mixes. Using a closely spaced grid of such spheres below the masonry walls could only require a thin, lightly-reinforced diaphragm slab above the isolation level, further reducing construction costs (Figure 1).

For the tests, we obtained used tennis balls for free from tennis clubs that would have otherwise dumbed them. In fact, the waste created by tennis balls is a waste management issue on its own. Every year 300 million tennis balls are discarded globally. In the US alone, 125 million tennis balls are sold every year, with most of them ending up in landfills [31]. This is because, after each tennis game, the balls become softer and unsuitable for further use [32]. No viable solution towards the mass-scale reuse and sustainable management of this large number of tennis balls is proposed so far, to the best of the authors' knowledge. In the present study, tennis balls are employed as molds for the grout spheres. This mold is permanent since it is not removed after casting. This offers an additional advantage; the 5mm-thick walls of the tennis balls are made of a rubber-like material, which offers stress distribution at the contact area between the rolling sphere and the rolling surface, avoiding extensive localized failures.

This study presents the manufacturing process, the test setup, and the results of cyclic and compressive tests of grout-filled tennis balls. This is the first time that a cement-based material is used to construct rolling isolators since previous studies used either steel or rubber.
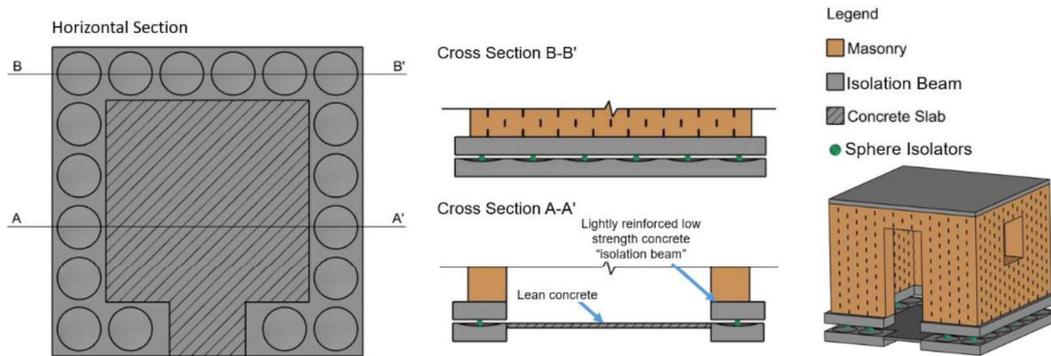
Fig. 1: Implementation of a low-cost isolation scheme based on rolling spheres, with a potential application to a single-story residential masonry building in the developing world.

2. Experimental Setup

2.1 Manufacturing of the rolling spheres and the rolling surfaces

A total of 21 grout-filled tennis balls was cast. Five of them were tested under monotonic uniaxial compression, and the rest were used in cyclic shear tests.

Manufacturing of grout-filled spheres was completed by the following steps: Initially, the tennis spheres were cut in half. The two hemispheres were filled with cement-water grout, with a water-to-cement ratio of 0.5, using conventional Portland cement (CEM I 52.5). Subsequently, the two pieces were placed together and left to cure for 28 days (Figure 2). The external diameter of each tennis ball is equal to 65 mm, with the width of the walls being approximately 5 mm. The walls are made of rubber material, offering stress distribution at the contact areas and energy dissipation. The grout core inside the sphere had a diameter of 55 mm.

Concrete plates were made of plain concrete since steel reinforcement increases cost and construction time, making implementation harder in developing countries. The geometry of the plates is shown in figure 3. The radius of curvature of the concave concrete plates (R) was R = 0.75 m, which corresponds to an isolation period equal to T = 1.74 sec. The diameter of the concave plates in plan view was 350 mm (Figure 3). A commercial low-cost M15 mortar was selected, with a maximum aggregate size of 4 mm. The mean compressive and flexural strength was equal to 27.62 MPa, and 4.63 MPa, respectively, tested according to EN 1015-11 (1993) [33].
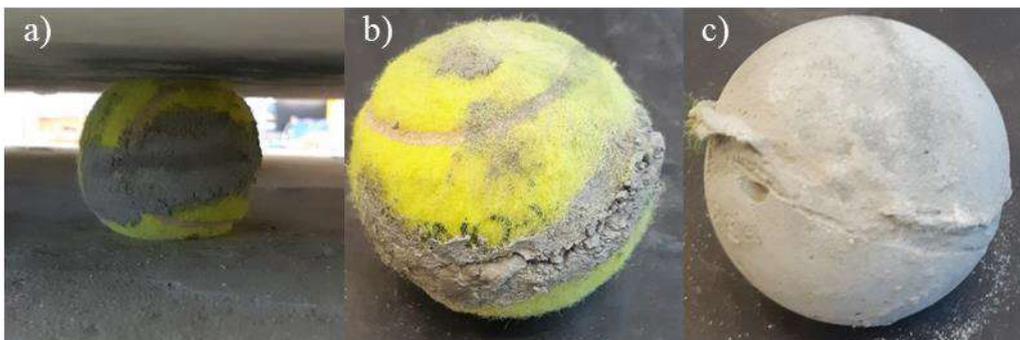

Fig. 2 - Grout rolling isolator cast in tennis balls, a) under compression between two concrete plates, b) after cyclic testing, c) detail of the grout core
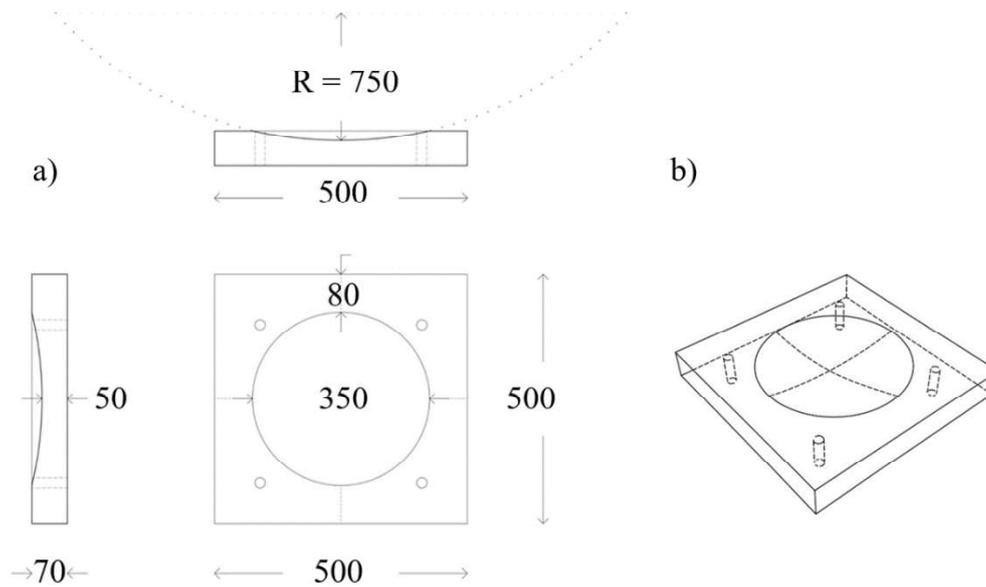
Fig. 3 - Schematic representation of the utilized concave concrete plates (dimensions in mm); a) Plan and side view, b) 3D view

2.2 Testing equipment and instrumentation of the cyclic tests

Cyclic tests were performed using the shake table of the ETH [34] as an actuator. The shake table is a stiff steel box with dimensions of 1 x 2 m, operated by a servo-hydraulic actuator of 100 kN, which acts only in one direction. The stroke, maximum velocity, and maximum payload is 240 mm, 220 mm/second, and 7.5 tons, respectively. Before testing, the accuracy of the shake table was assessed by performing preliminary tests and comparing the applied to the expected motion, with the two being closely correlated.

The setup is shown in Figures 4-6. Four isolators (i.e., four pairs of plates) were placed on top of the shake table. A 30mm-thick steel slab was mounted on the top plates, and weight was placed on top of it. The slab was connected to a stiff column via two rigid rods to constrain its motion along the table axis (x) and around the vertical axis (z). Side stoppers and a rail in the middle prevented it's out of axis motion. Variable weight in the form of steel beams was placed on top of the structure to apply vertical load on the bearings.
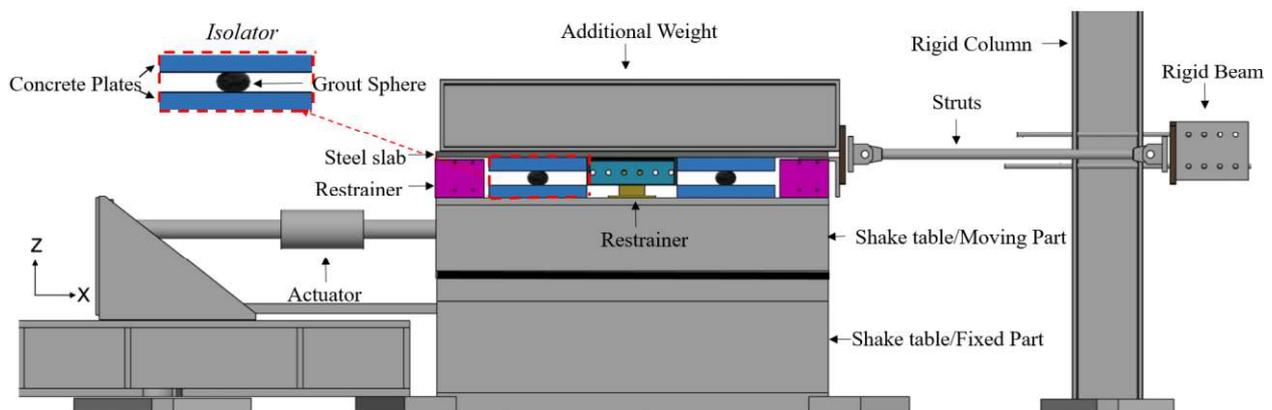

Fig. 4 - Schematic representation of the utilized experimental setup (side view).
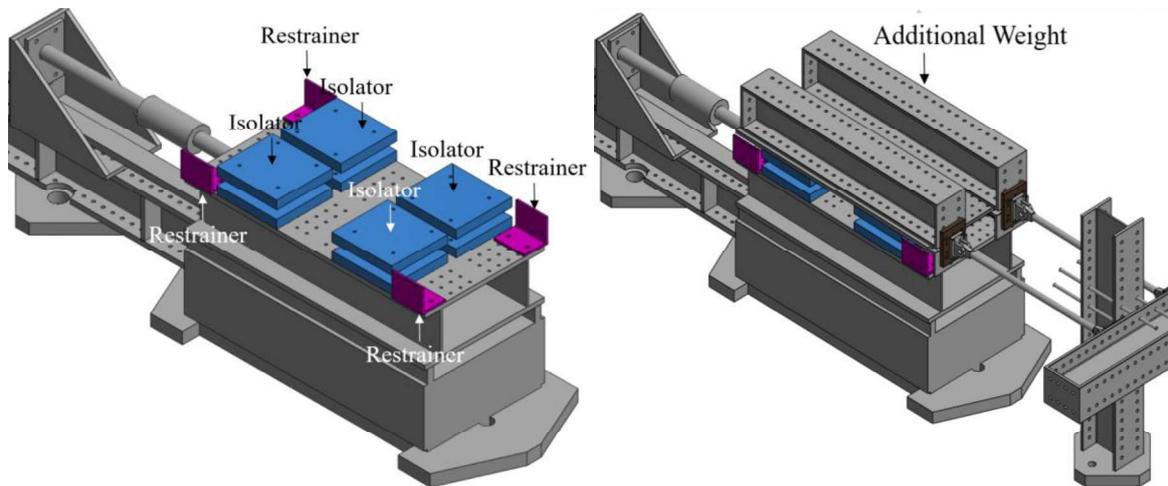
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Fig. 5 - Schematic representation of the utilized experimental setup (3D view). Left: Detail focusing on the isolators and the restrainers. Right: Detail focusing on the additional weight.
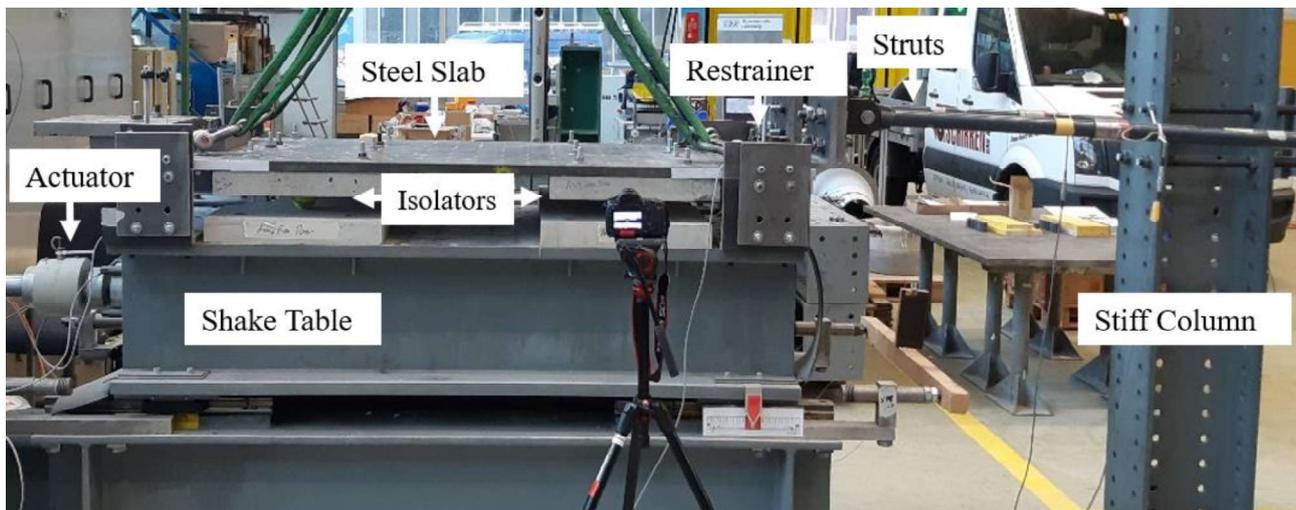

Fig. 6 - Picture of the experimental setup.

Displacements were measured using an NDI Optotrak Certus system, which consists of a camera and optical markers. The accuracy of this system is 0.1 mm. Force was measured by the two struts which held the steel diaphragm in place (Figures 4-6).

2.3 Tested configurations

This study tested bearings comprising a) two flat concrete plates (denoted as "flat") and b) a flat and a concave concrete plate (denoted as "concave"). For both configurations, two different vertical loads were examined a) 2.08 kN and 3.23 kN per sphere.

The load under the walls of a modern unconfined masonry house in Cuba is 2.80 kN/m². Assuming a wall height of 2.8 m, gives an unfactored weight of the masonry wall of 7.8 kN/m. A 10 cm slab at a typical 5x5 m room would add 3 kN/m to each wall, giving a total weight of 11 kN/m. Assuming isolators are placed every 1 m, the vertical load of each isolator is 11 kN. Therefore, the 3.23 kN vertical load discussed in this work would correspond to tennis balls placed every roughly 30 cm. Further reducing the distance between two consecutive isolators could reduce the vertical load on each isolator. However, this is feasible only for flat concrete surfaces. When concave concrete surfaces are used, the distance between two isolators should be larger than the diameter of the concave isolator (i.e., 350mm in the present study, Figure 3). Therefore, more

tests with larger vertical loads are needed – but are not discussed in this paper. A representation of the isolation scheme in a masonry structure is shown in figure 1.

3. Test Results

3.1 Monotonic Uniaxial Compression tests

Monotonic uniaxial compression tests were performed 28 days after casting to characterize the behavior of the grout spheres under vertical loading. The spherical shape of the isolators leads to a force-displacement graph which has increasing axial stiffness as the loading progresses (Figure 7, Right). Five grout-filled tennis balls were tested. The average strength and the standard deviation of the compressive strength were 13.24 kN and 2.73 kN, respectively. It is noted that the applied load was vertical to the surface which connects the two hemispheres. This loading direction is not conservative since it does not lead to sliding-shear failure of this weak interface; however, it serves as an upper limit of the strength of the grout isolators. The compressive strength of such grout-filled tennis balls can be increased by using high-performance grout. The cost is not a drawback, as the total volume needed is very small.

3.2 Cyclic tests

Figure 7 presents the results of the cyclic tests in the form of force – deformation loops. For each of the four tests, a different set of spheres was used. All configurations were subjected to at least 3 circles of the same sinusoidal excitation, with an amplitude of ±100 mm and a frequency of 0.2 Hz. A summary of the main quantities of the cyclic tests appear in Table 2.

The rolling friction coefficient (μ_{roll}), is defined as the ratio of the horizontal-to-vertical force at zero displacement. In all tests, the rolling friction coefficient was low, ranging from 5.2 to 8.6 %, with this range being appropriate for seismic isolation applications (Table 1). As expected, it increases with increasing vertical load. This is also observed in Constantinou and Cilsalar [28-30], and it is due to the change of the geometry of the spheres under larger load, due to the compressibility of the rubber-like material of the tennis spheres.

The force-deformation loops are not symmetric, especially for the configuration where W = 2.08 kN and flat plates are used; however, the fluctuation of force is consistent over the circles. This behavior has been observed by Nikfar and Konstantinidis [35] in tests of equipment supported on caster tires and is called "flat spotting".

Unexpectedly, the loops of the concave isolators do not show a consistently larger restoring force. This is partially due to the small displacement amplitude of the excitation that was dictated by the displacement capacity of the setup. It seems that for such small displacements, the geometrical imperfections of the spheres were more important than the uplift induced by the concave surface of the bearing. Therefore, more work is needed under larger displacements.

Table 1 - Rolling friction coefficient for each tested configuration

Rolling Friction Coefficient (μ_{roll}) (%)			
W = 2.08 kN, Flat	*W = 2.08 kN, Concave*	*W = 3.23 kN, Flat*	*W = 3.23 kN, Concave*
5.9	5.2	8.6	7.7

Table 2 – Main quantities of the cyclic tests

Quantity	Radius of curvature of concave concrete plates	Eigenperiod of concave configuration	Diameter in plan view of concave plates	Vertical load per sphere	Amplitude of cyclic test
Value	750 mm	1.74 sec	350 mm	2.08 or 3.23 kN	±100 mm

4. Conclusions and limitations

This paper investigates the use of grout rolling isolators, cast in tennis balls, as a low-cost and sustainable seismic isolation technique for the developing world. Cyclic tests proved that the rolling friction coefficient (μ_{roll}) of the system is within the desirable range for seismic isolation applications, with μ_{roll} increasing with an increasing vertical load. The cyclic loops are significantly different from the ones that a rigid-rolling-body would suggest, indicating that localized compression at the contact area cannot be neglected. The cyclic graphs demonstrate significant fluctuations, which are however, consistent over the different circles.

The main limitations of the present study are the weight applied to each sphere and the amplitude of the displacements in the cyclic tests, which are probably lower than the corresponding magnitudes in a real application. This was a limitation of the utilized experimental setup. Therefore, further research on the cyclic response of grout spheres under larger vertical load and lateral displacement is proposed.
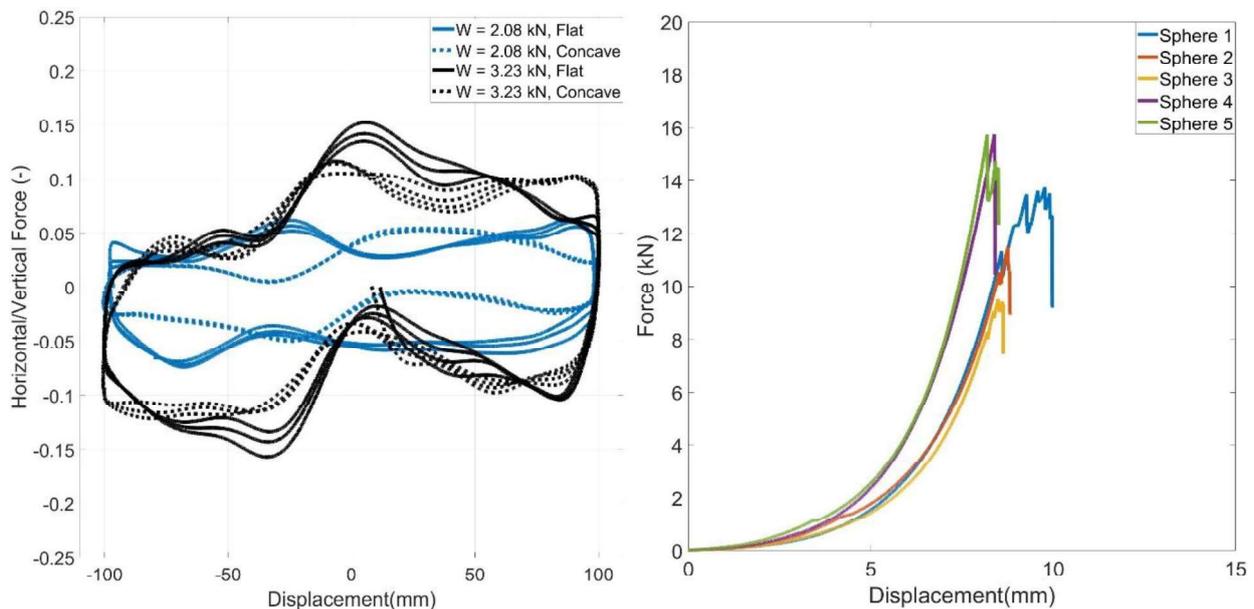

Fig. 7 - Experimental results. Left: Cyclic tests of the various configurations, Right: Compression tests of five grout-filled tennis spheres

5. Acknowledgment

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