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ROLLING-BALL RUBBER-LAYER ISOLATION SYSTEM: STATE OF THE ART, PERFORMANCE AND DESIGN PROCEDURE

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Abstract. *A rolling-ball rubber-layer (RBRL) isolation system was developed at TARRC to enable isolation of lightweight structures. The system is very versatile, a great range of equivalent natural frequencies and coefficients of damping being achievable through the independent choice of rubber spring and rubber-layer rolling track. It is suitable for isolating light structures, and much more effective at low excitations than an equivalent sliding system would be. In this paper the state of the art and the dynamic behaviour of RBRL isolation system will be restated. Subsequently, a simple and efficient procedure will be described for the design of the system: this is aimed to get the principal value of the system parameters to meet the chosen values of isolation period and damping ratio. In particular, it will be emphasized that a certain value of rolling resistance of the device could result from different combinations of the device parameters, thus leaving the final specification to be made on the basis also of preferences regarding small-deflection behaviour and cost. Finally, a future application of the isolation system for the seismic protection of a statue is presented and discussed.*

1 INTRODUCTION

While in the last decades the main studies and applications performed in the field of seismic isolation were aimed toward the isolation of structures, in the last few years attention was also dedicated to the protection of the contents, since they may have an extremely high value, sometimes even more than the structure in which they are contained. The lack of effective techniques, which are sufficiently developed and applicable for the seismic risk mitigation of lightweight objects, make the seismic protection of contents a crucial and worldwide issue.

Some data from Taghavi & Miranda [1], reported in Figure 1, illustrate the typical investment in structural framing, non-structural components and building contents, for three common types of commercial construction: office, hotel and hospital. Clearly the investment in non-structural components and building contents is far greater than that for structural components and framing (Whittaker & Soong [2], FEMA E-74 [3]).

The value of the content objects might be high not only from an economical point of view, e.g. for special medical or industrial equipment, but also from a cultural or historical one: this is the case for museum contents and art objects in general. The need to prevent or mitigate the devastating effects of earthquakes on cultural heritage assets is acute for countries in which this heritage is concentrated, and which suffer the highest seismic risk level: such as the case of Italy, and many other sites in the Mediterranean basin. Awareness of this issue has recently grown in Italy too, as a result of the quakes of Umbria-Marche (1997), l'Aquila (2009) and Emilia (2012).

Although the basic theories and concepts of seismic isolation are the same, the isolation techniques to be used for the content are not a mere extension of the ones used for civil structures. Indeed, the following technical peculiarities have to be considered:

- the contents involve masses orders of magnitude smaller than those characteristic of civil structures, whereas the demand for relative displacement is not likewise scaled down, and the combination may fall outside the range feasible with a conventional isolator suitable for large masses;

- lightweight structures are often very vulnerable, even for small seismic actions, since they often are merely supported on the base without possibility to be anchored (because of architectural or preservation requirements); this leads to the necessity to design a base isolation considering the possible rocking/overturning and sliding phenomena;

- besides being technically proficient, the isolation systems at the base of items of content have to observe conservation and aesthetic requirements too.

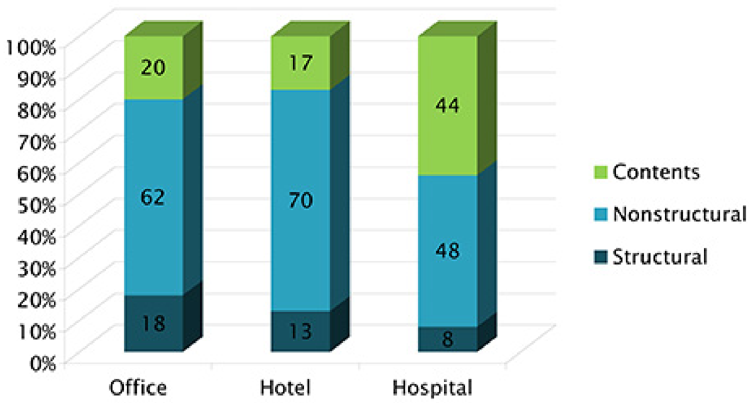


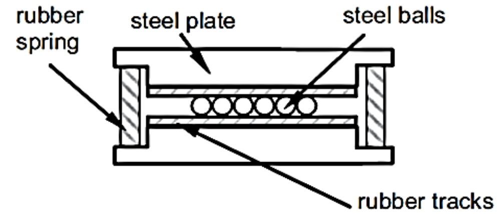
Figure 1: Typical cost breakdown in building construction, according to Taghavi & Miranda [1], for three different occupancies (image from FEMA E-74 [3]).

2 BACKGROUND OF RBRL ISOLATION SYSTEM

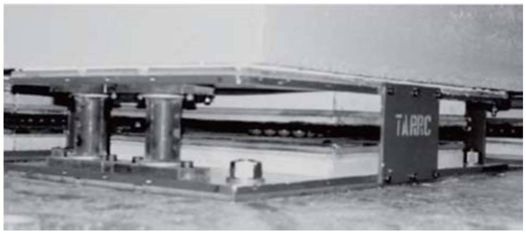
2.1 Presentation of the isolation system

The rolling-ball rubber-layer isolation (RBRL) system, originally proposed by Prof. A.G. Thomas, was developed at TARRC to enable isolation of low-mass (< 10 t) structures. The principal system components are visible in Figure 2, from Guerreiro et al. [4], and their principal functions are:

- steel rolling balls system – enables support of gravity loads and accommodation of large horizontal displacements;
- rubber-layer tracks – provide appropriate energy dissipation capacity and adequate resistance for horizontal non-seismic actions;
- rubber springs – provide recentering function and system stiffness in steady-state rolling phase.



a)



b)

Figure 2: a) Simplified representation and b) image of the RBRL system (from Guerreiro et al. [4]).

Extensive experimental studies of this system were undertaken by TARRC and collaborating research centres in the period 1995 – 2002 (Donà et al. [5]), resulting in four publications on shaking table tests and two more publications restricted to laboratory characterisation of the system itself. A new experimental campaign for the characterization of the system behaviour was performed at TARRC's engineering laboratory in 2014 for a Ph.D. project (Donà [6]), in a collaboration between TARRC and University of Padova.

All these experimental studies are briefly reported in Table 1. The RBRL systems investigated were diverse, involving different design natural frequencies and levels of damping.

2.2 Highlights of the system behaviour

Previous experimental studies have shown that the RBRL isolation system has three key types of behaviour, differentiated according to the magnitude of the displacements relative to the ground.

1. <u>Inside-pit behaviour</u>

For small displacements the system has nonlinear force-displacement characteristics, with high damping and high stiffness, albeit the stiffness declining rapidly as the displacement amplitude is increased. In this regime the behaviour is dominated by the continued location of the balls within a viscoelastic depression, or pit, formed during the long period under static load in the absence of seismic excitation. This behaviour contrasts with that of a sliding system, which presents a very high elastic stiffness, bordering on rigidity, for small excitations.

2. <u>Fuse behaviour</u>

If a characteristic threshold horizontal force is applied, for example by a sufficiently large ground acceleration, the balls will escape from the locality of the viscoelastic depressions, and roll with an approximately constant opposing resistance, significantly lower than the characteristic threshold force. In this regime, the system behaves like a mechanical fuse, the force

Project / Publication	Type of tests	Tracks	Springs	Superstructure
INCLUDING SHAKING TABLE TESTS				
EERC (Foti and Kelly [7])	monoaxial	high damping, Jakarta compound (Lab Rep 96. Compound 009-06)	steel coil, soft	flexible – model building
ENEL/ISMES/TARRC collaboration (Muhr and Bergamo [8])	monoaxial	high damping, probably the same as EERC	steel coil, soft	rigid – concrete slab
REEDS (Bettinali et al. [9])	triaxial	low damping A, inside ϕ of 190 mm; high damping B outside (ball array ϕ ~ 190mm)	rubber B, stiff (1.3Hz)	flexible - electrical substation structure
ECOEST (Guerreiro et al. [4])	monoaxial biaxial triaxial	low damping A, both or upper; high damping B, lower	rubber A, soft and none	rigid or flexible model building
LABORATORY BASED STUDIES				
DEGREE PROJECT (Cook et al. [10])	monoaxial	unfilled NBR	none	none
PhD PROJECT (Muhr et al. [11])	monoaxial	unfilled NR (two levels of curatives) and NBR	none	none
PhD PROJECT (Donà [6]) (Donà et al. [12])	monoaxial	unfilled NR, 3 different compounds: A, A+, A-	rubber A, 3 different diameters	none

Table 1: Summary of experimental studies done by TARRC and collaborators, on RBRL device.

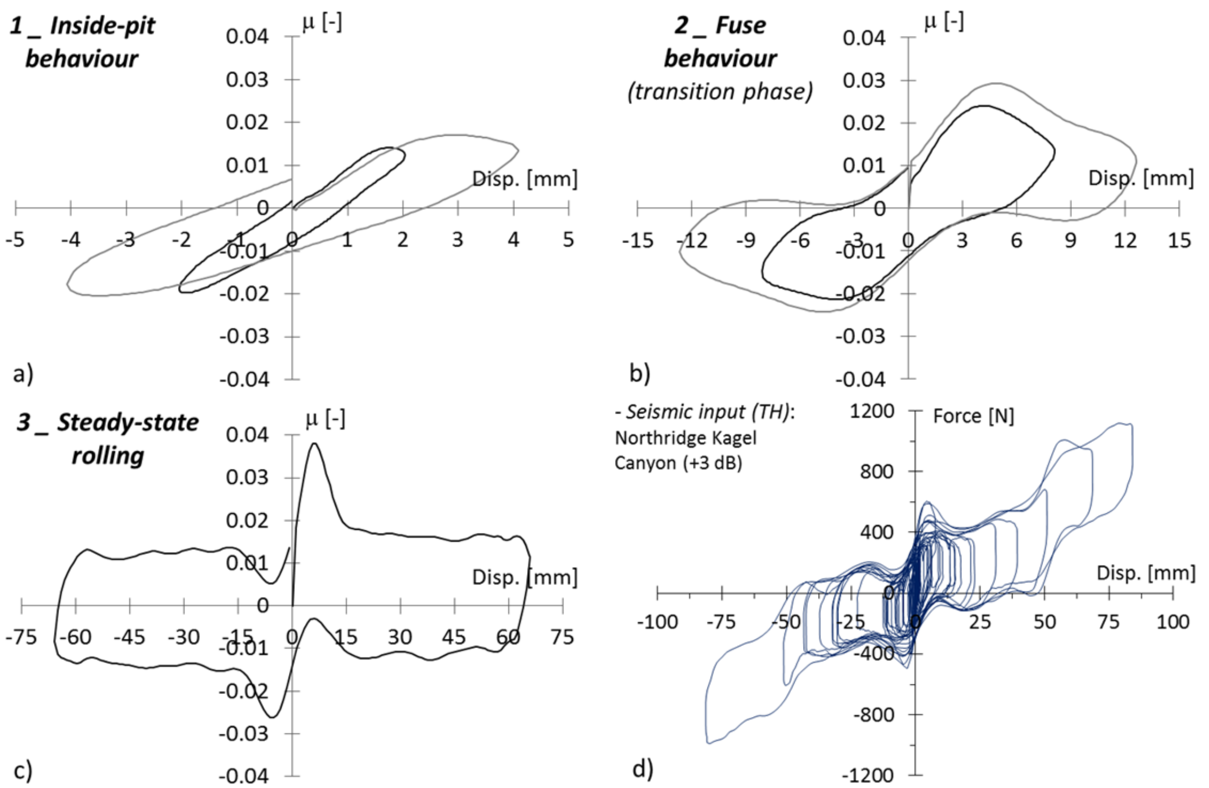


Figure 3: a), b), c) Rolling friction-displacement (μ-Disp) loops, representative of the types of behaviour of the RBRL system without springs (Donà [6]). d) Overall behaviour form a shaking-table test of the ECOEST project.

applied to the superstructure being truncated at the value of the characteristic peak, or threshold, force. This behaviour is akin to that of a sliding system subjected to moderate excitations, but with the additional feature that there is a memory effect of the viscoelastic depressions that tends quite strongly to recapture the rolling balls in their initial reference configuration. The displacement time history of the isolated structure therefore exhibits periods of small displacement, with occasional larger excursions; the force-time history is clipped at the characteristic threshold force.

3. Steady-state rolling behaviour

For strong excitations with many fluctuations (as opposed to a discrete pulse), continuous free rolling will be induced. In this regime, the recentering springs provide a well-defined stiffness so that a natural frequency of isolation may be defined: it is not strongly amplitude-dependent, and can be designed to have any desired value. The equivalent linear damping level can be calculated for the design displacement from the rolling resistance of the balls and the spring stiffness, as will be shown later, and there is very good scope for meeting any desired level of damping. The system thus behaves like a classical linear isolation system, but enables great scope for choice of natural frequency and damping ratio.

These key types of the system behaviour are visible in Figure 3 a, b and c. These rolling friction-displacement (μ-disp) loops, in which μ is the horizontal resistance divided by the vertical load applied on the RBRL system, derive from a new parametric experimentation conducted at TARRC for the Ph.D. project of Donà [6]. These tests involved different RBRL systems and different imposed sinusoidal motions, but only a few representative results of the system behaviour are herein shown, related to a RBRL system so configured:

- rubber tracks, 2 mm thick, of type A - an unfilled natural rubber with low-damping (see Guerreiro et al. [4] and Donà [6]);
- steel balls with 25 mm diameter;
- stress parameter $W/ER^2 = 1.2$, where W = vertical load per ball, E = Young's modulus of the rubber, R = radius of the ball;
- no recentering springs.

The choice to not consider the recentering springs in these tests was for better characterizing the pits effect on the small-deflection behaviour of the system.

Rubber springs provide a recentering stiffness that simply acts in parallel with the behaviour of the RBRL device without springs. The overall behaviour of the isolation system, with springs, is shown in Figure 3 d for a shaking-table monoaxial test of the ECOEST project, considering the RBRL system with rubber A, the "Mass Down" configuration and the real accelerogram of the earthquake "Northridge Canyon" (for more details see Guerreiro et al.[4]).

2.3 Advantages of the RBRL isolation system

- The RBRL system is relatively economical.
- The device assembly is easy to tailor for the specific case, in terms of geometry and performance, a great range of equivalent natural frequencies and coefficients of damping being achievable. Depending on the choice of parameters, the RBRL system provides a rich variety of possibilities, including primary seismic mitigation strategies of isolation, damping or fuse functions.
- The RBRL isolation system provides very effective reduction of excitation of the first mode of the isolated structure for small seismic events, for a wide range of frequency content, despite its being very much stiffer when the deflections across the isolators are small (< 5mm). The primary factor responsible is probably the very high damping, together with the changed

mode shape resulting from the compliance of the isolators, although the non-linear behaviour may also be significant (Donà et al. [5], Donà et al. [12]).

These considerations make the RBRL isolation system very attractive for the protection of works of art in a museum, which are present in large quantity and characterized by very different shapes, dimensions and masses.

3 NEW TESTS: ROLLING FRICTION AND RECENTERING STIFFNESS

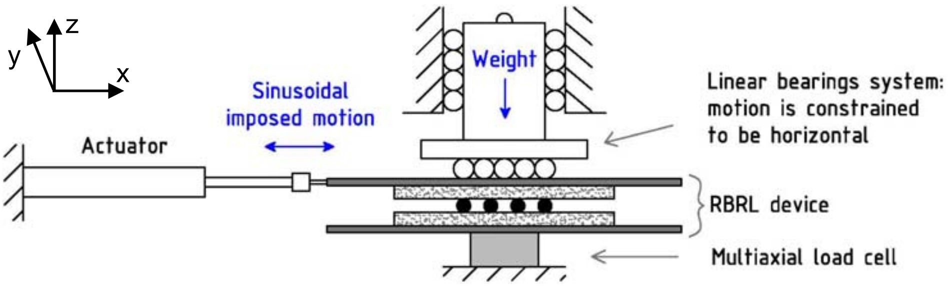
Although the small-deflection behaviour of the RBRL system requires a complicated model, the design of the isolation system is relatively simple, as it can be based only on the main performance parameters: the steady-state rolling force and the stiffness of the recentering rubber springs.

For design purposes, parametric experimentations were carried out at TARRC in 2014 [6] regarding the steady-state rolling and the dynamic behaviour of the recentering rubber springs.

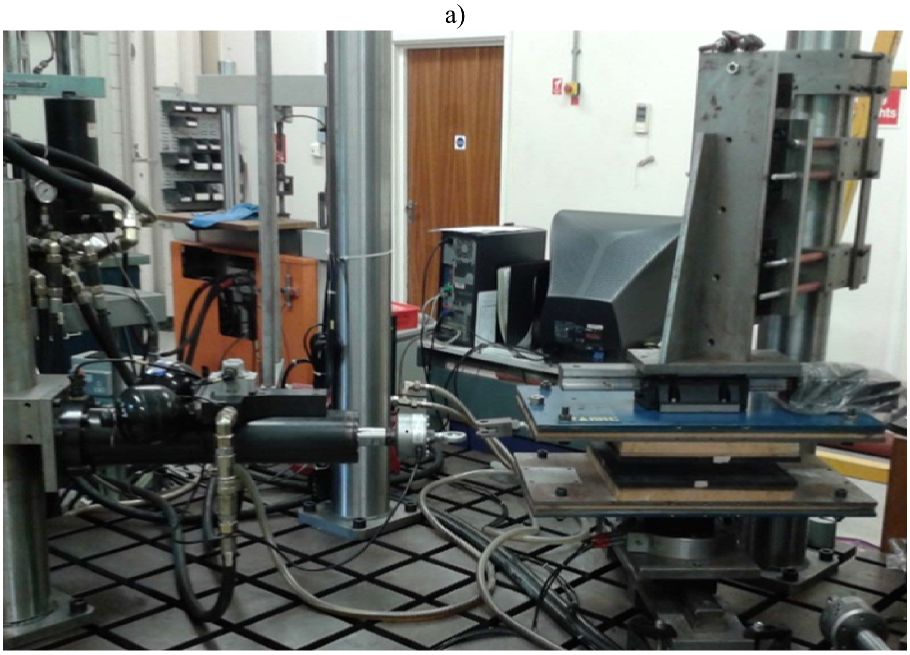
These tests and some useful results for the design of the system are presented below.

3.1 Tests on the RBRL devices for the steady-state rolling friction

All the tests were performed in single shear configuration for one RBRL device with no recentering springs: the test setup is shown in Figure 4.



a)



b)

Figure 4: Setup of the sinusoidal uniaxial tests: a) schematic drawing, b) photo.

The steel linear roller bearings shown in Figure 4 permit translation of the top plate in the x and z directions, but prevent rotation of it about any axis. The sinusoidal motion was controlled by the actuator and transmitted to the top steel plate of the device, that supports the weight, through a rose joint connection that permits small rotations. This connection was necessary to avoid bending stresses related to a non-perfect vertical alignment between actuator and top plate of the device, and to accommodate the small z-displacement as the balls roll out of and into their pits. The horizontal force (x-axis) was measured by the multiaxial load cell placed under the bottom plate of the device, which was fixed on it. This was preferred to the direct measurement of the force by the actuator load cell, to avoid inclusion of the friction inside the linear rolling bearings which constrain the top plate motion.

153 tests have been carried out changing the principal device parameters that control behaviour, i.e. the rubber compound, the thickness t of the rubber layers, the radius R of the balls and the stress parameter W/ER^2 per ball. Each test consisted of 3 sinusoidal cycles, with a displacement amplitude of 65 mm and a frequency of 0.5 Hz.

The rolling friction force in steady state condition was obtained, for each test, from the second of the three sinusoidal cycles performed. These force values were then divided by the vertical load used in the relative test, obtaining the rolling friction coefficients μ.

Some of the obtained results for rubber type A are reported in Figure 5, where the rolling friction μ is plotted versus coefficient t/R (thickness of rubber layers / radius of balls) for chosen values of the stress parameter.

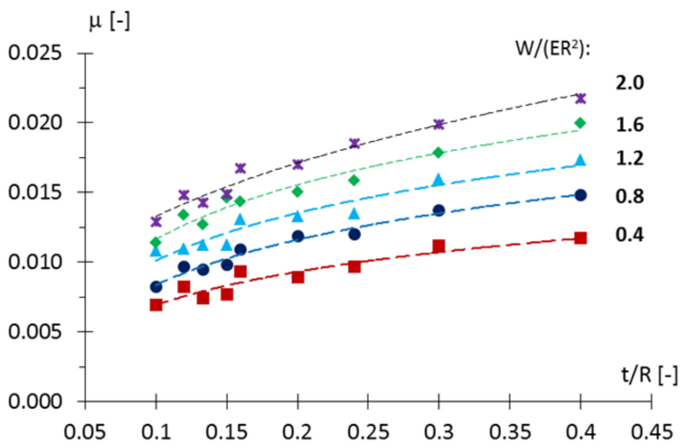


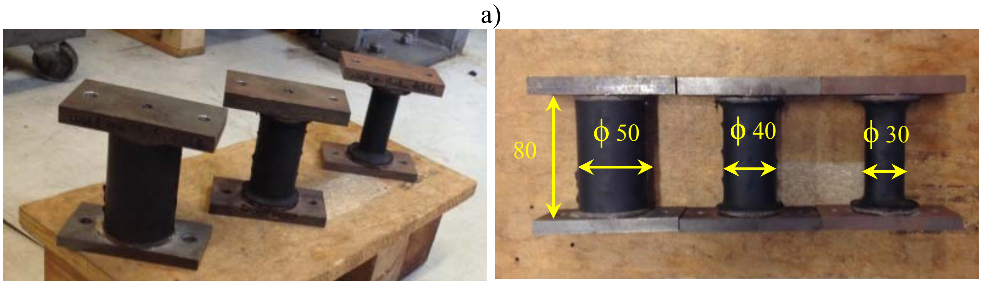
Figure 5: Rolling friction μ values of the RBRL system with rubber A, for different t/R and W/ER^2.

3.2 Tests on the recentering rubber springs for the system stiffness

Figure 6a shows the setup for the double shear tests carried out for the behaviour characterization of the recentering rubber springs. These springs are cylinders of rubber 80 mm long, bonded to steel endplates; they were moulded for the ECOEST Project (Guerreiro et al. [4]) from rubber compound A, in three different diameters: 30, 40 or 50 mm (Figure 6b). Every test was conducted using two springs with the same diameter, constrained into a steel frame appositely designed for this purpose. The steel plate connecting the two spring endplates was linked to the arm of the actuator.

Both sinusoidal and quasi-static tests were considered, according to Table 2. In particular, concerning the imposed sinusoidal motion, tests were carried out with different amplitudes (from 1 to 75 mm) for the same frequency (1 Hz) and with different frequencies (from 0.1 to 2 Hz) for the same amplitude (75 mm).

a)



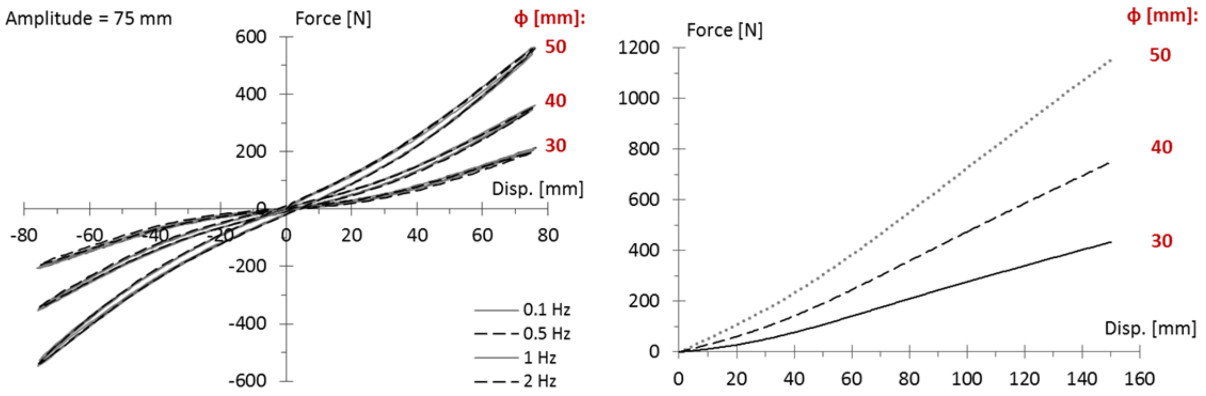
b)

Figure 6: a) Double shear test setup for the behaviour characterization of the recentering rubber springs. b) Tested recentering rubber springs; diameter (ϕ), from left to right: 50, 40, 30 mm.

Sinusoidal tests *different amplitudes*	*Frequency* *Amplitudes*	**1 Hz** 2.5; 5; 7.5; 10; 20; 30; 40; 50; 60; 75 mm
Sinusoidal tests *different frequencies*	*Amplitude* *Frequencies*	**75 mm** 0.1; 0.5; 1; 2 Hz
Quasi-static tests	*Velocity* *Displacements*	**1 mm/s** from 0 to 150 mm

Table 2: Double shear tests carried out on the recentering rubber springs.

Results from the sinusoidal tests with different frequencies are reported as force-displacement loops in Figure 7a. These show a not significant dependence on the velocity and a negligible hysteretic dissipation for the dynamic behaviour of the recentering springs, in particular for the smaller diameters. Figure 7b presents the results of the quasi-static tests, which were needed to extend the information about the stiffness of the springs for amplitudes bigger than 75 mm, this being the maximum stroke of the actuator in each direction and hence the amplitude limit for the dynamic tests. Both types of test show a slight dependence of the springs behaviour on the amplitude of deflection. The parameter needed for design purposes of the isolation system is the storage stiffness $K^{/}$ (from dynamic tests) or the secant stiffness K_{sec} (from static tests). These values are plotted versus displacement and compared in Figure 8. In particular, the values of the storage stiffness were calculated by the force-displacement loops of the sinusoidal tests with different amplitudes, using the Harmonic method (Ahmadi & Muhr [13]).



a) b)

Figure 7: Results from tests for springs of different diameter ϕ: a) dynamic – with different frequencies; b) quasi-static.

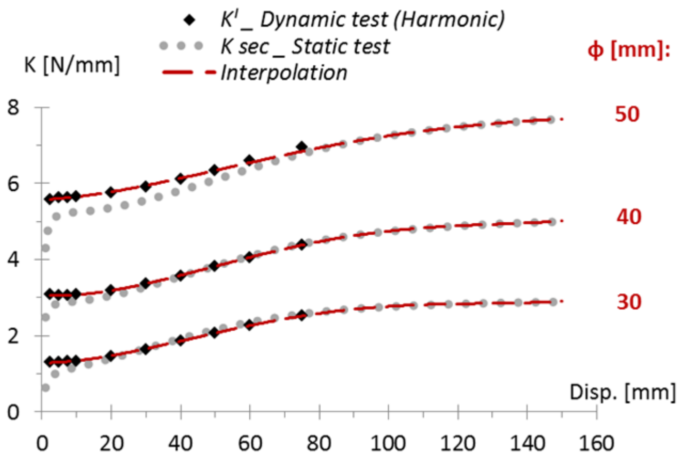


Figure 8: Comparison between the storage stiffness $K^{/}$, from dynamic tests, and the secant one K_{sec}, from quasi-static tests. The stiffness finally considered derives from $K^{/}$ values until 75 mm, and from K_{sec} values for higher deflections (as indicated by the dashed lines).

4 DESIGN PROCEDURE OF THE RBRL SYSTEM

According to Cook et al. [10], the values of the stiffness K and rolling friction coefficient μ of the RBRL system can be determined through the equations reported below, if the values of period T and damping ratio ζ have been decided and if the design displacement D, e.g. from the damped spectrum, and the mass M to be isolated are known.

$$K = \frac{4\pi^2 M}{T^2} \tag{1}$$

$$\mu \equiv \frac{F_R}{Mg} = \frac{1}{g}\,\frac{2\pi^3 D\zeta}{T^2\left(1-\pi\zeta/2\right)} \tag{2}$$

These equations were obtained considering an elasto-plastic hysteresis loop (Figure 9) as dynamic response of the RBRL system, and using the Secant linearization method (Ahmadi & Muhr [13]). These can be used if parameter ζ does not grossly exceed 20% and if the seismic excitation is sufficient for the peak roll-out force to be generated for much of the time history. For lower seismic excitations, the behaviour of the device will be governed by the effective dynamic stiffness of the balls rocking in their static depressions or “pits”: for this reason the

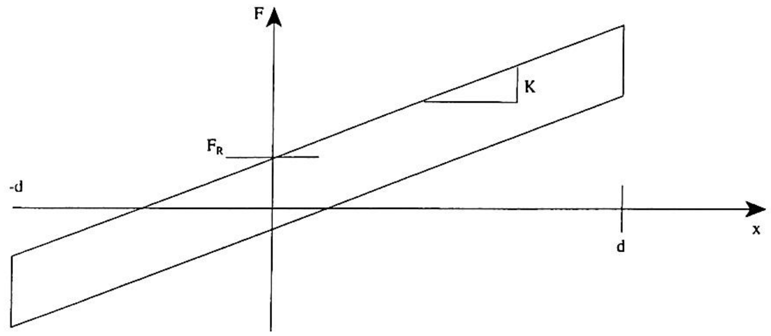


Figure 9: Schematic hysteresis loop for isolation system comprising rolling-ball dissipative-layer isolators and springs (from Cook et al. [10]).

method here presented is proposed for use only for design purposes, considering the maximum response spectrum as the design spectrum.

When the values of K and μ have been calculated, together with the ultimate displacement by the damped response spectrum, the geometric characteristics of the RBRL system can be determined through the previous experimental results. Using the plots of Figure 8, the correct diameter of the recentering springs to achieve the target stiffness of the system can be easily found by entering the figure with the values of displacement and K. Once the stress parameter has been decided, then, the value of the ratio t/R needed to get the correct μ can be obtained using the results as those presented in Figure 5. Finally, after the choice of R, it is possible to determine the number of balls to meet the stress level previously established.

Design procedure calls for two free choices to be made, the values of W/ER^2 and R. A different combination of the stress parameter W/ER^2 with the parameter t/R, that leads to the same μ, does not change the steady-state behaviour of the device. The appropriate value of this stress parameter is thus a compromise between cost and the necessity to avoid the creation of semi-permanent rolling tracks on the rubber layers. Also the choice of R is important from an economic point of view, the steel balls being one of the principal cost components.

Cost consideration is not so significant for a single application of the RBRL system. However, as the system is relatively economical and easy to tailor for the specific case in terms of geometry and performance, it is envisaged to be appropriate for projects such as a museum needing to isolate single artefacts, showcases and podia, where a large number of discrete isolation systems are needed, and hence the total cost becomes a key choice-determining factor.

5 FUTURE APPLICATION: ISOLATION OF THE STATUE "TEMPERANZA"

The University of Padova, in collaboration with TARRC, Numeria s.r.l. and the local authority of Verona, is working on a pilot project that involves the seismic isolation of one of the statues of the Scaliger Tombs (Arche Scaligere). The statue, the "Temperanza", is shown in Figure 10.

The principal features of the statue, with base (see Figure 10 b), are:

- total weight: ≈ 372 kg
- maximum dimension: ≈ 483 x 463 x 1665 mm

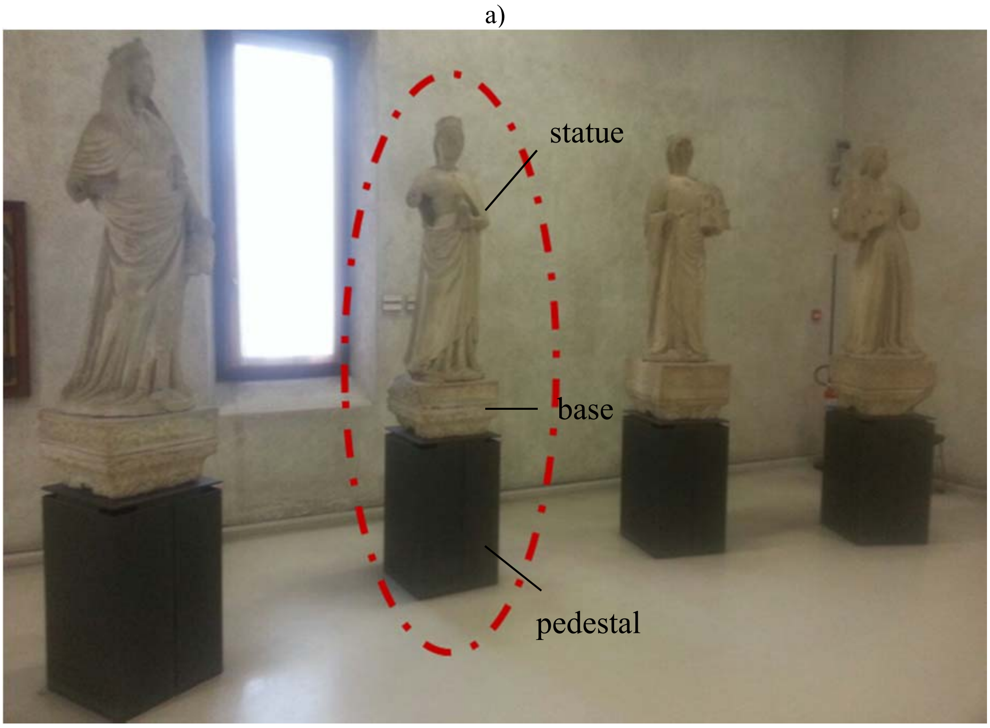
The principal features of the statue, without base, are:

- maximum dimension: ≈ 483 x 455 x 1372 mm
- height of the centre of gravity, relative to the plane between the statue and base: ≈ 536 mm.

The statue is placed in the "Museum of the frescoes of G.B. Cavalcaselle" in Verona (IT); the SLV (Life Safety) seismic response spectrum of that area is shown in Table 3.

Figure 11 presents a possible scheme of the RBRL system for this pilot project.

a)



b)

Figure 10: a) Optical scanning of the statue "Temperanza" (images provided by UNOCAD s.r.l. – Vicenza IT). b) Images of the statues of the Scaliger Tombs in the "Museum of the frescoes of G.B. Cavalcaselle", Verona IT.

Verona Response Spectrum	
Limit state	**SLV**
Reference period (V_R)	50 years
Return Period (T_R)	475years
Exceedance probability in V_R	10%
a_g	0.157
Soil type	B
Topographic height effects	T1
Behaviour factor q	1
PGA [g]	0.188

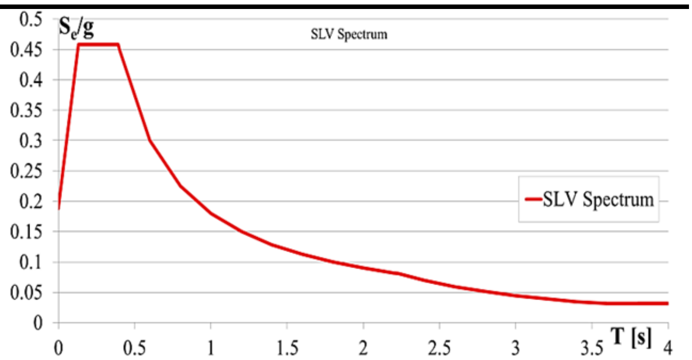


Table 3: SLV (Life Safety) acceleration response spectrum (ARS) of Verona.

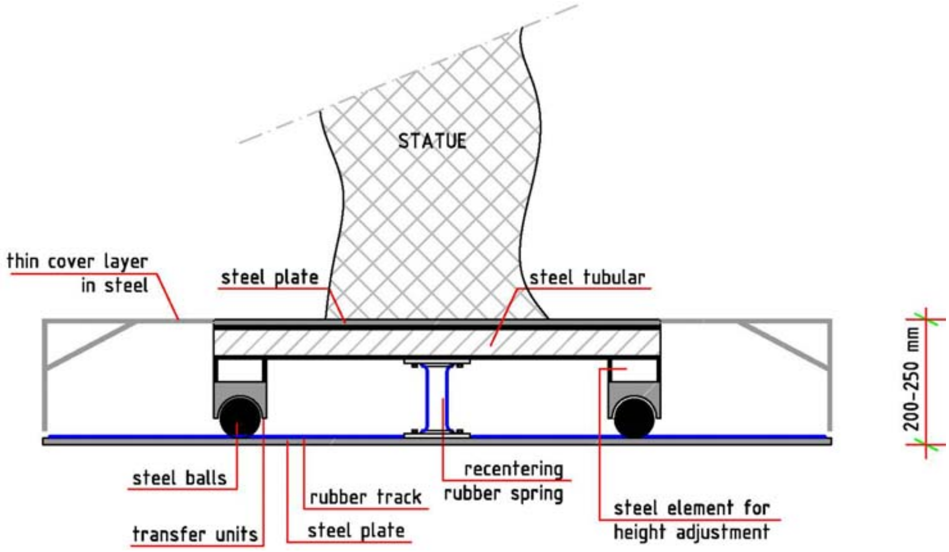


Figure 11: Scheme of the RBRL system (1 rubber layer) for seismic isolation of the statue "Temperanza". The same for both directions.

The choice to use the balls inside transfer units, thus only one rubber track, minimises the vulnerability of the system to the effect of overturning moment. However, it also results in a rolling resistance that is half with respect to the associated RBRL system with a double rubber-layer.

6 CONCLUSIONS

- The state of the art of the RBRL seismic isolation system is reported. The principal components and characteristics are presented. The three key types of its behaviour, differentiated according to the magnitude of the displacements relative to the ground, are shown and discussed.
- The principal advantages of this system, for the seismic isolation of lightweight structures, are highlighted. Briefly: the RBRL system is relatively economical and is easy to tailor for the specific case, in terms of geometry and performance, a great range of equivalent natural frequencies and coefficients of damping being achievable; the RBRL system presents a good performance also for small seismic events, which induce small deflections (< 5 mm) across the isolator, resulting much more effective at low excitations than an equivalent sliding isolation system (Donà et al. [12]).
- Two new experimentations, carried out at TARRC in 2014 for a Ph.D. project (Donà [6]) and addressing the steady-state rolling resistance and the recentering stiffness of the system, are presented. The results of these investigations are presented in a suitable form for the design of the RBRL system.
- A design procedure for the RBRL system is presented, based on that proposed by Cook et al. [10]. This procedure allows the determination of the parameters that influence the system behaviour, for a specific design spectrum and vertical load, starting from the choice of isolation period and damping ratio.
- A future application of the RBRL system for the seismic isolation of a statue is briefly introduced.

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