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RESEARCH ARTICLE

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Rolling devices for seismic isolation of lightweight structures and equipment. Design and realization of a prototype

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Summary
The present paper shows the results of an experimental study on new rolling seismic isolators made with steel cylindrical elements arranged on two levels, interposed between flat rubber layers, and rolling in the same direction. It is a rather simplified version of an isolator designed to have the cylinders disposed on two levels, according to two directions perpendicular to one another in the horizontal plane, in order to uncouple any component of the seismic force. In the original basic idea, the rolling planes present a concave surface with a high radius of curvature for recentering capabilities of the device. The rolling of the cylinders allows the isolation of the structure uncoupling the motion of the structure by the ground motion, although the rubber layers have to activate a viscous dissipation process, thanks to the steel-rubber contact. A prototype of the simplified version of the device has been realized and tested to obtain the hysteresis behavior and the equivalent viscous damping under increasing values of the axial preload, either with glued or vulcanized rubber layers. The results have been finally discussed also to identify the possible future developments and improvements of the proposed device.

KEYWORDS
base isolation, characterization tests, dynamical parameters, simplified prototype, viscoelastic behaviour

1 | INTRODUCTION

Base isolation is a well-known technique capable of reducing the seismic vibrations in a structure with respect to a nonisolated structure (fixed base). This reduction occurs by mean of devices (isolators), which are usually inserted between the base of the structure and its foundation. In the literature, it is possible to find many types of isolators, which are based on different mechanisms and, however, can reduce the seismic effects on a structure.[1-5] The presence of the isolators results in a greater flexibility of the structure and, consequently, in an increase of its vibration period (descending branch of the response spectrum). However, with the increase of the period, there is also an increase of the displacements with respect to the same structure with a fixed base.

Apart from base isolation, other passive techniques have been investigated in the last 30 years for an innovative antiseismic design such as energy dissipation systems[6,7] based both on the hysteresis of the material[8,9] and on the dissipation produced by viscous materials,[10] tuned mass dampers,[11] and so on.

The rolling isolator here considered is referred to as rubber-layer roller bearing (RLRB).[12] It is able to reduce the seismic energy by shifting the fundamental frequency of the structure and to dissipate the input energy. The device consists of cylinders free to roll in-between two thin layers of elastomer to provide load-bearing capability and damping. It shows considerable advantages compared with traditional seismic isolators. Indeed, through a simple and low-cost construction technology, this isolator allows the reduction of the inertia forces and the resulting stresses produced by the earthquake on the structure, the reduction of interfloor displacements, and the partial dissipation of the seismic energy thanks to the viscoelastic behavior of the rubber. One can attribute to such a device the same advantages of friction isolators. The latter possesses two important characteristics; the shear force is proportional to the mass on the device, and it is effective over a wide input frequency range. The first characteristic gives to RLRB isolator the important advantage to reduce the torsional effects, typical of sliding and friction devices. The proportionality involves the absence of eccentricity between the center of stiffness of the isolation system and the center of gravity of the masses of the superstructure and the absence of a characteristic frequency that avoids the risk of resonance with the ground motion. In addition, differently from other friction devices already on the market (i.e., those produced by the Japanese company THK Global (www.thk.com)), the device is able to reduce the accelerations of the structure due to the seismic force and, consequently, the displacements at the isolation level, thanks to the viscoelastic behavior of the rubber in the steel–rubber contact of the cylinders rolling on the rubber layers. The latter are suitably connected to steel plates good to give support and stiffness to the superstructure. The rolling of the cylinders in contact with the rubber layers allows the activation of a viscous dissipation process due to the presence of the rubber itself. The amount of energy dissipated depends on the number of cylinders and the geometrical characteristics of the parts composing the device. In this first study, RLRB device has been designed for light structures and equipment; anyway, a higher number of cylinders and different dimensions of the device itself would improve its behavior to fit also for ordinary buildings. The cylinders are arranged on two levels, according to two directions perpendicular to one another in the horizontal plane, in order to uncouple any component of the seismic force. It was also hypothesized a curvature of the rubber layers' ends and the supporting steel plates in order to confer a recentering capability to the designed device (Figure 1a). In another configuration, only the rubber layers present a curvature at their ends as shown in Figure 1b.

It should be noted that the isolators here proposed facilitate the operations of inspection and maintenance and, being composed by easily separable elements, provide operational benefits in case of total or partial replacement for malfunction or deterioration of the materials and the individual elements.

The main purpose of the research here reported is to investigate in detail the behavior of an RLRB used to base isolate a low-rise structure during horizontal ground motions.[12] The presence of the rubber has the objective of introducing a higher dissipation of energy between the base and the structure.[13,14] Furthermore, by adopting a suitably elastomeric

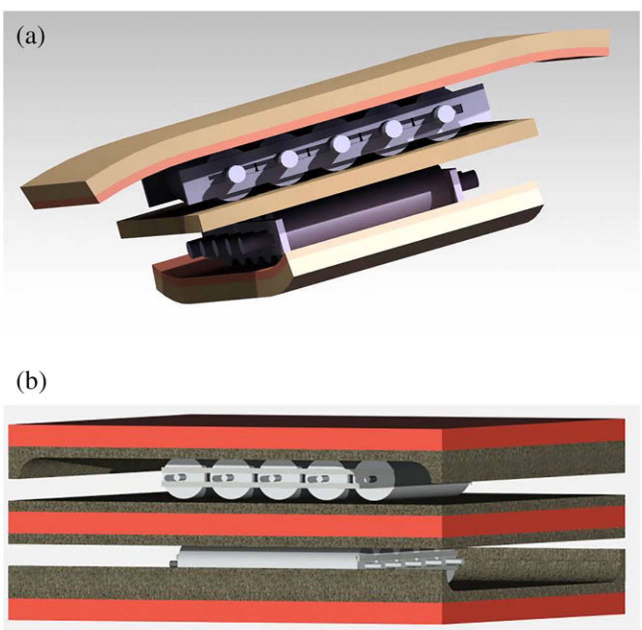

FIGURE 1 Sketch of a full-scale model of rubber-layer roller-bearing isolator with (a) curved plates and (b) curved rubber ends

curved surface, it is possible to provide the recentering function,[15,16] however, reducing the vertical accelerations that a geometry of this type entails.[17]

Because the contact between the elastomer and the cylindrical elements is the key point of these devices, it has been necessary to understand this phenomenon in detail.[14] The achievement of this goal will enable the realization of the geometric optimization of the devices according to the load of the structure and the seismic stresses.[18]

Studies have been conducted on roller devices by Butterworth[19]; he proposed a rolling isolation system consisting of rollers with nonconcentric spherical upper and lower surfaces, in which the isolation period becomes a nonlinear function of the isolator displacement. Compared with a conventional isolator with a constant period, a nonlinear rolling system is able to reduce the peak acceleration with smaller reduction in peak displacement for high-intensity earthquakes.[20]

A device similar to a double friction pendulum[21] but with the rolling balls covered by a damping material has been studied by Tsai et al.[22] It is called SDI-BPS isolator and comprises two spherical concave surfaces and a steel-rolling ball covered with a special damping material to provide damping and prevent any damage and scratches to the concave surfaces during the dynamic motions. The proposed system provides excellent capability in protecting the vibration sensitive equipment and exhibits a stable behavior under long terms of service loadings and earthquakes.

Harvey et al.[23] proposed a rolling solation system realized with steel balls rotating on thin low and high damping rubber layers applied to bottom and top frames connected to the structure and to the foundation, respectively. The device behavior is based on a rolling pendulum mechanism. The frames, in fact, contain four concave-up bowls and four concave-down bowls, respectively, at their corners. The proposed model was shown to effectively predict peak relative displacements, peak total accelerations, and the occurrence of impacts for a wide range of disturbance amplitudes and periods.

In the study of Donà et al.,[24] the isolation device here proposed is similar to the RLRB isolators studied and designed in the present paper, but instead of cylinders, they used balls. The layers are flat, and the testing and auxiliary rubber recentering springs are utilized to recenter the structure after the earthquake motion. Also, the testing setup utilized was quite different, and the experimental results gave more information regarding the steady-state and small displacement rolling behavior of the isolation system and the behavior of cylindrical rubber recentering springs.

Studies highlighted the necessity to obtain a reasonable combination of damper and rolling friction that can highly decrease the relative displacement of the isolation system while keeping the acceleration of the isolation system within an allowable range.[25] This characteristic has been reached thanks to the contact of the steel cylinders with rubber, like in the RLRB devices.

A quite detailed review of the state-of-the-art in the field of rolling isolators is rather recent.[26] It has been pointed out how these isolators are also good if applied in bridges.[27]

In the present study, definition and implementation of an RLRB prototype were developed in consecutive stages. Based on the final design, a reduced scale prototype of an RLRB isolator was realized. It was obtained by a simplified design of the proposed rolling seismic isolator where the steel cylindrical elements are interposed between flat rubber layers and arranged in two levels, rolling in the same direction.

In the final design of the simplified RLRB, in addition to the necessary connecting elements between the device and the testing machine, also details were designed to avoid instability phenomena during the execution of the tests.

Tests were carried out to determine the seismic response of the device and its hysteresis cycles. The results gave the possibility to make a critical analysis of the behavior of RLRB device paying attention to the significant advantages that are obtained in the seismic protection of lightweight structures.

2 | TECHNOLOGICAL AND DESIGN CHARACTERISTICS OF RLRB

In the experimental phase, a prototype of the device was designed, built, and then characterized by laboratory tests. The objective was to verify the correct behavior of the individual elements that make up the device as a whole.

The benefits expected from this type of isolator consist of a limited stress in the rubber through the use of cylindrical elements (not punctiform support as in the case of spheres[12]), in a recentering function to be activated through the curvature of the rubber layer, avoiding, in this way, the use of mechanical elements of "geometrical return" and in a type of viscous dissipation process due to the presence of the rubber in contact with steel cylinders. It must be underlined that these benefits, however, are obtained by a very simple and economic construction technology and assembling way.

From the point of view of material characterization and dimensional design of an RLRB isolator, a preliminary design was developed and then finalized. It was a first step towards the final realization of the prototype to be tested. The aim was to get a behavior able to return meaningful data regarding the benefits achieved through the use of the proposed system.

2.1 | The prototype

In order to characterize the behavior of an RLRB device, a smaller simplified prototype was designed according to the size of the Instron testing machine of the testing and materials laboratory "*M. salvati*" of the Polytechnic University of Bari. Due to operational problems at this stage of characterization, a simplified prototype was, in fact, proposed, and the curvature at the ends of the elastomeric layers, useful for the recentering function (postearthquake) of the device was not realized. Therefore, the simplified testing prototype was composed of three S275 steel plates, with a thickness equal to 20 mm, arranged with 2 mm-thick natural rubber. The mixture used for the devices is of the "hard" type called "Over," whose characteristics have been preliminarily tested in order to use a suitable elastomer type with respect to the performances required by the devices to be tested.

The reference codes for the tests on the elastomer are EN 15129 and ISO 48, ISO 37, and ISO 815.

The characteristics of the rubber are shown in Table 1. Hardness has been provided in International Rubber Hardness Degrees.

Two plus two steel cylinders—radius $R = 15$ mm and length $L = 310$ mm—were positioned between the plates and were free to roll in contact with two elastomeric layers. The cylinders were connected one another by means of steel ties, which ensure a uniform overall displacement of the cylinders (Figure 2). The link (length 110 mm, height 21 mm, and thickness 4 mm) is important to avoid differential displacement between cylinders due to a different pressure on the rubber layer.

The dimensions, shape, and structural details of the device are reported in Figures 2 and 3.

The steel plates present holes useful to connect the different components of the seismic isolator and to link it to the testing equipment itself.

The elastomeric layers were applied only to surfaces in contact with the cylinders. In this way, the rolling of the cylinders in contact with the rubber layers, thanks to the viscosity of the latter, allows the reduction of the seismic energy transmitted to the superstructure from the ground.

The behavior of the isolation device essentially depends on the characteristics of the rubber, described extensively in the study of Foti et al.[14]

TABLE 1 Characteristics of the rubber utilized for the layers of rubber-layer roller-bearing device

Stiffness k [kN/mm]	Shear Modulus G [MPA]	Damping S [%]	Shore A hardness (without aging) [°IRHD]	Shore A hardness (with aging) [°IRHD]	Tensile strength (without aging) [MPa]	Tensile strength (with aging) [MPa]
0.6726	0.70	16	69.6	69.7	15.41	17.29

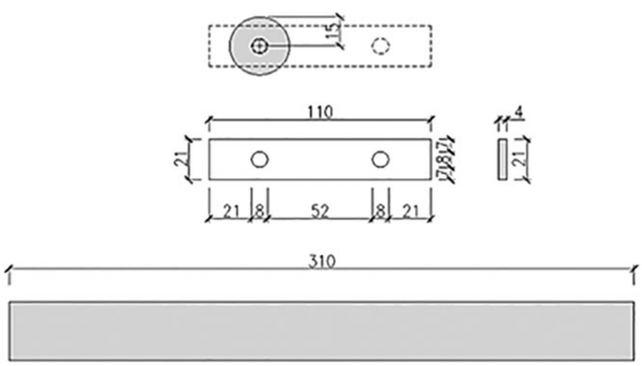

FIGURE 2 Steel cylinders and connecting steel ties. Lateral view

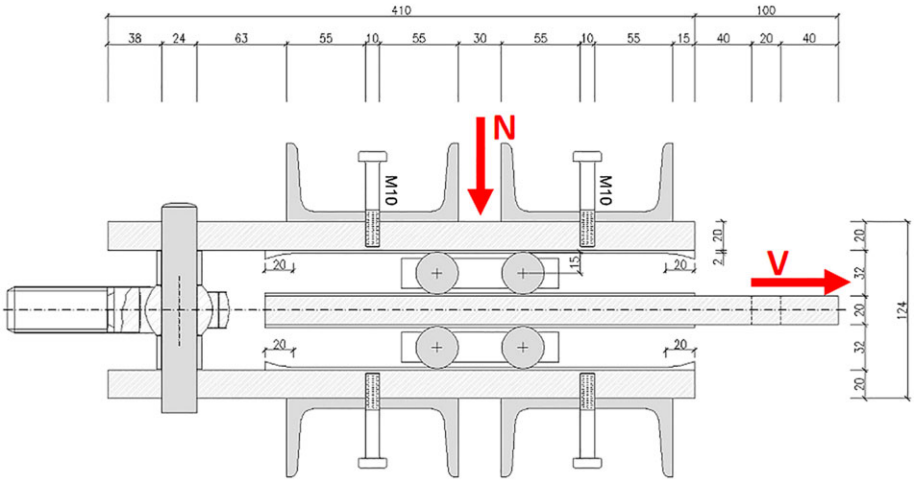

FIGURE 3 Longitudinal section of the testing prototype and the mechanical connections

The simplified testing prototype, therefore, in its assembled composition, appears to be mainly made up of three steel plates with interposed steel cylinders, free to roll in contact with elastomeric layers (Figure 4).

In the first tests, the elastomer was simply glued on the steel surfaces in direct contact with the steel cylinders (Figure 5) by means of a hot gluing process. The aim was both to reduce the operational difficulties in the manufacturing process of the prototype and to optimize the procedure in terms of time and costs.

In the second series of tests, a process of vulcanization of the rubber was carried out in order to avoid phenomena of detachment from a steel support in the event of transmission of high loads.

In particular, bearing in mind what was found in previous studies[18,28] on the drag phenomena and the geometrical and mechanical characteristics, the rubber layers were designed with such a thickness as to avoid excessive sinking of the cylinders in the rubber layer and a consequent excessive and inadequate extension of the rubber–steel contact surface.

The length of the cylinders was chosen greater than the width of the plates so as to obtain, in this way, a homogeneous contact surface and to avoid interference between the layer of the elastomer and the end circular surfaces of the cylinders.

For the prototype previously described, UPN steel elements (following the European UPN steel profile specifications) were utilized. They were connected by bolts to the outer plates and connected together with metal elements, useful to uniformly distribute the load on the entire device to simulate the load expressed by a real structure.

In the characterization tests, the use of UPN elements necessary for the load distribution was considered fundamental both to ensure the assembly of the individual elements constituting the prototype during the test and to avoid a possible abnormal behavior as a result of a buckling force. Without such elements, in fact, a mutual rotation of the two plates might have arisen.

The connection of the plates to the laboratory machine was then obtained through a mechanical connection with a rod end then connected to a Φ24 plug that affected the two outer plates. For the center plate, however, a fork

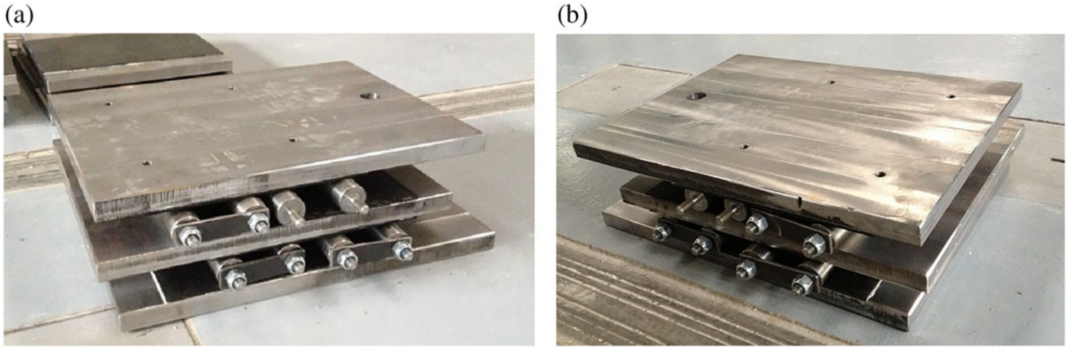

FIGURE 4 Assembled testing prototype

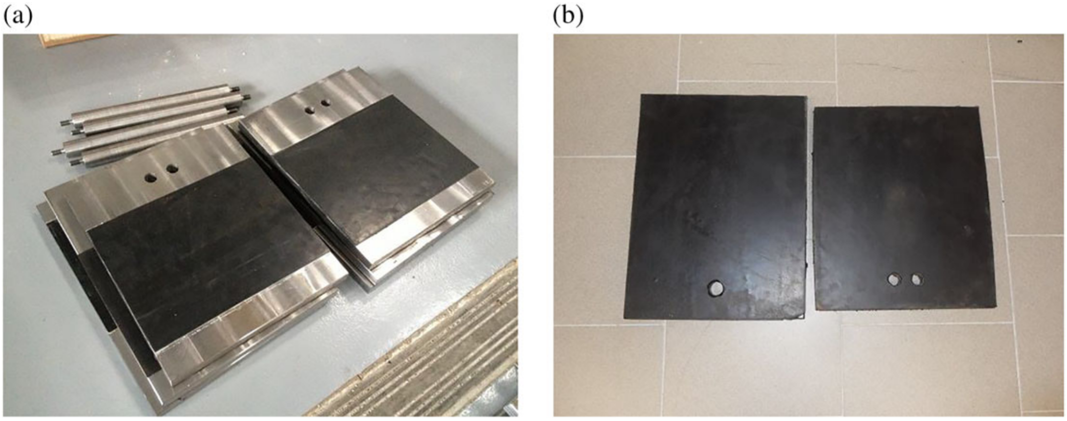

FIGURE 5 Steel plates with (a) glued elastomer and (b) vulcanized elastomer

with two points of connection to the central plate was chosen in order to eliminate the risk of a constraints' alignment (Figures 3 and 6).

3 | CHARACTERIZATION TESTS OF THE PROTOTYPE

The characterization tests were performed at the testing and materials laboratory "*M. salvati*" of the Department of Civil Engineering and Architecture (DICAR), Polytechnic University of Bari, Italy.

The experimental campaign on three simplified prototypes had the aim of testing the behavior of RLRB isolators in dynamic conditions as possible as similarly to those of the design.

In particular, the tests conducted allowed the assessment of the behavior of the device and the acquisition of the force-displacement diagrams and the resulting hysteresis cycles to investigate the capacity of the devices to dissipate energy through the rubber-to-steel contact.

The tests were carried out on an Instron 5869 testing machine by applying to the isolator a crescent preload in the direction perpendicular to the steel plates. The preload simulated the load that a structure transmits by a column to the foundation and, therefore, to the device. The aim was to verify the response of the device and the increase of the energy dissipation up to the maximum deformation supported by the devices and, in particular, by the rubber layers. In addition, in the case of a damage in the elastomer, the consequences in terms of seismic response and energy dissipation capacity were also considered.

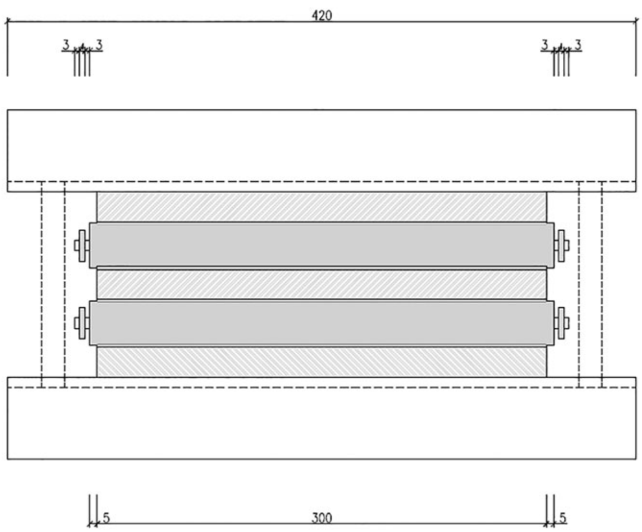

FIGURE 6 Transversal section of the testing prototype and the mechanical connections

The tests were performed with an unidirectional displacement by fitting the prototype vertically in the testing machine (Figure 7a,b). The load and the displacement were then applied to the central plate. In this way, it was possible to verify the behavior of the device along one single direction.

The tests showed an excellent behavior of RLRB devices, with very encouraging dissipation values. They were subjected to tests consisting of five cycles of displacement at a low frequency equal to 0.25 Hz and a maximum displacement of +/−250 mm.

Low-frequency tests were conducted by imposing a maximum value of the total displacement equal to 50 mm.

The results of the tests carried out previously on the elastomer and later on the designed devices allowed the calibration of a model of the isolators with parameters estimated on the basis of the tests' results.

The model so realized, finally, allowed a complete characterization of the device behavior and can be used for nonlinear dynamic analyzes of structures whose seismic retrofitting is carried out by means of the proposed devices.

The characterization tests were carried out on three prototypes manufactured with two different technologies. As mentioned before, first, devices with elastomeric layers simply glued to steel plates were used. Then, however, the elastomer underwent a curing process to the plates so as to obtain greater resistance to the detachment phenomenon and possible subsequent lesions, with the possibility to record optimal performance even with high loads.

3.1 | Characterization tests on simplified RLRB prototypes with glued rubber

In this case, the rubber layers were simply glued to the surfaces of the steel plates. Three samples of the device have been considered, RLRB1, RLRB2, and RLRB3.

Characterization tests with sinusoidal input were carried out on the devices with a maximum total displacement equal to 50 mm and a frequency of 0.05 Hz (Table 2).

In order to investigate the dissipative behavior of the device, the preload was increased up to the limit condition when the detachment of the rubber layer from the steel plate occurred.

The hysteresis loops obtained through the tests showed a clear dissipative behavior of the RLRB device. For the first two cases, however, it was not possible to increase the preload further than 80 kN due to the occurrence of a detachment between the rubber layer and the underlying steel plate for the excessive increase of friction between steel cylinders and elastomer.

(a) (b)

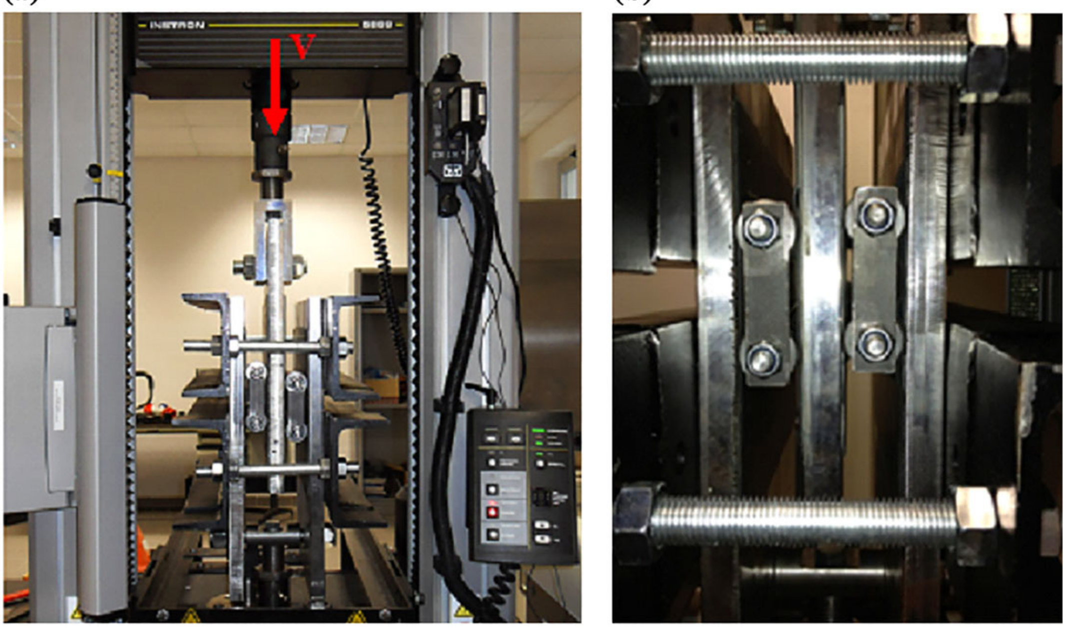

FIGURE 7 (a) A prototype of rubber-layer roller-bearing isolator installed on the Instron testing machine; (b) rolling contact between steel cylinders and rubber layers of the rubber-layer roller-bearing isolator prototype

TABLE 2 Laboratory test program on rubber-layer roller-bearing prototypes with glued rubber

Test ID	RLRB ID	Preload [kN]
Test 1	RLRB 1 (glued rubber)	30
Test 2	RLRB 1 (glued rubber)	40
Test 3	RLRB 1 (glued rubber)	60
Test 4	RLRB 1—Failure (glued rubber)	80
Test 5	RLRB 2 (glued rubber)	40
Test 6	RLRB 2—Failure (glued rubber)	80
Test 7	RLRB 3 (glued rubber)	80
Test 8	RLRB 3 (glued rubber)	100
Test 9	RLRB 3 (glued rubber)	120
Test 10	RLRB 3 (glued rubber)	160
Test 11	RLRB 3—Failure (glued rubber)	200

In any case, despite the phenomena of detachment, we proceeded with the third device with design features identical in order to try to improve the connection between the device and the testing machine, with the goal of reaching increasingly higher load values.

The maximum reached value of the preload, in fact, was equal to about 200 kN. This value, though not comparable with the total weight of ordinary reinforced concrete structures, is similar to the general weight of lightweight structures and equipment.

3.2 | Characterization tests on RLRB prototypes with vulcanized rubber

In this case, the rubber layers were vulcanized to the surfaces of the steel plates.

Ten characterization tests were performed on one RLRB device. A sinusoidal input was utilized, with a maximum displacement (in a single direction) equal to 25 mm and a frequency of 0.05 Hz.

Table 3 reports the tests that were carried out.

Like for the case of glued rubber devices, in order to investigate the dissipative behavior of the device during the earthquake, we proceeded to an increase of the load perpendicular to the steel plates of the device (preload). In this second stage, the rubber vulcanization process avoided the phenomena of detachment previously observed and allowed us to reach horizontal force values (vertical load on the device in the case of positioning it at the base of a generic structure) much higher than those achieved by isolation devices with simply glued elastomer. In fact, in these tests, the preload reached a value equal to 280 kN.

TABLE 3 Laboratory test program on rubber-layer roller-bearing prototypes with vulcanized rubber

TesT ID	RLRB ID	Preload [kN]
Test 12	RLRB (vulcanized rubber)	30
Test 13	RLRB (vulcanized rubber)	40
Test 14	RLRB (vulcanized rubber)	60
Test 15	RLRB (vulcanized rubber)	80
Test 16	RLRB (vulcanized rubber)	100
Test 17	RLRB (vulcanized rubber)	120
Test 18	RLRB (vulcanized rubber)	160
Test 19	RLRB (vulcanized rubber)	200
Test 20	RLRB (vulcanized rubber)	240
Test 21	RLRB (vulcanized rubber)	280

Also, in this case, the hysteresis loops obtained through the tests show an obvious dissipative behavior of the RLRB device and larger hysteresis cycles compared with those obtained during the previous tests.

However, the limited economical possibilities and the short time did not allow to immediately address some of the critical issues detected during the tests. However, these activities will certainly fall in future developments related to the further characterization of RLRB devices.

The maximum value of the preload equal to about 280 kN, although not comparable with the total weight of ordinary reinforced concrete structures is the punctual force with reference to the single floor of a generic reinforced concrete building with standard dimensions and regular geometry.

4 | ANALYSIS OF THE RESULTS

4.1 | Hysteresis cycles of RLRB prototypes with glued rubber

Figure 8a–d relates to the laboratory tests carried out on RLRB devices with elastomeric layers glued to the steel plates. The hysteresis loops obtained during Tests 7, 8, 9, and 10 are relevant; they show force-displacement diagrams characterized by vertical preload values of respectively 80, 100, 120, and 200 kN.

It is clear that, when the imposed load is higher, the area bounded by the cycles increases, showing an increasing value of the energy dissipated through the contact between rubber and steel.

In Tests 4, 6, and 11, the recorded values were not considered to be reliable because the detachment between elastomer and steel plates occurred. However, the behavior of the isolator in terms of stress and strain was not affected by this accident and the device allowed to continue running the test but keeping a lower dissipation value and the motion decoupling.

The isolating behavior obtained during the laboratory tests on the devices can be quantified using the parameters proposed by AASHTO standards[29]: effective stiffness k_{eff} and equivalent viscous damping coefficient β defined, for each cycle, by the following:

$$k_{eff} = \frac{F_p - F_n}{\Delta_p - \Delta_n},$$

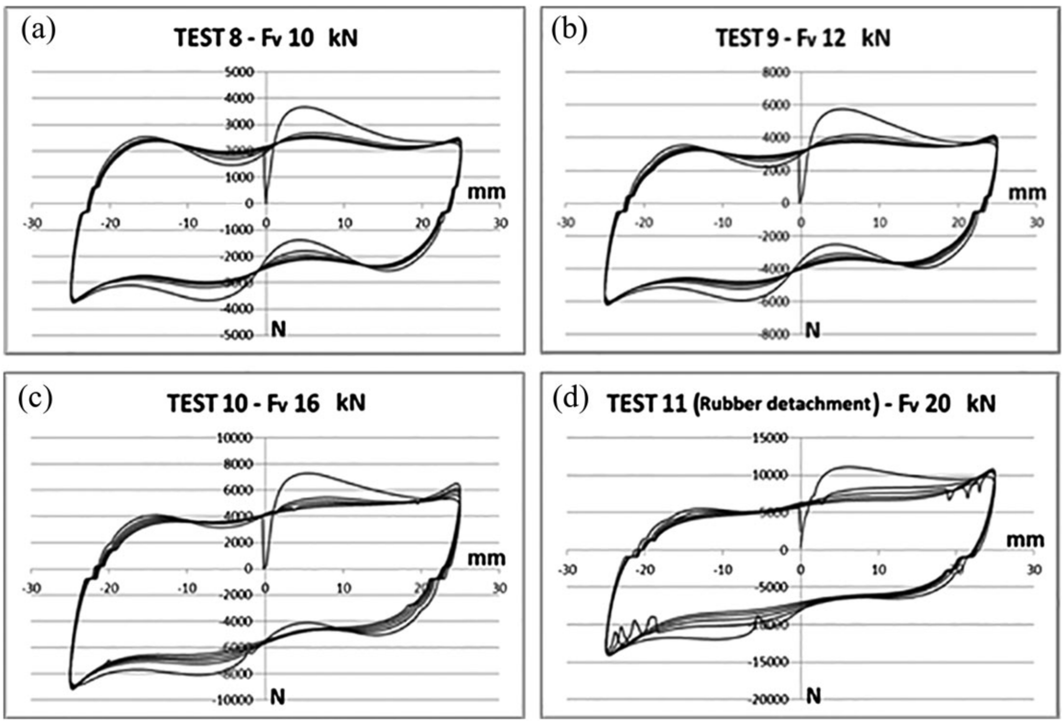

FIGURE 8 Hysteresis cycles obtained from cyclic tests with increasing preload values on devices with elastomer simply glued to the plates

where Δ_p and Δ_n are the values of the maximum positive and negative displacements reached during the cycle; F_p and F_n are the corresponding values of the force;

$$\beta = \frac{1}{2\pi k_{eff}} \frac{A_{cycle}}{\Delta_0{}^2},$$

where A_{cycle} represents the area included in the hysteresis cycle, and Δ_0 represents the average value of the displacement

$$\Delta_0 = \left(\Delta_p - \Delta_n\right)/2.$$

Table 4 reports the values of such parameters obtained in the different characterization tests.

k_{eff} and β have been determined with reference to the maximum values obtained in the various cycles.

The effective stiffness increases gradually as the imposed preload increases. The dissipation capability, expressed by the coefficient β, is around 7%. During the tests, it was noticed that the equivalent viscous damping β reduces when the detachment of the rubber layer occurred during tests 4, 6, and 11.

Except for this condition, the cycles are stable: As the displacement increases, sensitive force reductions do not occur as evidenced by the hysteresis loops related to the tests.

Furthermore, the cycle on Test 11 (Figure 8d), conducted with a maximum preload value equal to approximately 200 kN does not present abrupt reductions of the force except when the phenomenon of detachment of the elastomeric layer occurred.

The modest settlements detectable in all cycles for low values of the force are due to the tolerance values between the fixing pins of the device and their relative housings. The effect of these phenomena, quite evident during the first tests, became less relevant in the tests carried out with high-preload values.

4.2 | Hysteresis cycles of RLRB prototypes with vulcanized rubber

Figures 9a–d refer to tests carried out in laboratory on devices with elastomeric layers vulcanized to the steel plates. During such tests, a compressive force was applied to the plates with a maximum value equal to 280 kN in order to simulate the load transmitted by the superstructure.

In this case, it was also noted that increasing the imposed load, the area bounded by the cycles increases, showing a higher value of the energy dissipated through the rubber–steel contact.

TABLE 4 Effective stiffness k_{eff} and equivalent viscous damping β

Test ID	RLRB ID	Preload [kN]	Effective stiffness k_{eff} [kN/m]	Equivalent viscous damping β [%]
Test 1	RLRB 1	30	54.07	6.74
Test 2	RLRB 1	40	62.35	7.29
Test 3	RLRB 1	60	160.73	6.22
Test 4	RLRB 1—failure	80	48.52	6.09
Test 5	RLRB 2	40	91.82	7.09
Test 6	RLRB 2—failure	80	48.10	6.81
Test 7	RLRB 3	80	97.84	7.35
Test 8	RLRB 3	100	148.58	7.44
Test 9	RLRB 3	120	239.02	7.20
Test 10	RLRB 3	160	329.29	6.96
Test 11	RLRB 3—failure	200	503.93	6.33

Rubber-layer roller bearing with rubber glued to the steel plates.

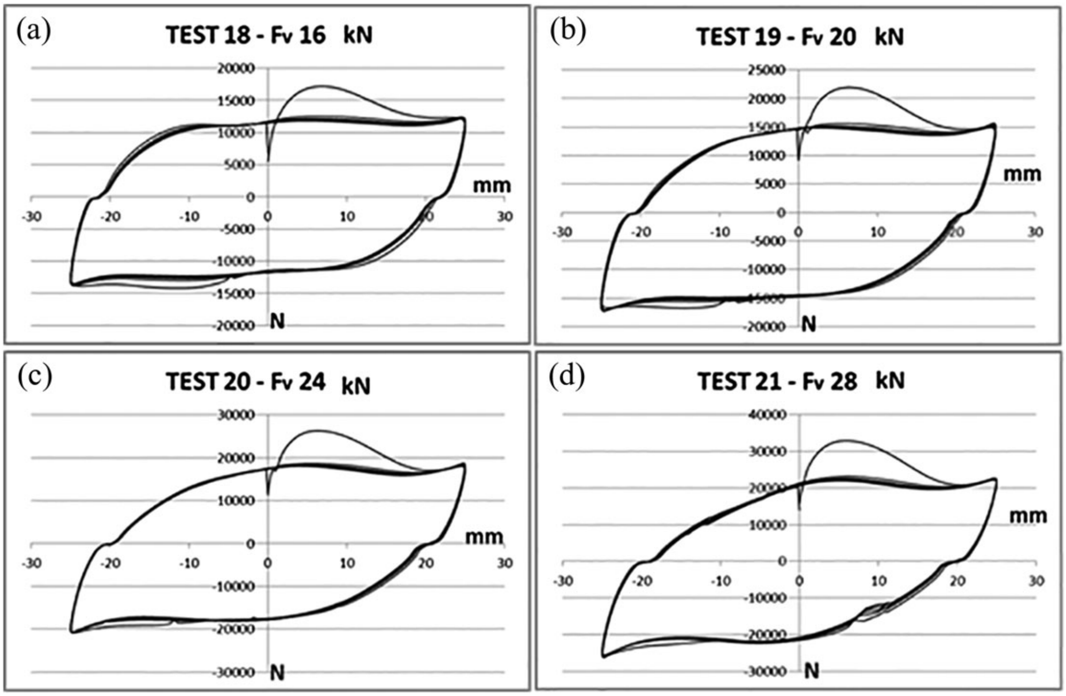

FIGURE 9 Hysteresis cycles obtained from the cyclic tests on devices with vulcanized rubber and increasing preload values

Despite the high values of the load applied, the elastomer did not present detachments from the steel support, or lesions, thus ensuring the dissipation processes and decoupling of the motion.

Also for the case of vulcanized rubber, the behavior obtained during the laboratory tests carried out on the devices can be quantified using the parameters proposed by AASHTO standards[29] for the effective stiffness k_{eff} and the coefficient β of equivalent viscous damping.

Table 5 shows the values of these parameters obtained during the characterization tests. The two parameters were calculated with reference to the maximum values obtained for the different cycles.

The effective stiffness increases gradually with the increase of the imposed preload. The dissipation capability, expressed by the coefficient β, is equal to about 7.5%.

The cycles are stable, and as the displacement increases, sensitive strength reductions did not occur as highlighted by the hysteresis loops related to the tests performed.

In addition, the cycle relative to Test 21, conducted with a maximum preload value of about 280 kN, showed no strength reduction and an excellent behavior of the RLRB isolator (Figure 9d).

TABLE 5 Effective stiffness k_{eff} and equivalent viscous damping β

Test ID	RLRB ID	Preload [kN]	Effective stiffness k_{eff} [kN/m]	Equivalent viscous damping β [%]
Test 12	RLRB	30	24.15	6.75
Test 13	RLRB	40	35.24	7.96
Test 14	RLRB	60	96.54	7.62
Test 15	RLRB	80	139.21	7.88
Test 16	RLRB	100	245.66	7.96
Test 17	RLRB	120	345.12	7.53
Test 18	RLRB	160	628.41	7.74
Test 19	RLRB	200	784.54	7.31
Test 20	RLRB	240	942.20	6.95
Test 21	RLRB	280	1182.99	6.35

Rubber-layer roller bearing with rubber vulcanized to the steel plates.

During the tests, the isolator, on the whole, behaved very well, and the vulcanization process ensured an excellent rubber–steel connection despite having assigned to the device rather high-compression values, simulating the load resulting from the superstructure. It must be also emphasized that in this design phase, the loads acting on RLRB isolators are not high; they are therefore hypothesized to be transmitted by a superstructure with maximum two floors.

5 | CONCLUSIONS AND FUTURE RESEARCH

In this article, the design of a seismic isolation device based on the rolling of steel cylinders on elastomeric layers (RLRB) was carried out. The relative seismic behavior was analyzed through a design verification process, developed for subsequent steps, which also led to the realization of simplified prototypes.

The simplified prototypes were subjected to laboratory characterization tests with increase of the vertical load in order to produce an increasing stress on the elastomeric layers and to obtain meaningful data with reference to the energy dissipation.

The tests gave back reference values on the seismic response of the designed device and supplied the hysteresis loops corresponding to different settings. The results allowed us to make a critical analysis of the RLRB behavior and the significant advantages that can be obtained in the seismic protection of lightweight structures, equipment, and museum artifacts.

The tests showed that in the case of constant speed, the device shows a behavior with large enough cycles and a high amount of energy dissipation during each displacement cycle.

It must be noted that RLRB isolators are not suitable when the seismic energy is concentrated on low frequencies because of the risk of resonance phenomena. However, the results evidenced that this type of isolators allows the dissipation of energy in a wide-frequency range.

Despite the number of isolators tested has to be considered insufficient to reach some general conclusions, it can be observed that the compound utilized has allowed us to avoid the presence of failures in the elastomeric layers even for particularly onerous preload conditions. Moreover, in cases of detachment between a rubber layer and the steel plate (elastomeric layers simply glued to the plates), no significant negative impact was found on the overall behavior of the device nor serious reductions in terms of energy dissipation.

The present study has to be considered prior to the implementation of the final device that will consist of three levels of plates with vulcanized rubber and two levels of cylinders arranged so as to rotate in the two horizontal directions perpendicular one another.

The results, however, also showed that for the proposed RLRB device, some technical design improvements are necessary, such as an increase of the thickness of the rubber layers to a value at least equal to 4 mm, in order to avoid the problems of detachment of the elastomeric layers detected during tests on devices with glued rubber and caused by a high concentration of stresses on the rubber cylinder contact surface. The vulcanization process, in fact, required a minimum thickness of the elastomer equal to 3–4 mm.

Despite the numerous activities carried out have resulted in very encouraging results, further investigation and a careful optimization process are still necessary because the solution to contact problems requires significant computational efforts. It is be highly foreseen to study the behavior of the device when the excitation acts in two perpendicular directions. It could be reached by testing RLRBs by mean of 2DOF shaking tables.

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