16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3776

Registration Code: S-A1465991781

SHAKING TABLE TESTS OF A RECYCLED RUBBER FIBER-REINFORCED BEARINGS ISOLATED STRUCTURE

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Abstract

This paper details the findings of an experimental program that assessed the seismic performances of a novel low-cost base isolation device. The proposed bearings are referred to as Recycled Rubber – Fiber Reinforced Bearings (RR-FRBs).

Devices composed of a low-cost recycled elastomer and reinforced with fiber sheets were manufactured and tested.

The main revolutionary concepts investigated in this study are as follows: low-performance elastomers can be used to produce rubber isolators, and vulcanization can be prevented by bonding different layers with an elastic compound.

This study addresses all design and technical aspects related to the implementation of the proposed base isolation system.

Shaking table tests showed a significant improvement in the seismic performance of a RR-FRB isolated building with respect to a corresponding fixed-base structure.

Keywords: Recycled Rubber – Fiber Reinforced Bearings, shake table testing, base isolation, unbonded fiber reinforced bearings, low-cost seismic devices

1. Introduction

1.1 Motivation for the Research

Many large urban areas, especially in developing countries, are extremely vulnerable to seismic events. New housing buildings are constructed daily in nations with a significant population growth. Older existing buildings are generally vulnerable in case of an earthquake. For example, in cities such as Istanbul, Tehran, and Lima, thousands of buildings were designed for gravity loads without specific provisions for lateral loadings. Based on these considerations, it is deemed that the introduction of low-cost seismic isolation systems can have a significant impact on society. Technologies that can be easily produced by relatively simple manufacturing processes may stimulate the application of base isolation systems in new construction and the retrofitting of existing buildings.

1.2 Scope of the Study

Seismic isolation technology is frequently applied to computer centers, chip fabrication factories, emergency operation centers, and hospitals. The isolators used in these applications are expensive, large, and heavy [1]. In some cases, an individual device can weigh more than one tonne. To extend this valuable earthquake-resistant strategy to housing, schools, and commercial buildings, the cost and weight of the isolators must be reduced [2]. The high cost of producing conventional devices is attributed to the labor involved in their preparation, in which the steel plates need to be bonded to the rubber layers via a vulcanization process. The steel plates are cut, sandblasted, acid-cleaned, and subsequently coated with a bonding compound. Next, the compounded rubber sheets with interleaved steel plates are placed in a mold and heated under pressure for several hours to complete the manufacturing process [3].
The premise of this study suggests that the weight and cost of an isolator can be reduced by replacing steel reinforcing plates with fiber reinforcements. The novel belief investigated in this study is that a substantial cost reduction is possible by replacing the natural rubber with a recycled elastomeric compound, such as the

compound obtainable by exhausted tyres or industrial scraps. An innovative technology is presented in this study.

The scope of this research includes the following objectives:

-To introduce RR-FRBs as a cost-effective alternative to existing conventional devices.

-To assess the performance and the characteristics of a RR-FRB isolated building by shaking table experiments.

-To assess the suitability of the proposed technology to reduce the seismic demand on a prototype-scaled building.

-To validate the application of simple design tools and their potential applications in the prediction of the dynamic response of a RR-FRB isolated building.

1.3 Recycled Rubber–Fiber Reinforced Bearings

Several base isolation systems have been introduced lately with the common aim of reducing the cost of application (*e.g.*, [4], [5], and [6]). Among them, the most promising technology seems to be the so called Fiber Reinforced Bearings (FRBs).

FRBs are laminated rubber bearings in which the steel reinforcements are substituted with fiber layers. FRBs were introduced by Kelly [2]. This technology exhibits several advantages compared with traditional devices. FRBs can be produced by a relatively simple manufacturing process: each device can be cut from a pad with large dimensions. They are also lighter than conventional devices because steel is substituted with lighter materials with similar mechanical properties. In buildings with masonry walls, rectangular bearings can be positioned directly under the foundation of the building, which reduces the need for stiff and costly transfer beams and produces a significant reduction of the total construction costs.

The main aspect of FRBs is their behavior in shear. The use of a flexible reinforcement in an unbonded device has the advantage of eliminating the presence of tensile stresses in the bearing when sheared. Rolling off from the supports can develop without constraints. This eliminates the need for costly vulcanization bonding that is typical of conventional bearings and, as examined in this study, allows the use of elastomeric materials with lower mechanical qualities and lower costs compared with natural rubber, which is commonly used in seismic engineering.

As a result of this latter consideration, devices for the experimental program were composed of a low-cost/low-performance Tire Derived Material (TDM). The production process of the TDM involves the pressing of a mixture of rubber granules, which are obtained from the reuse of scrap tyres or industrial scraps, and a polyurethane binder in a mold. The material has an easy to implement production process that requires low energy consumption and minimal demand for labor. The resulting elastomer is low-cost and eco-friendly because exhausted tires are abundant, they constitute an environmental problem, and the number of tyres has significantly increased [7].

Note that the reuse of rubber tyres is currently being investigated in numerous research projects. The problem that generally emerges from common procedures for rubber recycling is that highly sophisticated treatments require a higher energy consumption compared with the energy consumption of the polymers they replace (*e.g.*, [8]). A detailed description of the production technologies and the results of extensive experiments on the described material are given in Calabrese [9]. From these laboratory tests emerged a peculiar behavior of TDMs: their range of shear modulus G is comparable to the range of G for the natural rubber used in seismic applications (0.4-1.2MPa at 100% shear strain) and an equivalent viscous damping in the range of 10-20% as for compounds currently applied to the production of High Damping Rubber Bearings (HDRBs). A drawback of the TDM considered here is a low elongation at break and a low tensile strength. These characteristics can affect its employment in modern isolators, in which a maximum shear strain of 300% can be expected [1]. However, as demonstrated in this study, there are no limits for its use in unbonded fiber reinforced devices due to a low demand on the materials.

2. Test Structure and Experimental Setup

To validate the performances of the novel RR-FRBs, a base isolation system was designed for a prototype building, which was employed for several other experimental programs conducted at the Department of Structures for Engineering and Architecture (DiSt) at the University of Naples Federico II in Italy.
The 1/3 scale test rig consists of a steel frame with two degrees of freedom. The test rig has a total height of 2900mm and plan dimensions of 2650×2150mm. The columns of the test building are composed of welded square hollow sections (150×150×15mm), whereas the beams are composed of hot-formed square hollow sections (120×120×12.5mm). Pin connections were used between the beams and the columns. Each floor contains additional concrete blocks to provide a total mass of 7.7tonnes. The base level has a mass of 3.6tonnes, whereas the top floor has a mass of 4.1tonnes.
The set-up of the instruments for the acquisition of the structural response consisted of nine Laser Displacement Sensors (LDSs), each with a resolution of 50 μm, connected to a reference steel frame external to the table. Two transducers on each floor were used to measure the absolute displacements in the direction of the applied motion. One laser transducer was mounted at the rear of each floor and orthogonal to the direction of motion to measure any significant in-plane rotation of the masses. Two additional vertical transducers were used to detect the rocking of the structure. These latter transducers were positioned on the external frame and pointed at a corner beam of the base floor. A LDS was also used to measure the displacement of the table.
The absolute accelerations of the floor masses were measured by a total of six triaxial accelerometers. An accelerometer was also used to measure the motion of the table to identify any potential influence of the base isolated structure on the dynamics of the shaking table. This measurement was necessary because the Tab. 1s a new piece of test equipment and the unintended behavior of the testing machine was unknown.
The sampling frequencies of the measured quantities were set at 500Hz and filtered at 50Hz.
Fig. 1 (a) shows a cabinet projection of the prototype isolated structure and measuring apparatus. Fig. 1 (b) shows a view of the shaking table laboratory at the DiSt.

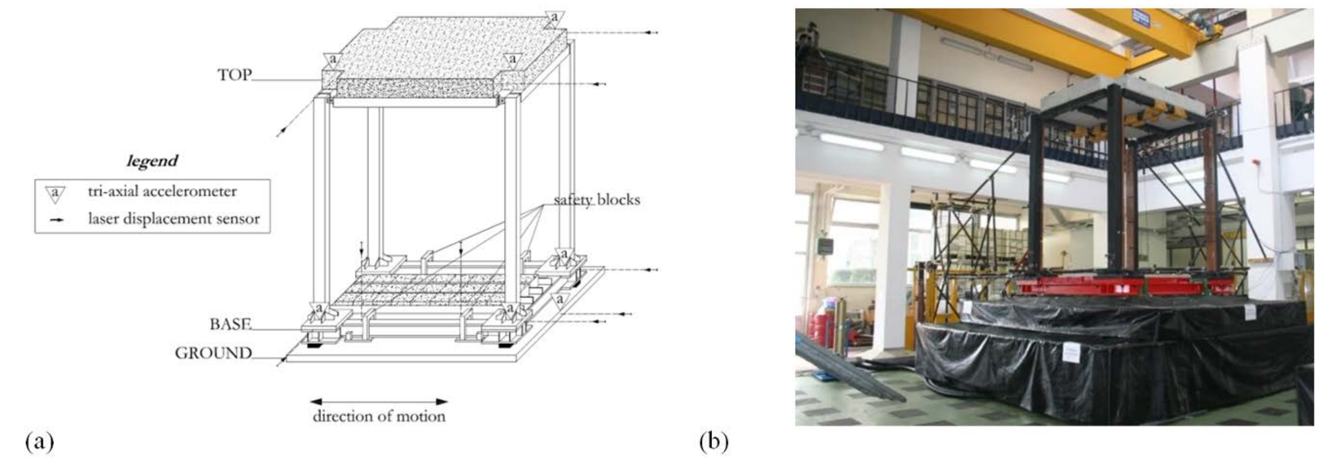


Fig. 1. (a) Cabinet projection of the prototype building and the instrumentation set-up. (b) View of the test frame of the shaking table at the DiSt laboratory.

2.1 Ground Motion Selection and Test Input

Spectrum-matching accelerograms were employed in the tests. A set of seven waveforms, which are compatible with the new Italian Seismic Code (ISC) [10], was selected from the European Strong-motion Database [11] using REXEL v3.4 beta [12]. The selection reflects the provision of the ISC and others found to be important, which are detailed in several studies on this topic.
The selected horizontal accelerograms are in compliance with the ISC for the life safety limit state of a strategic structure (functional class IV, [10]) located in Naples, Italy (14.2767° longitude, 40.863° latitude) on soil type A

(stiff soil or rock) with a nominal life of 100 years (which corresponds to a 1898-year return period according to the code).

Only events in the magnitude (M_w) interval [5.3, 7.3] and an epicentral distance (R) interval [0-80 km] were considered, which reflects the hazard disaggregation for the spectral acceleration Sa(T) for the period of interest in the nonlinear structural behavior. The applied procedure has been frequently recommended for the selection of design earthquakes in different studies (*e.g.*, [13]).

This selection is representative of regions in Italy with a moderate to high seismic risk.

Given a geometry scale factor, S_L, of 1/3 and an elastic moduli scale factor, S_E, of 1 to satisfy the dynamic similitude requirements, the selected earthquakes were compressed in time by a time scale, S_T, of $1/\sqrt{3}$. The 5% damped-scaled horizontal spectra are provided in Fig. 2. The maximum value of the scale factors (SF_{max}) is approximately two, whereas the mean scale factor (SF_{mean}) is approximately one.

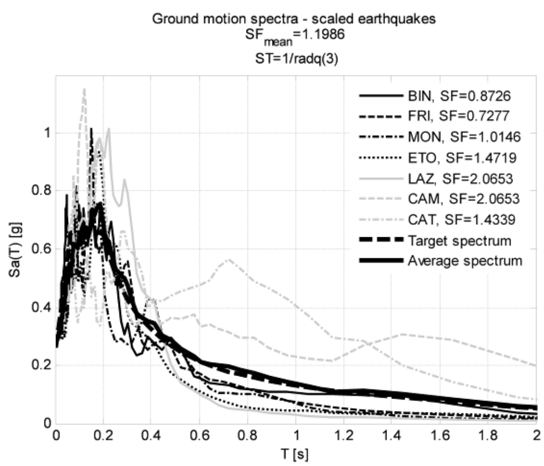


Fig. 2. Scaled ground motion spectra and target spectrum according to the ISC $\left(S_T = \sqrt{3}\right)$.

The ground motion specifics for the original and scaled records are provided in Table 1. The Housner Intensity (HI) of the scaled events, which is a measure of the damaging potential of the input earthquakes over a wide period range, is provided [14]. For the scaled records, Tab. 1 lists the index as the area under the 5% damped pseudo-velocity spectra over the period range 0.05-1.25s. The Peak Ground Accelerations (PGAs) for all events are equivalent. The seven selected records were run as listed in Tab. 1. As depicted in Fig. 1, ground motions were only applied in one direction, in which the frame span is 2650 mm. As will be briefly discussed, one-directional (1D) excitations were selected for multiple reasons. To examine the reliability of the isolation system to resist aftershocks and subsequent events and to determine any potential degradation of the recycled rubber devices, the Campano Lucano 290ya (CAM) ground motion was run 20 consecutive times based on the seven inputs.

This record exhibits the highest HI of the set and a significant content at frequencies of the tested isolation system. Therefore, a total of 27 ground motions were run during the tests. The results of the degradation analyses will be presented in following works.

2.2 Description of the Isolation Devices Used for the Tests

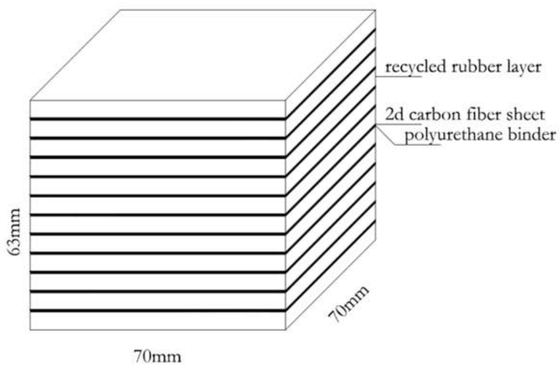
The use of rubber in an unbonded application is relatively common; its frictional behavior is discussed in several studies (*e.g.*, [16], [17]). Various authors have verified that a natural elastomer can have a maximum friction coefficient of one when it in contact with clean steel plates.

Similar to natural rubber, the coefficient of friction for the TDM used in the tests is large for a clean steel interface. Calabrese [9] verified that the coefficients of friction for the TDMs are in the same range as natural rubber with a maximum value of one.
Therefore, when designing unbonded bearings, in which the contact surfaces are composed of steel and rubber, a friction coefficient of 0.7 is reasonable.
The frictional behavior of RR-FRBs should be considered when designing the devices.
Whether the sliding resisting force is higher than the resisting force of the bearing at peak horizontal displacement should be verified. The displacement capacities of fiber reinforced devices and simple design criteria for the technology are derived and discussed in Kelly *et al.* [18] and Kelly and Calabrese [19].
Based on these criteria, imposing a vibration period of 2sec for the isolated structure, which corresponds to 1sec for the scaled model, and considering an elastic modulus of G=1.1MPa, the bearings were designed with in-plane dimensions of 210×210mm and a total thickness of the rubber of 190mm.
Correspondingly, for the scaled model $\left(S_L = 1/3\right)$, devices with in-plane dimensions of 70×70mm and a total rubber thickness of 63mm were produced.

Tab. 1. Selected ground motion, specifics and significant parameters.

Record	Waveform ID	Station ID	Date	SF	Mw	R	Full-scale earthquake PGA	PGV	PGD	Scaled earthquake (SL=1/3) PGA	PGV	PGD	HI
			[dd/mm/yy]			[km]	[m/s^2]	[cm/s]	[cm]	[m/s^2]	[cm/s]	[cm]	[mm]
Bingol (BIN)	7142ya	ST539	01/05/2003	0,87	6,3	14	2,55	18,29	3,25	2,55	10,56	1,08	337
Friuli (FRI)	55xa	ST20	06/05/1976	0,72	6,5	23	2,55	15,25	9,29	2,55	8,80	3,10	233
Montenegro (MON)	200ya	ST68	15/04/1979	1,01	6,9	65	2,55	12,87	9,60	2,55	7,43	3,20	206
Etolia (ETO)	428ya	ST169	18/05/1988	1,47	5,3	23	2,55	12,46	6,06	2,55	7,19	2,02	204
Lazio Abruzzo (LAZ)	372ya	ST274	07/05/1984	2,06	5,9	68	2,55	15,02	6,80	2,55	8,67	2,27	172
Campano Lucano (CAM)	290ya	ST96	23/11/1980	0,80	6,9	32	2,55	44,10	16,20	2,55	25,46	5,40	1010
Campano Lucano (CAT)	287ya	ST93	23/11/1980	1,43	6,9	23	2,55	43,90	14,00	2,55	25,35	4,67	854
			mean	1,19	6,4	35							

For the experimental program, each bearing was manufactured by bonding with a polyurethane adhesive 12 layers of a rubber-like material and 11 bi-directional carbon fiber sheets.
As shown in Fig. 3, no external reinforcing layers were used, which was required to obtain a steel-rubber contact interface. Studies conducted by Kelly *et al.* [18] showed that the layers nearest to the supports are laterally confined due to the frictional restraint.



(a)

(b)

Fig 3. (a) Sketch of the tested RR-FRBs and (b) picture of two of the tested devices.

The manufacturing of the bearings was simple. The entire process for the curing of the binder required only a few hours. Each bearing was shaped by a table cutting machine that divided a long pad with large dimensions.
The design vertical pressure on the bearings was approximately 3.85MPa. This value is realistic for the majority of base isolated frame structures. Prior to the shaking table experiments, a set of twelve prototype bearings was tested under static and dynamic loads in compression and shear [20].
For the dynamic tests under the design vertical load, a horizontal displacement with increasing amplitude was imposed. The frequency of the imposed displacement was 0.87Hz. The displacement amplitudes ranged from 10 to 30mm.
Fig. 4 shows the time history of the applied displacement. The measured hysteresis loops are shown in Fig. 5.
Based on the measured quantities, the base isolation frequency for a design displacement of 30 mm was 1Hz ($K_{h,isolator} \approx 80kN/m$). The vertical frequency under the applied vertical load was approximately 0.1Hz ($K_{v,isolator} \approx 7000kN/m$). This behavior is satisfactory for seismic isolation because the ratio of the vertical stiffness to the horizontal stiffness is on the order of magnitude of hundreds.
For the applied vertical load, an equivalent viscous damping of 30% was measured for a design displacement of 30 mm.

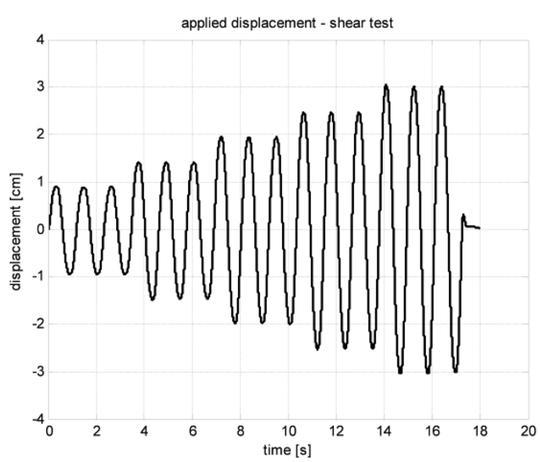


Fig 4. Time history of the applied horizontal displacement for the tests of the prototype bearings.

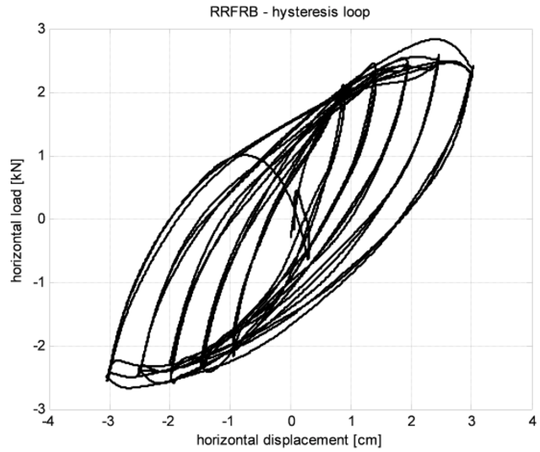


Fig 5. Measured hysteresis loops from the dynamic testing.

3. Results of the Investigation

In this section, the experimental data are presented and discussed. The analysis considers the relative displacements, the shear force at each level and the absolute accelerations of the floor masses for the isolated building and the corresponding 5% damped fixed-base structure. Because the displacement transducers were mounted on an external reference system, absolute displacements were measured. The relative quantities were simply derived by changing the reference system (*i.e.* subtracting the table motion). The shear forces at each level were obtained by summing the inertial forces at the levels above the considered one. The inertial forces at each level were computed by multiplying the floor mass and the corresponding measured acceleration.

3.1 Peak Responses

table indicate adequate capacity of the proposed technology in reducing the seismic demand on the structure.
The response reductions in terms of interstory drift and top floor acceleration for each ground motion are shown in Fig. 6. For the seven records, an average reduction of 55% was measured for the roof acceleration (*i.e.*, columns shear), whereas an average reduction of 33% was determined for the interstory drift.
The tests indicated different performances of the bearings with increasing energy content of the seismic events at the isolator's frequency. For instance, for both Campania records (CAM and CAT), significant reduction in the top floor acceleration (almost 60%) was observed. Conversely, the interstory drift slightly increased with respect to the fixed-base building in the events.
This finding can be attributed to a considerable energy content of the records at the frequency of the isolated structure. The Campania records also yielded the largest base displacements.
At the peak lateral displacement during the Campano Lucano earthquake (CAT), rolling off was detected.
The deformation of the bearings occurred with detachment from the top and bottom horizontal surfaces. This detachment confirms the theoretical models proposed by Kelly *et al.* [18], who estimated that an unbonded square fiber reinforced bearing can deform in shear and exhibit a stable roll-off with detachment from the top and bottom surfaces for displacements smaller than half of the base of the device. For larger displacements, the bearing would deform in an unstable range, rotate until contacting the horizontal subgrades, and eventually slide on the supporting plates, generating heat and consequential damage. According to the theoretical model, the maximum stable horizontal displacement for the tested bearings is 35mm.
Each of the tested bearings displaced in a stable range with a maximum deformation of 43mm. In the first analysis of the phenomenon, no instability occurred due to the high compressibility of the elastomer, which improves the adaptability of the bearing to changing loads on supporting surfaces, increases the contact areas and significantly reduces the rolling behavior of the device.

An external reference indicated a complete re-centering of the system after each ground motion. No residual displacements were measured, and, as said, all bearings deformed in a stable range. A visual inspection of the bearings after the tests confirmed no delamination or visible signs of degradation. Fig. 7 includes a plot of the peak roof acceleration for the base isolated structure and the corresponding fixed-base 5% damped system.

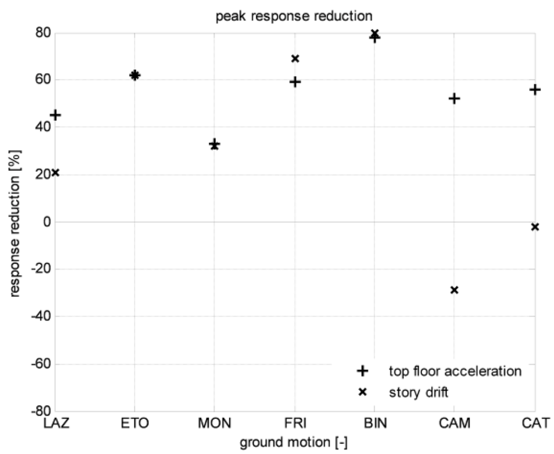


Fig 6. Response reduction: RR-FRB isolated building vs. 5% damped fixed-base structure.

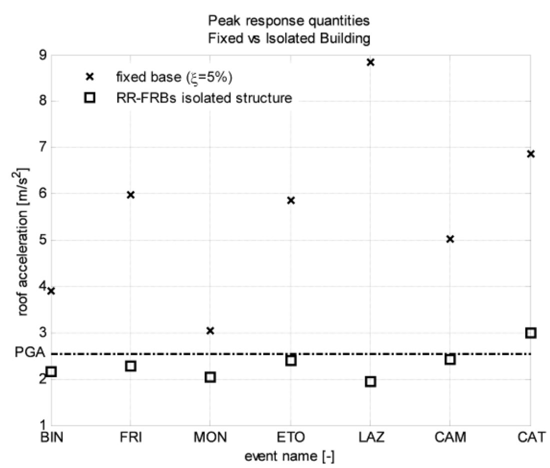


Fig 7. Peak roof acceleration: Isolated building vs. 5% damped structure.

The effectiveness of the isolation system can also be observed in the amplification envelopes in Fig. 8, which show the peak floor acceleration over PGAs for all input earthquakes.

As expected, the response envelopes of the base isolated structure are substantially reduced.

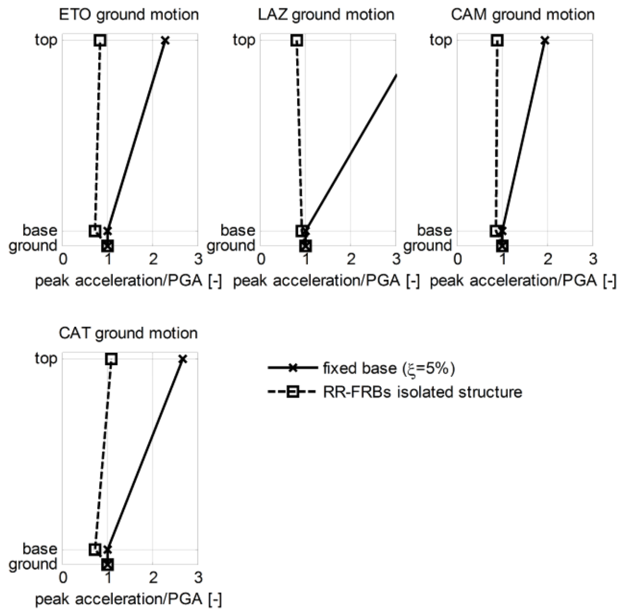


Fig 8. Amplification envelopes: Isolated building vs. 5% damped structure.

Fig. 9 displays a comparison of the peak interstory drift for the isolated and the fixed-base frame.

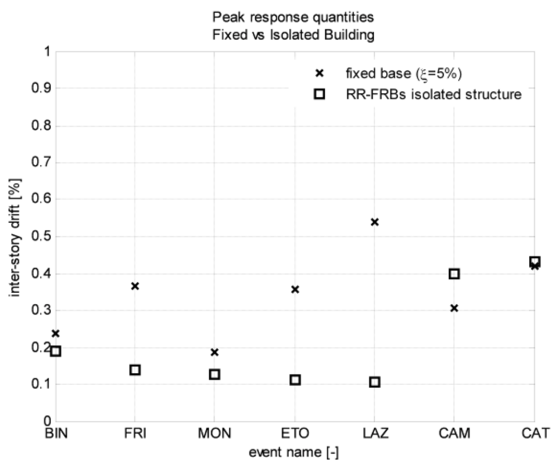


Fig 9. Peak interstory drift.

Top floor displacement of three events are shown in Fig. 10 for the fixed-base and the isolated structure. The elongation of the period and the consequent response mitigation due to the introduction of the RR-FRBs are distinct.

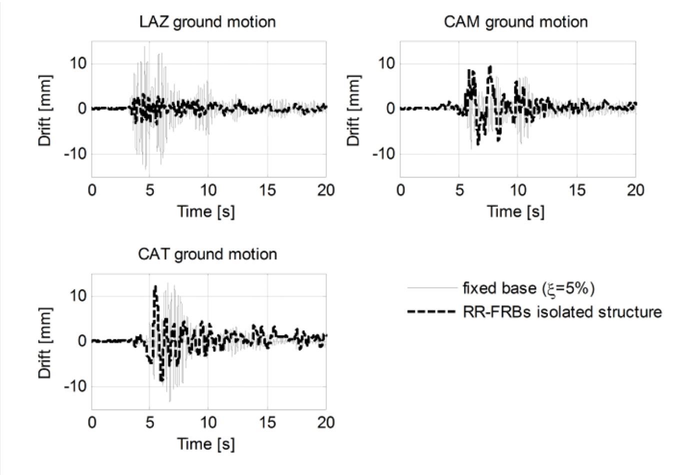


Fig 10 Top floor displacement time histories for the seven ground motions.

3.2 Dynamic Characteristics of the Model

For the seven events, the fundamental periods of the base isolated structure were determined by FFTs of the recorded top floor accelerations.

The fundamental frequencies derived from the FFTs are plotted in Fig. 11. The Figure shows the peak base displacement for the seven events.

The plot clarifies the influence of an increasing base displacement on the dynamic properties of the structure. Because the behavior of the bearings is highly nonlinear for large base displacements, the frequency decreases as the efficiency of the seismic isolation increases.

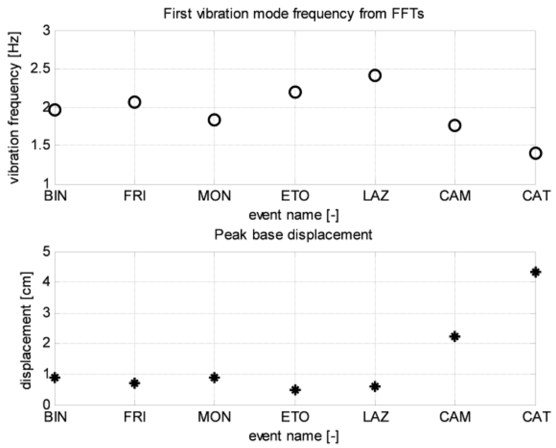


Fig. 11. Peak base displacement and vibration frequencies of the FFTs for the seven events.

4. Conclusions

The tests demonstrated the potential for the use of low-cost and low-quality elastomers for the production of fiber reinforced bearings.

Low-performance materials are suitable because the bearings are unbonded and reinforced with flexible fiber sheets. In this configuration, devices can deform freely without generating high tensile stress, which is common in transversal layers of conventional isolators.

The absence of tensile stresses prevents the vulcanization of rubber to the reinforcements. For instance, devices for the tests were manufactured by gluing layers of a recycled elastomer to layers of fiber reinforcements with a polyurethane adhesive, without the need for costly and high-energy demanding vulcanization processes. The proposed devices are low-cost and eco-friendly.

To facilitate the understating of the dynamic behavior of a building isolated with RR-FRBs, one dimensional tests were conducted. A series of 27 records was employed for the shaking table experiments. The selected ground motions were representative of moderate to high seismic regions in Italy. With such severe inputs, the bearings performed exceptionally well. They demonstrated robust behavior and re-centering capabilities in all tests; a visual inspection of the devices confirmed no damage.

The tests gave a preliminary assessment of the viability of the concept. Future multi-directional experiments are required for a complete understanding of the nonlinear behavior of the proposed base isolation system and for its acceptance by the construction industry.

The proposed technology could influence the retrofitting of historic buildings and unsafe public housing in seismic-prone regions of the world.

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