

3D Shaking Table Tests Of A Full Scale 2-Storey Building With Fiber-Reinforced Elastomeric Isolators

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Abstract. During the last two decades fiber-reinforced elastomeric isolators (FREIs) emerged as a promising option to reduce both the cost and weight of rubber bearings. The project ERIES-FREISUST (Fiber-Reinforced Elastomeric Isolators for seismic resilient structures with SUSTainable Solutions) aims to demonstrate the reliability of FREIs in limiting damage to structural and nonstructural components and contents. Two FREI systems were designed for a full-scale 2-story reinforced concrete (RC) infilled frame, differing in standardization and cost levels, namely a Virgin-rubber Carbon-fiber FREI (VC-FREI) and a Reclaimed-rubber Polyester-fiber FREI (RP-FREI). These isolation systems were installed in unbonded configuration at the base of the building and tested at the ST3D shaking table facility of Laboratório Nacional de Engenharia Civil (LNEC), Lisbon, Portugal. The novel base-isolation systems demonstrated lateral stability and re-centering capability, as well as adequate vertical stiffness and load-bearing capacity under different ground motions. RP-FREIs were designed and tested up to a design displacement of 105mm corresponding to 150% shear strain. Due to recessing plates VC-FREIs were tested with higher scaling factors compared to RP-FREIs showing higher displacement capacity with negligible residual. The building had no minor damage after the whole testing sequence with contents undergoing limited accelerations and displacements thus ensuring functionality even after major earthquakes.

Keywords: Base Isolation, Unbonded Elastomeric Isolators, FREI, 3D Shaking Table Tests, Non Structural Components.

1 Introduction

According to the UN's Office for Disaster Risk Reduction [1], the annual average deaths due to earthquakes (2001-2020) is approximately equal to 38,000, the highest number of deaths due to any natural hazard. Base isolation is widely accepted as one of the most effective seismic protection measures for both structural elements and nonstructural components, including building contents [2-6]. Conventional seismic isolators available on the market are too costly for common housing projects, thus preventing a large-scale application of the technology in both developed and developing countries of the world. Fiber-reinforced elastomeric isolators (FREIs) were developed recently with the aim to reduce both cost and weight of conventional steel-reinforced rubber bearings, by replacing the steel shims with fiber mesh fabric [7-8]. The unbonded configuration of FREIs nearly eliminates tensile stresses and the need for stringent bonding requirements within the isolator (Fig. 1a and 1b). Furthermore, it promotes roll-over, which reduces the effective lateral stiffness of the isolator and thus increases the isolation effectiveness (Fig. 1c).

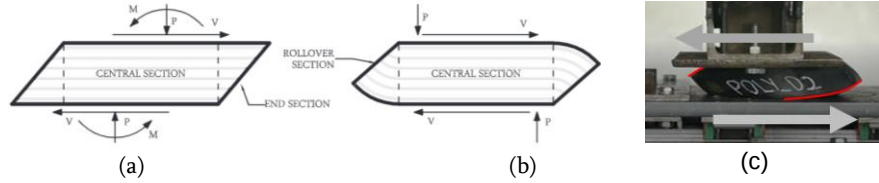


Fig. 1. a) Bonded versus b) unbonded isolator under lateral displacement [9]; c) Roll-over of a prototype RP-FREI [10].

Previous studies investigated the effect of different rubber matrices and fabrics on small-size FREI prototypes in a number of experimental programs, including shaking table tests [9, 10-16]. The Reclaimed-rubber Polyester-fiber FREI (RP-FREI) system (Fig. 1c) was recently developed [10] at the University of Naples Federico II in collaboration with ITALGUM (patent number 102022000013360). The reclaimed compound was subjected to a comprehensive physical and mechanical characterization, showing mechanical properties that are not significantly different from a soft virgin rubber with lower tensile deformation capacity. Preliminary characterization tests showed promising performance (lateral stability up to 150% shear strain and equivalent damping ratio up to 19%) and paved the way for the development of low-cost, environmental-friendly seismic isolators for housing buildings [10]. Along the same line, De Domenico et al. [17] recently carried out an extensive experimental characterization of two full-scale prototype

FREIs under EN15129 [18] compliant protocols including bidirectional orbits up to maximum shear strain level of 100%.

Recent studies by Losanno et al. [19-20] demonstrated that base isolation with FREIs can also be effective in reducing seismic fragility of one- and two-storey unreinforced masonry buildings in developing countries where a significant increase in new construction is expected in the coming years. Even though geometrical limitations imposed by stability criteria for FREIs resulted in lower isolation period T_{is} (i.e. 1.3s to 1.7s) compared to that considered for conventional design ($2.0 \leq T_{is} \leq 3.0$ s), FREIs proved to be an affordable solution for seismic protection of low-rise buildings.

It is in this context that the ERIES-FREISUST (*Fiber-Reinforced Elastomeric Isolators for seismic resilient structures with SUSTainable Solutions*) project was conceived to provide an increase of the Technology Readiness Level of FREIs, demonstrating the combined reliability of the base-isolation system (i.e. lateral stability and re-centering capacity as well as adequate vertical stiffness and load-bearing capacity under different loading conditions) and its potential in reducing damage to nonstructural components and contents. To the best of the authors' knowledge, no shaking table tests had been performed on a full-scale building prototype under different ground motion intensities that could lead to a standardization of the FREI technology. A limited number of reduced-scale shake table tests were conducted under horizontal excitation only [13-15, 21-23]. However insightful these tests were, a series of knowledge gaps and open issues remained to be addressed, including: 1) previous characterization tests were mainly carried out on scaled specimens without implementing seismic records that are actually representative of site-specific hazard, 2) there is a need to investigate whether these bearings can provide enough isolation capacity to both structural and nonstructural building components in case of limited mass of the superstructure, 3) more experimental data is needed to model the complex hysteretic behaviour of FREIs experiencing roll-over under lateral deformation. This is of paramount importance in light of the European Green Deal and the development of the next generation of standards for anti-seismic devices EN15129 and structural bearings EN1337-3 [24], which may include specific recommendations for use of FREIs.

2 Experimental program

Within FREISUST project a relevant number of 3D shaking table tests have been performed at LNEC (Lisbon, Portugal) on a full-scale prototype subjected to three simultaneous components of the ground motion. The size of the ST3D shaking table at LNEC (5.6mx6.4m) made it possible to test, for the first time, a full-scale frame isolated with FREIs under combined horizontal and vertical ground motions, including independent excitations of various types (sinusoidal, random, shock and seismic ground motion) and vertical component.

The project aims to evaluate the effectiveness of two FREI base isolation systems for enhanced seismic resilience of new or existing buildings: (1) a Virgin-

rubber Carbon-fiber FREI (VC-FREI) base isolation system, and (2) a RP-FREI base isolation system. Among these two systems, the first one is more prone to standardization due to the improved axial stiffness, rubber and reinforcement properties. With a lower cost and environmental impact of both the reclaimed rubber compound and polyester reinforcement (i.e. commonly adopted in the textile industry), RP-FREI system represents an eco-friendly, cheaper and more sustainable solution than VC-FREI and can be a very good option for developing countries where people still live in unsafe buildings designed and built with no seismic provisions in mind. The focus of the project is on both structural and non-structural components (infill masonry wall, plasterboard partition system, contents and equipment) of buildings under horizontal and vertical ground motions of increasing intensity.

The prototype building (Fig. 2a and 2b) consists of a three-dimensional two-storey one-bay square-plan RC frame. The frame is provided with masonry infills and plasterboards along the two main directions (X and Y, respectively) as shown in Fig. 2, and tested on two base isolation systems (Fig. 2b and 2c). The prototype was mounted on four FREIs (RP-FREIs first, then VC-FREIs) installed in unbonded configuration beneath the corner columns. The replacement of the base isolation is executed through proper uplift at the foundation level.

With regard to the bearings' characteristics (Fig. 2c), the VC-FREI system consists of alternated layers of virgin rubber and quadri-axial carbon fabric and is characterized by higher compression modulus compared to RP-FREI where biaxial polyester fabric is adopted. Due to different fabric thickness the two isolators measured different height, namely 80 mm and 95 mm for RP-FREI and VC-FREI, respectively.

Even if previous tests demonstrated that rubber-concrete friction would prevent any sliding of the isolators, a recessed configuration (e.g. two additional steel plates for each bearing installed beneath the base beam and above the table with a central hole having the bearing diameter) was adopted for VC-FREIs to comply with EN15129 fixing methods for transmission of lateral force. For ease of installation and further reduction in construction cost, no recess was provided to the RP-FREIs in order to assess the adequacy of a friction-only restraint for the isolators.

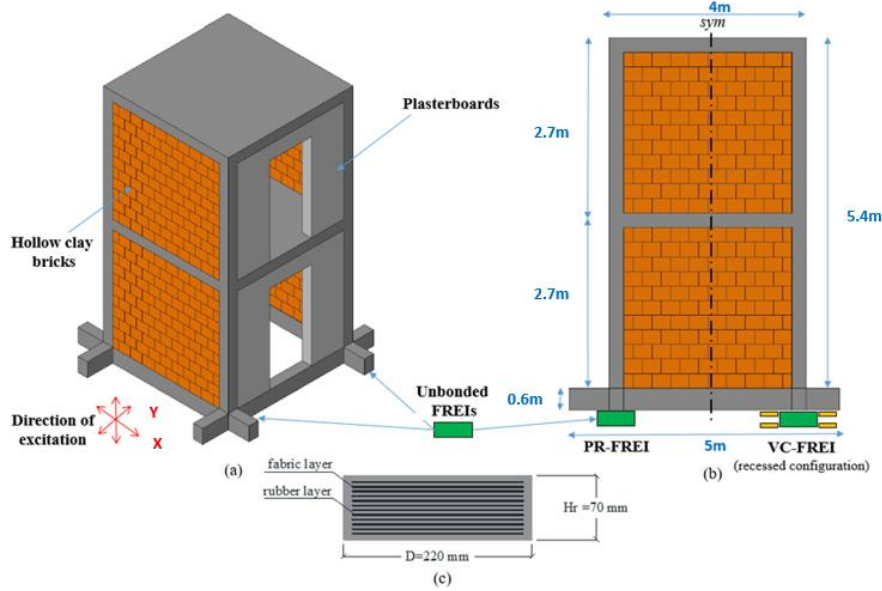


Fig. 2. a) 3D view and b) side view geometric details of the prototype, c) FREIs cross section (VC-FREI and PR-FREI).

The RC frame had been designed as non-dissipative structure according to EN1992-1-1 [25] and EN1998-1 [26] to be more representative of existing buildings. It has plan dimensions of 4.0m x 4.0m and a storey height of 2.70m. The class of concrete is of medium compressive strength (e.g. C28/35 strength class). The columns have square section of 35cm x 35cm and are reinforced with B450 steel rebars. The beams' cross section is 30cm x 40cm in size, whereas the slab is 12cm-thick and is reinforced with a double-layer welded wire mesh. The total weight of the 2-storey infilled frame is equal to 40t including the ring beam and nonstructural components. Ring beams at the base (with, e.g., 35cm x 60cm section) provided adequate stiffness under horizontal excitation as well as vertical stiffness under lifting and handling operations. The frame had no special foundation since it rests on four FREIs transferring horizontal force by friction. In this regard, a concrete-filled plate was installed on the shaking table providing realistic friction conditions of rubber-concrete type. Two different infill systems were tested along the two horizontal directions. In one direction (X), a single-leaf, around 20-cm thick, hollow-clay brick wall was considered, which is very common in Europe also for its thermal insulation properties. Hollow clay bricks with vertical and horizontal holes were adopted for the first and the second storey, respectively. In the other direction (Y), a plasterboard partition system was installed as a lower-weight and more versatile internal partition alternative. The infills have been tested both in-plane and out-of-plane due to the biaxial horizontal excitation. Non-structural elements installation at the first-storey consisted in common housing

and office contents, including a closet, a desk with a computer and a suspended pipe.

A numerical model of the building considering the infill systems provided a fundamental period of 0,15s and 0,07s along Y and X directions, respectively. It can be noted that masonry infills along X provide a significant contribution to the lateral stiffness of the bare frame, resulting in a period approximately 50% lower than the bare frame.

2.1 Base Isolation Design

Preliminary design of the base isolation system considering a superstructure mass of 40t resulted in 4 FREIs with 220mm diameter and 70mm total rubber height and a second shape factor around 3.0 as per stability requirements [27-28]. Assuming a soft compound ($G=0.4\text{MPa}$ at a shear deformation γ of 150%) and a 30% reduction of the contact area at ultimate limit state due to roll-over [14], the equivalent isolation period T_{is} was set at 1.6s, corresponding to an equivalent stiffness of 600 kN/m of the isolation system (150 kN/m per unit). A target displacement of 105mm corresponding to $\gamma=150\%$ shear strain (i.e. prior to full roll-over) was assumed. In terms of hazard level, a spectral demand of 150mm would be obtained for T_{is} and a 5% equivalent damping ratio; consequently, the target displacement is consistent with this value accounting for damping reduction factor as per EN1998-1 (equal to 0.7 for 15% damping ratio). Such hazard level is deemed representative of high seismicity regions in Italy with a 5% probability of exceedance in 50 years. Full roll-over (at around 200% shear strain) could be achieved under very-rare events (e.g. maximum-considered earthquake, MCE) but in order to prevent damage this condition was tested at the last stage of the testing protocol for VC-FREIs with recessed configuration only.

For preliminary characterization two specimens for each system were tested under compression and shear-compression protocols. Tests were performed at the University of Naples Federico II to evaluate axial stiffness and hysteretic behaviour of FREIs providing useful data for bearing model calibration and ground motion selection. Equivalent horizontal stiffness and damping ratios for different strain levels γ ($= u/t_r$) up to 150% are reported in Fig. 3. It can be noted that at $\gamma=150\%$ RP-FREI finely matched the target stiffness and damping ratios whilst VC-FREI resulted more flexible due to lower aspect ratio with around 20% higher damping capacity.

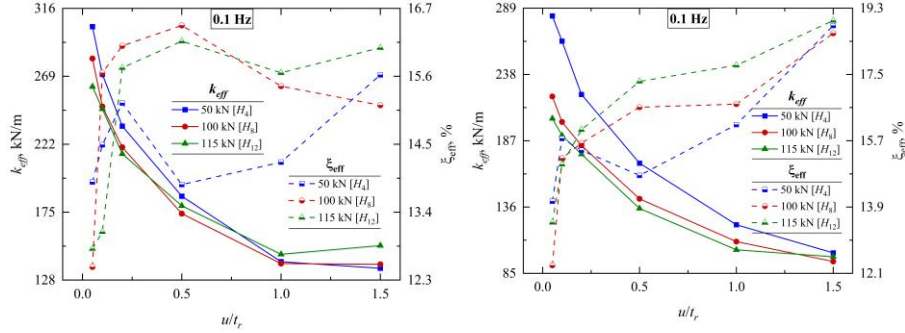


Fig. 3. Equivalent shear properties of the isolators: (a) RP-FREI and (b) VC-FREI.

3 Ground motion selection

A targeted selection of natural ground motions from the PEER NGA strong motion database [29-30] was performed. The selection was conditioned on the spectral characteristics of the ground motions seeking for ground motions that matches with relatively low scaling (i.e., scale factors close to 1) the spectral displacement of the isolated structure for the target hazard level. At the same time, records of different characteristics in terms of the intensity correlation between the horizontal components and the inherent characteristics of the ground motions (pulse-like, non-pulse-like) were searched in order to investigate the response of the isolators and the isolated structure under different conditions of shaking. In all cases for the scaled selected ground motions the peak acceleration, velocity, and displacement values had to be lower than the limits of the shaking table.

After setting the criteria for the selection, ground motions were searched in the NGA-West2 database. Specifically, assuming as target the 5% damped spectral displacement for the equivalent period of the specimen, $S_d(1.6s, 5\%)=150$ mm, ground motions were searched with at least one of the two horizontal components the $S_d(1.6s, 5\%)$ matching this value with low scaling. To avoid selecting ground motions with a local peak of the spectral displacement at 1.6s an extra check was imported to ensure that the peak is long enough in case the actual period of the specimen is in the range $\pm 0.2s$. Both non-pulse-like and pulse-like ground motions were searched. For the latter the ground motions that were identified as pulse-like by Shahi and Baker [31] were employed as the baseline list for the search.

Three ground motions that met the predefined criteria for the selection were chosen for the test. Two of them are non-pulse-like ground motions which depict the most common type of earthquake shaking during the lifetime of a structure. The first one (Loma Prieta 1989 event) refers to a strong ground motion where the horizontal component scaled to the targeted displacement (assigned in X-direction) is considerably stronger than the other (assigned in Y-direction). For the second (Kobe 1995 event) similar intensity in terms of the peak values of the

ground acceleration and velocity is shown between the two horizontal components. The last selected ground motion refers to a pulse-like ground motion record from the Jiashi 1997 earthquake. This ground motion was selected because the period of the extracted pulse in the direction of the stronger observed pulse was close to the equivalent period of the specimen ($T_p = 1.09$ s). Before assigned to the structural model and the specimen the horizontal components of the pulse-like ground motion were rotated accordingly to the orientation of the strongest observed pulse [32]. In all cases, a uniform scale factor close to 1.00 (in between 0.90 and 1.20) was assumed for the two horizontal and the vertical component per record. The unscaled acceleration and displacement ground motion response spectra are reported in Fig. 4.

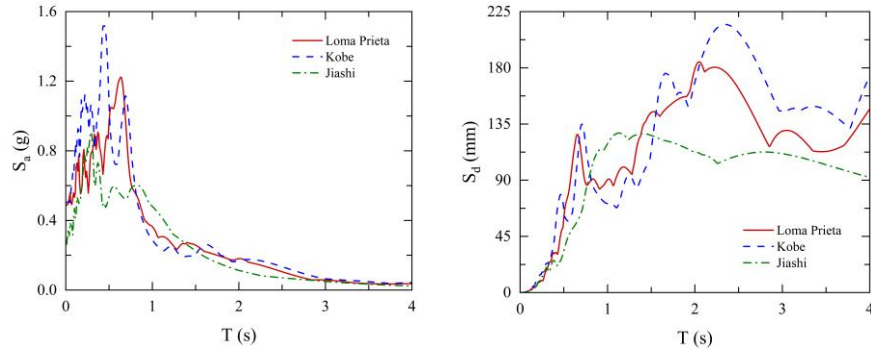


Fig. 4. Response spectra of selected ground motions: (a) acceleration and (b) displacement.

Numerical analysis of the isolated prototype was then performed by taking into account the behavior of the isolator through a non-linear Bouc-Wen model, in order to finely tune the scale factors by additional correction factors. The final values of the scale factors were assumed equal to 1.04, 1.15 and 1.26 for Jiashi, Loma Prieta and Kobe records, respectively. Hereafter the scaled ground motions will be referred as target level corresponding to 100% intensity level.

4 Shaking Table Tests

4.1 Test Program

The base isolated building was built and tested at LNEC (Fig 5). Input random noise was used to characterize the dynamic properties of the system under service conditions, as well as to monitor its changes during the test. The test sequence comprised 107 steps in between shake table operation, calibration, dynamic identification, seismic test and specimen preparation. Before testing the base isolated configuration, a characterization of the fixed-base prototype was run under free vibration. Additional characterization and sine sweep tests were run for the base

isolated prototype which are outside the scope of this paper. Imposed ground motions at different intensity levels for RP-FREI and VC-FREI are listed in **Table 1**. In a few runs tridirectional motions were imposed while in other cases only unidirectional or bidirectional components were applied for the sake of comparison in terms of multi-axial coupling and uni-axial response of FREIs to complement previous experimental findings from the literature [17].

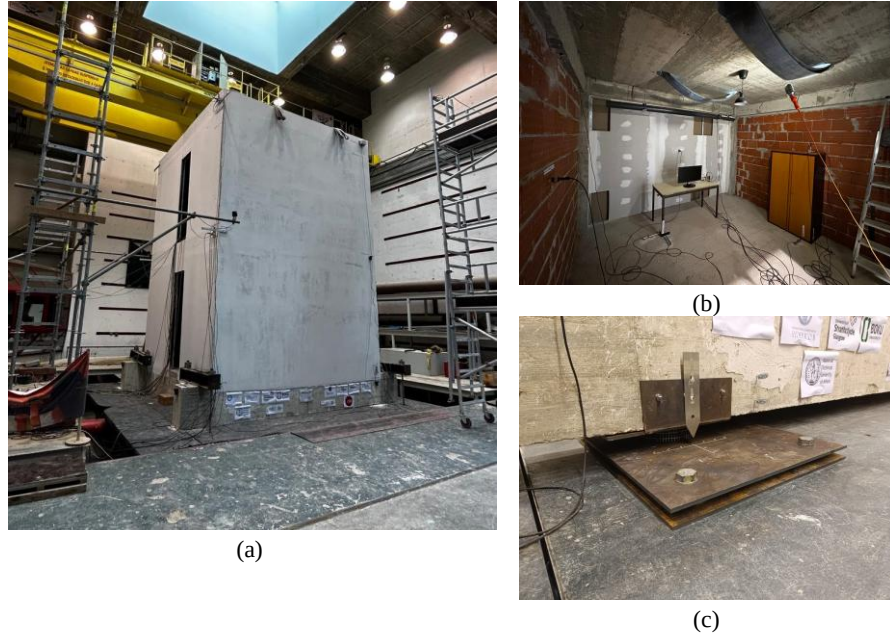


Fig. 5. (a) View of the prototype fixed at the base, (b) contents installed at the second storey, (c) VC-FREI system.

Table 1. Test matrix for selected ground motions.

System	Input	Intensity	dir	System	Input	Intensity	dir
RP-FREI	Loma Prieta	50%	X	VC-FREI	Loma Prieta	50%	X
		50%	XY			50%	XYZ
		50%	XYZ			75%	X
		75%	X			75%	XY
		75%	XY			100%	XY
		100%	XY		Jiashi	50%	X
	Jiashi	50%	X			50%	XY
		50%	XY			50%	XYZ
		50%	XYZ			100%	XY

		75%	X		Kobe	100%	XYZ	
		75%	XYZ			50%	X	
		100%	XY			50%	XY	
		100%	XYZ			50%	XYZ	
	Kobe	50%	X			100%	XY	
		50%	XY			100%	XYZ	
		50%	XYZ			120%	XYZ	
		75%	XYZ			Jiashi	125%	XYZ
		100%	XY					
		100%	XYZ					

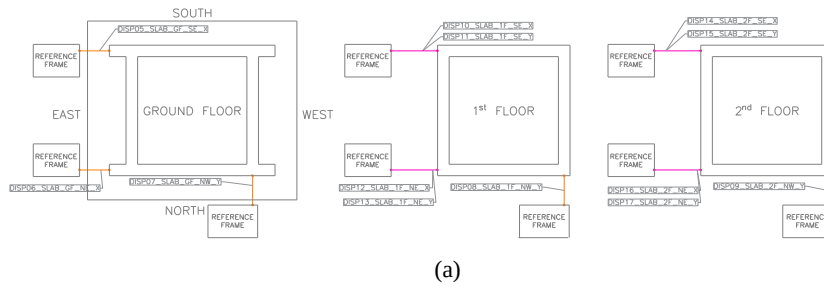
In case of VC-FREI the scaling factors for Kobe and Jiashi were further increased beyond 100% to trigger higher displacements and demonstrate higher stability limits by 20% and 25%, respectively.

In this paper experimental response under highest intensity levels (test runs **bold in Table 1**) have been considered for the sake of brevity.

4.2 Instrumentation layout

Absolute horizontal displacements and accelerations at every floor were recorded for monitoring the response of the prototype (Fig. 6a and 6b). Relative displacements of the infills were recorded along both diagonals and across adjacent columns and beams. Vertical displacements at the base corners of the prototype were monitored through LVDTs to detect the rocking behavior due to compliance of the bearings. A few additional displacement and acceleration sensors were installed on the contents at the first floor. The instrumentation used included 32 accelerometers, 4 optical transducers, 15 LVDTs and 9 wire potentiometers for a total of 64 available channels.

The following preliminary results mainly refer to displacement measures of the experimental layout.



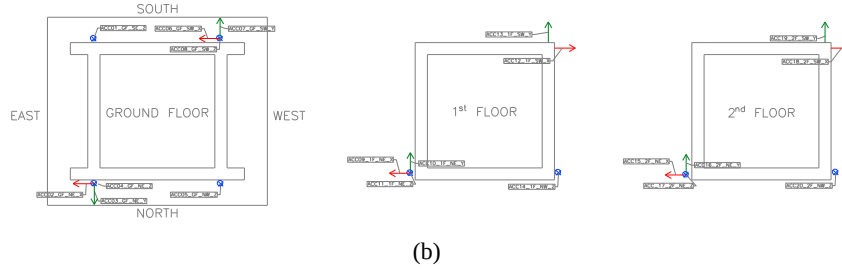


Fig. 6. Layout of (a) horizontal displacement transducers and (b) accelerometers.

4.3 Base isolation performance

FREIs performed in a stable manner under all the tests attaining peak displacements (i.e. combining X and Y components) of 103 mm and 130 mm corresponding to 147% and 186% shear strain in case of RP-FREI (Fig. 7a) and VC-FREI (Fig. 7b), respectively. Fig. 7a and Fig. 7b show the picture of the devices at peak displacement under Jiashi 100% and Jiashi 125% for RP-FREI and VC-FREI, respectively.

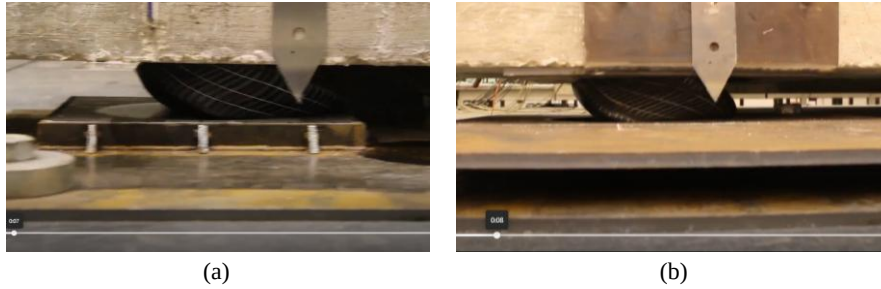


Fig. 7. Videoframe at peak displacement (a) RP-FREI under Jiashi 100% and (b) VC-FREI under Jiashi 125%.

When imposing Jiashi 100% the same total displacement was obtained perfectly matching the design target of 105 mm for both RP-FREI (Fig. 8a) and VC-FREI (Fig. 8b).

Even under significant roll-over, FREIs demonstrated remarkable recentering behavior. After completing the test sequence and removing the isolation units no significant damage was detected on the bearings.

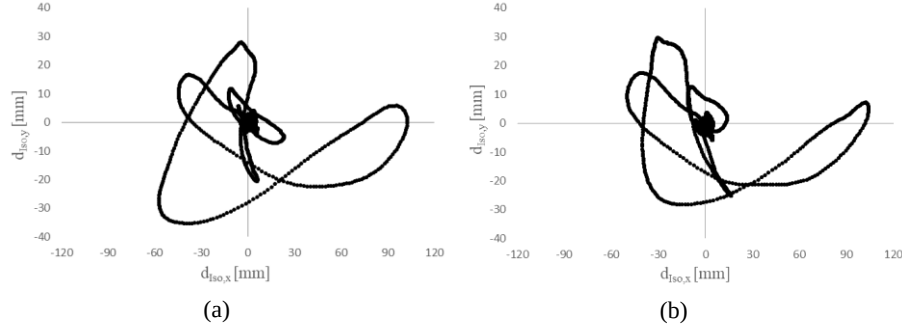


Fig. 7. Isolators displacements under Jiashi 100%: (a) RP-FREI and (b) VC-FREI.

4.4 Superstructure response

Base isolation effectiveness was measured both in terms of inter-storey drifts and peak accelerations.

In plane horizontal rotation angle above the foundation level (α) was calculated due to horizontal relative displacement between two points: values of $\alpha_{\max}$ were generally of the order of 1×10^{-3} implying minimum torsional behavior of the prototype (Fig. 8a).

Due to higher axial compliance of FREIs compared to steel laminated bearings, amplification of lateral response due to rocking was properly investigated. Rocking motion was measured in terms of rigid rotation (ϑ) in the vertical plane and set equal to the relative vertical displacement at the base corners over the relative distance between measurement points. Under different ground motions $\vartheta_{\max}$ was measured between 0.04% and 0.14% (Fig. 8b) corresponding to storey drifts of the order of a few millimeters.

For VC-FREI under Jiashi 125% and Kobe 120% both α and ϑ attained significantly higher values compared to 100% intensity level thus requiring further analyses which fall outside the scope of this work.

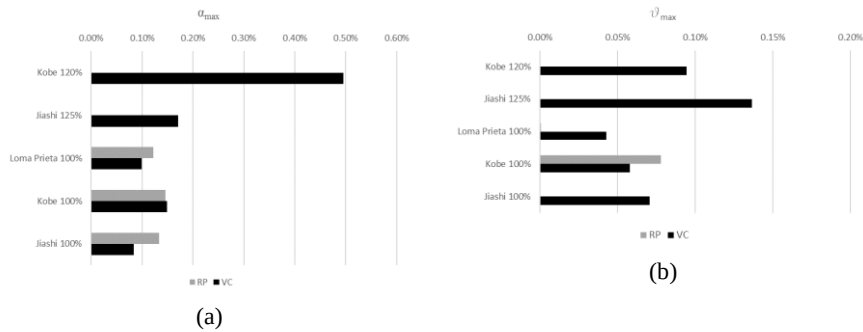


Fig. 8. Maximum rotations: (a) in horizontal and (b) vertical plan.

The rocking component may turn into higher storey drifts [33-34] and has to be filtered out when considering the bending mode of the frame providing the inter-storey drift ratio (IDR) as a measure of potential damage. Second storey drifts are plotted in Fig. 9 a and 9b for RP-FREI and VC-FERI under Kobe 100%. The influence of rocking is of the order of 2 mm and 1.5 mm for RP-FREI and VC-FERI, respectively. It can be noted that the drift time-history for RP-FREI shows some spikes especially after 15 seconds thus requiring further analysis. Corresponding IDRs are of the order of 0.50% which may have triggered slight damage to the prototype that was not confirmed by visual inspection. Further processing of signals will be developed to detect any measurement error of the optical system.

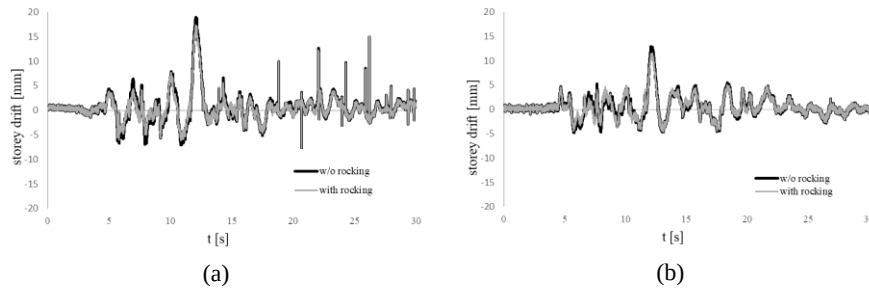


Fig. 9. Storey drift time-histories under Kobe 100%: (a) RP-FREI and (b) VC-FERI.

Imposed peak ground accelerations (*PGA*) along X and Y were in the range of 0.25g to 0.90g for the considered intensity levels. Peak floor accelerations (*PFA*) at the top of the building were normalized to *PGA* in order to check the filtering effect of the isolation system (Fig. 10a and 10b). This ratio was found always lower than one, with a peak value close to 0.8 for both systems up to 100% intensity level. It is worth mentioning that under the same intensity level, VC-FREI tends to provide slightly lower relative accelerations due to higher isolation effectiveness.

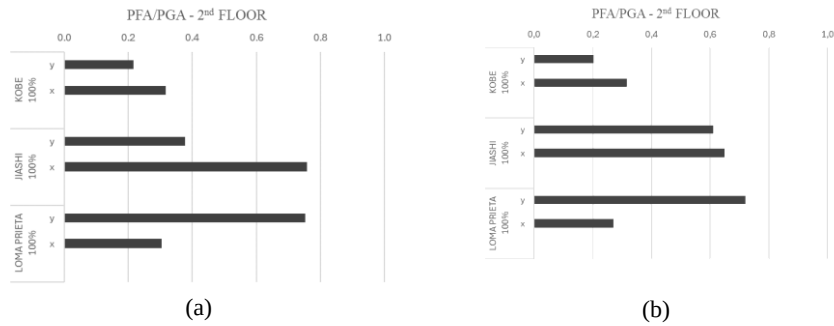


Fig. 10. Maximum top floor accelerations compared to PGA for (a) RP-FREI and (b) VC-FERI.

Non-structural components experienced no visible damage after the whole shaking sequence. In terms of contents, maximum displacement of the table was around 20mm along both X and Y, while the closet did not experience significant movement. The monitor on the table did not overturn: it was found in right position a few centimeters away from its original print marked on the table. The suspended pipe did not show any distress.

5 Conclusions

The FREISUST project demonstrated that FREIs can provide a fundamental period shift and protection of nonstructural components and contents, thereby significantly improving the seismic resilience of low-rise normal importance buildings. This goal was pursued through both innovative (e.g. carbon fabric) and low-cost eco-friendly materials (e.g. reclaimed rubber and polyester fabric). The 3D shaking table tests on a 2-storey full-scale prototype provided the required validation of FREI technology paving the way for EU standardization and implementation in the next-generation set of standards for anti-seismic devices (e.g. EN15129).

The isolators were designed for a target shear deformation of 150% with their geometry capable to ensure lateral stability up to 200% in case of very rare earthquakes. Although the target isolation period was lower than 2.0s for stability limits, under three lightly scaled real ground motions the superstructure experienced limited accelerations due to adequate filtering effect of the base isolation system. Maximum displacements of the isolation units perfectly matched design levels confirming the high potential of FREIs for low to mid-rise buildings under peak ground accelerations as high as 0.9g.

The project will have both scientific and practical impact related to the development and validation of innovative base isolation with FREIs through the protection of societies and citizens.

6 Acknowledgements

This work is part of the transnational access project “ERIES- FREISUST”, supported by the Engineering Research Infrastructures for European Synergies (ERIES) project (www.eries.eu), which has received funding from the European Union’s Horizon Europe Framework Programme under Grant Agreement No. 101058684. This is ERIES publication number C8.

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