Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 44 (2023) 1498–1505

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XIX ANIDIS Conference, Seismic Engineering in Italy

Full-scale experimental tests on unbonded fiber reinforced elastomeric isolators under bidirectional excitation

Dario De Domenico[a]*, Paolo Longo[a], Daniele Losanno[b], Natale Maugeri[a], Giuseppe Ricciardi[a], Nicolò Vaiana[b]

[a] *Department of Engineering, University of Messina, Contrada Di Dio, 98166 Sant'Agata, Messina, Italy*
[b] *Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples*

Abstract

Unbonded fiber reinforced elastomeric isolators (UFREIs) represent a lower-cost alternative to conventional steel reinforced elastomeric isolators (SREIs), in which the internal steel shims are replaced with fiber reinforcement and the installation is accomplished without anchorage bolts or dowels, but only relying on frictional mechanisms and interfacial roughness. In the literature, experimental tests on UFREIs were generally presented under unidirectional seismic excitation and considering small-scale devices. In this contribution, the hysteretic behavior of UFREIs is investigated experimentally by testing full-scale devices (diameter 620 mm) not only under unidirectional loading, but also including bidirectional orbits, thus quantifying the degree of biaxial coupling. A simple phenomenological model is then set up to numerically simulate the experimental outcomes. This model consists of a set of nonlinear springs arranged in a circular configuration. The spring parameters are calibrated by either curve-fitting 1D test results or considering 2D tests, thus selectively incorporating the lateral coupling. This model makes it possible to investigate the influence of bidirectional interaction of UFREIs on the seismic performance of base-isolated structures. Nonlinear time-history analysis on a regular three-dimensional reinforced concrete building with UFREIs modeled through the proposed approach demonstrates that the lateral coupling of the UFREIs leads to lower seismic response, of around 10-20%, in comparison to a simpler, uncoupled model that ignores the bidirectional interaction of the isolation devices.

Keywords: Seismic isolation; Fiber reinforced elastomeric isolator; Unbonded isolator; Full-scale experimental testing; Bidirectional excitation.

* Corresponding author. Tel.: +39-0906765921
E-mail address: dario.dedomenico@unime.it

10.1016/j.prostr.2023.01.192

1. Introduction

Seismic isolation represents a well-established technology to mitigate the seismic vulnerability of structures located in earthquake-prone regions (De Domenico et al. 2020; Di Cesare et al. 2021). Fiber reinforced elastomeric isolators (FREIs) (Kelly 1999; Moon et al. 2002; Kelly & Takhirov 2001) represent isolation devices that can be seen as an alternative to classical steel reinforced elastomeric isolators (SREIs) (Kelly & Konstantinidis 2011). FREIs are manufactured by placing fiber reinforcement (either as fiber fabric or as dispersed short fibers) within the elastomer compound and eliminating the internal steel shims. Moreover, FREIs are usually installed without any anchorage system, i.e., according to a so-called unbonded configuration (unbonded FREIs – UFREIs) that exploits a simple frictional mechanism arising at the interface between the top/bottom face of the isolator and the structure (Van Engelen et al. 2015; Russo & Pauletta 2013). These isolators have been recognized in the literature as an emerging low-cost isolation strategy that can be particularly useful especially for developing countries (Kelly 2002; Losanno et al. 2022a). However, further research is needed on these devices, to investigate, especially at the full scale, the peculiar hysteretic characteristics and compare to those of classical SREIs (Mordini & Strauss 2008).

In this contribution, full-scale experimental tests on two circular full-scale (diameter 620 mm) FREIs in unbonded configuration are presented. These tests, carried out at the EUROLAB of the University of Messina, Italy, involve both unidirectional tests (at various amplitudes, frequencies and under different axial loads) and bidirectional tests, i.e., application of imposed displacements along two orthogonal directions with simultaneously applied vertical load. The wide range of experimental results offer a comprehensive understanding of the hysteretic behavior of FREIs, encompassing both low-amplitude and high-amplitude motion scenario representative of weak and severe earthquake excitations, respectively. Furthermore, the comparison of main hysteretic parameters (typically, effective lateral stiffness and equivalent viscous damping ratio) obtained from unidirectional and bidirectional tests (at comparable amplitude levels) makes it possible to scrutinize the biaxial coupling effects of this type of isolators. To simulate such bidirectional interaction effects, a nonlinear phenomenological model, called multiple spring exponential model, is set up and calibrated based on the experimental findings. Finally, the seismic response analysis of a three-dimensional reinforced concrete building isolated with FREIs that are simulated through the proposed model is illustrated, accounting for and neglecting the lateral coupling of isolation devices.

2. Specimens and testing equipment

Two circular FREIs (diameter 620 mm) were realized with the same geometry and rubber compound (Fig. 1), constituted by 38 rubber layers (thickness 7.3 mm per layer, soft compound with shear modulus 0.6 MPa), with an overall rubber thickness 280 mm, reinforced with 37 layers of polyester bidirectional fabric (thickness 1.1 mm and elastic modulus 1176 MPa) alternatingly placed between the rubber layers (similar to the steel shims in the classical SREI configuration).

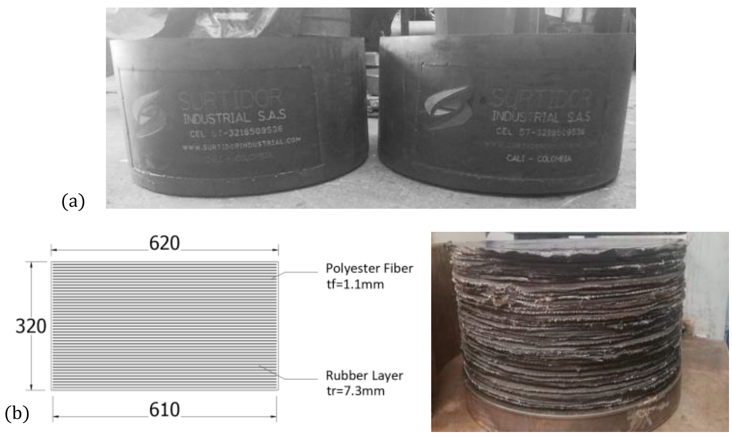

Fig. 1. Photograph of the two full-scale FREIs tested in this work (a) and illustration of their stacking sequence (units in [mm]) (b).

The FREIs were tested at EUROLAB of the University of Messina, Italy, through the 3D testing apparatus shown in Fig. 2. In particular, a shaking table (area 2.0 x 2.0 m) is moved by four vertical actuators along the z axis (load capacity 16000 kN) and two pairs of horizontal actuators in two orthogonal directions (load capacity 3100 kN and 1400 kN, stroke ±550 mm and ±375 mm along the x-axis and y-axis, respectively), which allows performing fully 3D tests on isolators. A peculiar low-friction hybrid technology is embedded in the vertical actuators, which minimizes the friction coefficient (measured value <0.035%) and reduces the stick-slip phenomena during dynamic tests. A battery of eight accumulators (capacity up to 4500 liters of gas oil) storages the hydraulic oil necessary for the test execution, while a hydraulic power centralized manifold (615 kW maximum power) ensures pressure levels up to 31.5 MPa during the dynamic tests.

To simulate an unbonded configuration of FREIs, the tested devices were installed without anchorage bolts or dowels, by exploiting friction and roughness at the rubber-concrete interface. Indeed, as shown in Fig. 2, two concrete-filled steel plates were placed above and below the tested FREI; these two plates were anchored to the shaking table (bottom) and to the reaction frame (top), but not to the tested device. This testing configuration made it possible to observe roll-over phenomena of the isolation device under large displacements (Losanno et al. 2019).

Fig. 2. 3D testing apparatus for full-scale testing of FREIs at the EUROLAB of the University of Messina, Italy.

3. Experimental campaign

A set of unidirectional and bidirectional tests were carried out on the two FREIs. The range of investigated parameters is listed in Table 1. Some selected tests are discussed in the following subsections.

Table 1. Range of testing parameters investigated in the experimental campaign on FREIs.

Parameter	Units	Range (min-max)
Amplitude	mm	14-280
Vertical load	kN	900-3600
Frequency	Hz	0.1-0.5
Velocity	mm/s	7-880

3.1. Unidirectional tests

Unidirectional tests were performed by imposing a sinusoidal displacement waveform at frequency 0.5 Hz and various amplitudes (14, 28, 56, 140, 280 mm, corresponding to shear strain of 5, 10, 20, 50, 100%, respectively), under a constant axial load equal to 1800 kN (bearing pressure 6 MPa). From the force-displacement (f-d) cycles, the main hysteretic properties of FREIs were calculated in terms of effective lateral stiffness k and equivalent damping ratio ξ as per EN 15129 provisions (2009), which are illustrated in Fig. 3.

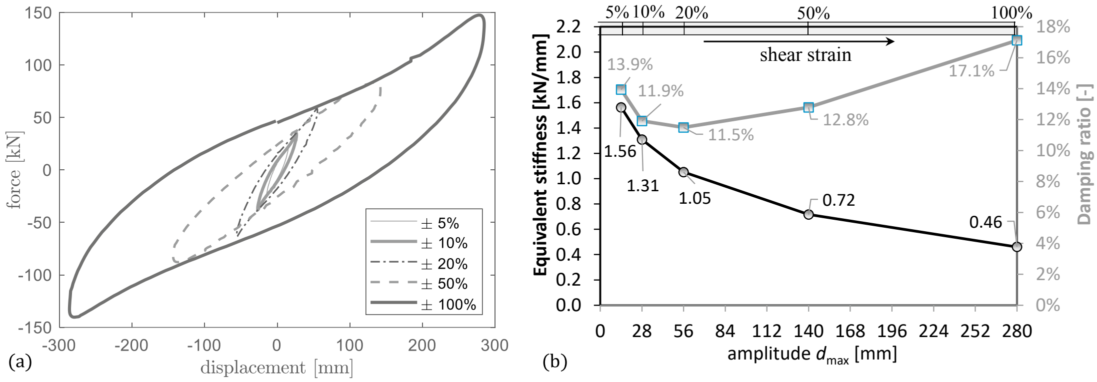

Fig. 3. Influence of excitation amplitude (a) on the force-displacement curves of UFREIs and corresponding hysteretic properties (b).

It can be observed that the influence of the amplitude on the resulting hysteretic properties of UFREIs is quite marked: as normally observed for SREIs, the effective stiffness decreases with increasing amplitude (from 1.56 kN/mm to 0.46 kN/mm passing from 14 mm to 280 mm) and the damping ratio follows an exactly opposite trend, tending to increase with the excitation amplitude up to 17% at shear strain 100%. It was also noted that the vertical stiffness measured during compression (quasi-static) tests was around 200-300 times higher than the horizontal stiffness at shear strain 100% (i.e., values of 100-150 kN/mm were measured). Increasing the axial load led to higher values of the damping ratio and lower effective stiffness, as typically observed for SREIs (Losanno et al. 2022b).

3.2. Bidirectional tests and comparison with unidirectional tests

To improve the knowledge of the hysteretic behavior of FREIs under bidirectional excitation and to investigate the sensitivity of hysteretic parameters with respect to the direction of loading, two bidirectional orbits (see Fig. 4) were imposed through the 3D testing apparatus shown in Fig. 2, namely the cloverleaf path, which is the displacement path recommended in the EN 15129 §8.3.4.1.5 (2009) for 2D tests on sliding isolation devices, and the Dürer folium (De Domenico et al. 2018), which is a circular-like orbit. These orbits were imposed via the concurrent movement of two couples of actuators along the orthogonal directions via extension/retraction mechanisms, by keeping the axial load constant and equal to 1800 kN.

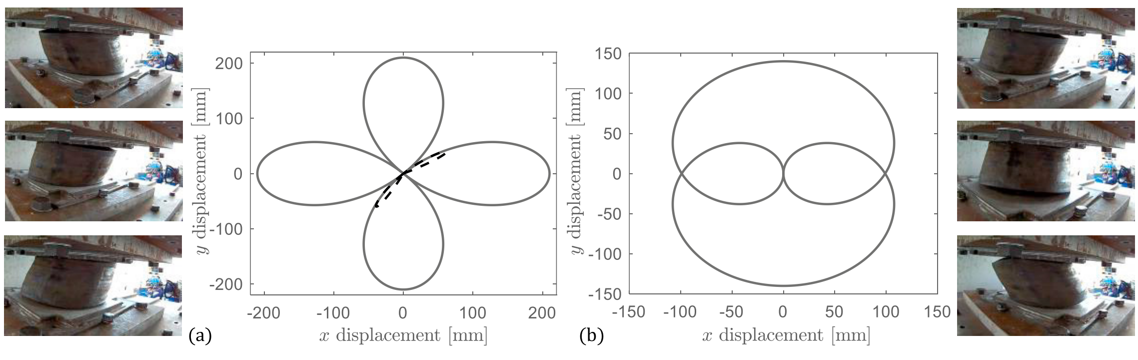

Fig. 4. Bidirectional orbits investigated: cloverleaf path (a) and Dürer folium (b).

The force-displacement loops and the resulting directional stiffness and damping ratio parameters for cloverleaf tests performed on two FREIs (sample 1 and sample 2) at shear strain 50% and peak velocity 50 mm/s are depicted in Fig. 5. It can be observed that, despite minor differences in the two samples, the damping ratios measured in the 2D tests (in the range 16-20%) are larger than those computed from the 1D tests at comparable amplitudes/velocities. Moreover, the values of directional stiffness measured along the x and y directions (in the order 0.51-0.57 kN/mm) are lower than those obtained from 1D tests at comparable amplitude 140 mm (0.72 kN/mm shown in Fig. 3). Similar trends were obtained for other tests, here not shown for the sake of brevity, with an increase of damping ratio and a substantial reduction of the effective stiffness in 2D tests compared to 1D tests; the latter trend is in line with test results reported in the literature for SREIs (Abe et al. 2004; Kim et al. 2019) and for friction-based devices (Lomiento et al. 2013; Furinghetti et al. 2019).

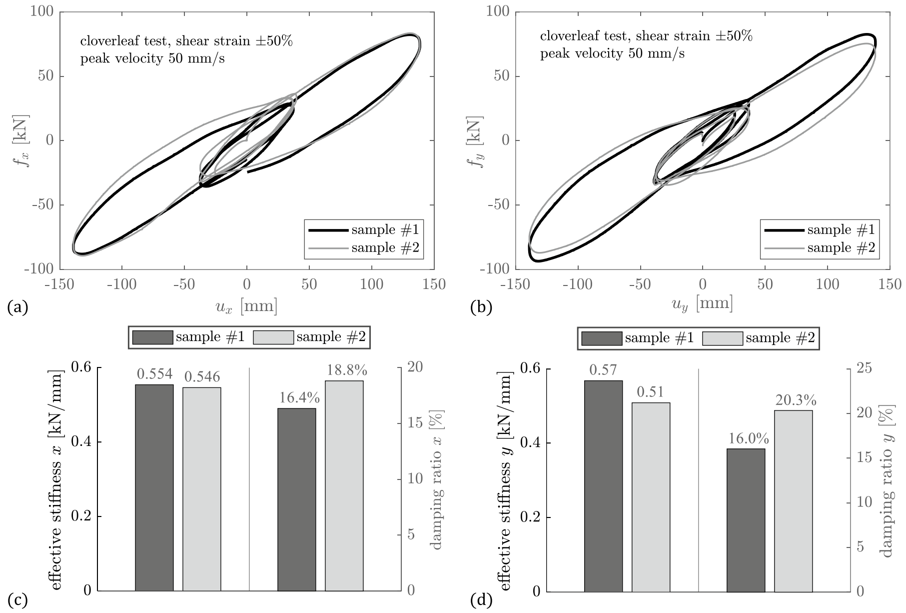

Fig. 5. Force-displacement curves (a) and (b) and hysteretic parameters (c) and (d) obtained under cloverleaf tests on two UFREIs samples.

4. Numerical model of UFREIs with and without bidirectional interaction

A phenomenological model, called multiple spring exponential model (MSEM), developed by Vaiana et al. (2021), is here employed to simulate the biaxial hysteretic behavior of UFREIs. The model is formed by n uniformly spaced springs, having rate-independent hysteretic behavior, arranged in a circular configuration around the origin of a coordinate system x-y-z, as shown in Fig. 6. The forces along the x and y axes can be calculated through:

$$f_x = \sum_{i=1}^{n} f^{(i)} \cos\varphi^{(i)}; \quad f_y = \sum_{i=1}^{n} f^{(i)} \sin\varphi^{(i)}; \quad \varphi^{(i)} = \frac{\pi}{n}(i-1) \tag{1}$$

where $f^{(i)}$ is the force of the spring placed along the i-th axis, whereas $\varphi^{(i)}$ is the angle between the i and x axes.

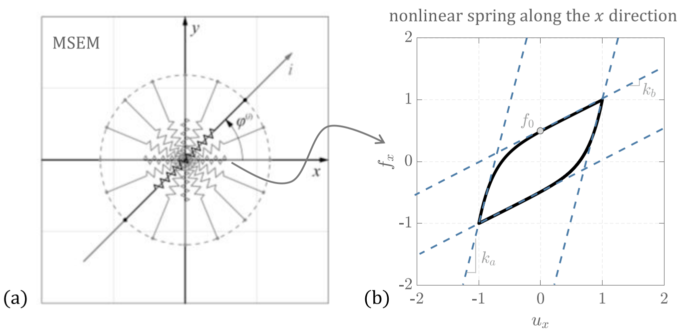

Fig. 6. Multiple spring exponential model (MSEM) (left) and meaning of the three model parameters (right).

The MSEM is governed by three independent parameters, namely k_a, k_b, and f_0, representing the tangent stiffness at the beginning and end of the generic loading or unloading phase and the ordinate of the intersection point of the upper limiting curve at zero displacement, respectively, as illustrated in Fig. 6. Through some algebraic manipulations, it is possible to express, through closed-form analytical relationships, the *i*-th spring internal parameters $k_a^{(i)}$, $k_b^{(i)}$, $f_0^{(i)}$ as functions of k_a, k_b, and f_0. Moreover, it is worth noting that using just two nonlinear springs (i.e., $n = 2$) leads to an uncoupled isotropic biaxial hysteretic behavior, whereas setting $n > 2$ makes it possible to simulate the coupling effect between the forces along the x and y axes.

To test the validity of the proposed phenomenological model, the experimental cloverleaf tests at amplitude 140 mm and 210 mm are simulated with and without accounting for bidirectional interaction. In the former case, the MSEM parameters are calibrated upon 2D tests, with $n = 16$; in the latter case, the MSEM parameters are obtained by curve-fitting the 1D test curves and ignoring the lateral coupling of the devices. The comparisons between experimental and numerical force-displacement curves and force paths are shown in Fig. 7. The parameters employed in the MSEM are listed in Table 2 for the two representative cases. While a very good agreement is observed with the former set of MSEM parameters ($n = 16$), the accuracy considerably worsens with the uncoupled biaxial rate-independent hysteretic behavior simulated with $n = 2$. Similar results were obtained for other orbits, here not shown for brevity.

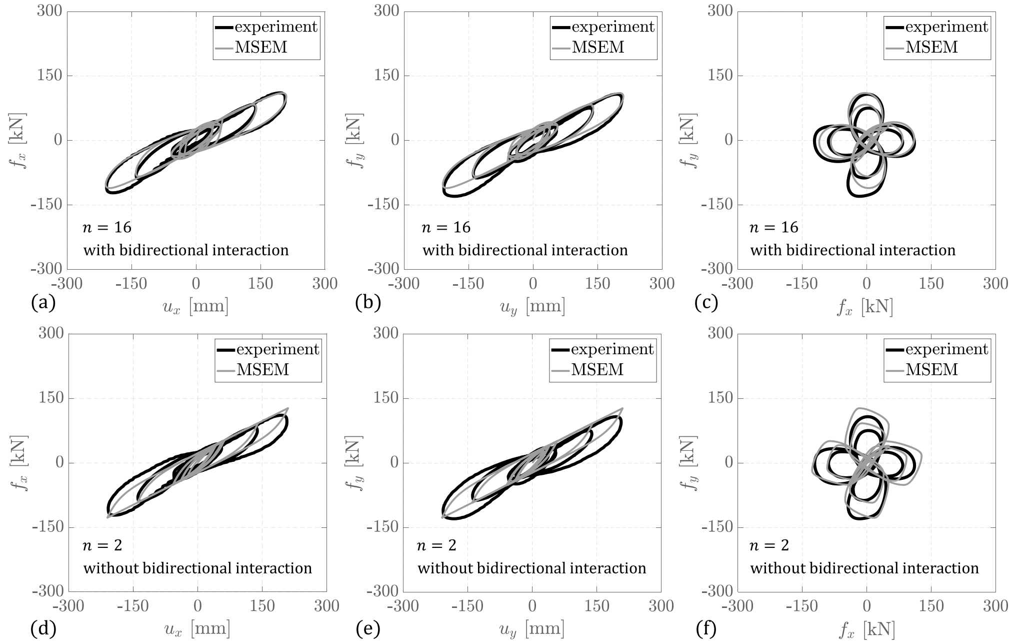

Fig. 7. Cloverleaf tests at amplitudes 140 mm and 210 mm simulated through the MSEM with *n* = 16 (a-c) and *n* = 2 (d-f).

Table 2. MSEM independent parameters used for simulating the cloverleaf tests.

Modelling approach	n	k_a **[kN/mm]**	k_b **[kN/mm]**	f_0 **[kN]**
with bidirectional interaction	16	8.50	0.42	31.07
without bidirectional interaction	2	2.20	0.50	22.36

5. Nonlinear time-history analyses on a 3D base-isolated building with UFREIs

The numerical approach presented in the previous section allows one to selectively incorporate, through a proper selection of model parameters, the biaxial interaction of UFREIs observed in the experiments. To investigate the influence of lateral coupling of UFREIs on the structural performance of base-isolated structures, nonlinear time-history analyses are performed on the regular three-dimensional reinforced concrete building previously studied by

Losanno et al. (2022b), in which the isolation bearings are modelled through the two sets of parameters listed in Table 2, i.e., with and without bidirectional interaction. The structure is isolated by 20 UFREIs, and the seismic response in terms of isolator displacement (of one isolator located at the corner of the building) and base shear under seven pairs of natural records (selected and scaled to be compatible with the elastic response spectrum for the site of Messina, Italy, soil A, importance class III, return period of 1462 years according to the Italian Technical Code NTC 2018) is illustrated in Fig. 8. It is noted that for almost all the earthquake events, as well as for the average seismic response (AVG), the results obtained without accounting for bidirectional interaction are a bit higher (of around 10-20%) than those obtained with bidirectional interaction included in the model of UFREIs. These conclusions are valid for both isolator displacement and base shear. These results interestingly suggest that the results obtained with a numerical hysteretic model of FREIs calibrated on 1D tests, as usually performed in practice, provide conservative estimates of the seismic response than a more accurate model that explicitly incorporates the bidirectional coupling of the devices.

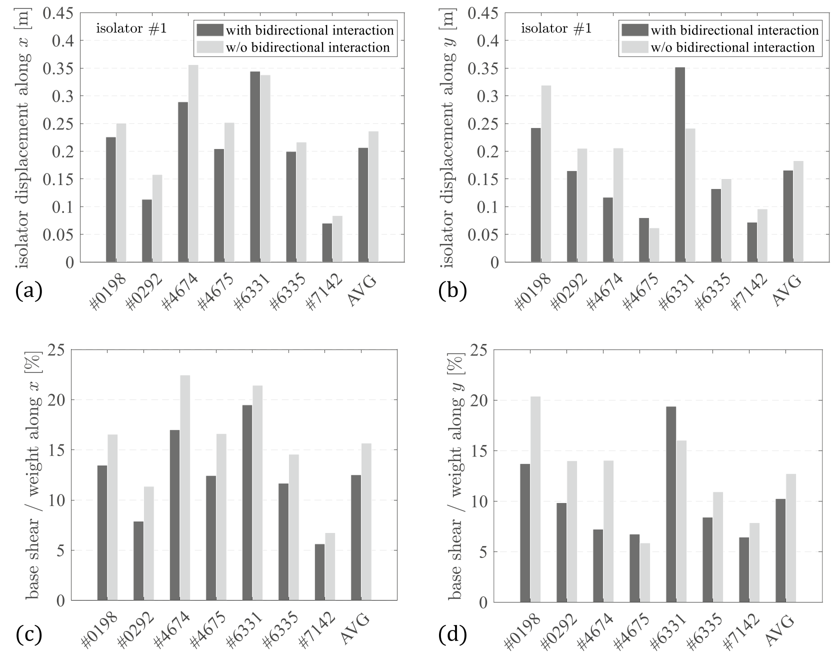

Fig. 8. Seismic response, in terms of (corner) isolator displacement (a) and (b) and base shear (c) and (d), of a base-isolated building with and without bidirectional interaction of UFREIs.

6. Conclusions

This contribution has presented an experimental campaign on full-scale FREIs tested in unbonded configuration at the EUROLAB of the University of Messina, Italy. The tests involved in the experimental campaign were inspired to the recommendations of the UNI EN 15129 (2009) regulations and included both unidirectional and bidirectional tests. In this contribution, only selected tests have been discussed for the sake of brevity. Based on unidirectional test results, it has been found that the effective stiffness of FREIs tends to decrease while the equivalent damping ratio tends to increase with increasing amplitudes, in a similar fashion to the trends noted in conventional SREIs. Additionally, by comparing results from 2D tests with those from 1D tests at comparable amplitudes, it has been found that the bidirectional coupling leads to a reduction of the equivalent stiffness (i.e., a reduction of the peak-to-peak secant slope) and an increase of the damping ratio (i.e., a larger energy dissipation capability), which may be related to higher friction mechanisms between fiber layers arising under bidirectional motion.

A phenomenological model has been adopted to simulate the experimental results, through a set of nonlinear springs arranged in a circular configuration and governed by just three parameters. Two sets of the model parameters have been studied: the former, obtained by curve-fitting 1D test results and ignoring the bidirectional interaction; the latter, calibrated upon 2D tests and incorporating the lateral coupling of the devices. These two sets of model parameters have been used to study, comparatively, the seismic performance of a base-isolated building with FREIs modeled with and without accounting for bidirectional interaction effects. From nonlinear time-history analyses under a set of natural spectrum-compatible records, it has been found that numerical errors in the order of 10-20% would be obtained in a simpler model that neglects the lateral coupling of the hysteretic behavior. However, in case of uncoupled model the estimates of the resulting seismic response would be conservative (i.e., higher isolator displacements and base shear) compared to those obtained by a more refined model calibrated through 2D tests and explicitly incorporating the biaxial coupling of the isolation devices.

Acknowledgements

This research was carried out in the framework of Programme STAR (2017 LO-CO-ISO project – PI Daniele Losanno), financially supported by UniNA and Compagnia di San Paolo. The authors would like to acknowledge the technical support from Dr. Ingrid Elizabeth Madera Sierra from the Universidad del Valle, Cali, Colombia, and the company Surtidor Industrial S.A.S., Colombia, for the manufacturing process of the FREIs.

References

Abe, M., Yoshida, J., Fujino, Y., 2004. Multiaxial behaviors of laminated rubber bearings and their modeling. I: Experimental study. Journal of Structural Engineering 130(8), 1119-1132.

De Domenico, D., Gandelli, E., & Quaglini, V., 2020. Adaptive isolation system combining low-friction sliding pendulum bearings and SMA-based gap dampers. Engineering Structures, 212, 110536.

De Domenico, D., Ricciardi, G., & Benzoni, G., 2018. Analytical and finite element investigation on the thermo-mechanical coupled response of friction isolators under bidirectional excitation. Soil Dynamics and Earthquake Engineering, 106, 131-147.

Di Cesare, A., Ponzo, F. C., & Telesca, A., 2021. Improving the earthquake resilience of isolated buildings with double concave curved surface sliders. Engineering Structures, 228, 111498.

EN 15129 Anti-seismic devices, 2009. European Committee for Standardization. CEN/TC 340, Brussels, Belgium.

Furinghetti, M., Pavese, A., Quaglini, V., & Dubini, P. 2019. Experimental investigation of the cyclic response of double curved surface sliders subjected to radial and bidirectional sliding motions. Soil Dynamics and Earthquake Engineering, 117, 190-202.

Kelly, J. M., & Konstantinidis, D., 2011. Mechanics of rubber bearings for seismic and vibration isolation. John Wiley & Sons.

Kelly, J. M., 2002. Seismic isolation systems for developing countries. Earthquake Spectra, 18(3), 385-406.

Kelly, J.M., 1999. Analysis of fiber-reinforced elastomeric isolators. Journal of Seismology and Earthquake Engineering 2(1), 19-34.

Kelly, J.M., Takhirov, M.S., 2001. Analytical and experimental study of fiber-reinforced elastomeric isolators. PEER Report 11, Pacific Earthquake Engineering Research Center, College of Engineering, University of California Berkeley.

Kim, J.H., Kim, M.K., Choi, I.K., 2019. Experimental study on seismic behavior of lead-rubber bearing considering bi-directional horizontal input motions. Engineering Structures 198, 109529.

Lomiento, G., Bonessio, N., & Benzoni, G., 2013. Concave sliding isolator's performance under multi-directional excitation. Ingegneria Sismica, 30(3), 17-32.

Losanno, D., De Domenico, D., Madera Sierra, I.E., 2022b. Experimental testing of full-scale fiber reinforced elastomeric isolators (FREIs) in unbounded configuration. Engineering Structures, 260, 114234.

Losanno, D., Nagavinothini, R., Parisi, F., 2022a. Seismic fragility of base-isolated single-storey unreinforced masonry buildings equipped with classical and recycled rubber bearings in Himalayan regions. Journal of Building Engineering 45, 103648.

Losanno, D., Sierra, I. E. M., Spizzuoco, M., Marulanda, J., & Thomson, P., 2019. Experimental assessment and analytical modeling of novel fiber-reinforced isolators in unbounded configuration. Composite Structures, 212, 66-82.

Moon, B.Y., Kang, G.J., Kang, B.S, Kelly, J.M., 2002 Design and manufacturing of fiber reinforced elastomeric isolator for seismic isolation. Journal of Materials Processing Technology 130: 145-150.

Mordini, A., & Strauss, A., 2008. An innovative earthquake isolation system using fibre reinforced rubber bearings. Engineering structures, 30(10), 2739-2751.

Russo, G., Pauletta, M., 2013. Sliding instability of fiber-reinforced elastomeric isolators in unbonded applications. Engineering Structures 48, 70–80.

Vaiana, N., Losanno, D., Ravichandran, N., 2021. A novel family of multiple springs models suitable for biaxial rate-independent hysteretic behavior. Computers and Structures 244, 106403.

Van Engelen, N.C., Tait, M.J., Konstantinidis, D., 2015. Model of the shear behavior of unbonded fiber-reinforced elastomeric isolators. Journal of Structural Engineering 141(7), 04014169.