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EFFECTIVENESS OF THE RBRL ISOLATION SYSTEM: EVIDENCES FROM SEISMIC TESTS AND NUMERICAL SIMULATION

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Abstract. *The Rolling-Ball Rubber-Layer (RBRL) system was developed to enable seismic isolation of low-mass structures, such as works of art or special equipment, and is very versatile, a great range of equivalent natural frequencies and coefficients of damping being achievable through the independent choice of the system parameters. The paper presents new results from a previous campaign of shaking-table tests (PSTRBIS ECOEST 2 Project, 1999), related to a superstructure model consisting of two concrete slabs separated by four M16 studs 500mm long, which give a first mode fixed-base response at about 2.5 Hz. In particular, attention is given not only to the global behaviour of the system, which includes the steady-state rolling, but also to its small-deflections behaviour, influenced by the creation of pits in the rubber layer due to its viscoelastic properties. These experimental results are compared to those obtained from numerical simulations, conducted in OpenSees, using a FE fixed-base model previously calibrated using other shaking-table tests performed at fixed-base. These comparisons, isolated (test) versus fixed (model) case, are presented in terms of peak values of acceleration and inter-storey drift, time-history accelerations and displacements and by means of response spectra ratios for both the slabs, and show the effectiveness of the system not only at large displacement but also for small deflections if compared with an equivalent sliding isolation system. Attention is here restricted to uniaxial behaviour. Finally, some considerations are made regarding a possible characteristic frequency of roll-out of the balls from their initial pits.*

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1 INTRODUCTION

The rolling-ball rubber-layer isolation (RBRL) system was developed at TARRC to enable isolation of low-mass (< 10 t) structures. The system comprises RBRL bearings and rubber recentering springs; these may be combined in single packages as shown in Figure 1 [1].

The principal device components and their functions are:

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

Previous studies [1, 2, 3, 4] have shown that the RBRL system has three key types of behaviour, differentiated according to the magnitude of the displacements relative to the ground.

1) Inside-pit behaviour. For small displacements, up to ~5mm, the system has nonlinear force–displacement characteristics, with high damping and relatively high stiffness, albeit the stiffness declining rapidly as the displacement amplitude is increased (Figure 2a). In this regime, the behaviour is dominated by the continued location of the balls within a viscoelastic depression, or pit, formed during the long period under static load in the absence of seismic excitation. This compliance and damping at small deflections has the great advantage of both changing the mode shape and suppressing excitation of the vibration modes of the isolated structure even for small seismic intensities, as tentatively shown by Donà et al. [5, 6]. This behaviour contrasts with that of a sliding system, which presents a very high and predominantly elastic stiffness, bordering on rigidity, for small excitations. The springs have little influence in this regime, because their stiffness is negligible compared to that associated with the pits.

2) Fuse behaviour. If a characteristic threshold horizontal force is applied, for example by a sufficiently large ground acceleration, the balls will escape from the locality of the viscoelastic depressions, and roll with an approximately constant opposing resistance, significantly lower than the characteristic threshold force. In this regime, the system behaves like a mechanical fuse, the force applied to the superstructure being truncated at the value of the characteristic peak, or threshold, force. This behaviour is akin to that of a sliding system subjected to moderate excitations, but with the additional feature that there is a memory effect of the viscoelastic depressions that tends quite strongly to recapture the rolling balls in their initial reference configuration, as can be observed in Figure 2b in the displacement range 5 to 15 mm. The displacement time-history of the isolated structure therefore exhibits periods of small displacement with occasional larger excursions, while the force time-history is clipped at the characteristic threshold force. The spring stiffness plays a crucial recentering role after the large excursions, but the associated nominal natural frequency is not a significant design parameter for this regime.

3) Steady-state rolling behaviour. For strong excitations with many fluctuations (as opposed to a discrete pulse), continuous free rolling will be induced, as shown in Figure 2c. In this regime, for displacements greater than 15mm, the recentering rubber springs provide a well-defined natural frequency of isolation that need not be significantly amplitude dependent and can be designed to have any value. The equivalent linear damping level is determined predominantly by the rubber tracks, and for low design frequencies can be very high if desired [1], whereas for high frequency systems it may be necessary to use high damping rubber for the springs. The system thus behaves like a classical linear isolation system, but enables a wide margin for choice of natural frequency and damping ratio.

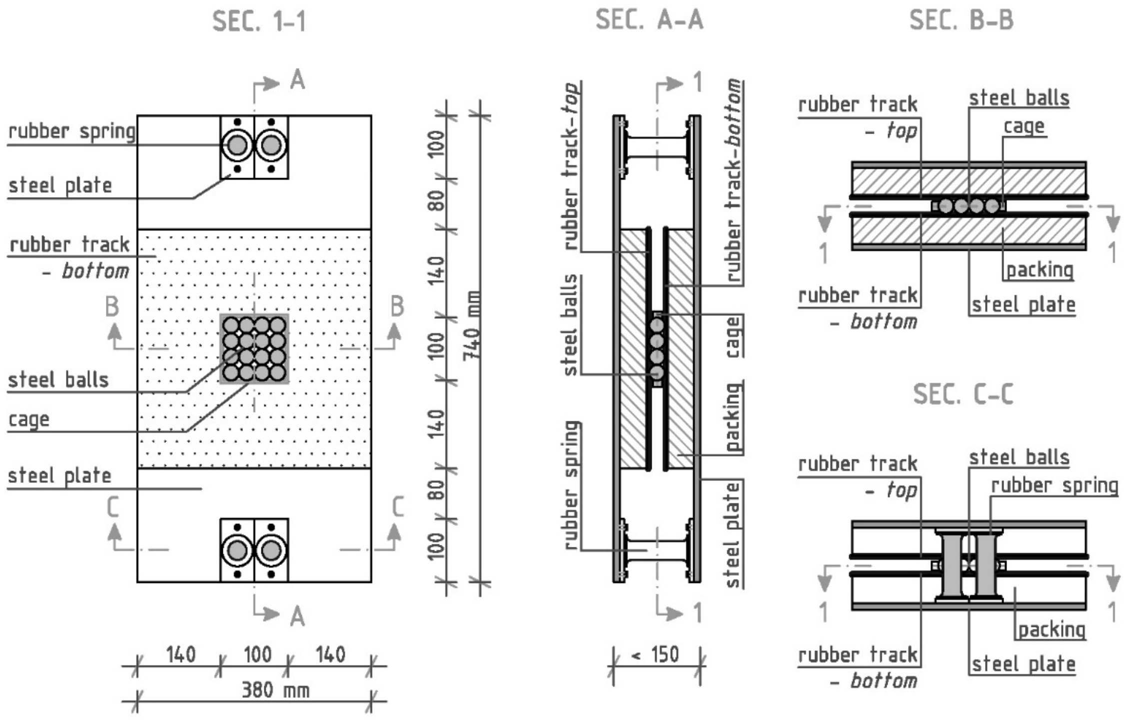


Figure 1: Combined package of RBRL bearing and recentering springs as used for PSTRBIS ECOEST 2 project.

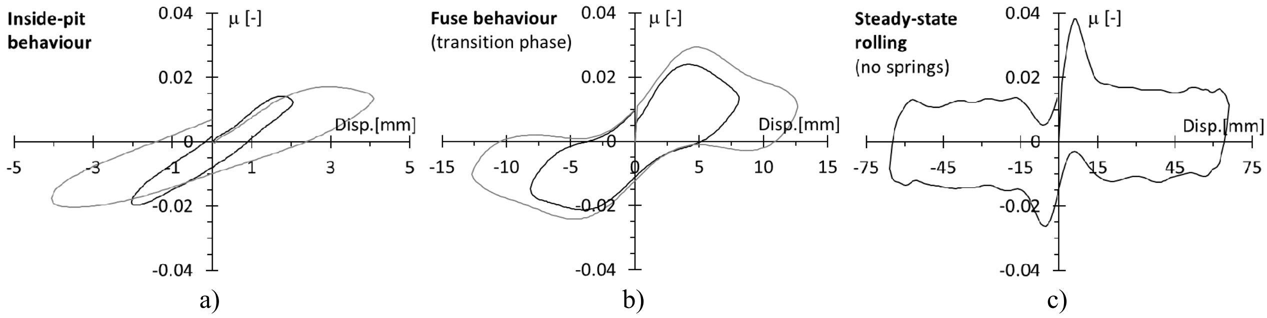


Figure 2: Figure 2. a), b), c) Rolling friction-displacement (μ-Disp) loops, representative of the behaviour types of the RBRL system without springs. Rubber tracks 2mm thick of type A - Young's modulus E=1.14MPa; ball radius R=12.5mm; stress parameter W(=load per ball)/ER^2=1.2; dwell time under load 25 hours; sinusoidal tests at 1Hz frequency.

The rolling friction–displacement (μ–disp) loops of Figure 2, in which μ is the horizontal resistance divided by the vertical load, derive from the parametric experimentation conducted at TARRC in 2014 [3]: the choice to not consider the springs in these tests was to better focus on the effect of the pits on the small-deflection behaviour of the system.

Extensive experimental studies of this system were undertaken by TARRC and collaborating research centres in the period 1993–1999 [in order 7, 8, 4, 9, 10, 2], but a more comprehensive test and numerical characterization, a design method and a time-domain model for the simulation of the unidirectional behaviour of the same are more recent [1, 3].

Among the experimental studies, the project 'Parametric Seismic Tests of Rolling Ball Isolation System' (PSTRBIS) funded in 1999 under the European Commission Earthquake and Shaking Tables 2 Programme (ECOEST 2), indicated in the following as the ECOEST 2 project, involved 34 shaking table tests of an isolation system comprising four RBRL devices; large amounts of data were gathered from this project, but only a summary of the findings with a few highlights has so far appeared in the literature [2].

This paper presents new experimental evidences from the ECOEST 2 project, related to both the behaviours of the system at small and large deflections, i.e. considering the "inside-pit" and the "steady-state rolling" behaviours respectively (see Figure 2). For this purpose, the experimental results are compared to those obtained from numerical simulations, conducted in OpenSees, using a fixed-base FE model previously calibrated using other shaking-table tests performed at fixed-base. These comparisons, between the isolated case studies (test) and the related fixed-base FE model (non-isolated), are presented in terms of peak values of acceleration and inter-storey drift (between the two slabs), time-history accelerations and displacement and through response spectra ratios for both the slabs, showing the effectiveness of the system. Attention is here restricted to uniaxial behaviour.

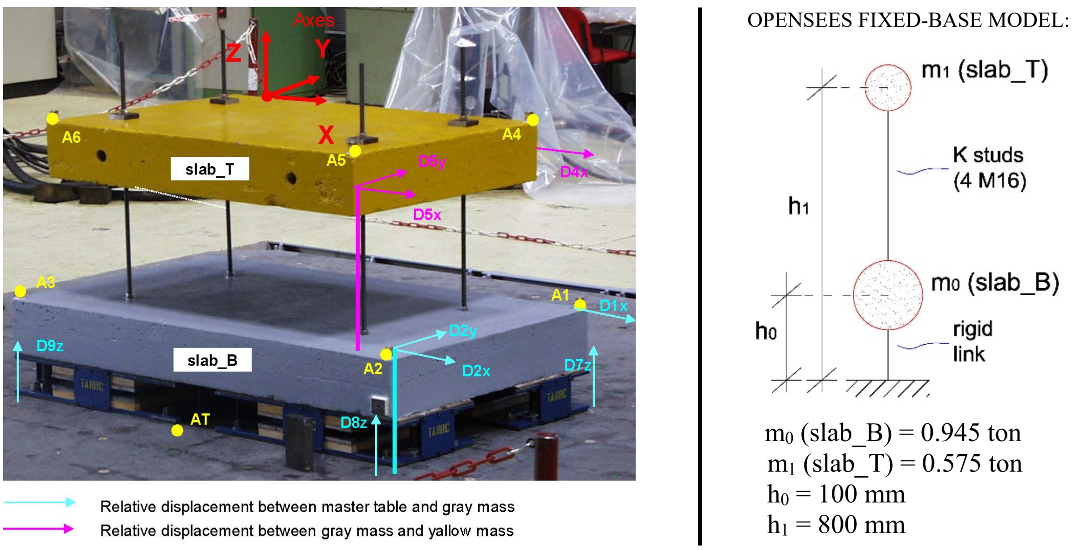
Finally, some considerations are made regarding a possible characteristic frequency of roll-out of the balls from their viscoelastic pits, which could be useful for developing a procedure to assess the transition from the inside-pit behaviour to the free rolling one, once the seismic input is provided.

2 CALIBRATION OF THE FE MODEL WITH FIXED BASE

2.1 Presentation of the ECOEST 2 shaking-table tests and the FE Model

The model superstructure in the ECOEST 2 project [2] consisted of two concrete slabs which could either be clamped together (Mass Down configuration) or separated by four M16 studs 500 mm long, as in Figure 3a), to give a first mode fixed base response at ~2.5 Hz (Mass Up configuration). Both the configurations, isolated on the RBRL system, were subjected to a range of acceleration time histories in one, two or three directions. The results recorded (see Figure 3a) consist of relative displacements, between the bottom slab and the shaking table and between the two slabs, and of absolute accelerations of table, bottom slab and top slab.

In this paper, further results from the uniaxial tests with the Mass Up configuration are presented and compared to those from numerical simulations of the related "fixed-base" case; for this purpose, a Finite Element (FE) model (Figure 3b) was developed in OpenSees and calibrated through some other shaking-table tests performed on the Mass Up configuration without base isolation (i.e. fixed to the table).



a) b)

Figure 3: a) Mass Up configuration with indication of transducers (A = accelerations; D = displacements), from ECOEST 2 project. b) Relative fixed-base FE model analyzed in OpenSees for comparisons.

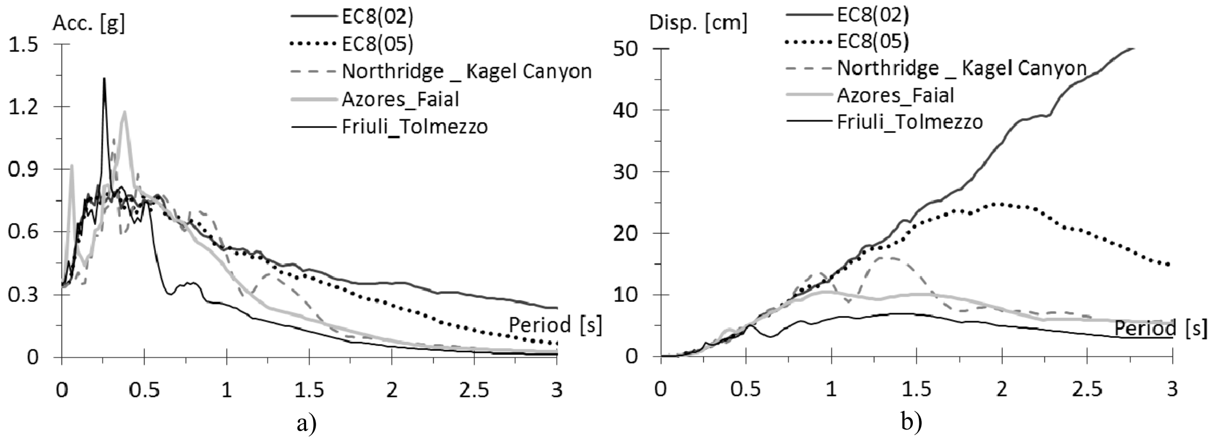


Figure 4: a) Acceleration and b) displacement response spectra of the ground motion selected for the tests with Mass Up configuration, as recorded at the table (ζ = 5%).

The earthquakes considered (Figure 4) were: Northridge-PCKC, Tolmezzo, Faial, EC8(05) and EC8(02), for tests with base isolation, while only EC8(02) for the fixed-base tests. Artificial records were used for EC(02) and EC(05) earthquakes, according to Eurocode 8 (Soil type B, ζ = 5%, peak ground acceleration 0.3g): (02) and (05) mean that the original records were applied with low frequency cut-offs of 0.2 and 0.5 Hz respectively because of the maximum displacement limitation of the table (±100 mm). For each case, the original record with a given peak ground accelerations (PGA_0) was scaled to different PGA levels through the parameter k[dB] = $20 \cdot \log \cdot (PGA/PGA_0)$ to vary the seismic intensity.

Finally, the low damping rubber, type A [1, 2], was used for both top and bottom rolling tracks of the devices in all the tests here considered, except for the earthquake EC8(02) where the devices presented one layer of rubber A and one of high damping rubber B [2].

2.2 Stiffness of the structural model measured during tests

The first step to calibrate the FE model (of Figure 3b) was the calculation of the total stiffness of the studs (K_{studs}), for horizontal displacements, directly from the test results, knowing the absolute accelerations of both the slabs (and so their inertial forces) and the relative displacement between them at the same instant.

Figure 5 presents, for some tests, the actual value of K_{studs} calculated for the entire duration of the test, for negative and positive relative displacements between the slabs. Besides observing a not very stable value of K_{studs} for small drift values, which is negligible for our purposes and seems reasonable considering the calculation method, it is also possible to note a slight difference between the values at positive and negative relative displacements; thus, after calculating an average value of K_{studs} for both the positive and negative drifts separately, disregarding the results for small drifts, we got the final K_{studs} value for each test as average of the previous values.

Table 1 reports all the results for K_{studs} obtained by all the tests performed at fixed-base.

The reduction of the studs' horizontal stiffness with increase in the seismic intensity of the test is probably due to some losses of the interlocking condition in the connection between studs and slabs, because of the high seismic excitation of the masses in the absence of base isolation.

For the calibration of the damping ratio ξ of the FE model (see next section), each test was simulated considering its specific mean value of K_{studs} while, for the subsequent comparisons between the results from tests with the RBRL system and those from the fixed-base FE model, the mean value 141 N/mm of the first fixed-base test was used for the following reasons: the drifts obtained with this test (*k*=-15dB) are the closest to those registered in the tests with base isolation and, also, the tests with RBRL system were performed before those at fixed base.

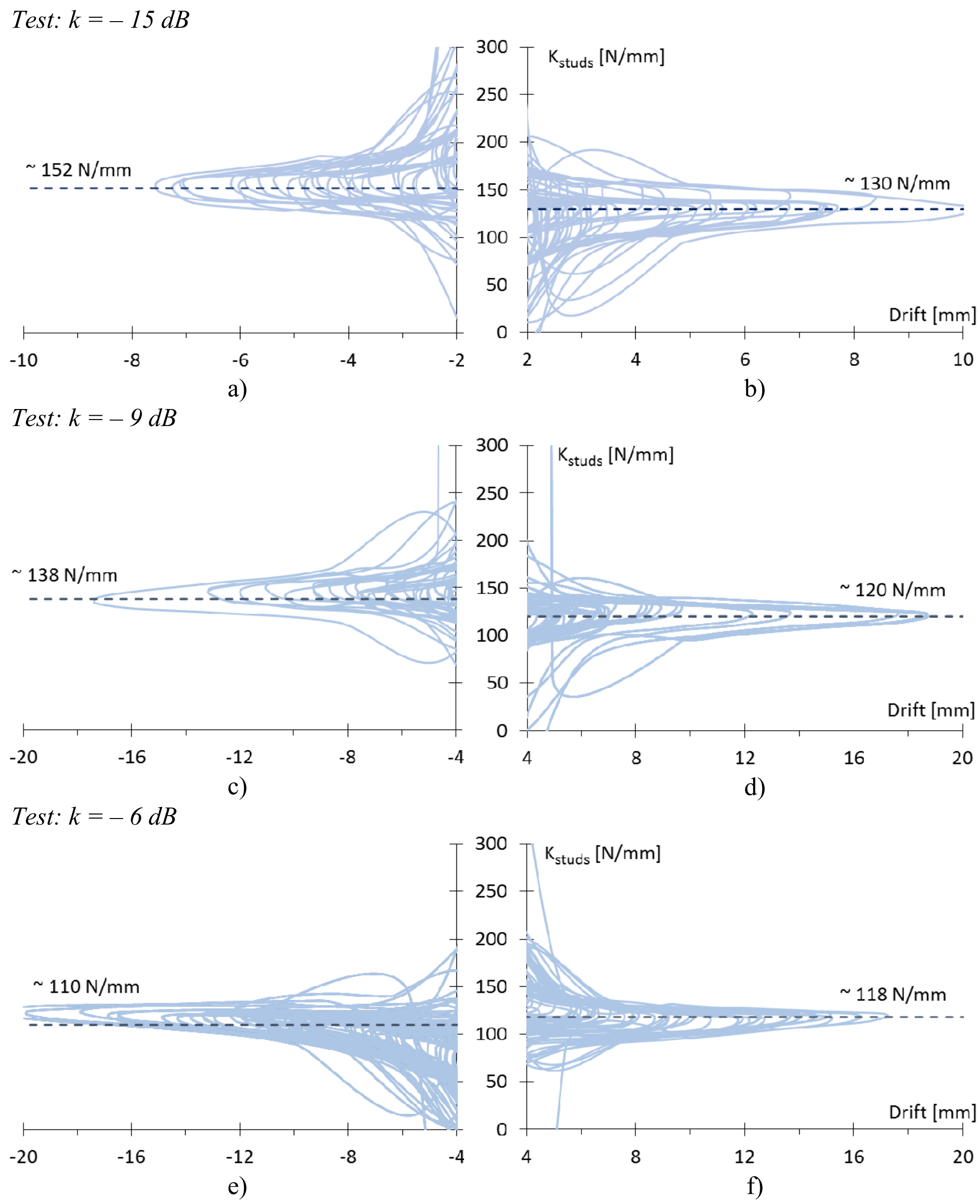


Figure 5: Stiffness K_{studs} of the studs calculated for different tests at fixed-base with earthquake EC8(02) (k=-15dB, -9dB, -6dB), for negative (a, c, e) and positive (b, d, f) displacements.

Tests k [dB]	 at negative drift	**K_{studs}** at positive drift	 mean
-15 dB	152	130	*141*
-12 dB	149	124	*136*
-9 dB	138	120	*129*
-7 dB	123	115	*119*
-6 dB	110	118	*114*

Table 1: Stiffness K_{studs} of the studs from all the tests at fixed-base, with earthquake EC8(02).

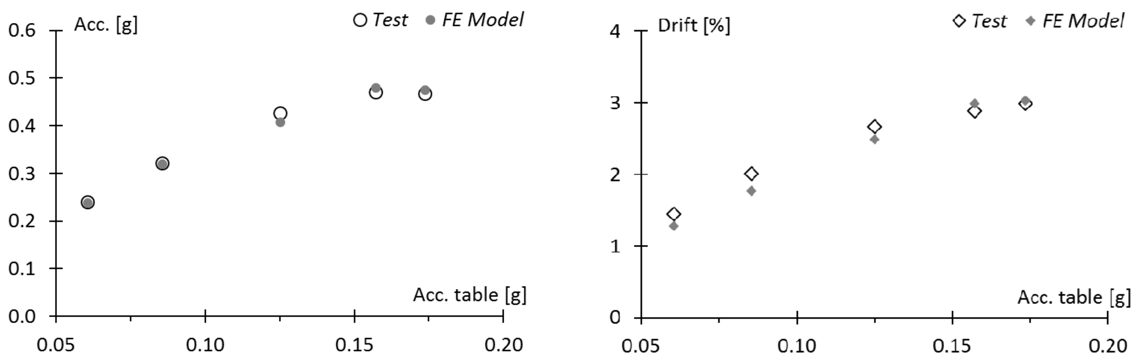
2.3 Calibration of the damping ratio for the FE Model

Considering the simple one-degree-of-freedom model of Figure 3b and the horizontal stiffnesses between the slabs reported in Table 1, the calibration of the damping ratio was performed so as to obtain the best fit between the experimental and numerical peak values of acceleration, of the upper slab, and drift between the slabs, as shown in Figure 6.

It has been found that a value of ξ=2.3% allows all the tests performed at fixed base to be fitted reasonably well and is also an appropriate value for steel structures.

Figure 7 compares the test and numerical results for the acceleration (of the upper slab) and drift (between the two slabs) time histories, for two different tests. Finally, Figure 8 reports comparisons for all the tests in terms of acceleration and displacement spectra, obtained from the previous time series.

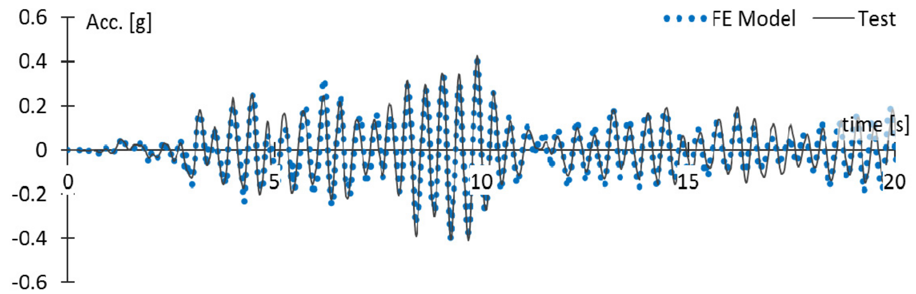
Figures from 6 to 8 prove the effectiveness of the FE model in predicting the dynamic behaviour of the model superstructure tested in ECOEST 2 project, as well as its appropriateness to be used as a comparison reference to study the performance of the RBRL isolation system.



a) b)

Figure 6: Prediction of the FE model using a damping ratio of 2.3% and comparison with the fixed-base tests results, in terms of peak values: (a) acceleration of the upper slab; (b) drift between the slabs.

Test: k = – 9 dB



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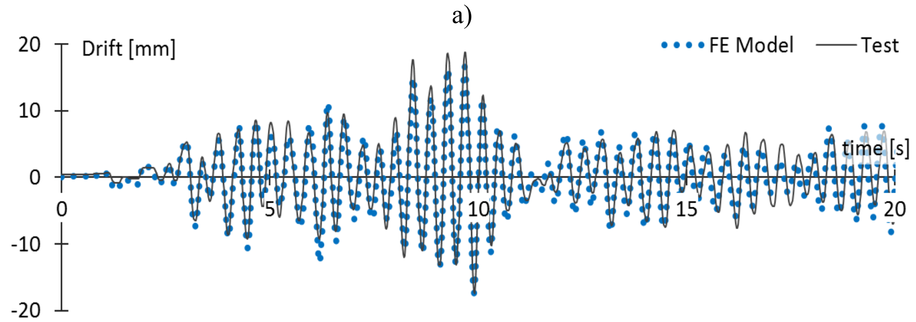

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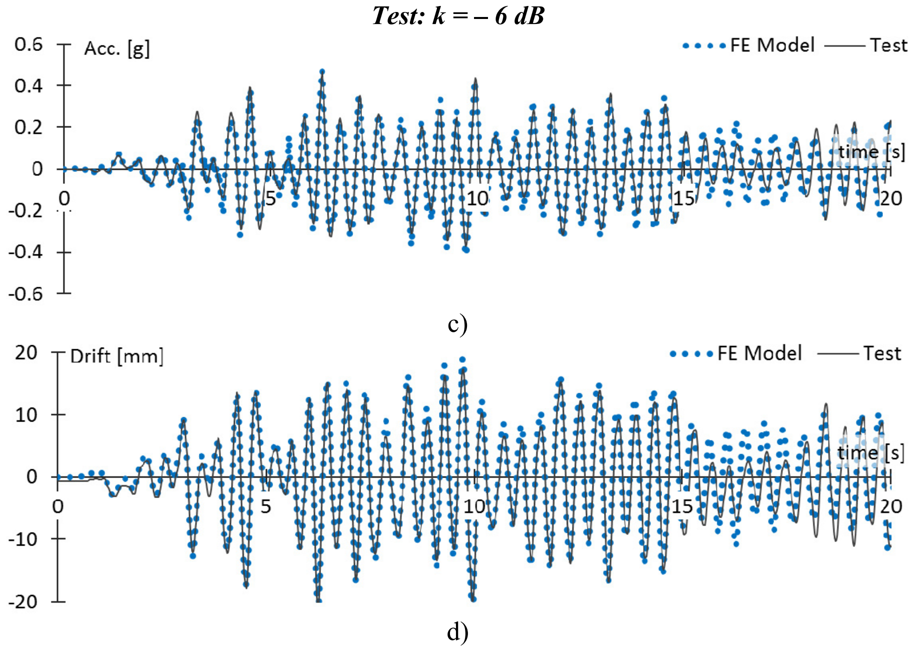

Figure 7: Comparison between numerical and test results in terms of acceleration (a, c) and drift (b, d) time series, for two tests: EC8(02), k = -9dB and k = -6dB.

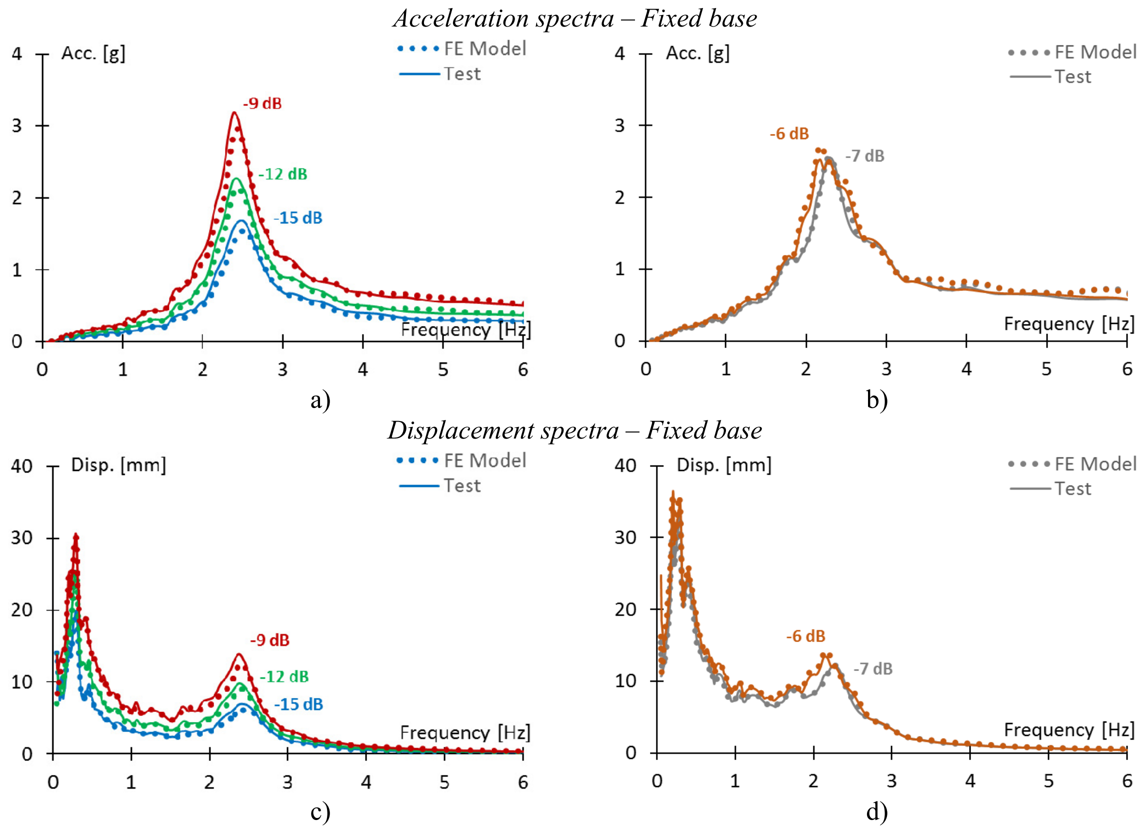

Figure 8: Comparison between numerical and test results in terms of acceleration (a, b) and displacement (c, d) spectra, for all the fixed-base tests.

3 SMALL-DEFLECTION BEHAVIOUR PERFORMANCE – INSIDE PIT

3.1 Identification of the balls roll-out event

To investigate the small-deflection (“inside-pit”) behaviour of the RBRL system, the time histories registered during the tests were truncated such that the steady-state rolling of the balls did not occur, but they merely rocked in the “pits” formed in the rubber tracks due to rubber creep and static load; the maximum displacement of the lower slab (relative to the table) for this to be so was taken to be 5 mm.

Figure 9 presents, for some tests, the table accelerations up to the moment in which the lower slab reached 5 mm of displacement and the related force-displacement loop: the assumption of 5 mm is thus appropriate to capture approximately the threshold of roll-out of the balls from their pits.

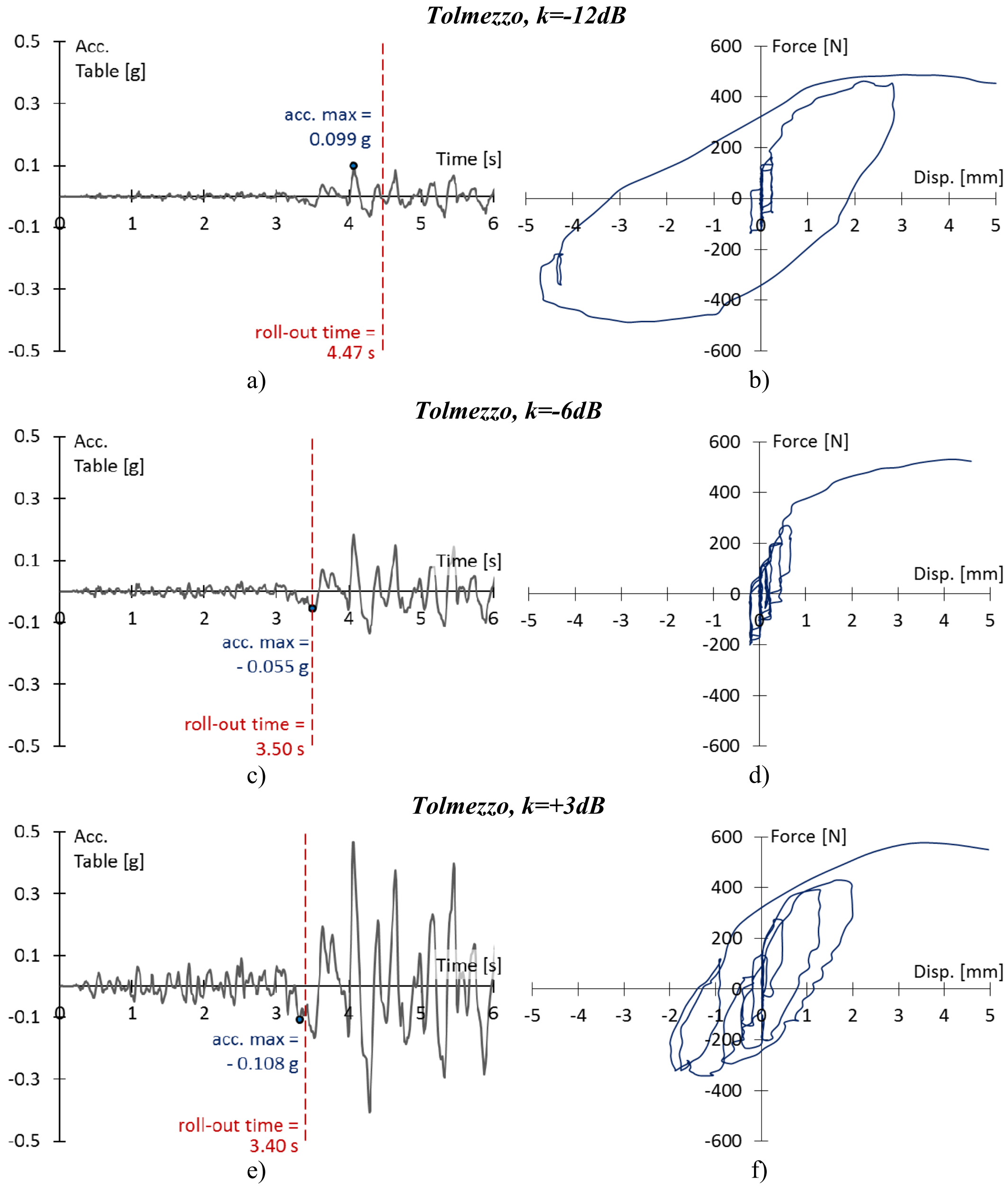

Figure 9: (Left) Table acceleration time series for the first seconds of some tests, with indication of the balls roll-out moment and of the peak acceleration before this moment; (right) related force-displacement loops.

These plots also allow to understand that the increase of seismic intensity not directly implies an increase of the peak acceleration for the oscillation of the balls inside the pits, because the roll-out event of the balls could be quite different due to the high non-linearity of the rocking phenomenon inside the pits (compare the plots of Figure 9 related to the test "Tolmezzo, *k*=-12dB" with those of the other tests: *k*=-6dB, *k*=+3dB).

3.2 Peaks of acceleration and drift: isolated versus non-isolated case

To evaluate the performance of the RBRL system, regarding its "inside-pit" behaviour, the previous calibrated FE model was used to carry out Time-History analyses up to the roll-out of the balls from their pits, with the aim of simulating the behaviour of the model structure with fixed base and to compare it to that with base isolation (from test results).

This comparison is quite interesting considering also that the fixed-base case could represents the behaviour of an equivalent sliding isolation system for excitations insufficient to overcome the static friction.

The measured table accelerations, rather than the command time histories, were used in the OpenSees simulations as seismic input to make the comparison as correct as possible.

The parameters compared in the graphs of Figures 10 are:

- for the real isolated system:

Acc. [g] - *table*: accelerations of the shaking table;
Acc. [g] - *slab_B*: accelerations of the bottom slab;
Acc. [g] - *slab_T*: accelerations of the top slab;
Drift [%] - *Isolated*: drift ratio between the slabs (relative displacement divided by height);

- for the fixed-base numerical model:

Acc. [g]-*slab_T-Fixed:* accelerations of the top slab;
Drift [%] - *Fixed*: drift ratio between the slabs.

For a better comprehension, in Figure 10 are also reported some labels indicating the type of test, through the parameter *k*[dB], related to those results.

For all the earthquakes analysed, the conclusions are the same: the compliance and damping at small deflections of the RBRL system have the great advantage of both changing the mode shape and suppressing excitation of the vibration modes of the isolated structure even for small seismic intensities, in contrast to the case of sliding bearings below their threshold force. For example, looking at the results of the case Northridge_PCKC (Figure 10c), it is possible to note that in case of fixed base and for peak accelerations at the table of 0.1 to 0.15g, the maximum accelerations at the top slab could be in the range 0.25 to 0.35g, due to resonance effects inside the structure: acceleration like these could be dangerous for many works of art; using the RBRL system, instead, these peak accelerations are greatly reduced to between 0.05 and 0.08g. In general, the maximum accelerations measured for both the masses, during the rocking of the balls inside the pits, are less than 0.1g.

The apparent inconsistency of some numerical results, which show a non-linear trend for the top slab acceleration as for the Tolmezzo earthquake, was previously explained looking at Figure 9: in particular, from Figure 9a) it is possible to note that roll-out for the test "Tolmezzo, *k*=-12dB" is postponed by about 1s if compared to the other tests of Tolmezzo; this also has consequences for the related force-displacement plot (Figure 9b), which presents a big loop without many vibrations inside the pit, unlike the other cases.

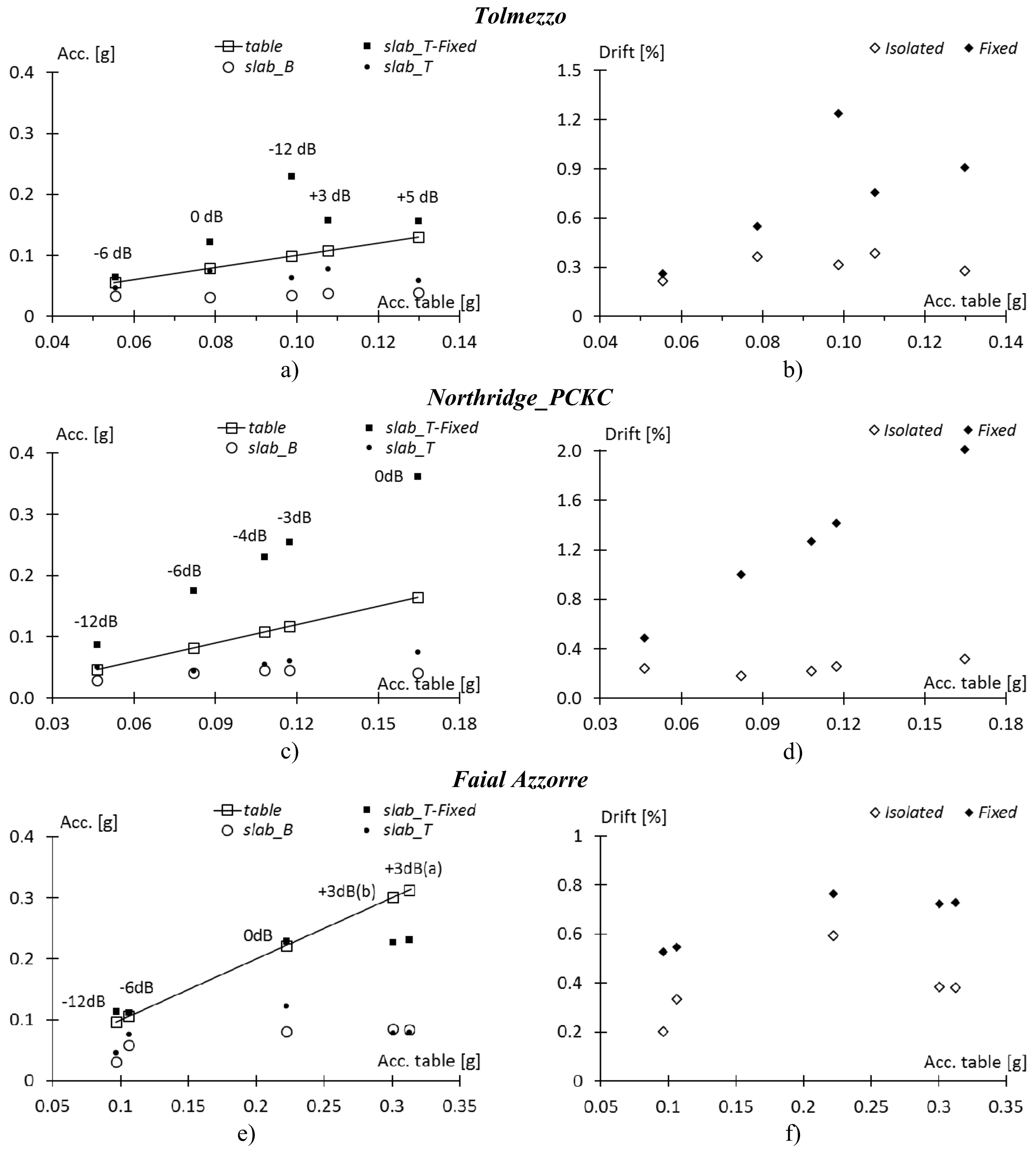

Figure 10: Peak accelerations (left) and drifts (right) for all the tests of Tolmezzo, Northridge_PCKC, Faial Azzorre: “inside-pit” behaviour of the isolated structure (test results) compared to that of the equivalent fixed-base structure (numerical results).

3.3 Acceleration and displacement time-history: isolated versus non-isolated case

In this last section about the performance of the RBRL system at small deflections, some acceleration and drift time series are presented up to the roll-out of the balls from their pits, in particular for two tests of Northridge: k=-6 dB and k=0 dB (see Figure 11).

This representation shows more clearly the effectiveness of the RBRL system when the balls rock inside the pits. Furthermore, it is possible to note a rapid and sudden increase in the values of the numerical results (from the FE model) in the last part of these time series: this is obviously due to quakes of higher intensities, which from that moment will bring the RBRL system to behave like a classic isolation system, involving the steady-state rolling.

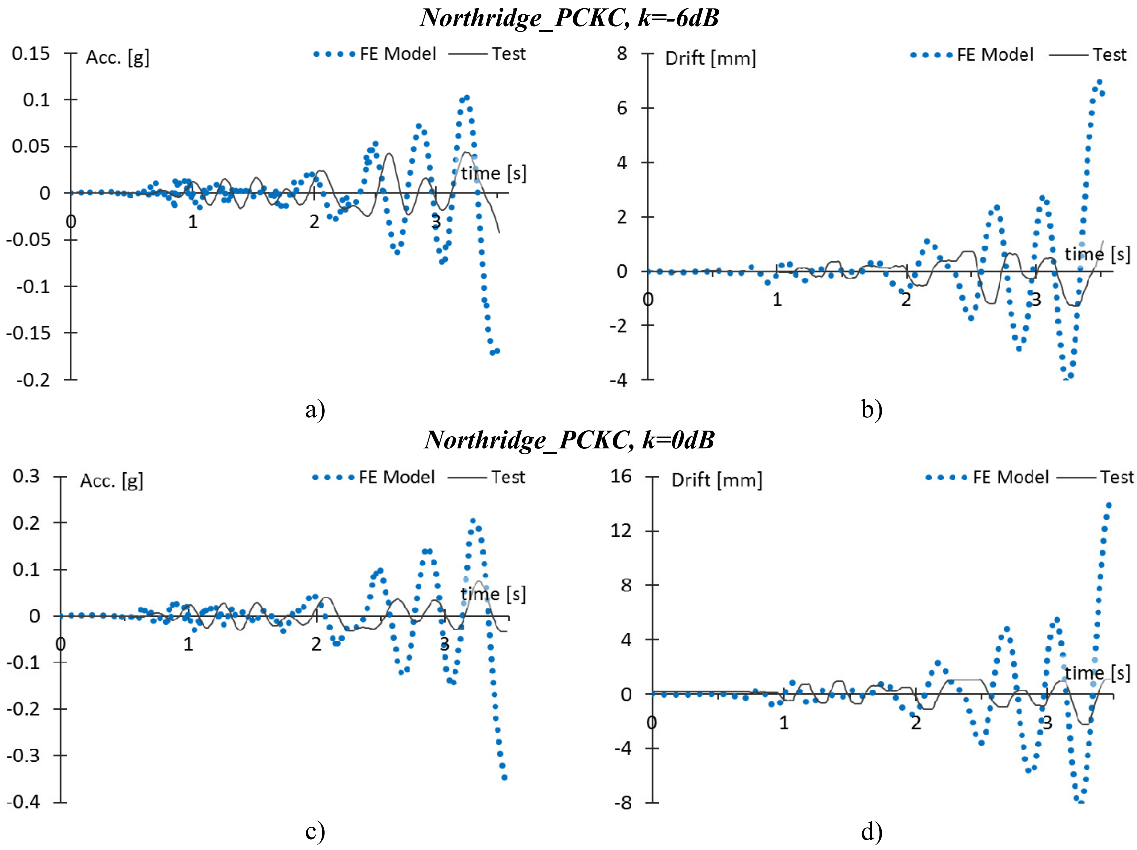

Figure 11: Acceleration (left) and drift (right) time series, up to the roll-out of the balls from their pits, for the tests of Northridge, k=-6, 0 dB: comparison between isolated (Test) and non-isolated (FE Model) case.

4 LARGE-DEFLECTION BEHAVIOUR PERFORMANCE – OVERALL

4.1 Peaks of acceleration and drift: isolated versus non-isolated case

To evaluate the overall performance of the RBRL system, the previous fixed base FE model was used to carry out Time-History analyses providing, as seismic input, the entire accelerogram for the various earthquakes analysed. The measured table accelerations, rather than the command time histories, were used in the OpenSees simulations also in this study, so that to make the comparison as correct as possible.

Therefore, this comparison presents the performance of the RBRL system when it behaves like a classic isolation system, with a well define damping ratio and period of isolation.

The parameters compared in the graphs of Figures 12 are the same as already presented in Figure 10, with the only difference being that the numerical results (fixed-base model) are indicated as labels over the various plots, because of their higher values.

The comparisons in Figure 12 clearly show the great effectiveness of the RBRL system when the balls are induced to roll freely outside the pit. In general, the use of this isolation system keeps the maximum accelerations close to 0.1g for the bottom slab and below 0.15g for the top slab, except for the test of Tolmezzo with the highest seismic intensity (k=+5dB) for which the accelerations slightly exceed these values; at the same time, the maximum drift values are also strongly reduced by using the RBRL system, always remaining below 1%.

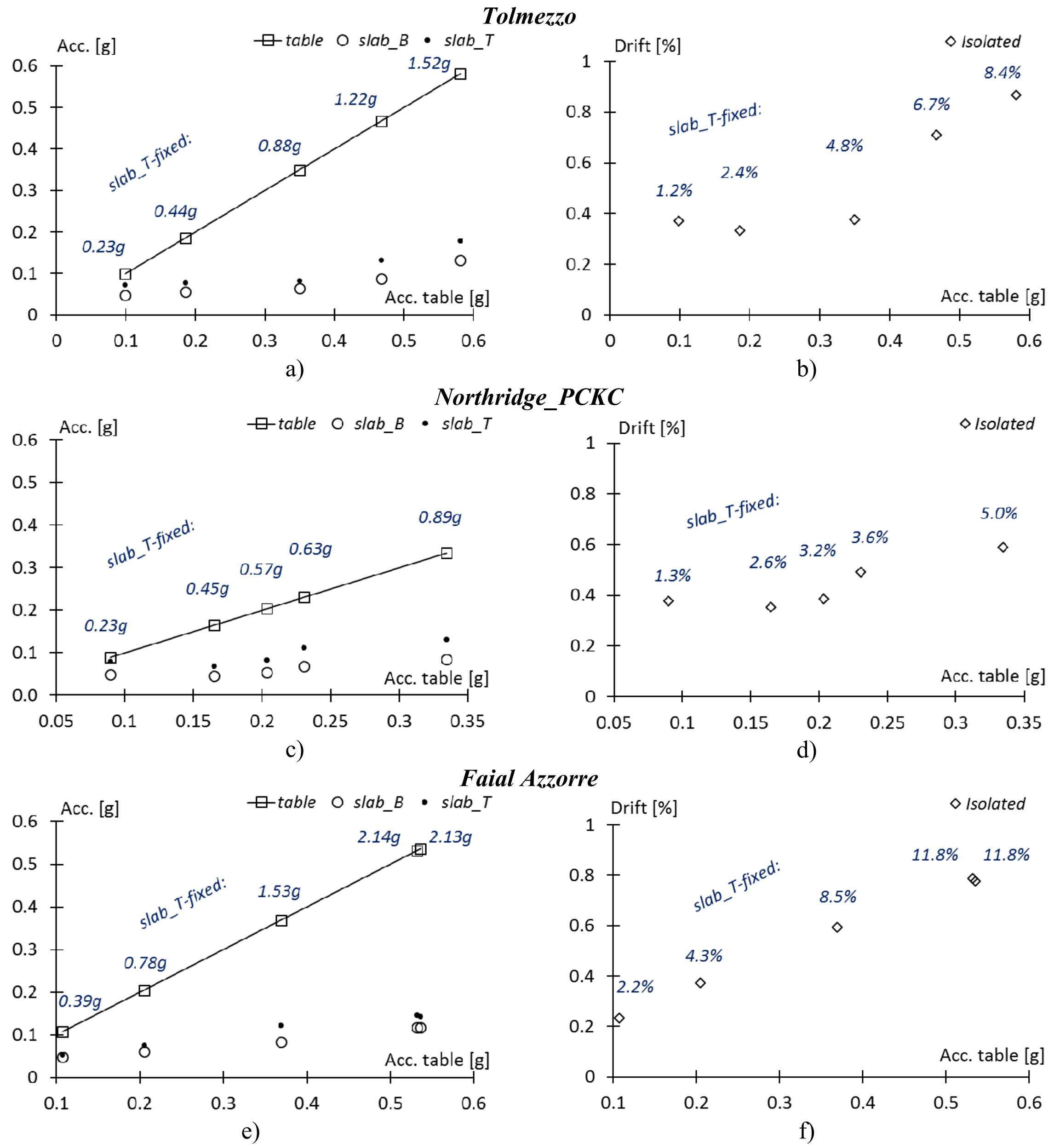

Figure 12: Peak accelerations (left) and drifts (right) for all the tests of Tolmezzo, Northridge_PCKC, Faial Azzorre: overall behaviour of the isolated structure compared to that of the equivalent fixed-base structure.

4.2 Response spectra ratio between isolate and non-isolated case

A simple measure of the effectiveness of an isolation system is the ratio between the peak acceleration values of the isolated and non-isolated structure, with values of this parameter lower than one meaning acceleration reduction.

Values of this ratio were evaluated as a function of the structural frequency and are displayed in Figure 13 for all the tests performed for the earthquake of Tolmezzo and Faial Azzorre. For structural frequencies higher than 0.5 Hz, the isolation system proved to be effective for the cases where $k \geq 0$ dB, with growing efficacy with increasing seismic intensity; for the tests with smaller seismic intensities, where $k < 0$ dB, the system is still effective but with lower performance and above about 1 Hz: this is due to the fact that the accelerations provided to the table in these tests are small or very small if compared to the other tests with $k \geq 0$ dB and thus, even if the absolute accelerations on the isolated structure are still very low, the response spectra ratio between isolated and non-isolated structure is higher. Finally, the efficacy of the system is even more evident looking at the response spectra ratio for the top slab (see Figure 13 b and d).

Figure 14 reports the Fourier transform for the bottom slab acceleration, comparing the inside-pit and overall analyses. From these results, a possible characteristic frequency for the roll-out of the balls from their pits may be identified in the range 3 to 4 Hz. These results are also consistent with those of Figure 13 where, especially for the bottom slab, it is possible to note a reduction in the system efficacy for this range of frequency. However, this does not represent a real problem considering that the cases which are more affected by the phenomenon of balls roll-out are those with smaller seismic intensities (k < 0 dB); in fact, as already explained before, even if the efficacy of the RBRL system is lower in these cases, the absolute

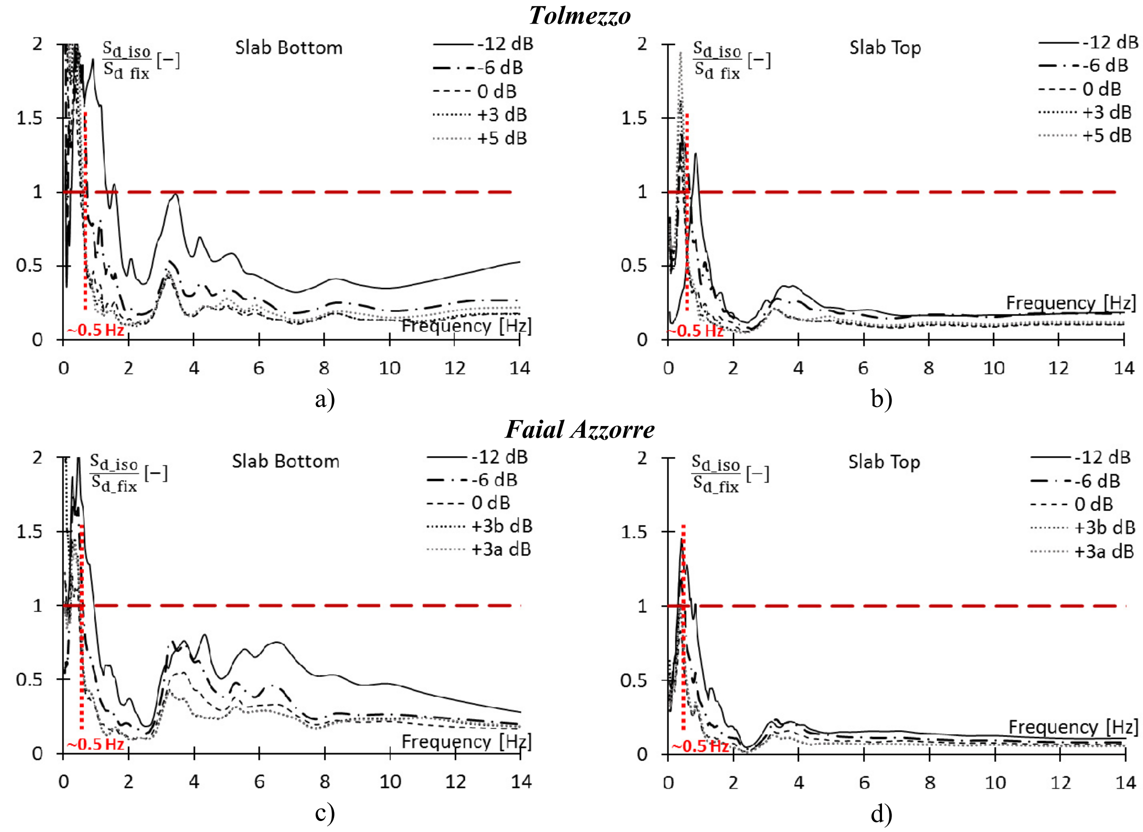

Figure 13: Response spectra ratio between isolated and non-isolated structure for the tests of Tolmezzo and Faial Azzorre: (left) bottom slab, (right) top slab.

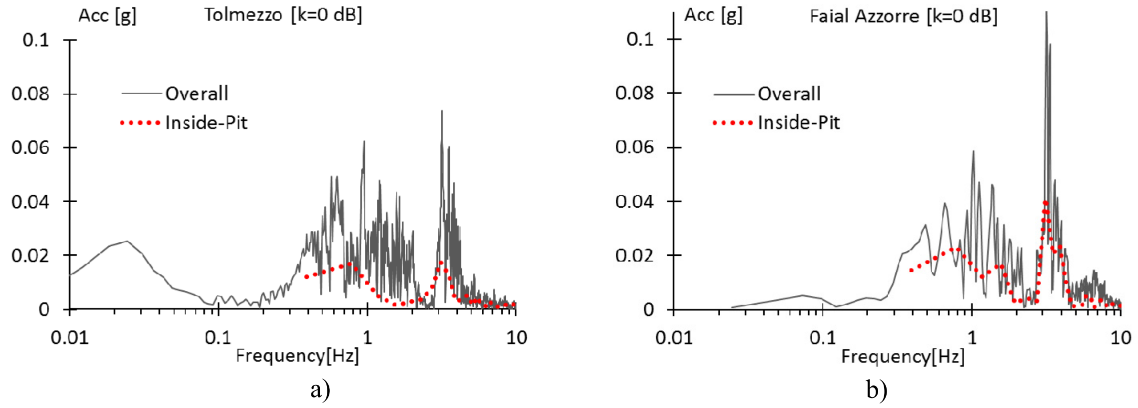

Figure 14: Fourier transform for the bottom slab acceleration: comparison of inside-pit and overall analysis.

accelerations inside the isolated structure are still relatively small. Furthermore, most of the museum items, considering their classic anchoring systems and their small masses, have vibration frequencies which are generally much greater than 3 or 4 Hz (as will be discussed more in detail in a later publication).
Finally, the identification of a "roll-out frequency" could be useful in determining an assessment method to evaluate whether, for a given earthquake, the RBRL system will work in small (inside-pit) or large (free rolling) deflections.

5 CONCLUSIONS

- The paper presented new experimental evidences on the RBRL system behaviour from a previous campaign of shaking-table tests (PSTRBIS ECOEST 2 Project, 1999), related to a superstructure model consisting of two concrete slabs separated by four M16 studs 500mm long, which give a first mode fixed-base response at about 2.5 Hz.
- To assess the behaviour of the RBRL system, a fixed-base FE model was calibrated (in OpenSees) through some shaking-table tests performed without base isolation; the FE model was then implemented in Time-History analyses to compare the behaviour of the isolated structure (from tests) to that of the related non-isolated structure (FE simulation).
- The RBRL isolation system proved to be effective at small deflection (balls rocking inside the pits), performing better than an equivalent sliding isolation system that, for small seismic intensities and up to the threshold force (due to the static friction), behaves like a fixed base. In general, the peak acceleration for both the slabs of the superstructure model, during the rocking of the balls inside the pits, was found to be smaller than 0.1g.
- A good performance of the system was also demonstrated for the steady-state rolling behaviour, i.e. when it behaves like a classic isolation system with a well define damping ratio and period of isolation. In general, using the RBRL system, the peak accelerations could be contained around 0.1g for the bottom slab and below 0.15g for the top slab.
- A characteristic frequency for the roll-out of the balls from the pits was identify to be in the range 3 to 4 Hz.

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