

RESEARCH ARTICLE

Seismic Isolation of Museum Artefacts: Experimental Validation Through Shake Table Tests

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ABSTRACT

Museum artefacts experience significant rocking and may overturn and collapse under moderate-to-large magnitude earthquakes. Use of base isolation (BI) is a viable strategy to enhance the resilience of such artefacts. However, experimental studies aimed at further investigating the effects of ground motion parameters on the response of statues/busts with BI are still scarce. This study illustrates comprehensive shake table tests to demonstrate the efficiency and robustness of double concave curved surface slider isolators (DCCSSs) as viable means to protect museum artistic contents. Different geometries and weights of typical bust-pedestal systems were considered during the tests. Uni- and bi-axial records with varying amplitudes and frequency contents were considered as inputs. Using DCCSS significantly reduces peak accelerations on the isolated platform. Bidirectional input has a weak influence on the response of artefacts with BI. Typical seismological integral parameters were utilized as engineering demand parameters (EDPs) to quantify the seismic response of the BI system. The ratio of integral parameters for isolated platform and shake table is an effective measure to quantify the response of DCCSS. Dynamic modification factors (DMFs) and component amplification factors (CAFs) were also selected as response parameters for isolated and non-isolated components, respectively. For solid systems it was found that values of DMFs are lower than CAFs, which, in turn, are higher typically than 1.5. Ratios of CAF/DMF for hollow systems are higher than solid counterparts. Further numerical investigations are required to validate the reliability of the multiple response parameter analysis illustrated in this study, namely, peak quantities and integral parameters.

1 | Introduction

Recent moderate-to-large earthquakes that occurred globally have caused severe damage to heritage buildings and museum artefacts (e.g., [1–5], among many others). Overturning and collapse of freestanding elements were observed in the aftermath of earthquakes that occurred in the Mediterranean region, i.e. the 2016–2017 Central Italy, the 2017 Kos Island (Greece), the 2020 Zagreb (Croatia) and the 2023 Kahramanmaras (Turkey) seismic sequences. Figure 1 highlights typical damage surveyed in museums where art objects experienced significant and widespread damage, including either overturning or collapse, thus causing

enormous financial and societal losses. Extensive damage to art museum objects, for example, induced by rocking and/or overturning, has been found even in cases of buildings that do not suffer significant structural damage (e.g., [6]).

Based on the evidence collected in technical surveys carried out in regions stricken by severe earthquakes in the last decade, numerous research projects were initiated to assess the viability of using advanced materials and technologies, such as base isolation (BI), active control and/or early-warning systems, to enhance the resilience of museum buildings and their contents (e.g., [7–11])—among many others). Whenever it is possible to



FIGURE 1 | Damage to art objects during recent earthquakes: (a) Archeological Museum in Kos, Greece (21/07/2017 earthquake); (b) Abruzzo National museum, Italy (9/4/2009 earthquake).

isolate the museum building as a whole, this is a preferable option [12, 13]. However, such an approach often represents a complex solution, especially for heritage buildings. Therefore, whenever the above option is not feasible, isolating individual art objects is the most effective seismic protection strategy. Towards this aim, rubber-BI is employed for statues with large masses, while devices that rely on sliding mechanisms are more efficient for lightweight components (e.g., busts, vases and museum displays). Decoupling the motion of artefacts from the floor through BI significantly reduces seismic demand, thus ensuring it remains within acceptable limits for safety and conservation of heritage assets.

A thorough assessment of the state of art of applications of BI worldwide has shown that the use of such technology for lightweight components has been adopted more frequently in regions that are prone to medium-to-high seismicity, namely, Italy (the Bronzes of Riace at the Archeological Museum of Reggio Calabria and three statues at the Opera del Duomo Museum of Orvieto [14], the Bernini's bust in Modena [15], the Ciborium in Spello [16], some marble architectural pieces in the National Roman Museum and many art objects in the MuNDA in L'Aquila [17]), Greece (Statue Hermes at the Archeological Museum Olympia [18]), the United States (Art objects in Getty Museum [19]), Japan (Rodin's 'The Gates of Hell' at the National Museum of Western Art in Tokyo [20]) and China (displays of Quanzhou Museum [21]).

To validate such applications and further investigate the seismic response of statues/busts with BI systems, recent experimental studies were conducted, especially using comprehensive shake table tests. Seminal laboratory dynamic tests on statue-like systems with BI were carried out by [7] to evaluate the efficiency of double concave curved surface slider isolators (DCCSSs). A simplified alternative BI application, relying on low-friction sliding plate isolation system has been tested by [8]; such simplified system is not self-centring, which may limit its application. Shake table tests have also been carried out to validate the efficiency of innovative devices based on a multiple articulated quadrilateral mechanism to enhance the resilience of statues [9]. Recent experiments have been focusing on the isolation of additional museum artefacts, e.g., vases [22]. The review of the state of art also shows that the design of the base isolators for lightweight museum artefacts is not straightforward; indeed, it poses a number of challenges that render such design distinctive from the approach typically employed for buildings and bridges equipped with BI systems.

The assessment of the current state of art has shown that existing approaches and protocols for seismic assessment of nonstructural elements do not easily apply to the case of unanchored artistic elements (ATC/FEMA 461 2007 [23], [24–26]). Such lightweight art objects tends to be sensitive to lower frequencies (e.g., [27]), which are not fully addressed in current testing protocols (ASCE 7–22 [28], EN 15129 [29] and NZSEE 2019 [30]). The reviewed existing standards and guidelines relate predominantly to building structures and anchored elements. Nevertheless, recent proposals have been focused on unanchored rocking-dominated elements (e.g., [31, 32]). As far as the finite element (FE) modelling of isolated bust and statues are concerned, it is found that there is a paucity of parametric numerical studies. It is thus expected that FE simulations should be further developed to generate robust analytical datasets for comprehensive probabilistic seismic assessment.

The discussion above confirms the complexity of characterizing the performance criteria for museum artefacts due to the uniqueness, (often brittle) materials, irregular geometry and uneven mass distribution, type of connection with support(s) and unavoidable restraints of exhibition rooms. It is therefore imperative to further study the seismic vulnerability of museum artefacts, especially slender, human-formed busts and statues, through the dynamic response of rocking rigid blocks, as well as to investigate viable and cost-effective seismic protection measures. Thus, it is still a relevant challenge to evaluate the effectiveness of using BI systems for statues and busts, which are lightweight and unattached components/elements.

In the present study, the efficiency and robustness of DCCSS BI systems to protect museum artistic contents are investigated experimentally through shake table tests. Comprehensive tests were carried out on typical marble busts and pedestals with different weights and slenderness, as arranged into realistic exhibition museum rooms. Such tests utilized historical earthquakes recorded in the Mediterranean regions; the ground motions were scaled at different levels of amplitudes and included both mono- and bi-directional components. Outcomes of such experimental tests, both with and without BI systems, are discussed hereafter.

2 | Research Motivation and Novelties

Extensive dynamic tests were conducted at the Commissariat à l'Énergie Atomique (CEA) laboratory in Saclay, Paris, utilising

TABLE 1 | Definitions of integral parameters.

ID	Name	Definition
I_A	Arias Intensity [35]	$I_A = \frac{\pi}{2g} \int_0^{\infty} [a(t)]^2 dt$
ASI_m	Acceleration Spectrum Intensity modified	$ASI_m = \int_{0.1}^{T^*} S_a(\xi = 0.05, T) dT$
HI	Housner Intensity [36]	$HI = \int_{0.1}^{2.5} PSV(\xi = 0.05, T) dT$

the Azalee 6-DOF shake table, [33]. These tests were funded by the European H2020 SERA (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe) project ‘SEismic REsilience of Museum contEnts—SEREME’, a collaborative research project between a consortium of University and Industrial partners (FIP MEC and Fallani Group, from Italy).

The objectives of the comprehensive experimental SEREME shake table tests were:

- Investigation of rocking motion of free-standing museum objects (as also further discussed in [27]).
- Evaluation the efficiency of existing seismic mitigation systems.
- Formulation of design guidelines for risk and cultural heritage managers.

The study encompasses a range of specimen geometries and weights, subjected to uni- and biaxial earthquake records with varying amplitudes and frequency contents.

Shake table tests are employed to assess the efficiency of bespoke isolation devices in reducing rocking risk in lightweight/unanchored elements. The outcomes of the tests will also contribute to the development of robust code provisions for designing seismic mitigation strategies and calibrating numerical models for comprehensive FE parametric analyses.

The motivations of the present study address the following research questions:

- What is the effect of strong motion amplitude, frequency contents and directionality on efficiency of BI to protect artefacts, as evidenced through shake table tests?
- Is it viable to extend seismological integral parameters to quantify effects of BI on earthquake response of artefacts?
- What are the dynamic modification factors (DMFs) for base isolated artefacts?

The response analysis carried out during dynamic tests was based on peak accelerations of seismic inputs measured on shake table, isolated platform and along the specimen height, respectively. Additionally, integral quantities, as summarized in Table 1, were utilized as intensity measures (IMs) as well as engineering demand parameters (EDPs) to quantify the dynamic response of the isolation system. Such an approach is an extension of previous work carried out by [34], which focuses primarily on

the characterization of floor motions for damage estimation of acceleration-sensitive non-structural components.

To define the integration limits of the integral quantities in Table 1, reference was made to intervals of period of vibration for isolators used in the case studies. The definition of Acceleration Spectrum Intensity (ASI) [37] has been extended by increasing the upper limit to $T^* = 2.5$ s, thus to match the integration limits adopted by Housner intensity (HI). Such quantity has been labelled as ‘Acceleration Spectrum Intensity modified (ASI_m)’. It is observed that $T^* = 2.5$ s is consistent with both the estimated equivalent periods of the isolation system. Such periods correspond to the maximum horizontal displacement recorded during the shake table tests ($\bar{T} = 2.21$ s, see Section 5.1.1) and with the equivalent period corresponding to the maximum isolator stroke ($T = 2.70$ s, see Section 4). For practical applications, the value of T^* for the upper integration limit of ASI_m will depend on the characteristics of isolators and seismic inputs.

For sake of clarity, it worth mentioning that the testing program presented herein is not a component qualification, but it investigates the earthquake performance of both base isolators and unanchored museum artefacts on pedestals, thus, natural records were selected as appropriate inputs for experimental analyses.

3 | Experimental Program

3.1 | Description

The comprehensive experimental tests conducted on the AZALEE 6-DOFs shaking table at the CEA facility (size 2.3×2.3 m, frequency range 0–100 Hz) include full-scale busts and statues made of solid marble, with different geometry and weights. They are human-form sculptures representing ancient Roman emperors’ busts and typical statues with female figures. To replicate realistic exhibition conditions, the busts were placed on three types of pedestals at eye level. The pedestals include solid and hollow concrete support—both designed to simulate the ordinary weight of marble support—plus a metallic one. The artefacts were initially surveyed via laser scanner (Faro Focus 3D Cam2.51) to create accurate 3D digital models. Such models were used to evaluate mass and geometrical properties, plus implement an FE model for parametric analyses.

To simulate realistic friction conditions, 3-cm-thick marble slabs were fixed to the concrete pedestals. Both isolated and non-isolated specimens were placed directly on a 3-cm-thick marble floor surface.

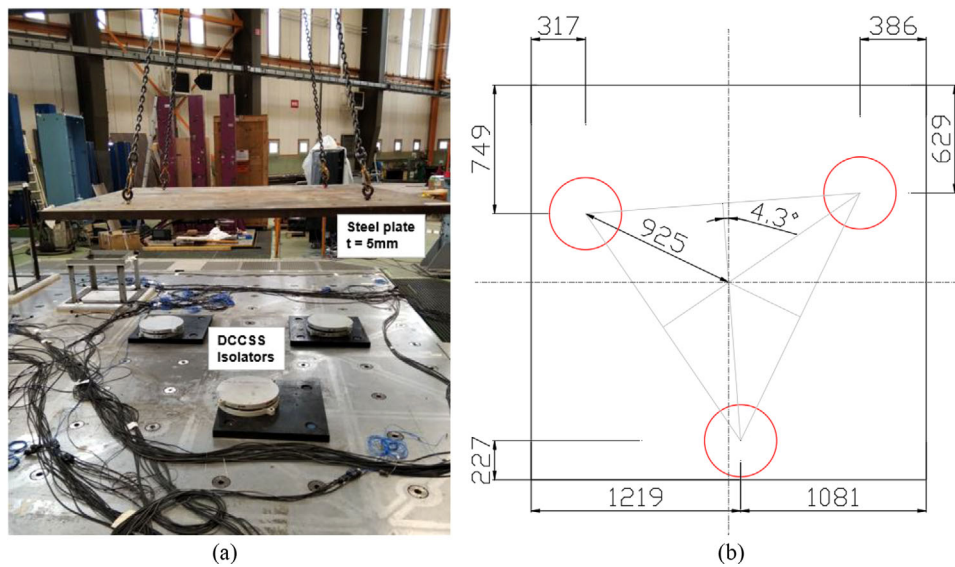


FIGURE 2 | Isolation system with three DCCSS isolation devices: (a) installation phase, (b) plan of the steel plate with device location (mm).

TABLE 2 | Geometry and weight of the elements above the isolation system.

	Busts	Solid pedestal	Hollow pedestal	Marble floor surface	Steel plate
Dimensions (cm)	60 × 30 × 82*	45 × 45 × 101	35 × 35 × 101 ($t = 8$)	110 × 110 × 3	230 × 230 × 5
Weight (kN)	~1.10	5.113	2.812	0.928	20.357

* = maximum dimensions.

Two BI systems, specifically designed for low-mass objects, were tested through a shake table: a DCCSS isolation system and a sliding isolator utilizing shape memory alloy (SMA) wires to control displacements and with re-centring capacities. In the DCCSS isolation system, a heavy steel plate (in the following named ‘isolated plate’) was installed on three isolator devices (Figure 2), and art objects were placed symmetrically on the same platform. Such configuration ensures uniform vertical forces on each device, and by increasing the weights, the friction coefficient is reduced (see Section 4).

Seven configurations were tested in more than 400 shake table tests, with accelerations ranging between 0.15 and 0.49 g and frequency content varying between 0.65 and 6.00 Hz. Each configuration includes multiple pairs of similar artefacts, with and without isolation, tested simultaneously.

The present study focuses on the configuration shown in Figure 3a. It investigates the dynamic response of the unanchored bust/pedestal system with and without DCCSS isolation devices considering two types (solid and hollow) of concrete pedestals. The geometry and weight of the sample specimens are reported in Table 2. For further details on the isolator device, see Figure 8.

A refined monitoring system was installed, including sensors on the specimens, the isolated plate and the shaking table. Their motion was recorded during the shake table tests using PCB accelerometers (ACC) for all elements (max acceleration 30 g); FGP500 displacement sensors were additionally installed on the

table and on the isolated plate (500 mm stroke), and the recording system was further complemented by LVDT displacement sensors for non-isolated pedestals and statues (50 mm stroke) and gyroscopes for all non-isolated specimens (velocity range $\pm 200^\circ/\text{s}$ for pedestals, $300^\circ/\text{s}$ for busts). In addition, a dedicated close-up video recording system was integrated into the monitoring system. All experimental data were recorded at a 512 Hz sampling rate with a 150 Hz low-pass filter. The instrumentation location for isolated specimens of case study configuration is shown in Figure 3b. Further details about the experimental tests can be found in [27].

3.2 | Seismic Input Motions

The experimental shake table tests included seismic input motions with various frequency contents and single and multiple components of accelerograms (uni-, bi- and triaxial). Four strong motions were considered; time histories represented historical near-field earthquakes that occurred either in Greece or in Italy: Emilia—T0800 station, Italy 2012 (L: PGA 0.33 g, T: PGA 0.25 g, M_w 6.0); Kalamata—Nomarchia station, Greece, 1986 (PGA 0.22 g, M_w 6.2); Athens—Syntagma Metro B station, Greece, 1999 (PGA 0.11 g, M_w 5.9) and L’Aquila—Aterno river-AQA station, Italy, 2009 (PGA 0.45 g, M_w 6.3) where PGA is the peak ground acceleration, L is the longitudinal component, T is the transverse component and M_w is the moment magnitude. Detailed ground motion characterization of the sample strong motions can be found in [27]. As discussed in [27], such motions were selected to cover a wide frequency spectrum. Furthermore, Kalamata record

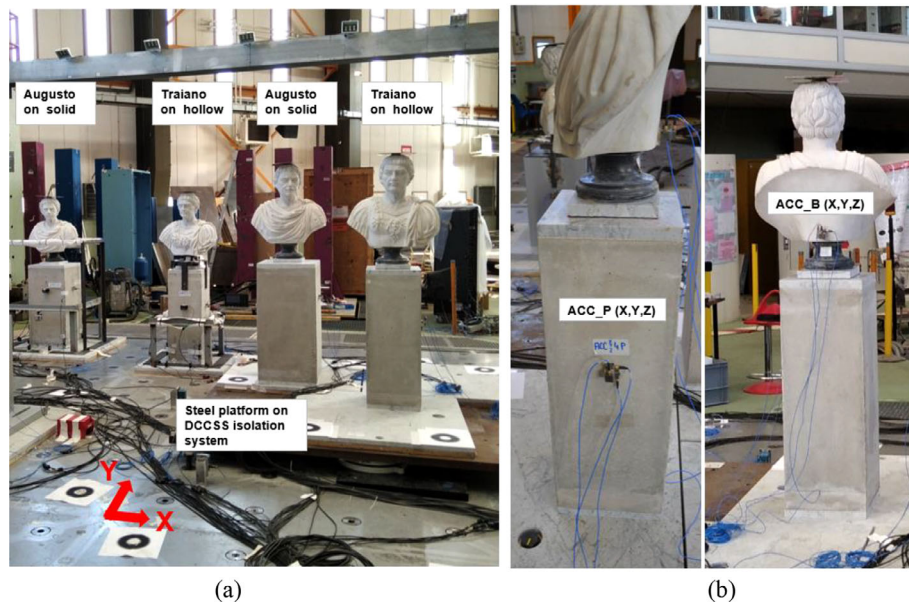


FIGURE 3 | (a) Test configuration on the shake table, (b) instrumentation location on the isolated artistic assets.

TABLE 3 | Properties of seismic input motions and test matrix for shake table configuration presented in the study.

Sample input motion (label)	Seismic strong motion	Input ID test (label)	PTA (g)	Scaling factor	I_A (m/s)	HI (cm)	ASI_m (g s)
Emilia	Emilia L in X-direction (Emilia-L_X)	401_EM_X	0.24	0.71	0.316	41.9	0.336
		402_EM_X	0.34	1.02	0.504	66.1	0.496
		407_EM_X	0.41	1.22	1.015	92.2	0.696
		412_EM_X	0.47	1.38	1.312	105.4	0.806
Emilia-XY	Emilia L in X-direction + Emilia T in Y-direction	413_EM_XY	0.22	0.66	0.257	41.6	0.360
			0.12	0.49	0.131	24.5	0.232
		414_EM_XY	0.34	1.00	0.538	67.2	0.564
Syntagma	Athens L in X-direction (Athens -L_X)		0.25	1.00	0.321	39.96	0.372
		427_SYN_X	0.20	1.88	0.182	39.6	0.321
		428_SYN_X	0.29	2.67	0.393	64.7	0.511
		429_SYN_X	0.43	3.95	0.751	90.4	0.715
Aquila	L'Aquila L in X-direction (L'Aquila-L_X)	445_SYN_X	0.47	4.36	0.958	102.5	0.811
		437_AQ_X	0.22	0.49	0.355	35.4	0.348
		438_AQ_X	0.27	0.61	0.609	48.9	0.479
		439_AQ_X	0.33	0.74	0.780	55.3	0.541
Kalamata	Kalamata L in X-direction (Kalamata-L_X)	441_AQ_X	0.35	0.78	0.996	62.4	0.614
		424_KAL_X	0.15	0.68	0.328	85.3	0.472
		425_KAL_X	0.26	1.18	0.764	140.7	0.764
		426_KAL_X	0.29	1.32	1.029	168.3	0.918

exhibits low frequencies with the peaks in the range 0.8–2.5 Hz. Additionally, the constant values of the displacement response spectra of the sample strong motions are consistent with the period T^* , as defined in Section 2.

The ensemble of natural strong motions illustrated above was used as a benchmark during the comprehensive shake table tests. Each seismic record was scaled to multiple intensity levels for

incremental experimental tests aimed at response analyses of artefacts. The present study focuses on the case study configuration of the SEREME test programme considered herein. Such a configuration includes a subset of 17 experimental tests, as also illustrated in Table 3.

The performance of the artefacts and the isolation system was investigated at different levels of acceleration. The scaling factors

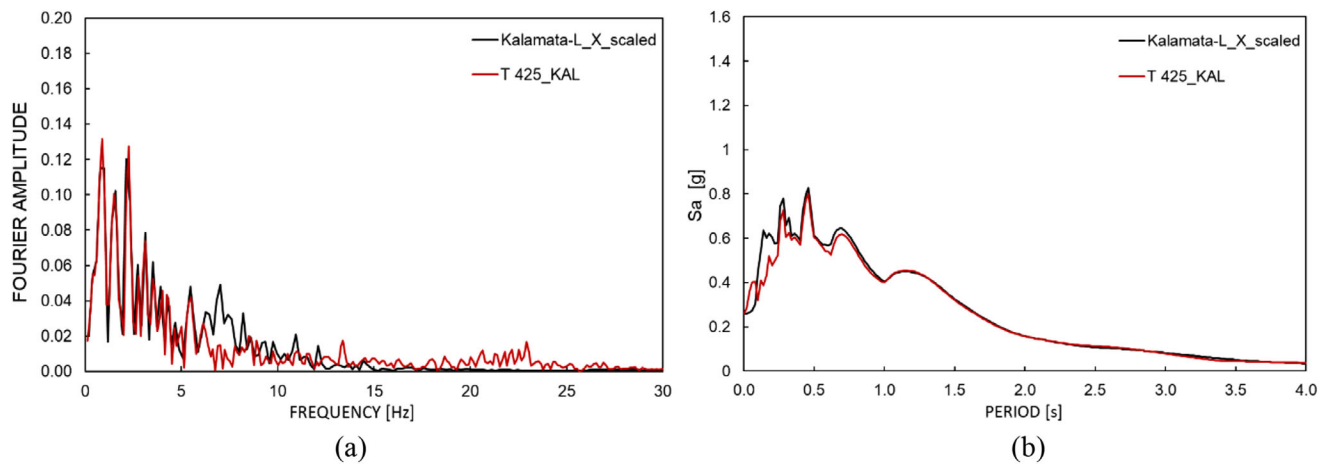


FIGURE 4 | Typical sample ground motion as simulated through shake table—test 425_KAL, PGA = 0.26 g: (a) Fast Fourier Transform, (b) acceleration response spectra.

used for the ground motions vary between 0.49 (for 437_AQ_X and 413_EM_XY-Y direction) and 4.36 for 445_SYN_X), as also shown in Table 3, which are acceptable for the target of the present study. Nevertheless, to compare results of the tests carried out with strong motion of the natural records at increasing levels of acceleration, it is worth investigating the reproducibility of the input motions on shake table at incremental levels of input for the range of frequency of interest for the specimens. As far as the frequency content is concerned, the analysis of the sample suite of signals recorded on the shake table shows that the table tends to increase high frequencies in the strong motion time history. For example, Figure 4 provides the comparisons between the Fast Fourier Transform (FFT) and acceleration response spectra of the natural record and the one reproduced on the shake table for the case of Kalamata earthquake (425_KAL).

For further investigations on the reproducibility of the input motion of the shake table at different intensity, it is also relevant to compare the ratio of the signal on the table and the scaled target signal. Figure 5a shows the variation of such ratios as a function of the period of vibration. The upper bound of T ($\bar{T} = 2.21$ s) is also included in the plot, as it corresponds to the equivalent period of the isolation system for the maximum horizontal displacement recorded during the experimental tests (see Section 5.1.1). It is evident that the matching of the target and simulated motions is less accurate at low periods (lower than 0.25 s). Such mismatch, however, does not significantly alter the response of the specimens with BI systems within the range of periods of interest, as further discussed herein. Additionally, Figure 5b displays the mean and confidence levels for the selected inputs of the ratio between the spectral acceleration recorded on the table and the counterpart for the scaled strong motion, computed over the range of period 0–2.5 s. Mean values range between 0.85 and 1.05, with the largest and smallest standard deviations computed for Aquila_441 and Emilia_412, respectively. The upper and lower bounds that define the maximum and minimum values of each seismic test have also been marked.

Integral response quantities for input motions, as introduced in Section 2, were also computed. They provide further insights into the reproducibility of the strong motions. Figure 6 shows the ratios of such quantities for the shake table and input motions

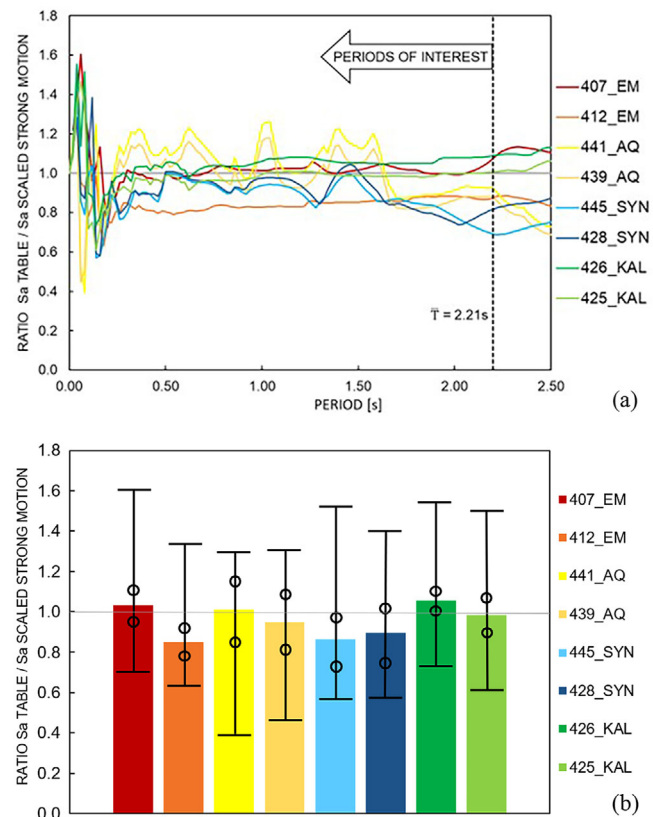


FIGURE 5 | Ratio of spectral acceleration between table and scaled input strong motions: (a) variation with the period T of vibration (b) mean values $\pm$ standard deviations, minimum and maximum values in the period range 0.0–2.5 s.

for the sample records. Housner intensity gives rise to the best response, with maximum dispersion of about 20%.

A similar analysis was performed for bidirectional input motions. In Figure 7 the results for 414_EM_XY (bidirectional input) are compared to those obtained for 402_EM (monodirectional input). Such input motions have similar peak table acceleration (PTA) in the X-direction (0.337 g and 0.343 g, respectively); thus, their comparison is appropriate and useful for input characterization

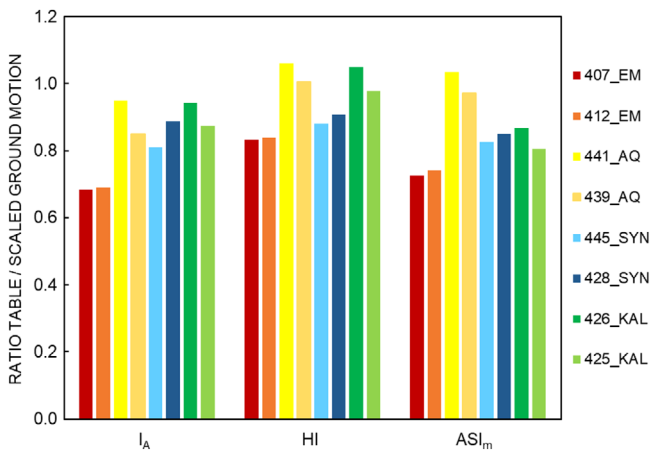


FIGURE 6 | Ratio of integral parameters between table and scaled ground motions.

when evaluating the dynamic response of specimens. Figure 7a presents mean and confidence levels of the ratio of spectral accelerations on the table and scaled counterparts. The latter ratios are computed for periods ranging between 0 and 2.5 s. Mean values are significantly lower than the corresponding values in Figure 5; however, they are more uniformly distributed, ranging from 0.73 to 0.76.

Figure 7b shows the integral response quantities for the input motions. HI is the quantity with least dispersions, thus appearing the most appropriate to utilize for response analysis. Furthermore, X- and Y-components of bidirectional test 414_EM_XY have the same scaling factor (see Table 3). Such components have similar ratios of table-to-scaled reference input for integral quantities.

The present study focuses primarily on the comparison of the response of isolated and non-isolated artefacts through natural ground strong motions with varying frequency contents and increasing PGAs; thus, minor mismatches computed when repro-

ducing the original seismic records are beyond the scope of the present work.

4 | Seismic Isolation Devices: Mechanical Characterization

The three seismic isolators, supporting the steel plate and the art objects (Figures 2 and 3), are DCCSS (Figure 8), according to the definition of the European Standard on Anti-seismic devices EN 15129:2009 [28]. These devices are suitable for seismic isolation of components with light mass; the effective period does not depend on the mass itself, as for elastomeric bearings.

The effective period T_e at a given displacement is given by:

$$T_e = 2\pi \sqrt{\frac{1}{g \left(\frac{1}{R} + \frac{\mu}{d} \right)}} \quad (1)$$

where g is the acceleration of gravity, R is the radius of curvature, μ is the coefficient of friction and d is the displacement. The restoring period, corresponding to the restoring stiffness, that is, the period of the simple pendulum with length equal to the radius of curvature, is as follows:

$$T_r = 2\pi \sqrt{\frac{R}{g}} \quad (2)$$

The equivalent radius of curvature of the isolators used in SEREME experimental programme is 2.5 m. The allowable displacement is ± 300 mm, and the vertical load capacity is 20 kN. It is worth noting that the displacement capacity of the sample devices is much larger than needed for the tests discussed in this study; the isolators were designed and manufactured to accommodate even larger earthquake-induced deformation demands for safety issues related to the shake table facility. The design of isolators is based on European Standard on Anti-seismic Devices EN 15129:2009 [28]. Some minor modifications in the

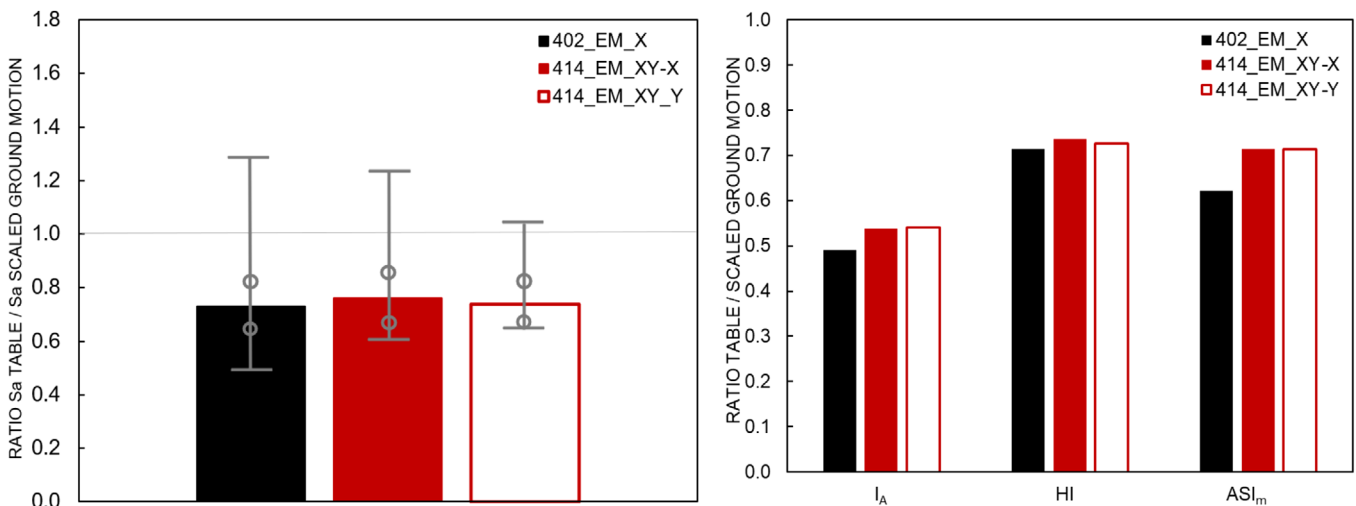


FIGURE 7 | Ratio of spectral acceleration between table and scaled ground motions 402_EM and 414_EM: (a) mean values $\pm$ standard deviations, minimum and maximum values in the period range 0.0–2.5 s; (b) integral parameters.

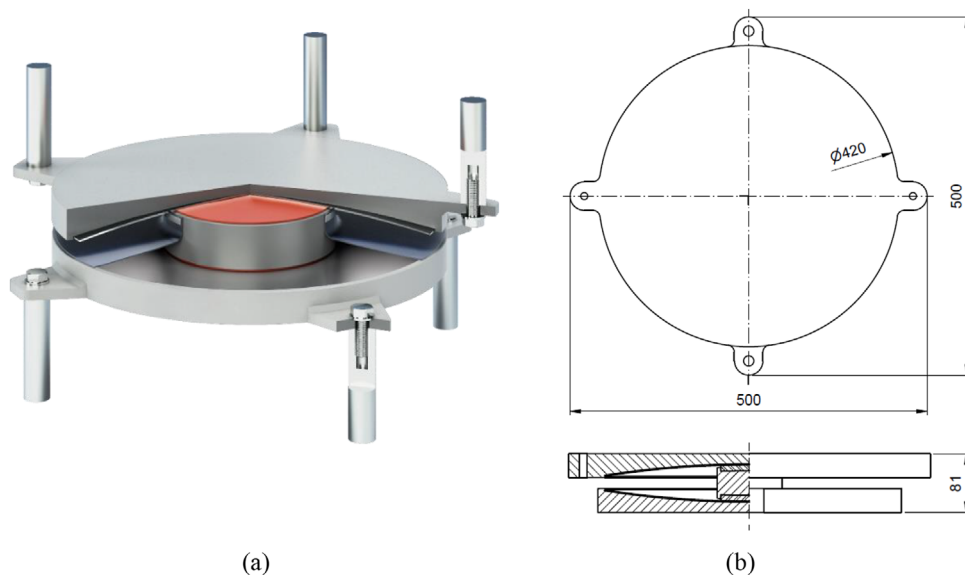


FIGURE 8 | DCCSS isolation device (a) 3D view, (b) geometrical layout (mm) (courtesy of FIP MEC).

design were introduced to account for the low weight supported by each isolator, which also dictated the small geometry of the device itself. The European Standard EN 15129:2009 refers merely to the design of isolators for large structures, such as buildings, bridges, etc.

The small weight acting on each isolator also renders the qualification test of the device a challenging task. Full-scale dynamic testing of isolators is explicitly required by standards to characterize the hysteretic behaviour and verify the loading-bearing capacity. Detailed preliminary experimental characterization of the isolators before shaking table tests was deemed essential for a better understanding of the test results. However, current testing rigs available in many structural laboratories worldwide are too large for the size of DCCSSs used for seismic isolation of artistic objects, as also used in the present study. It was thus necessary to develop a bespoke testing method to account for small horizontal forces. A specific testing rig was designed and built to test three devices simultaneously, installed between an upper and a lower plate. The upper plate is used for the application of the weight for each test: depending on the vertical load test requirements, steel plates above are added or removed. The lower plate is positioned on top of a sliding surface and is connected to an actuator able to impose the desired horizontal movement. This testing rig behaves like a small shaking table. The horizontal force of the isolators is measured as inertia force through a 3-axis accelerometer placed on the upper plate. The isolators' displacement is measured through displacement transducers placed on each side of both the lower and upper plates.

The characterization tests were first performed by applying to the lower plate five cycles of sinusoidal displacement with two values of maximum velocity, that is, 297 and 396 mm/s, an amplitude of ± 100 mm, and two values of weight W (29.43 and 39.24 kN—which define the limits of the weight range for the various objects tested) to check possible variation of friction coefficient with weight and velocity. The testing protocol is inspired by the European Standard EN 15129:2009, even though it is simplified.

Figure 9a shows the results of the hysteresis of two tests at the two values of weight and the comparison with the theoretical restoring stiffness W/R ('Mechanical model') as in [38]. The displacement is not constant in the different cycles as it would have happened in a normal testing rig, where the displacement is directly applied to the isolator through horizontal actuators. In Figure 9a it is also evident, in accordance with the fundamental mechanism of DCCSS, that the shape of the hysteretic curve changes with the load: both the friction force and the restoring stiffness are directly proportional to the weight acting on the isolators. The measured value of the friction coefficient does not depend significantly on the velocity in the range considered and slightly depends on the weight: the average value is 4.6% for the weight of 29.43 kN and 4.35% for the weight of 39.24 kN. For the weight of the configuration described in this study, for example, 32.37 kN, an average value of 4.53% can be calculated with linear interpolation.

The testing rig used for characterization tests was also used to apply displacement time histories corresponding to a couple of the acceleration records selected for the testing campaign (see Section 3.2), for example, Emilia and L'Aquila. The aim of these additional tests is mainly a comparison with the sinusoidal tests and a preliminary check of the effectiveness of the isolators when subjected to the above-mentioned strong motions. Figure 9b shows a comparison of the hysteretic curve of the isolators measured with sinusoidal characterization tests and time history tests. Both earthquakes have higher energy content at high frequencies and low energy content at low frequencies; consequently, the displacement is very small, much lower than the one applied with the sinusoidal characterization tests. The acceleration (force) peaks measured during these time history tests show the difficulty in reproducing such signals.

5 | Discussion of the Experimental Results

The section below presents the results of experimental tests carried out with uniaxial and biaxial input motions.

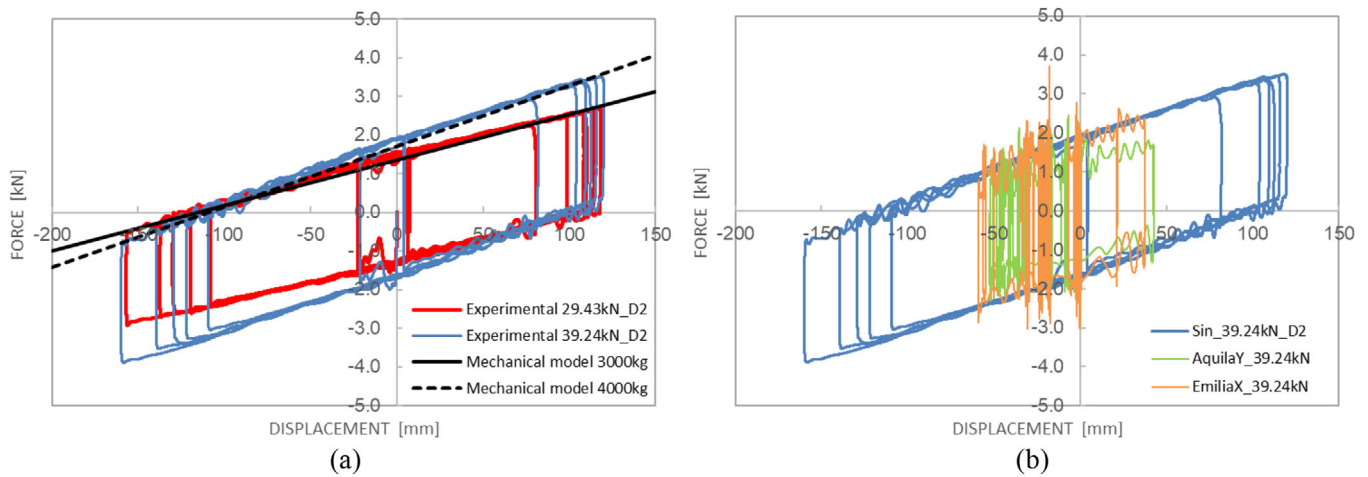


FIGURE 9 | Experimental force-displacement response curves: (a) sinusoidal tests with maximum velocity 396 mm/s and weight 29.43 and 39.24 kN; (b) tests with 39.24 kN with sinusoidal input, Emilia X and Aquila Y.

5.1 | Unidirectional Tests

5.1.1 | Time History and Spectral Response

The response of the isolator system to uniaxial input motion is discussed by comparing the acceleration signal on the shake table with the correspondent on the isolated platform. Figure 10a–d displays such a comparison for two input motions characterized by different frequency contents, that is, Emilia and Kalamata. For both input motions the signals with the highest accelerations are considered (i.e., 412_EM_X with PTA = 0.47 g and 426_KAL_X with PTA = 0.29 g).

As per Figure 10a,b, isolators effectively decouple the motion between the table and the isolated platform, leading to a relevant reduction of the acceleration experienced by the table for both Emilia and Kalamata records. This reduction is approximately 80% for 412_EM and 60% for 426_KAL, respectively. As observed in Berto et al. (2023) [27], the Emilia signal is characterized by two shocks, the 1st one between 9 and 11 s with a peak of acceleration of 0.27 g and the 2nd one starting from 11 s with a peak of acceleration of 0.47 g. Consequently, isolators were activated twice, in accordance with the two shocks, as shown in the displacement time histories (Figure 10e). The most pronounced effects were observed during the second shock.

Figure 10c,d shows the reduction of FFT peaks of acceleration between the table and isolated platform, especially for frequencies higher than 1 Hz, confirming the performance of the seismic isolation system. According to the lower predominant frequencies of the Kalamata record than the Emilia one, Kalamata is more displacement demanding. As shown in Figure 10e,f, 426_KAL, with a 40% lower PTA than 412_EM, exhibited a nearly 40% greater displacement due to the different frequency content.

Table 4 reports for all the considered 1D signals the PTA values, the values of the maximum acceleration on the isolated platform (named ‘PIA’ hereafter) and the maximum displacement of the isolated platform ($\text{Disp}_{\max}$). With the exception of Emilia 412, where the isolated platform acceleration reaches 0.25 g, the acceleration above the isolation devices ranges between 0.12 g

and 0.18 g for all other cases. The out-of-range value for 412_EM occurs at 9.4 s (at the first shock of the signal), concurrently to the first activation of the device with a negligible displacement value, as visible in Figure 10a,e. Table 4 further provides the occurrence time of the maximum acceleration. A significant time gap is observed between the occurrence of PTA and PIA. Indeed, PIA was recorded before the occurrence of the maximum acceleration on the shake table. Such a result may be relevant to formulate robust active risk mitigation techniques for seismic protection of museum contents.

The values of PIA are also reported in Figure 11, as a function of PTA. In this figure such values are represented by solid markers and compared with the values of the maximum acceleration on the isolated platform (PIA*) after the occurrence of the maximum acceleration on the shaking table, represented by empty markers.

It is worth noting that PIA values are relevant for the evaluation of the seismic vulnerability of artefacts since they represent the maximum acceleration transmitted by the isolators. Nonetheless, PIA* values are also significant as they allow the quantification of the actual acceleration reduction. Such reduction, for PTA exceeding 0.25 g, is at least approximately $\frac{2}{3}$, leading, for the considered case studies, to acceleration at the base of artefacts in the range 0.08–0.12 g. The results in the figure also clearly demonstrate that PIA is always minor than its PTA counterpart.

As far as the maximum displacement of the isolated platform ($\text{Disp}_{\max}$ of Table 4) is concerned, it is evident its strong dependence on the frequency content of the seismic signals (see Section 3.2). The results also confirm that Kalamata represents the most demanding displacement record among all those analysed. Furthermore, a trend of increasing displacement with increasing PTA for a given input motion is also observable. Such a trend is also visible in Figure 12, where displacement time histories of two sample inputs (i.e., Syntagma and Emilia) at increasing levels of acceleration are shown. Discrepancies from this trend can be ascribed to the imperfect reproduction of the signals on the shake table (see Section 3), leading to slightly different frequency content of signals from repeated tests of the same sample input motion.

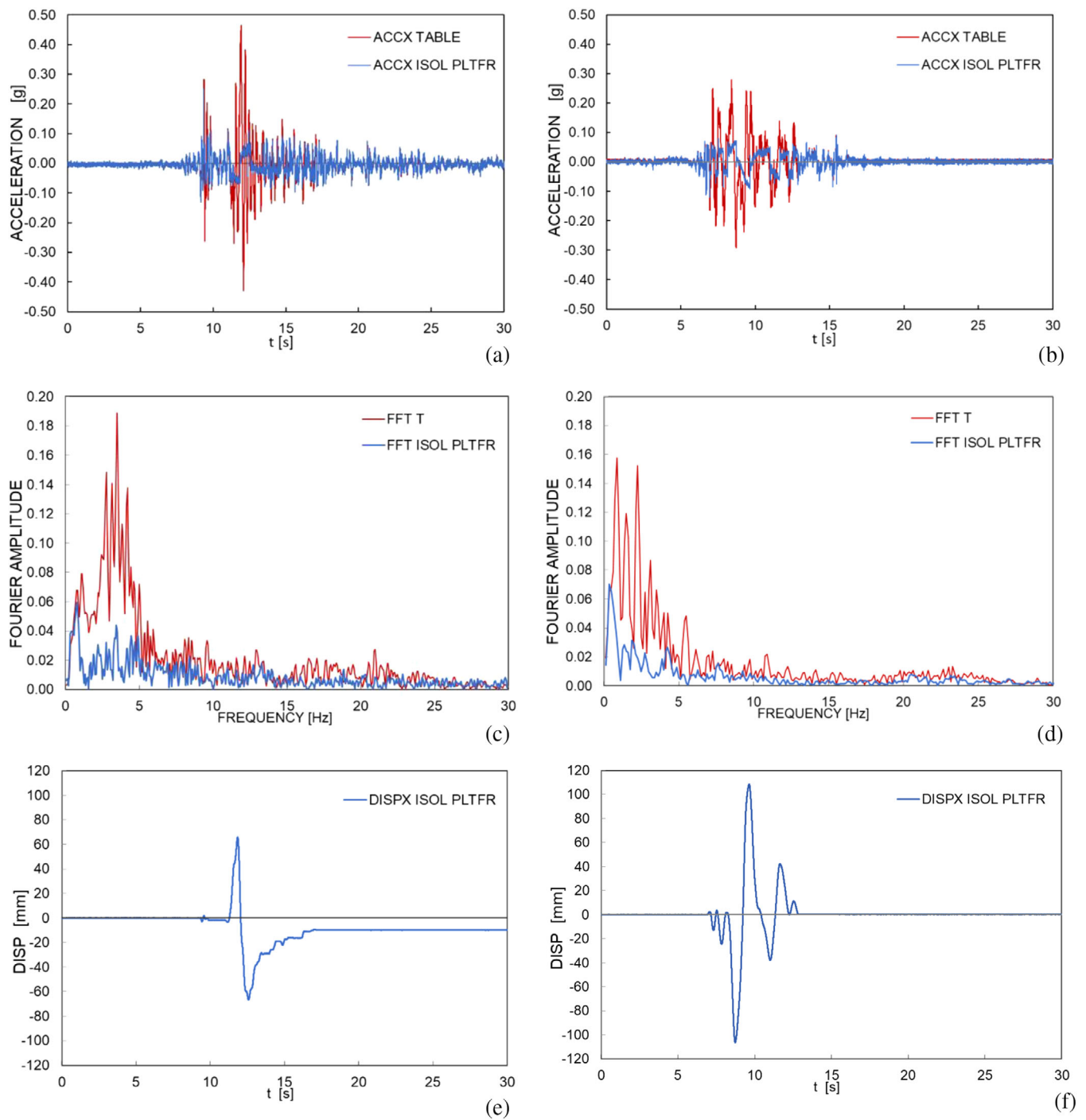


FIGURE 10 | Response of table (T) and isolated platform (ISOL PLTFR) subjected to 412_EM_X (left) and 426_KAL_X (right): (a)–(b) X-direction acceleration, (c)–(d) Fourier amplitude, (e)–(f) displacements.

Figure 13a,b compares the FFTs of the shake table (DLONG) and isolated platform (DISX_I) displacements for the two most demanding Kalamata signals (i.e., 425_KAL and 426_KAL). For such signals, Figure 13c,d compares the displacement time histories and the corresponding FFTs, respectively. The comparisons in Figure 13a,b show a substantial difference between the FFT of the isolated platform and the corresponding FFT of the shake table. The FFT of the isolation platform is indeed smoother than the shake table counterpart. Due to the nature of the shake table signal the frequency shift cannot be clearly determined.

The frequency values corresponding to the displacement FFT peaks on the isolated platform across two different Kalamata signals show reasonably good agreement, as illustrated in Figure 13d. Furthermore, Figure 13d shows that the dominant frequency peak $\bar{f}$ of the displacement FFT of the isolated platform matches the theoretically predicted frequency derived by the effective period of the isolator. This theoretical period ($\bar{T}$) was computed by means of Equation (1), assuming the friction coefficient of 4.53% (see Section 3) and the displacement d equal to the maximum value observed in the specific experimental test (i.e., $d = 82.3$

TABLE 4 | Maximum values of the horizontal accelerations on shake table and isolated platform and horizontal displacements on the isolated platform with occurrence times.

	Emilia				Aquila				Syntagma				Kalamata		
	401	402	407	412	437	438	439	441	427	428	429	445	424	425	426
PTA (g)	0.24	0.34	0.41	0.47	0.22	0.27	0.33	0.35	0.21	0.29	0.43	0.47	0.15	0.26	0.29
Shaking Table	9.6 s	11.9 s	11.9 s	11.9 s	18.5 s	18.5 s	18.5 s	18.5 s	9.6 s	9.6 s	9.6 s	9.5 s	8.7 s	9.3 s	8.7 s
PIA (g)	0.15	0.16	0.18	0.25	0.15	0.12	0.14	0.13	0.15	0.14	0.15	0.17	0.12	0.17	0.12
Isolated Platform	9.5 s	9.3 s	9.4 s	9.4 s	18.0 s	18.1 s	18.2 s	18.0 s	9.3 s	8.9 s	8.5 s	8.4 s	7.0 s	7.1 s	6.9 s
Disp _{max} (mm)	28.4	27.4	65.9	66.6	29.7	24.5	31.6	31.2	17.7	35.6	47.9	60.6	37.4	82.3	108.4
Isolated Platform	12.3 s	12.3 s	11.8 s	12.6 s	19.1 s	18.5 s	19.2 s	18.4 s	9.8 s	9.8 s	9.9 s	9.8 s	9.5 s	8.8 s	9.7 s

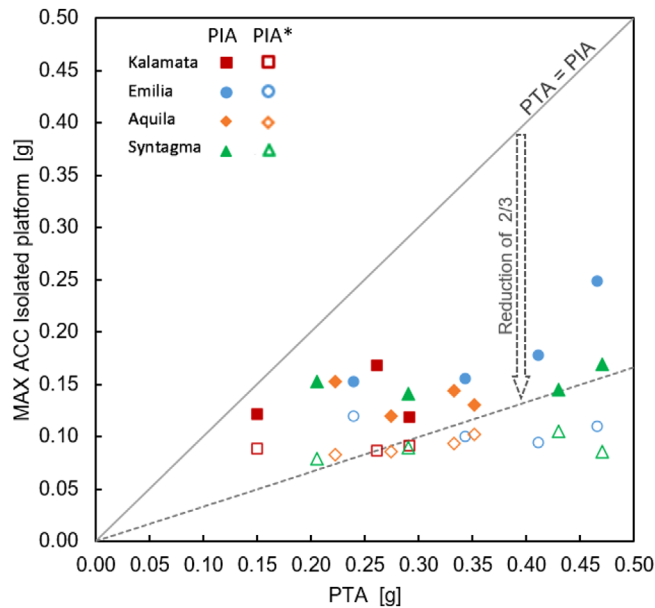


FIGURE 11 | PIA and PIA* values of isolated platform as a function of PTA.

and 108.4 mm for 425_KAL and 426_KAL, respectively). The corresponding effective periods are equal to 2.05 s and 2.21 s, respectively. Since 426_KAL is the most demanding displacement test for case study configuration, $\bar{T} = 2.21$ s represents the highest effective period obtainable for the tests considered in this study, as mentioned in Section 2.

5.1.2 | Peak and Integral Response Quantities

A direct way to evaluate the effectiveness of the isolation system can rely on the ratio between PIA and PTA. Figure 14a illustrates the trend of this ratio as a function of PTA for the different tests. Considering all the results, this ratio generally decreases with increasing PTA. With the exception of the 412_EM, this ratio remains below approximately 50% for PTA values exceeding 0.3 g. Even when analysing the results grouped by the specific ground motion records (i.e., within a single sample input motion), no clear trend emerges. Table 5 reports in the first column the Pearson correlation coefficient (R) calculated considering the results of all the tests together, as well as the mean of the Pearson

correlation coefficients computed considering each sample input motion separately, with their standard deviations.

As stated in Section 2, an EDP based solely on peak value may be insufficient to fully assess the performance of the isolation system. Peak values are inherently limited, as they represent a single point in time. As discussed in Section 5.1.1, the maximum acceleration registered on the isolated platform does not occur simultaneously with PTA. A relevant case is the Emilia earthquake, where PTA on the table occurs during the second shock, while the maximum acceleration on the isolated platform was recorded during the first shock. Therefore, an alternative measure can be defined as the ratio between the above-defined PIA* and PTA. In this case a higher value of the Pearson correlation coefficient can be found both by considering all the results together and by averaging the R coefficient computed for each sample input motion (Table 5, second column).

A limitation of these peak-based measures is their high sensitivity to local effects. To address this and to enable a more effective comparison for different signals, integral parameters are considered as EDPs. The ratio between these integral parameters calculated for the isolated platform and the counterpart for the shake table is proposed in this study as a measure to assess the performance of the DCCSS isolation system. Figure 14b–d shows the variability of such ratios as a function of PTA. Arias Intensity (I_A) ratio ranges between 0.52 and 0.20 in all but one case (427_SYN with PTA = 0.21 g). ASI-modified (ASI_m) ratio varies between 0.81 and 0.39, and the Housner intensity (HI) ratio between 0.82 and 0.47. Similarly to the trend of the ratio between peak acceleration, the ratios in terms of I_A and ASI_m generally tend to decrease with increasing PTA. The regression analysis leads to a rather high value of the Pearson correlation coefficient when considering the sample input motion separately, Table 5. The reduction of HI with increasing PTA is less evident, probably due to the parameter relation to the velocity.

Among the considered integral measures, the ratio based on I_A , a measure of energy content, is most effectively reduced by the isolator system. With the exception of the 427_SYN signal, which exhibits the lowest intensity (demand) measure I_A (Table 3), the implementation of the isolator results in a reduction of at least 50% for each PTA value, with the average reduction reaching 70%. The computed results show that the outcomes are promising and can provide viable assessment criteria. However, this topic is still an open research question and requires further investigations.

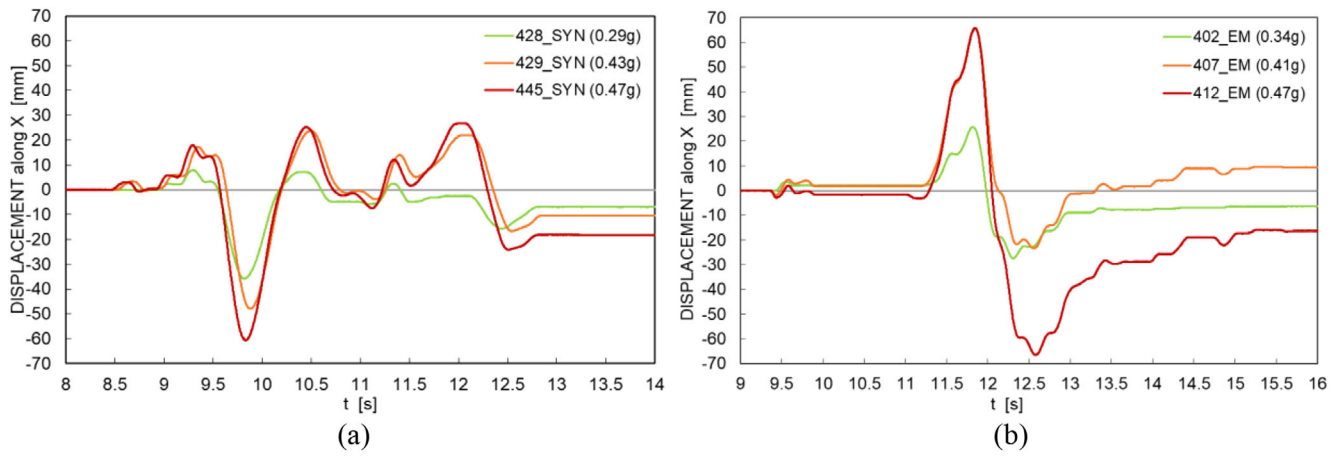


FIGURE 12 | Isolated platform displacements at increasing PTA: (a) Syntagma, (b) Emilia input motions.

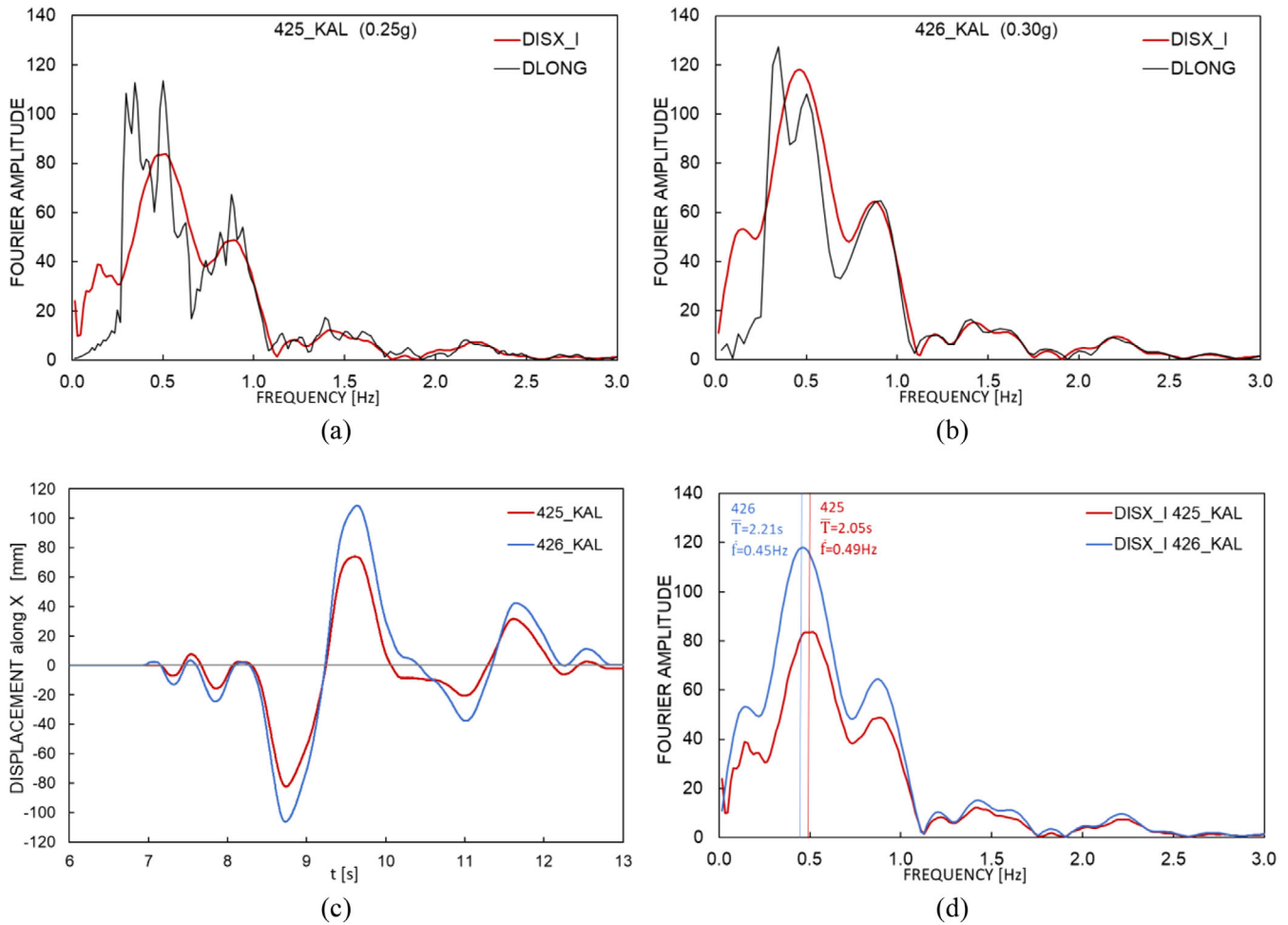


FIGURE 13 | Kalamata sample input, test 425_KAL and 426_KAL: (a)–(b) FFT of displacement response histories of table and isolated platform, (c) isolated platform displacements, (d) FFT of displacement response histories of isolated platform.

5.2 | Bidirectional Tests

The experimental programme allowed investigating the response of isolators under bidirectional earthquakes. Tests EMILIA-XY highlight reductions of peak accelerations between the table and the isolated platform higher than 60% in both directions with a corresponding reduction of the spectral acceleration.

Figure 15 shows the time history response of the acceleration of the isolated platform compared to the table counterpart for the test 414_EM_XY along X- and Y-directions separately, whilst Figure 16a shows the corresponding reduction of the spectral acceleration in the X direction. The study of the integral response quantities confirms the reliable performance of the isolators to mitigate earthquake-induced effects on museum artefacts.

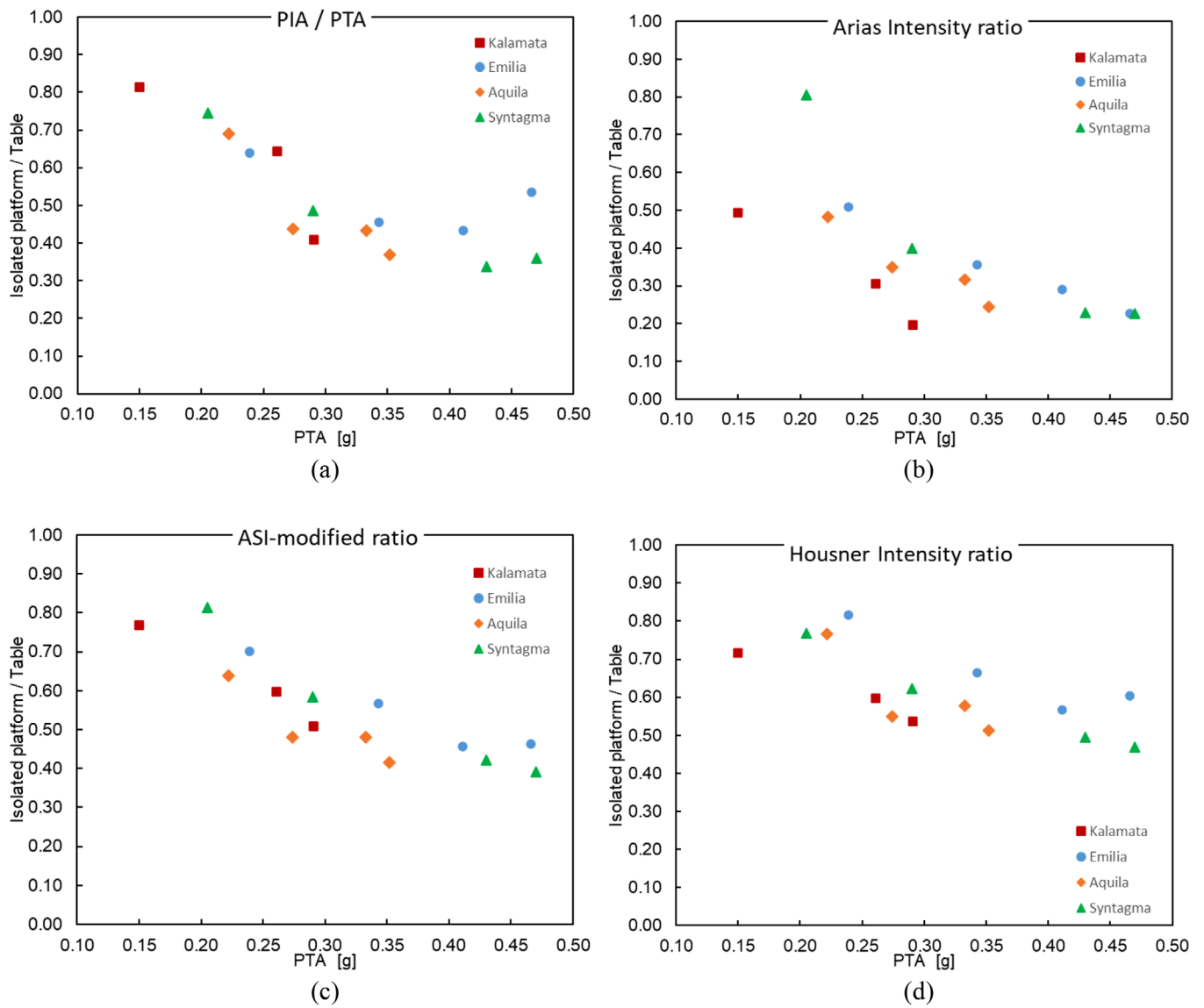


FIGURE 14 | Ratios of isolated platform and shake table for (a) maximum acceleration, (b) Arias intensity, (c) ASI-modified, (d) Housner intensity as function of PTA.

TABLE 5 | Pearson correlation coefficient R and standard deviation values of the considered EDP, computed considering the results of all the tests together and of each sample input motion separately.

	PIA/PTA	PIA*/PTA	I_A ratio	ASI _m ratio	HI ratio
All input motions					
R	0.779	0.869	0.716	0.856	0.715
Sample input motions					
Average R	0.835	0.962	0.966	0.960	0.936
Dev Stnd R	0.163	0.029	0.032	0.035	0.068

Figure 16b reports, for each integral parameter, the ratio between the value calculated with reference to the signal on the isolated platform and the corresponding value of the signal measured on the table. Such ratios, for the bidirectional case, vary from 0.30 to 0.60.

To further investigate the response of isolators to bidirectional excitations, Figures 15a and 16 compare the results of test 414_EM_XY in the X-direction with the counterpart of unidirectional test 402_EM_X, characterized by the same PTA value of 0.34 g in the X-direction. The figures show that the bidirectional

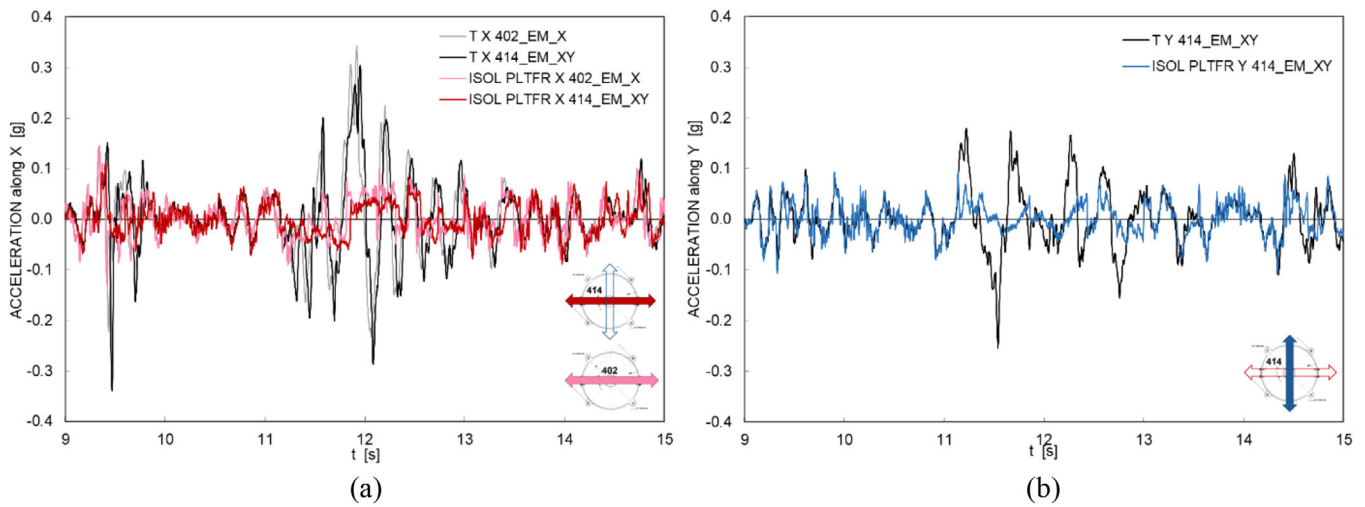


FIGURE 15 | (a) Comparison between table and isolated platform accelerations for 414_EM_XY test in (a) X-direction—compared to the result of 402_EM_X input—and (b) Y-direction.

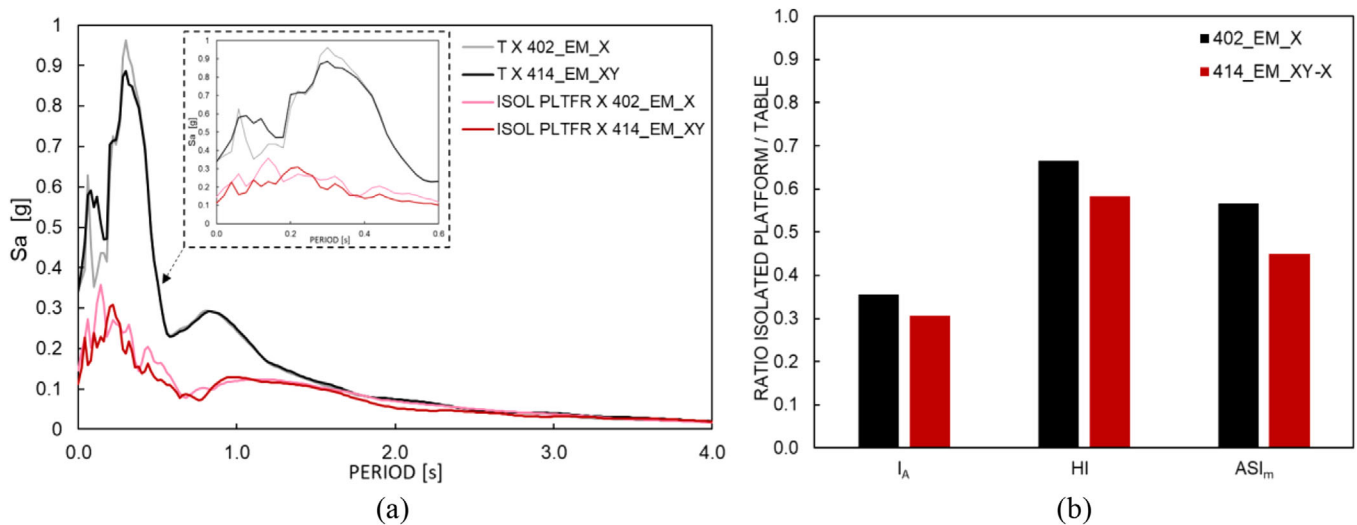


FIGURE 16 | Results of 414_EM_XY test in the X-direction compared to 402_EM_X: (a) Spectral accelerations of table and isolated platform. (b) Ratio of integral response parameters between isolated platform and table.

simultaneous input motion (seismic records in X- in Y directions) does not significantly alter the response of the isolator in the X-direction, in terms of both acceleration time history and spectral acceleration. Furthermore, by comparing the integral measures reported in Figure 16b, it is observed that for these tests the isolator seems to reduce the 2D signal even more effectively than the 1D signal. For ASI_m , the reduction of the table signal for 414_EM_XY in the X-direction due to the isolator is about 30% greater than the corresponding value for 402_EM.

When commenting on the results of this comparison, it should be emphasized that, despite the two tests being selected from the available signals to have the same PTA and consistency in terms of spectral accelerations (S_a), spectral velocities (S_v) and FFT, a perfect match between the two signals is not possible. This is evident by comparing the acceleration spectra of the two table signals in Figure 16a—particularly in the highlighted area—and the values assumed by the integral seismic parameters shown in Figure 7b.

The signal in the X-direction of 414_EM_XY on the table presents a value of ASI_m 15% greater than the corresponding 1D quantity.

5.3 | Comparison Between Seismic Response of Isolated and Non-Isolated Artefacts

In the following, the effect of isolators on the response of pedestals and busts is analysed. Figure 17 shows the acceleration time histories of the non-isolated artefacts and the isolated counterparts for 426_KAL for the solid system (Ss), that is the bust and the solid pedestal. The accelerations of pedestal and bust (measured respectively by the accelerometers ACC_P and ACC_B of Figure 3) are compared to the acceleration on the shaking table (Figure 17a) and on the isolated platform (Figure 17b). Similarly, Figure 18 presents the isolator effect for the case with hollow pedestal, named hollow system (Hs). As already observed in Berto et al. (2023) [27] for the solid system in the non-isolated

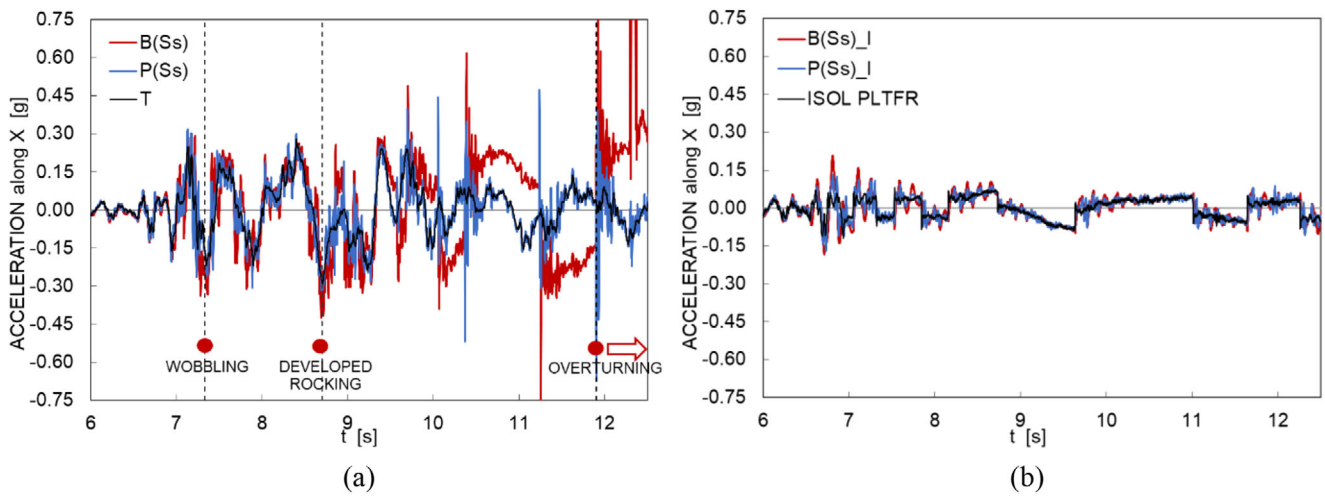


FIGURE 17 | Test 426_KAL, comparison for time history of the acceleration at the base of the pedestal and the acceleration measured on bust and solid pedestal for the solid system (Ss) in the (a) non-isolated case, (b) isolated case, showing the occurrence of bust motion.

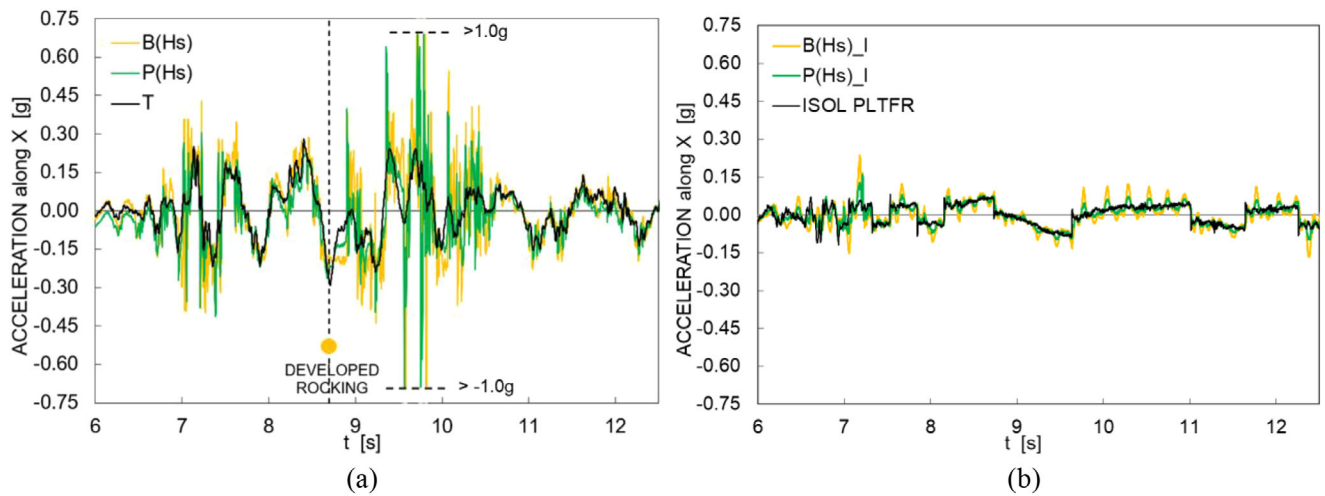


FIGURE 18 | Test 426_KAL, comparison for time history of the acceleration at the base of the pedestal and the acceleration measured on bust and pedestal for the hollow system (Hs) in the (a) non-isolated case, (b) isolated case showing the occurrence of bust motion.

case, the bust exhibits a minor rocking at approximately 7.2s, followed by a fully developed rocking starting from 8.7s, leading to overturning. On the other hand, in the isolated case, the bust reaches a maximum acceleration of 0.21 g and does not exhibit rocking. Similarly, the isolation effect on the bust of the hollow system causes a transition from a developed rocking motion with an acceleration value up to 1.0 g due to spikes, to an absence of relative motion between bust and pedestal with a maximum bust acceleration of 0.23 g.

To further investigate the different seismic responses of isolated and non-isolated artefacts, the ratio of the peak acceleration of the element (i.e., pedestal, bust) and of the shaking table (PTA) is considered. For the non-isolated case, such a ratio corresponds to the component amplification factors (CAFs) evaluated in [27]. On the other hand, for the isolated case, it may be assumed as a DMF since it also includes the effect of the isolator. Figure 19 presents such ratios for four different tests, corresponding to the highest level of PTA for each sample input motion for both solid and hollow systems. The findings demonstrated a relevant

reduction for the isolated elements with respect to the non-isolated counterparts, both for solid system (Ss) and for hollow system (Hs). The non-isolated solid pedestal $P(Ss)$ exhibits CAF values ranging from 1.08 to very high values for Kalamata test as a consequence of the spikes due to the fully developed rocking and overturning of the bust. Accordingly, the bust $B(Ss)$ has CAF values ranging from 1.48 to very high values. For the isolated systems, such ratios are scaled down by factors greater than 1.5. Such reduction factors are higher for the case of hollow systems. For the last system type, the reduction is from 2.5 to 6.8 times for bust $B(Hs)$.

In the isolated case, the DMF of the bust tends to match that of the pedestal, especially in the solid system. This is because the isolator effect causes the multi-block system to behave nearly as a rigid body, as evidenced by the nearly overlapping acceleration time histories in Figure 17b. Greater discrepancy is observable for the hollow system being more prone to slight vibration. Finally, concerning the isolated platform, for all these tests a reduction of the PTA of more than 60% is observed.

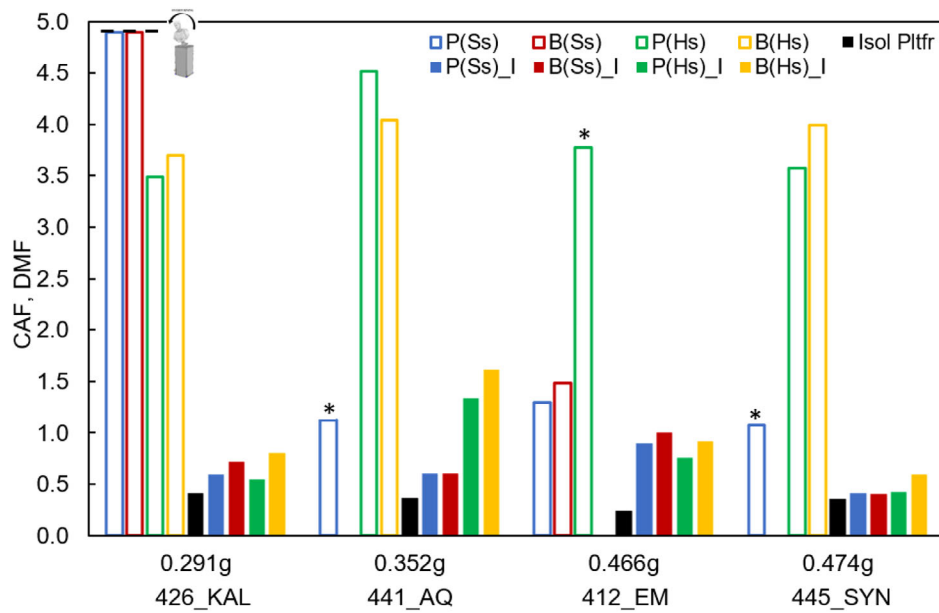


FIGURE 19 | CAF and DMF computed during the shake table test carried out with the subset of sample input motions with the highest PTAs. * = pedestal without bust.

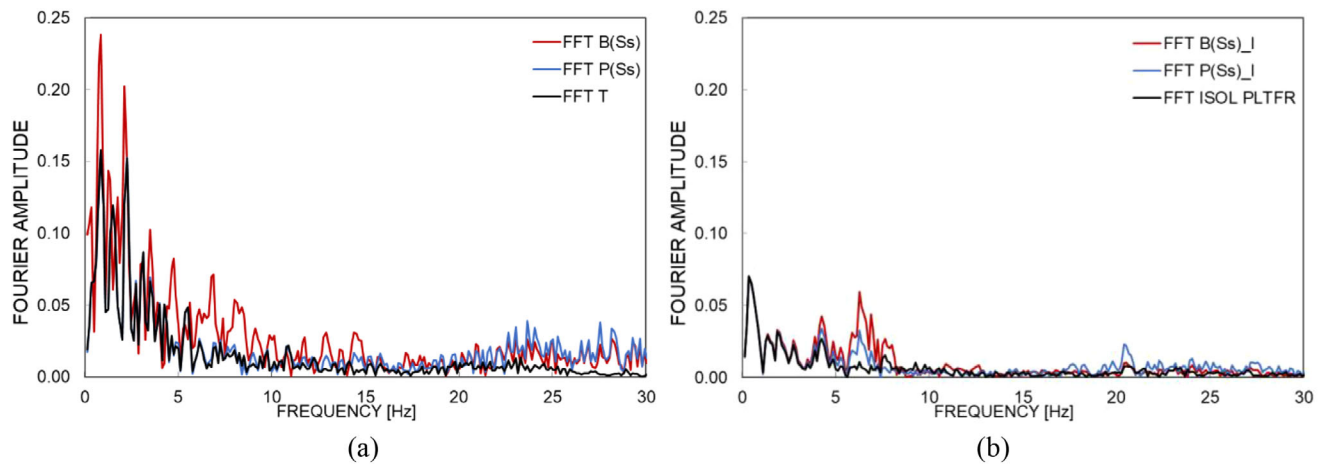


FIGURE 20 | Test 426_KAL FFT computed for specimen, shake table and isolated platform (solid system): (a) non-isolated case, (b) isolated case.

A typical example of the dynamic modification of seismic excitation due to the presence of the isolator system is shown in Figure 20 for the solid system subjected to 426_KAL input. This figure compares the FFT spectra of the accelerations measured on the table, pedestal and bust in the non-isolated case (Figure 20a) with the corresponding spectra in the isolated case (Figure 20b). The isolation system significantly reduces FFT spectrum peaks. The beneficial influence of isolation is particularly pronounced at low frequencies. Moreover, in the isolated case, the FFT for bust, pedestal, and isolated platform tend to overlap, except for the range between 5 and 8 Hz. This behaviour differs significantly from the non-isolated case, where bust rocking and overturning drastically change the overall dynamic response. Finally, the isolation system clearly filters high-frequency spikes present in the non-isolated response.

As far as the seismic performance of the isolator system with the bidirectional loading, Figure 21 compares the acceleration

time histories of the bust above the solid pedestal in the isolated and non-isolated cases the in X and Y directions for test 414_EM_XY (PTA-X = 0.34 g and PTA-Y = 0.25 g). As proved in Berto et al. (2023) [27], the bust in the non-isolated case exhibits two distinct types of rocking modes: rocking periods are approximately 0.2–0.3 s during the first shock, increasing to around 0.4 s in the second shock. This behaviour is reflected in the FFT spectrum (Figure 21c), which shows peaks at 2.2, 3.3, 4.2, and 5 Hz. The comparison with the isolated case evidences the effectiveness of the isolator in mitigating the dynamic response of the bust, reducing the acceleration and preventing rocking motion. However, the isolation effect is limited during the first shock, consistent with observations from the unidirectional case; see Section 5.1. Finally, Figure 21d shows that the DMFs of the isolated elements are almost 20% lower than the corresponding CAFs for the unprotected case in the X-direction. The reduction is more relevant in the Y-direction.

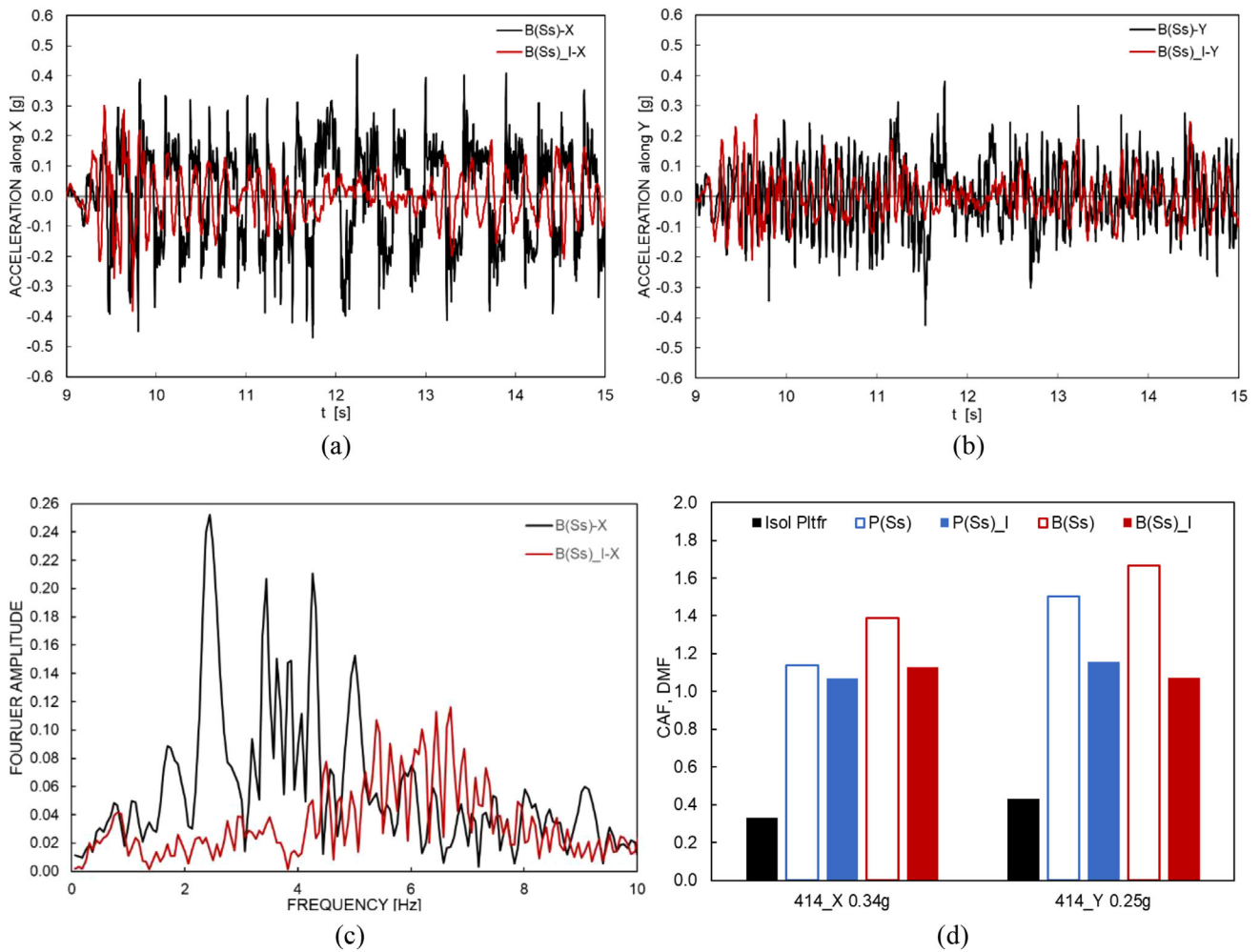


FIGURE 21 | Bidirectional test 414_EM_XY, for isolated and non-isolated bust: (a) X-direction acceleration, (b) Y-direction acceleration, (c) FFT, (d) CAF.

6 | Conclusions and Further Work

The study presents outcomes of a comprehensive shaking table programme on freestanding marble statues and busts with the BI system (double concave curved surface slider isolators, DCCSS), subjected to both uni- and bi-axial earthquake records. The input motions are derived by scaling four natural strong motions as recorded in the Mediterranean region. Such motions have PTAs ranging between 0.15 and 0.49 g, plus high energy contents varying between 0.65 and 6.00 Hz.

The results of experimental tests have emphasized that the reproducibility on shake table testing facilities of strong motions at incremental levels of PTA is not straightforward. Matching of target and realized motions is less accurate at low periods (lower than 0.25 s), but such mismatch does not significantly affect the response of base-isolated specimens. To allow efficient comparative analyses, both non-isolated and seismically isolated specimens were tested simultaneously on the shake table with the same input.

As far as the effect of input motion amplitude, frequency content and directionality are concerned, the results of shake table tests

allow to draw the following conclusions for the efficiency of BI to protect unanchored artefacts:

- The use of DCCSS led to a significant reduction of peak accelerations on the isolated platform (PIA) with respect to the table counterparts; such reduction, which does not depend on the input frequency contents, exceeds 60% when the PTA is higher than 0.29 g.
- For all tests, a significant time-gap between the occurrence of PTA and PIA was observed. PIA occurs before the onset of PTA.
- The horizontal displacement of the devices generally increases with increasing PTA for a given strong motion, as expected. Such response was significantly influenced by frequency content of the seismic inputs.
- Bidirectional input was found to have a weak influence on the seismic response of museum artefact protected through isolators.

Additionally, traditional seismological integral parameters were conveniently modified (considering the extended elongated period of seismic isolation) and used as EDPs to quantify the

seismic response of the isolation system. The benefits of using such modified parameters stem from their inherent time and peak-value independence.

Using the outcomes of the shake table tests and the following integral parameters— I_A , ASI_m , HI —it is possible to observe:

- The ratio of integral parameters for the isolated platform and the counterpart for the shake table is an effective measure to quantify the response of the DCCSS isolation system.
- The ratio based on I_A is the most effectively reduced by the isolator system. For almost all the cases, the implementation of the isolator results in a reduction of at least 50% for each PTA value, with the average reduction reaching 70%.
- The ratios for I_A and ASI_m tend to decrease with increasing PTA. The regression analysis leads to a good correlation when considering the sample input motion separately. The reduction of HI with increasing PTA is less pronounced.
- The isolation system demonstrated greater attenuation of the 2D signal compared to the 1D signal, especially for ASI_m .

The seismic response of the tested components was quantified by the ratio between the peak acceleration of the museum freestanding objects and PTA. ‘Dynamic modification factors (DMFs)’ and ‘component amplification factors (CAFs)’ were selected as response parameters for isolated and non-isolated components, respectively. Based on the shaking table test carried out, it was observed that:

- In the isolated case, the dynamic response of the bust tends to match that of the pedestal, especially in the solid pedestal system. This is because the isolator effect causes the multi-block system to behave predominantly as a rigid body.
- For solid systems it was found that values of DMFs are lower than CAFs, which, in turn, are higher typically than 1.5. Ratios of CAF/DMF for hollow systems are higher than solid counterparts.
- For bidirectional input, a reduction of DMFs with respect to CAFs of nearly 20% in the X-direction was detected. Such a reduction is more pronounced in the Y-direction.

Additionally, the shake table tests also demonstrate that the isolation system significantly reduces FFT spectrum peaks relative to the dynamic response of the tested components. Moreover, the BI system filters high-frequency spikes present in the non-isolated tested museum objects.

Further numerical investigations, for example, utilizing computationally efficient digital twins of art objects and/or simplified data-driven models for fragility analysis, are required to corroborate the experimental outcomes and validate the reliability of the multiple response parameter analysis presented in this study, namely peak quantities and integral parameters. Finally, to preserve the integrity of museum artefacts, it is foreseen to formulate seismic risk mitigation methodologies based on the combined use of BI and innovative structural health monitoring based on bespoke machine learning approaches.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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