EXPERIMENTAL EVIDENCE OF SEISMIC PERFORMANCE OF BASE ISOLATED ARTISTIC ASSETS

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Abstract: *The seismic protection of artistic assets is a fundamental risk mitigation strategy for many countries worldwide, especially in the Mediterranean regions. This work illustrates experimental results of a recent European research project aimed to investigate the seismic response of museum contents and develop risk mitigation strategies to improve their resilience. Such project consists of comprehensive experimental shake-table tests conducted on the large-scale Azalee facility at CEA, Saclay in France. Full-scale free-standing marble statues and busts were assessed seismically by considering various scenarios, i.e. different types of pedestals, with and without innovative isolation devices at their base. The present paper evaluates the efficiency of seismic isolation on the rocking behaviour of artefacts. Response of busts and statues mounted on a seismically isolated steel plate supported on three pendulum isolators is compared to the behaviour of non-isolated counterparts. Strong ground motions with different seismological characteristics are employed to evaluate the effect of frequency contents on the dynamic response of the sample artistic components.*

1. Introduction

Consequences of seismic risk of cultural heritage in several European countries was dramatically highlighted in the aftermath of recent earthquakes which caused enormous losses to museum artifacts. Widespread damage to free-standing sculptures and a few collapses were surveyed during major past earthquakes worldwide. Such detrimental response was induced by the collision and/or impacts of the artefacts due to sliding, uplift, rocking or overturning (e.g. Erturk, 2012; Zhao, 2016). Thus, in addition to the incalculable losses relative to artistic assets, risk to life-safety may be imposed on museum visitors and employees. The above discussion points out the need to setting-up adequate performance criteria to artistic non-structural components. The contained components are characterised by high vulnerability and require thorough seismic assessment, which was recently prioritised in several seismic Standards worldwide, especially in Europe, US, China, Japan and New Zealand.

As a consequence, it is of paramount importance to acquire deeper insight into the seismic response of museum objects and, when appropriate, adopt cost-effective yet efficient protection measures, e.g. base isolation systems (Lowry et al. 2008). It is to note that dealing with seismic protection of artistic asset requires evaluations about the building that houses the artistic objects, for example related to the position of the object inside the building (e.g., Berto et al. 2020) and to the seismic vulnerability of the building itself, and in some cases to consider the possibility to protect the entire structure with isolation devices.

The assessment of seismic vulnerability of artefacts, especially human-shaped sculptures, is a complex and still open active research topic. It requires a comprehensive assessment of the dynamic behaviour of rigid blocks, both single and multiple, which can experience different response modes.

Over the past few decades, numerous researchers have focused on rocking and overturning of freestanding rigid blocks, primarily through analytical and numerical investigations. Such studies were developed from the seminal work by Housner (1963). Additional numerical and experimental studies have shown the high sensitivity of rocking response of freestanding single block to even small changes in their geometry, boundary conditions (support surface, defects presence, imperfect planarity) and input seismic motions (type and frequency), e.g. Ishiyama (1982), Zhang and Makris (2001), Purvance et al. (2008), Konstantinidis and Makris (2009), Diamantopoulos and Fragiadakis (2019), Berto et al. (2021), among others. Nonetheless, fewer studies have investigated the response of multiple block systems subjected to earthquake motions (e.g. Kounadis (2015), Wittich and Hutchinson (2017), Arredondo et al. (2019), Al Abadi et al. (2019)). The layout with multiple blocks is, however, frequently encountered with museal freestanding components placed on top of a pedestal or high support.

Although quite extensive research has been conducted on seismic response of freestanding elements, to the Authors' knowledge there is still paucity of bespoke studies dealing with seismic assessment and protection of museum artefacts via experimental or numerical approaches. Furthermore, there is an evident gap for ad-hoc design and assessment standards. Simplified yet robust guidelines would also be useful for practitioners and museal collection curators.

The "Seismic Resilience of Museum contEnts" - SEREME project, a synergy between National Technical University of Athens, Greece, University of Liverpool, UK and IUAV University of Venice, together with the industrial partner FIP MEC, represents a step toward in this direction. This project was sponsored by the European H2020 - SERA (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe) funding scheme. It involved an extensive experimental seismic testing programme. Such experiments were conducted on the 6-degrees of freedom AZALEE shake table at Commissariat à l'énergie atomique et aux énergies alternatives, CEA, in Paris Saclay. Real-scale freestanding statues and busts were tested to evaluate their seismic performance with different pedestals. Ground motions with different frequency contents and amplitudes were considered to assess the performance of the sample specimens which were protected with various innovative base isolation devices.

This paper focuses on the experimental outcomes derived to assess the seismic performance of double concave curved surface sliders isolators (DCCSS) to protect busts on slender solid pedestals.

2. The experimental SEREME Project

The experimental project SEREME aimed at the assessment of the seismic response of different real-scale artistic assets (busts, pedestals, statues) and different isolator types.

The tested specimens are all free standing and hand-made of solid marble. They are classical figures similar to those that are typically installed in museums worldwide: 3 ancient Roman emperors (Traiano, Augusto and Tito) and 2 female figure statues (Figura Femminile with a low marble pedestal and Fanciulla). The busts have similar weights of about 110kg, while the statues weigh between 260kg (Fanciulla) and 440kg (Figura Femminile). Every specimen has a replica.

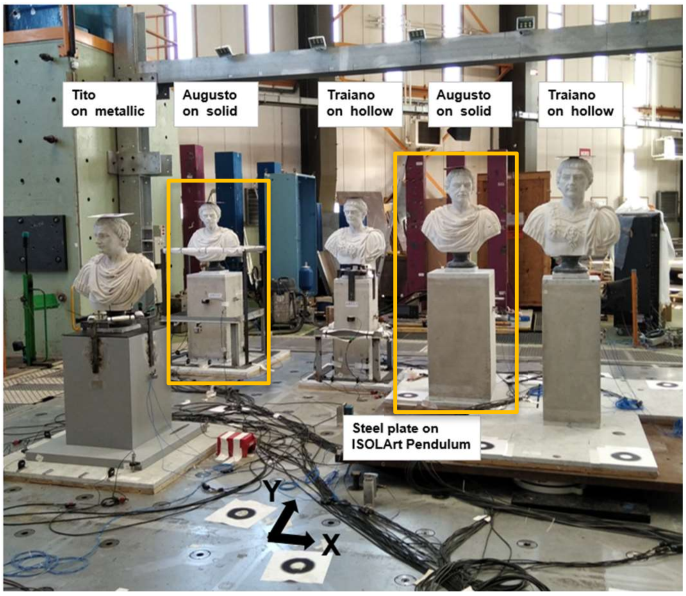
To simulate the typical exhibition condition of the artifacts at the eye level, the busts are placed on parallelepiped pedestals. To account for both traditional and modern pedestals, three different types of supporting blocks were considered: a solid one (45×45 cm, height 101 cm, weight about 500 kg), a hollow one (35×35 cm, thickness 8 cm, height 101 cm, weight about 220 kg) and a metallic one (85x85 cm, height 86 cm, weight about 90 kg). The traditional pedestals were made of concrete, which has a specific weight close to that of marble but was easier to manufacture, and 3 cm-thick marble slabs were affixed to the upper and lower face of the pedestals to reproduce realistic conditions for friction coefficient. In order to simulate the typical museums' floor, non-isolated specimens were placed (without any connection) on a 3 cm-thick marble floor surface on a stiff wood plate (3 cm thick). Both marble and wood plates were bolted to the shake table.

Two base isolation systems were tested on the AZALEE shake table. They are ISOLArt® Pendulum, a double concave curved surface sliders isolator, and ISOLArt® SMA, an isolator based on Shape Memory Alloy (SMA) wires, both specifically designed for low-mass such as art objects and produced by FIP MEC, a global leading manufacturing company. Concerning the ISOLArt® Pendulum, which is presented in details in this paper, a heavy steel plate over three isolators was placed, with two or three artefacts over it. The steel plate was covered with a marble floor surface (3 cm thick).

Seven different configurations were tested. Each configuration compares one or more pairs of similar artefacts, with and without isolation, tested simultaneously on the shaking table. Figure 1 shows "Configuration III", illustrated herein, with the tested specimens and the steel plate isolated with DCCSS isolation system. This paper focuses on the comparison between the isolated and non-isolated case for the of bust – solid pedestal system. These specimens are schematically represented in Figure 2, where the labels used in this work to refer to them are also reported, and their characteristics are listed in Table 1.

The experimental test set-up included a very refined monitoring system. The accelerations of table, pedestals, busts, statues, isolated steel plate were measured through PCB accelerometers, the angular velocity of the artistic assets through gyroscopes, the uplift of pedestals and statues through LVDT and the lateral displacement of the pedestals and the isolated steel plate through FGP500. To complete the monitoring system there was a close-up video recording system.

The experimental tests were conducted with earthquakes exhibiting different frequency contents and with one or more components in different directions (uniaxial, biaxial and triaxial records). Four different ground motion records (Emilia 2012, Kalamata 1986, Athens 1999 and L'Aquila 2009), each one scaled to different levels of seismic intensity, resulted in more than 400 experimental seismic tests. Among them, in this work Emilia and Kalamata records are considered. Table 2 reports the main characteristics of the ground motion records as well as the uniaxial shake table tests considered with the corresponding PTA (Peak Table Acceleration) value. All these records were applied along X-direction.



(a)

(b)

Figure 1 (a) Configuration III with indication of tested artistic assets and the isolated steel plate (b) view of the isolation system.

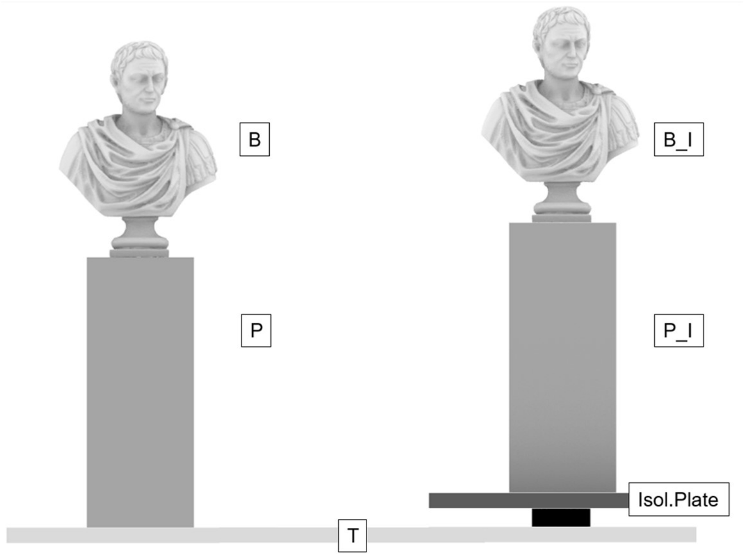


Figure 2 Schematic illustration of the analysed specimens in non-isolated (left) and isolated (right) configurations.

Table 1. Geometrical characteristics and weight of bust and solid pedestal.

	Height (cm)	**Width (cm)**	**Depth (cm)**	**Weight (kg)**
Bust	81.6	60(max) – 22.2(base)	29.5(max) – 22.5(base)	110
Pedestal	101	45	45	500

Table 2. Seismic tests considered in this paper and corresponding ground motion records characteristics.

Earthquake characteristics	**Test label**	**PTA [g]**
Location: **Emilia, Italy** Date: 29.05.2012 Mw: 6.0 Station: T0800 Component: Longitudinal Distance hypocentral: 14.4 km Soil category: C* (EC8) PGA: 0.33 g PGV/PGA: 0.83 m/(sg) Arias intensity: 0.99 m/s	402_EM_X 407_EM_X 412_EM_X	0.34 0.41 0.47
Location: **Kalamata, Greece** Date: 09.13.1986 Mw: 6.2 Station: Nomarchia Component: Longitudinal Distance hypocentral: 5.0 km Soil category: Stiff soil PGA: 0.22 g PGV/PGA: 1.59 m/(sg) Arias intensity: 0.63 m/s	424_KA_X 425_KA_X 426_KA_X	0.15 0.25 0.30

Key: L=Longitudinal

Considering Emilia and Kalamata records allows to evaluate the isolation effect in a wide range of PTA. As reported in Table 2 the PTA values of Emilia_L signals span between 0.34g-0.47g, while the PTA range of

Kalamata_L covers lower values (0.15g-0.30g). Moreover, as shown in Table 2 the two earthquakes are characterized by different values of PGV/PGA. Kalamata presents a higher value of PGV/PGA which corresponds to lower predominant frequencies and so it is more demanding for isolated structures. This can be directly inferred from Figure 3a, which compares the acceleration response spectrum of the two recorded signals 402_EM_X and 426_KA_X, characterized by similar PTA values (i.e. 0.34g for Emilia and 0.30g for Kalamata respectively). Moreover, from the comparison of the displacement response spectra of the two records, Figure 3b, it is evident that Kalamata earthquake is more displacement-demanding than the Emilia counterpart.
Additional details on the SEREME research project can be found in Berto et al. (2023).

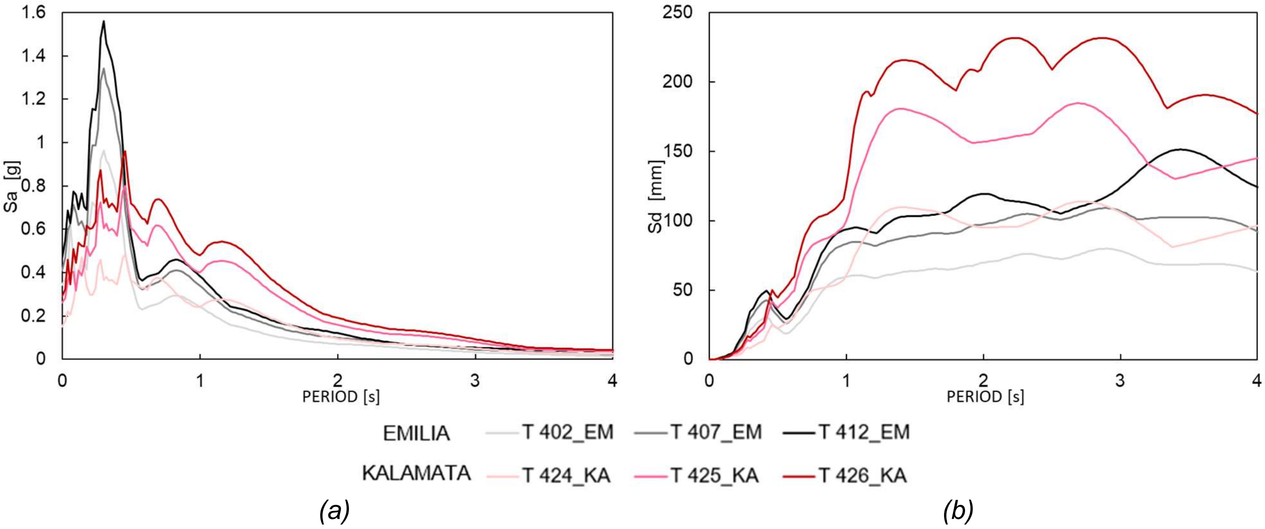


Figure 3 Comparison between the response spectra of Emilia X (test 402_EM_X) and Kalamata X (test 426_KA_X) recorded on the shaking table, in terms of (a) acceleration (5% damping), (b) displacement (5% damping).

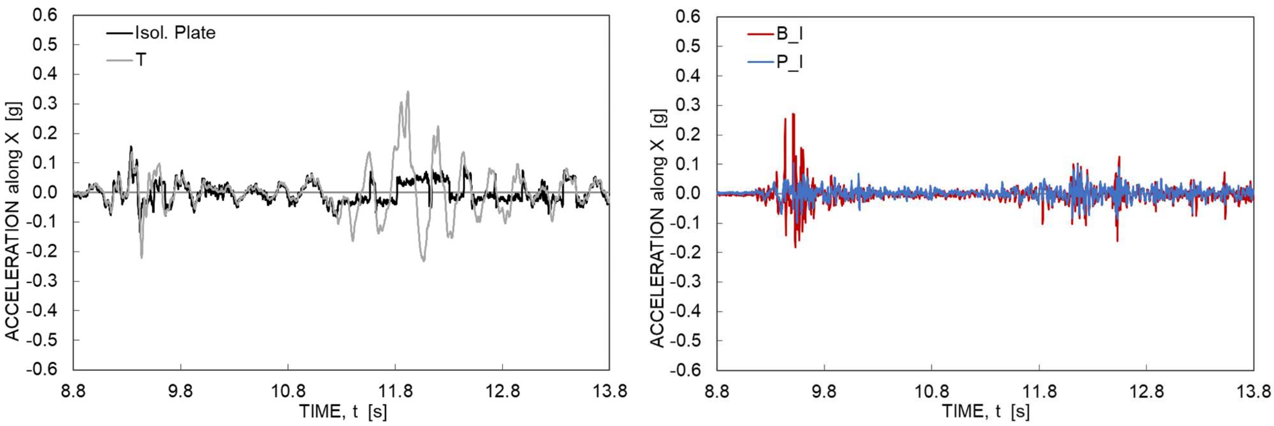
3. Seismic isolators: DCCSS characterization

The base isolation system analysed in this paper consists of three double concave curved surface sliders (DCCSS), i.e. ISOLArt® Pendulum, designed and manufactured by FIP MEC. Based on the characteristics of the artistic components to isolate and the seismic inputs to be considered in the campaign, isolators were designed with an equivalent radius curvature R_{eq}=2.5m and a maximum displacement capacity ±300mm that is compatible with the maximum displacement demand, computed for all the seismic input of the campaign. The vertical load capacity for each isolator is 20 kN.
In order to verify the performance of the isolation system, it was tested in the Testing Laboratory of FIP MEC. A series of static and dynamic sliding tests, with sinusoidal movements applied along the two primary axes, at different amplitude, frequency and vertical load, were performed. The average dynamic friction coefficient μ measured for a vertical load of 9.8kN for isolator, is about 4.6%. Additional details on the isolation system and its mechanical characterisation can be found in Di Sarno et al. (2023).

4. Response of bust and pedestal with base isolation

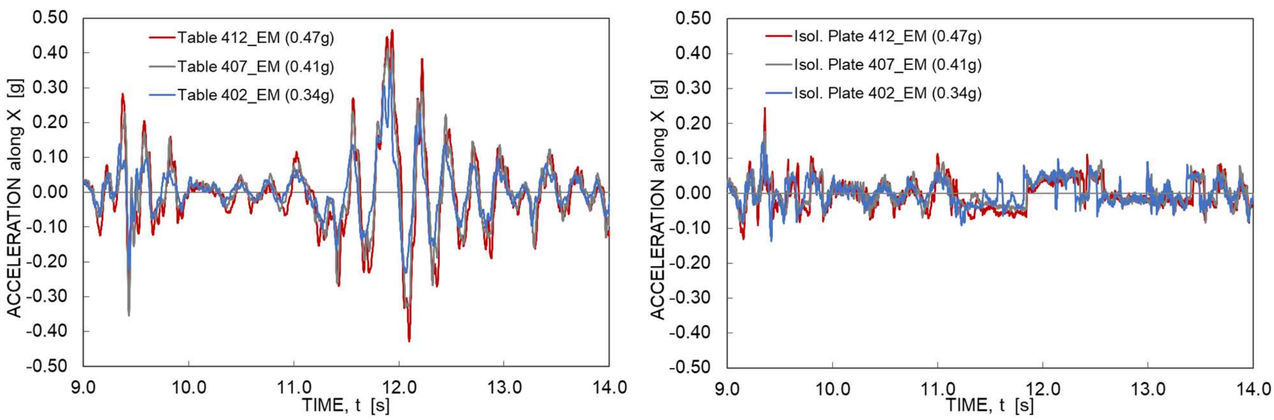
In this section the response of busts on solid pedestals isolated with DCCSS devices is presented in terms of acceleration time history, registered during the SEREME shake table tests.
As an example, concerning Emilia signals, Figure 4 shows the effect of the adopted isolation system for the test with the lowest PTA value (i.e. 402_EM with PTA=0.34g). It clearly displays the decoupling between the table and the isolated steel plate motions, with a clear reduction of the acceleration recorded on the isolated plate. As reported in Berto et al. (2023) the Emilia signal presents two strong motion bands. In the case of Emilia 402 one with a peak acceleration of 0.22g (1st shock) and the other with a peak equal to 0.34g (2nd shock). The isolators are activated for both shocks: the first time at 9.5s and the second time at 11.4s. In correspondence of the first activation of the devices (at a relatively low PTA value) a clear amplification in the bust acceleration with respect to solid pedestal (Figure 4b) is evident, which decreases for higher PTA levels (2nd shock), in accordance with the outcomes for Kalamata tests shown in Di Sarno et al. (2023).

Correspondingly, the de-amplification of the input strong motion due to the activation of the isolators is more significant for higher values of PTA (as for Emilia - 2nd shock) than in the counterparts at lower accelerations (as for Emilia - 1st shock). This tendency is detectable for all the tests, as shown in Figure 5 and Figure 6 where the acceleration time history of the shake table and the isolated steel plate is depicted for increasing value of PTA for Emilia and Kalamata records respectively. For Emilia tests, Figure 5, for 402_EM it is observable a reduction of about 40% of the maximum acceleration in the 1st shock (PTA = 0.22g) compared to about 70% in 2nd shock (PTA = 0.34g). The most demanding Emilia test (412_EM, PTA 0.47g) has a de-amplification of about 80%. Similarly for Kalamata tests, the reduction due to base isolation system ranges from about 20% for the lowest PTA test (424_KA, PTA 0.15g) to 60% for the highest one (426_KA, PTA 0.30g). These outcomes can be directly derived from Table 3 which summarizes the acceleration peak values recorded for shaking table and isolated plate together with the occurrence time. It can be observed that the two maxima are always asynchronous. For Emilia earthquake tests the peak on the table occurs in the 2nd shock, while on the isolated plate in the 1st one. It is to note that for the test 412_EM the maximum value of acceleration recorded on the isolated plate reaches 0.24g and it occurs at the 1st shock concurrently with the first activation of the isolation devices. Then, after this instantaneous maximum the acceleration on the isolated plate reaches at most 0.10g.



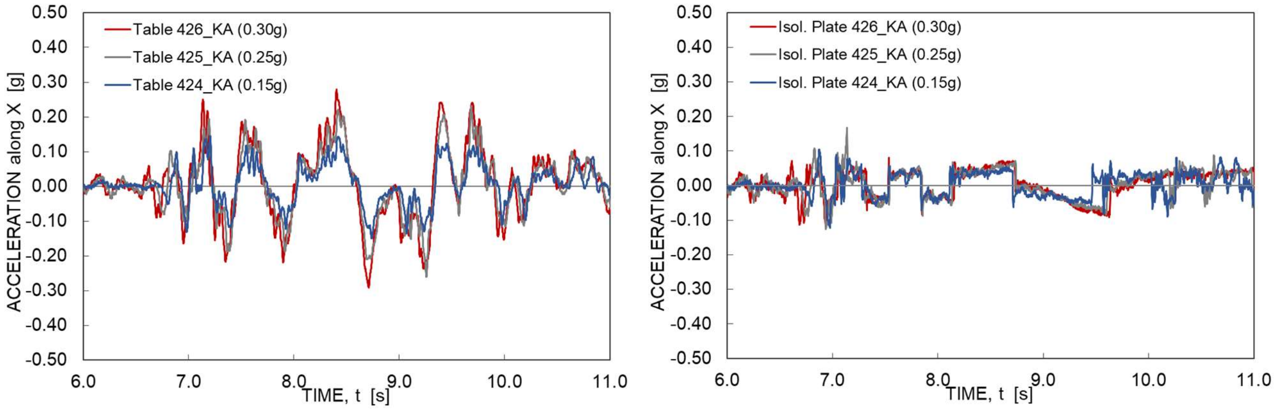
(a) (b)

Figure 4 Test 402_EM, acceleration along X direction (a) table-isolated plate comparison, (b) isolated solid pedestal-isolated bus comparison (Keys: T = shaking table, B_I = isolated bust, P_I = isolated pedestal).



(a) (b)

Figure 5 Accelerations for Emilia earthquake tests of (a) shaking-table, (b) isolated plate.



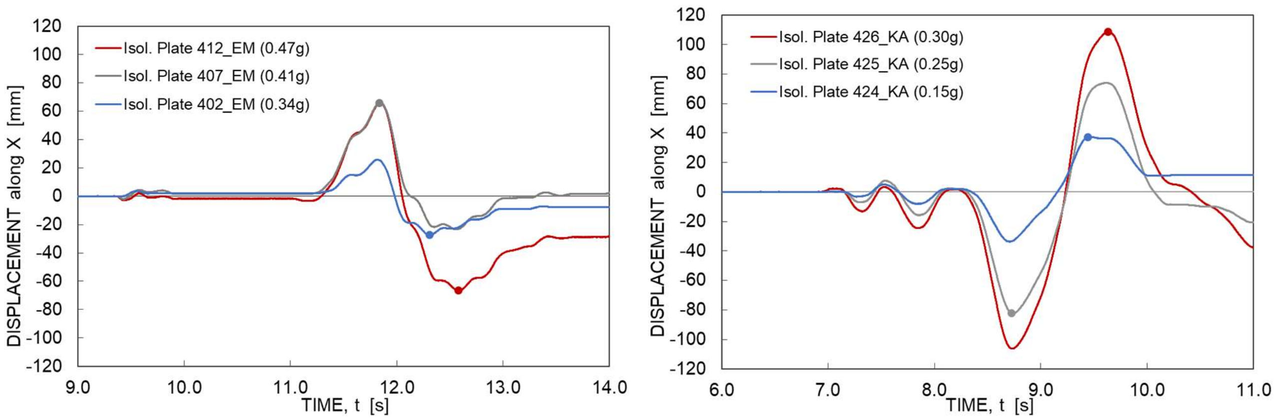
(a) *(b)*

Figure 6 Accelerations for Kalamata earthquake tests of (a) shaking-table, (b) isolated plate.

Table 3. Peak values of accelerations recorded for shaking table and isolated plate, with occurrence time and time gap.

		Max ACC_X [g]		
		SHAKING TABLE (PTA)	ISOLATED PLATE	TIME GAP
Emilia_L	**402_EM**	0.34 (*11.9s*)	0.16 (*9.3s*)	*2.6s*
	407_EM	0.41 (*11.9s*)	0.17 (*9.4s*)	*2.5s*
	412_EM	0.47 (*11.9s*)	0.24 (*9.4s*)	*2.5s*
Kalamata_L	**424_KA**	0.15 (*8.7s*)	0.12 (*7.0s*)	*1.7s*
	425_KA	0.25 (*9.2s*)	0.17 (*7.1s*)	*2.1s*
	426_KA	0.30 (*8.7s*)	0.12 (*6.9s*)	*1.8s*

With the increase of PTA, the lateral displacement of the isolated plate increases, Figure 7. Comparing the displacement measured on the isolated plate for the two set of records (Emilia and Kalamata tests) it is evident the dependence of the maximum displacement on the frequency content of the signal. According to Sect. 2, the maximum lateral displacement for Kalamata test with PTA equal to 0.30g (426_KA) is much larger than that for Emilia with PTA equal to 0.34g, confirming that Kalamata record is more displacement-demanding than the Emilia counterpart.



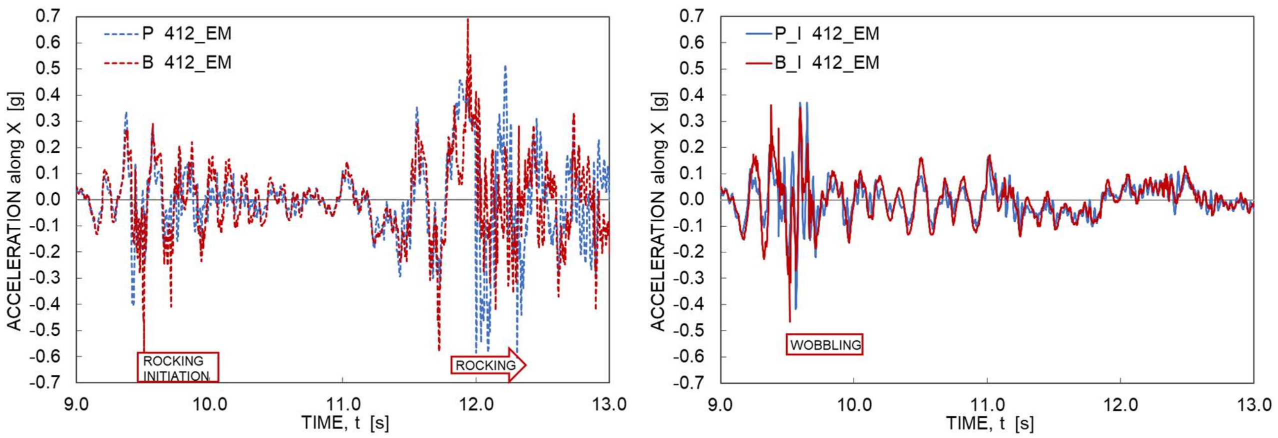
(a) *(b)*

Figure 7 Displacements of isolated plate for tests of (a) Emilia earthquake; (b) Kalamata earthquake, with peaks' indication.

5. Comparisons of unanchored and base isolated busts and pedestals

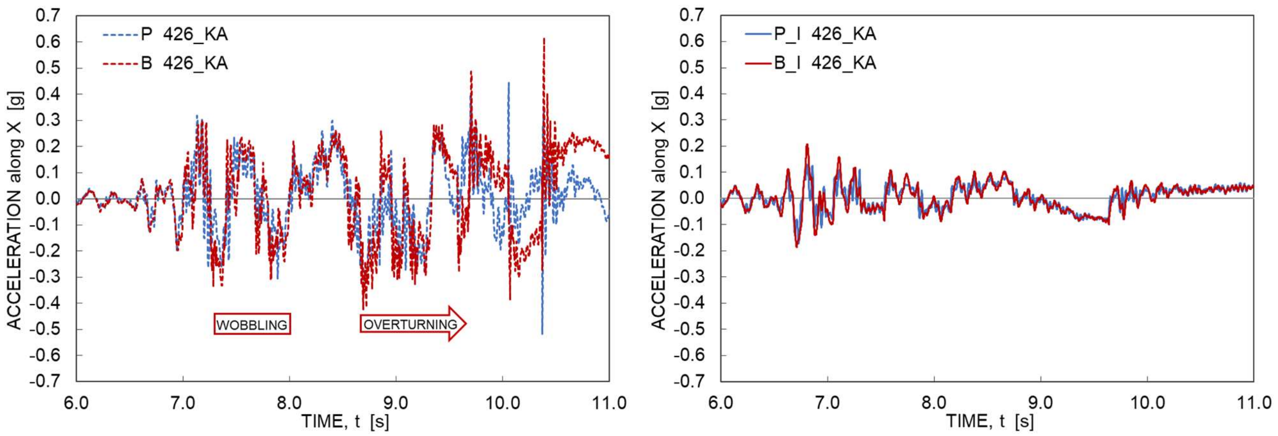
Figure 8Figure 9Figure 9 compare the response of isolated bust and pedestal with the non-isolated counterpart in terms of acceleration time history for the two seismic records Emilia_L and Kalamata_L respectively. The results of the strongest test of the two sets are shown (412_EM and 426_KA).

Beneficial effects of the isolation system in reducing the maximum acceleration transmitted to the bust are evident. In the test 412_EM with PTA=0.47g (Figure 8) for non-isolated case a first relevant decoupling of the motion of the bust from that of the pedestal is observed at about 9.4s, denoting an incipient rocking motion of the bust already at the 1st shock, followed by a second rocking activation at about 11.9s leading to a steady response with fully developed and persistent rocking in the 2nd shock, as described in detail in Berto et al (2023). For the isolated case a slight decoupling between the bust and pedestal response is observed at about 9.5s, which can be due to wobbling of the bust at the first activation of the isolators in the 1st shock. Then in the 2nd shock the dynamic response of the over-system is not activated. This behaviour is also confirmed by the visual observations carried out during the experimental campaign.
For the Kalamata record 426_KA with PTA=0.30g, the fully developed rocking and overturning of the bust observed in non-isolated case, was completely prevented by the isolation system. Figure 9b clearly shows the good match between the dynamic response of the bust and the pedestal in the isolated case and the strong reduction of the acceleration experienced by these elements.



(a) *(b)*

Figure 8 Test 412_EM (PTA=0.47g), acceleration along X direction, comparison between (a) non-isolated solid pedestal – non isolated-bust on solid pedestal, (b) isolated solid pedestal - isolated bust on solid pedestal. Initiation of bust wobbling, rocking and persistent rocking are marked.



(a) *(b)*

Figure 9 Test 426_KA (PTA=0.30g), acceleration along X direction, comparison between (a) non-isolated solid pedestal – non-isolated bust on solid pedestal, (b) isolated solid pedestal - isolated bust on solid pedestal. Initiation of bust wobbling and overturning are marked.

The isolation system's effectiveness is evident in Figure 10 where the FFTs of acceleration of isolated and non-isolated bust are shown for the two above mentioned earthquakes. Regarding the Emilia test, 412_EM, for the sake of clarity the FFTs were evaluated considering separately the 1st shock (Figure 10a) and 2nd shock (Figure 10b), in addition to the entire signal (Figure 10c). Generally, the isolation system strongly reduces the peaks in the FFT spectrum with respect to the non-isolated counterpart. Only the response to 1st shock in Emilia test does not vary much between isolated and non-isolated case. The beneficial influence of the isolation is also evident in minimizing the high-frequency spikes present in the response of the “fixed-base” counterpart, confirming the beneficial filtering effect observed for the Kalamata records in the recent work of Di Sarno et al. (2023).

To further compare the seismic behaviour of isolated and non-isolated busts, the amplifications of the horizontal accelerations between the shake table, the pedestals and the busts were assessed through the estimation of the component amplification factors (CAFs). These coefficients are reported in Figure 11. The CAF is defined as the ratio of the peak acceleration of the component to the peak acceleration of the shaking table. When referred to freestanding elements it can be considered a useful index of the component motion (Di Sarno et al., 2019). When referred to isolated plate CAF represents the “isolation ratio” of the isolation system. In this case the CAF acceleration values for 412_EM were calculated considering separately 1st shock, 2nd shock and whole record. The results confirmed the effectiveness of the adopted base isolation system, both considering the isolated plate and the artistic asset. With some little exception for the Emilia 1st shock, the CAFs of the isolated case are lower than that of the “fixed base” counterpart.

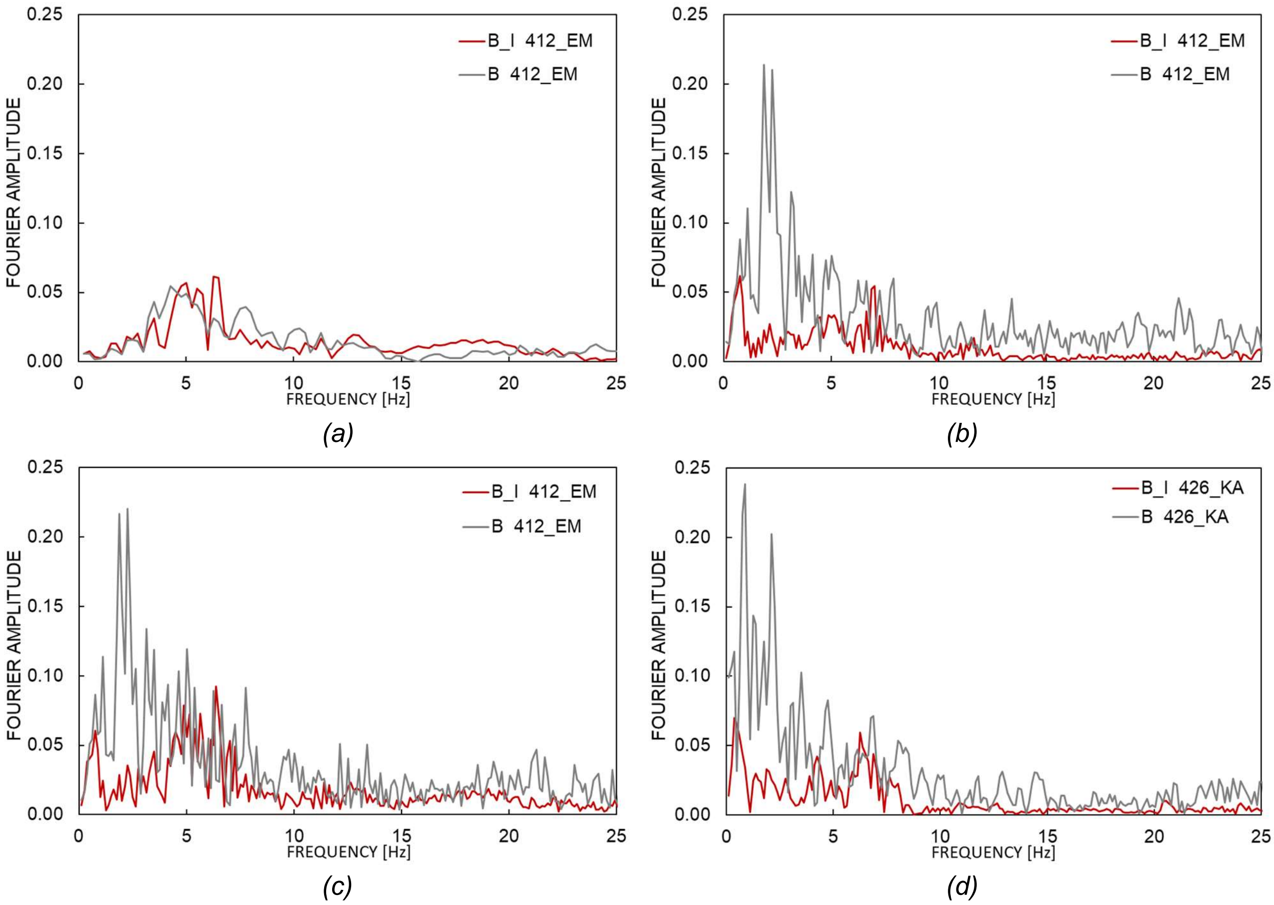


Figure 10 Comparison in terms of FFT of accelerations of isolated bust – non-isolated bust for test (a) 412_EM_X 1st shock, (b) 412_EM_X 2nd shock, (c) 412_EM_X whole record, (d) 426_KA_X.

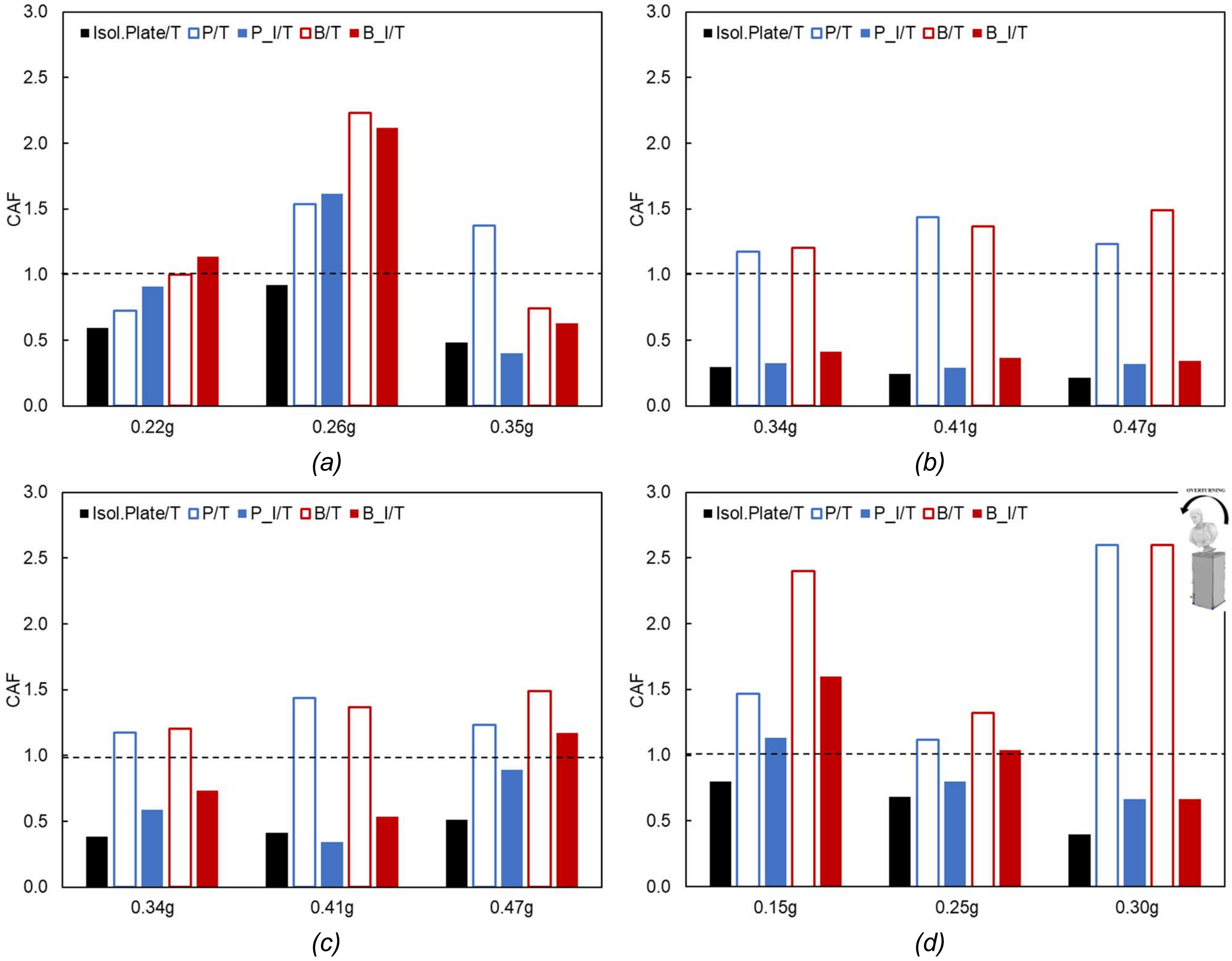


Figure 11 CAF acceleration values for tests of (a) Emilia X 1st shock, (b) Emilia X 2nd shock (c) Emilia X whole record, (d) Kalamata X.
(Keys: B = non-isolated bust, P = non-isolated pedestal, B_I = isolated bust, P_I = isolated pedestal)

The non-isolated pedestal (P) presents CAF values ranging from 0.73 to 1.54 for Emilia tests, and from 1.12 to very high values, for Kalamata tests as consequence of the overlying bust overturning. The corresponding results for the isolated case are more than 4 times lower (with the only exception of two cases of Emilia 1st shock). Concerning the non-isolated bust (B), CAF values range from 0.74 to 2.23 for Emilia, and for Kalamata tests from 1.32 to very high because of its overturning. In this case the corresponding CAFs for isolated bust are generally significantly lower.

Excluding the 1st shock of Emilia, which presented some amplification at the first activation of the isolators, the CAFs of the isolated cases tend to decrease as the input acceleration increases. Moreover, the CAF of the bust tends to approach the CAF of the pedestal, indicating that the multiblock system tends to behave as a whole rigid block for high acceleration values. These results will be corroborated by other tests.

Finally, the mean value of the CAFs evaluated for the isolated bust (B_I) is about 0.83 for all the Emilia signals (Figure 11a-b-c), and 1.10 for the Kalamata signal (Figure 11d), whilst the non-isolated counterpart (B) reaches 1.34 and 2.11 respectively. Then, for the bust a reduction of about 50% of the maximum accelerations was obtained on average through the isolation system during the shake tests.

6. Conclusions

This study presents experimental findings of base-isolated busts and pedestals, obtained through an extensive shake table testing conducted as part of the EU-funded SEREME project. Artifacts were isolated through double concave curved surface sliders isolators (DCCSS). The outcomes of two sets of tests with seismic inputs characterized by different frequency content are considered. The isolation effect is evaluated in a wide range of PTA (0.15g–0.47g). These results provide a basis for some preliminary observations useful to assess the response of DCCSS with light art objects:

- The comparison with the seismic response of non-isolated cases proves the effectiveness of the isolator system in preventing rocking/overturning motion of busts. The isolated bust experienced lower acceleration than the non-isolated counterpart: a mean reduction of about 50% of the maximum accelerations was observed. The acceleration on the isolated plate is on average scaled down by about 45% with respect to the ground motion input on the table. Additionally, a beneficial filtering effect minimizing the high-frequency spikes present in the response of the non-isolated bust is observed.

- As index of the motion of freestanding busts on the pedestals, with and without isolation system, the component amplification factors (CAFs) were computed. The mean value of CAF for the bust non-isolated case is about 1.7, whereas for the isolated case it is lower than 1. A comparison with the factors proposed by international Standards, such as ASCE (2010) is not effective since they usually considered anchored components.

- The maximum lateral displacement of the isolation system increases as the PTA increases and strongly depends on the frequency content of the seismic signal. In these tests, for the considered seismic signals, the maximum displacement is about 110mm. It is of paramount importance to stress that adequate horizontal gap needs to be allocated along the perimeter of artifacts protected through base isolation devices. Such gap depends on the hazard on the location and safety target levels to be achieved.

- Investigations on the effectiveness of connection systems between busts and pedestals and/or pedestals with isolated plate, as via metal cleats, are deemed necessary as well as suggestions for their design. This measure could be beneficial to prevent wobbling/rocking of the single elements and to control effectively the motion of isolated objects and prevent the occurrence of unexpected amplifications of the bust acceleration, which were detected at low-medium values of PTA. Nevertheless, these are not yet conclusive findings as further investigations are still in progress to account for more comprehensive earthquake scenarios.

7. Acknowledgments

The authors greatly acknowledge the financial support of the “Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe” (SERA) (European Commission, H2020-INFRAIA-2016-2017, Agreement No.730900) to the project “Seismic Resilience of Museum Contents” (SEREME). The findings and opinions, expressed in this paper are those of the authors and do not necessarily reflect those of SERA sponsors. Innovative seismic isolation devices tested in the SEREME project were kindly provided by FIP MEC srl and the metallic pedestal was kindly provided by Gruppo Fallani srl. Insightful discussions with research staff at Commissariat à l'énergie atomique et aux énergies alternatives (CEA) are also acknowledged. The PON-MIUR project “GEstioNE del rischio SISmico per la valorizzazione turistica dei centri storici del Mezzogiorno (GENESIS)” (ARS01_00883- CUP D96G18000160005), is also greatly acknowledged.

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