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Enhancing seismic resilience of museum artifacts: experimental response assessment of base isolated freestanding assets

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Abstract

The response of freestanding busts and statues exposed to the threats of moderate-to-high ground motions may cause significant damage through different mechanisms, namely sliding, rocking, and overturning. Seismic protection of museum artifacts has typically been based on best-practice approaches rarely supported by engineering evidence. Practice-oriented methods used to limit rocking may induce excessive stress concentrations at the base of statues and busts, which in turn may generate fracture or localized cracks. The present study investigates experimentally the efficiency of double concave curved surface slider isolators (DCCSSs) for protecting artistic assets. The study illustrates the results of comprehensive tests on real-scale busts and statues. Such tests were carried out at CEA laboratory, Saclay (France), utilizing the state-of-art six-degrees-of-freedom shake table Azalee. Earthquake records with different frequency contents, recorded from recent European earthquakes, along with building floor accelerations were used as input strong motions. Isolated and non-isolated artifacts were assessed experimentally with incremental loadings. The test results demonstrate that DCCSSs effectively reduce seismic acceleration amplifications. Such devices can be utilized to prevent rocking and overturning, thus enhancing the seismic resilience of vulnerable artworks and, in turn, mitigating potential losses.

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Keywords: museum artifacts; shake table tests; base isolation; rocking; building floor acceleration

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Nomenclature

PTA	Peak table acceleration	
PTD	Peak table displacement	
PIA	Peak acceleration on the isolated platform	
I_A	Arias intensity	$I_A = \frac{\pi}{2g}\int_0^{\infty}[a(t)]^2 dt$
HI	Housner Intensity	$HI = \int_{0.1}^{2.5} PSV(\xi = 0.05, T)dT$
ASI_m	ASI modified	$ASI_m = \int_{0.1}^{T^*} S_a(\xi = 0.05, T)dT$

1. Introduction

The dynamic response of museum contents, such as freestanding busts and statues, against ground motions of moderate-to-high intensity can lead to devastating consequences not only for the museum artifacts but also for local economies. The problem is present all over the world, while even quite recently various, damaging response patterns, including sliding, rocking, and overturning have been observed (e.g. Parisi and Augenti, 2013; Garini and Gazetas, 2017; Haselberg and Krist, 2020, among others).Traditional seismic protection strategies for museum artifacts have often relied on best-practice approaches lacking robust engineering validation. Moreover, conventional methods aimed at restraining rocking motions which can inadvertently lead to excessive stress concentration, thus increasing the risk of localized fracture and/or crack initiation. Given the irreplaceable nature of cultural heritage, there is a pressing need for scientifically-validated solutions that can effectively mitigate seismic risk without compromising structural integrity. Moreover, solutions with a reasonably low cost are also of importance since sometimes museum collections should be protected as a whole.

Base isolation is increasingly applied to protect lightweight museum artifacts in regions of moderate-to-high seismicity, with several notable implementations - see for example the discussion provided by Berto et al. 2025. Prominent examples are the Statue of Hermes in Ancient Olympia and the collection measures developed for the Getty Museum (Podany 2022). The exhibits of the Sanxingdui Museum in China is another recent application of the methods. Other well-known examples of art isolation are the isolation of the Francesco I d'Este in Modena (Baggio et al., 2013) and the David of Michelangelo (De Canio 2012). Moreover, several researchers have worked on the subject, i.e. Calio and Marletta (2003), Contento and Di Egidio A (2014), Wittich and Hutchinson (2017), among others. To validate such applications, recent experimental studies—primarily shake table tests—have investigated the seismic performance of statues and busts equipped with isolation systems. Despite promising results, designing isolation systems for lightweight, unanchored objects remains a distinct and challenging task, requiring approaches that differ significantly from those used in buildings or bridges. It is important to stress that seismic design codes can only partially address the problem at hand since artifacts differ from simple freestanding objects. A multidisciplinary approach including, for example archaeologists and museum experts, is always required in this case.

This study investigates the efficacy of double concave curved surface slider isolators (DCCSSs) in protecting artistic assets through experimental testing. A series of comprehensive shake-table experiments were conducted on real-scale busts and statues at the CEA laboratory in Saclay, France, within the European research project “Seismic Resilience of Museum Contents” (SEREME) (Fragiadakis et al. 2020a, 2020b). The tests incorporated earthquake records with varying frequency contents, derived from recent seismic events, as well as building floor accelerations to simulate realistic conditions. Both isolated and non-isolated artifacts were subjected to incremental dynamic loading to assess performance.

2. Experimental tests on Busts and Pedestals

As mentioned above, the paper presents some of the experimental findings of SEREME (Seismic Resilience of Museum Contents). The tests focused on enhancing the seismic safety of museum artifacts through experimental and numerical research. Real-scale statues and busts were subjected to earthquake shaking table simulations in order to

evaluate the vulnerability and the effectiveness of seismic protection systems. This paper investigates one of the configurations tested during the SEREME testing campaign involving five busts on different pedestals. More specifically, this study examines the seismic response of two elements standing directly on the shake table and two replicas placed on a base isolated steel platform (see Fig. 1). One of the busts was placed on a solid pedestal (concrete block 0.45x0.45 m x 1.01m) and the other on a hollow pedestal (concrete block 0.35x0.35 m x 1.01m, thickness 0.08m). Further information about the specimens can be found in Berto et al. (2023, 2025).

The isolation system investigated in this work is constituted by a heavy steel platform installed on three double concave curved surface sliders (DCCSS). These devices are characterized by an equivalent curvature radius R=2.5m, a maximum displacement capacity ±300mm and a maximum vertical load of 20 kN and were designed and manufactured by FIP MEC. From the results obtained through preliminary dynamic tests involving sinusoidal movements applied at different frequencies and for two values of vertical load, a dynamic friction coefficient of 4.53% was determined by linear interpolation considering the weight acting over the devices in the test configuration analysed in this study. Further details on the mechanical characterization of the devices can be found in Berto et al. (2025).

The isolated specimens were carefully placed on the steel platform, ensuring that the center of mass of the ensemble of artifacts and platform was as close as possible to the center of mass of the isolation system. This experimental setup allowed us to simultaneously compare the performance of isolated and non-isolated elements and different types of pedestals.

The experimental program employed shake table tests subjected to seismic inputs characterized by diverse frequency contents and varying numbers of acceleration components (uniaxial, biaxial, and triaxial). Four historical near-field earthquakes from Greece and Italy were selected as strong motion inputs, in order to account for a broad frequency spectrum: 2012 Emilia earthquake, 1986 Kalamata earthquake, 1999 Athens earthquake and 2009 L'Aquila earthquake, whose characteristics are fully described in Berto et al. (2023). In addition, in this configuration a floor input signal was considered. The acceleration time history of the first floor of a modern reinforced concrete (RC) two-stories wall structure museum subjected to 2012 Emilia earthquake was numerically obtained with nonlinear time history analysis through an OpenSees-based (McKenna, F. 2010) fiber model. As a two-story RC structure with RC structural walls, it exhibits high stiffness, with natural periods T_x =0.17s, T_y =0.14s. For the time histories considered, the PGA of the original signal was 0.25g and the corresponding peak acceleration at the first floor was 0.37g, thus leading to a moderate PFA/PGA ratio equal to 1.48.

For the purpose of response analysis of artifacts, each seismic record underwent scaling to multiple intensity levels during experimental tests.

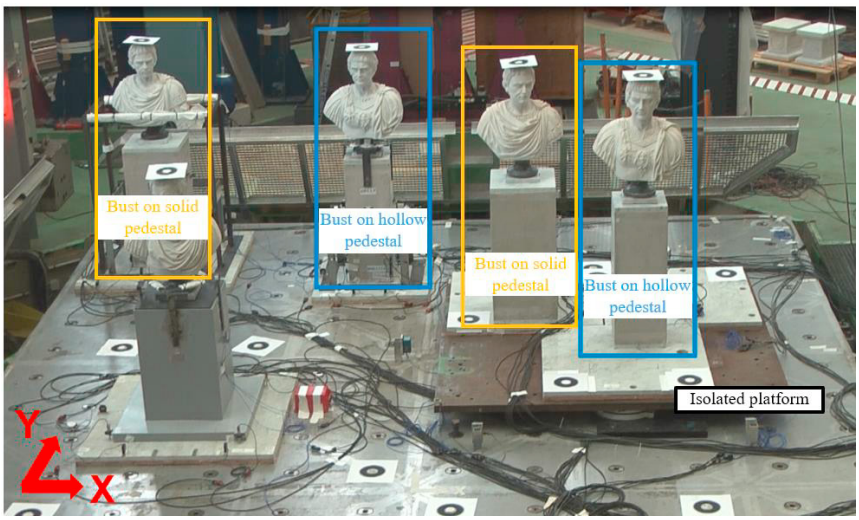
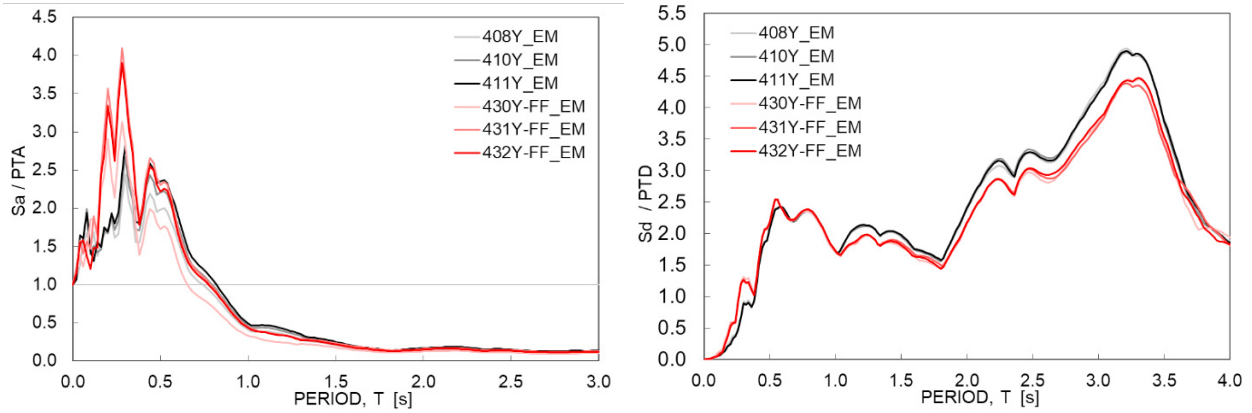


Fig. 1. Shake table with selected test configuration (the squared frames indicate the studied artifacts).

This work focuses on the tests of this configuration carried out with Emilia inputs in Y direction, the weakest direction of the busts for rocking occurrence including both ground and building first floor accelerations, labelled EMILIA Y and EMILIA Y-FF, respectively. Fig. 2 provides the normalized spectral acceleration and the normalized spectral displacement of the sample input signals: three runs of Emilia Y signal (PTAs within the range from 0.20g to 0.39g) and three runs of the Emilia Y-FF signal (PTAs within the range from 0.19g to 0.33g). The values of PTA and PTD for the six signals are reported in Table 1.

It is worth noting that the acceleration floor input spectra exhibit amplifications between 0.15s and 0.40s, whilst there are not relevant differences for higher values of periods both for acceleration and for displacement spectra. Such outcome is compliant with the high lateral stiffness of the RC wall-structure building. For further investigation, Fig. 3 provides the Fast Fourier Transform (FFT) for the two tests with the highest value of PTA of Emilia Y (411Y_EM, PTA 0.39g) and of Emilia Y-FF (432Y-FF_EM, PTA 0.33g). From the comparison of the two curves it can be observed that the FFT curve of the first floor signal presents a forward shift and an extension of the maximum amplification range. In the sample plots it is also evident the occurrence of additional frequencies, which can be attributed to the vibration modes of the structure. Finally, the integral parameters utilized by Berto et al. (2025) as Intensity Measures (IMs) as well as Engineering Demand Parameters (EDPs) were computed for the sample input motions and were used to describe the performance of the isolation system, as reported in Table 1.



(a) (b)

Fig. 2. For ground EMILIA Y and floor EMILIA Y-FF shake table signals: (a) normalized spectral acceleration, (b) spectral displacement

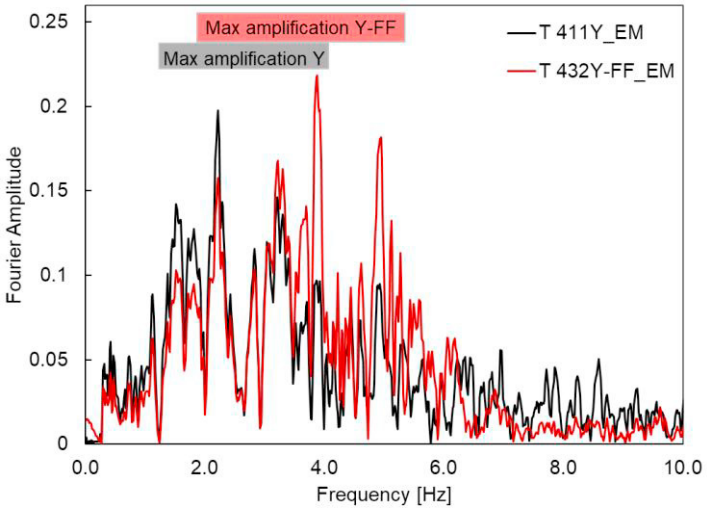


Fig. 3. Response of table (T) subjected to 411Y_EM and 432Y-FF_EM in terms of Fourier amplitude

Table 1. PTA and integral parameters of the shake table signals

		Emilia Y			Emilia Y-FF		
		408	410	411	430	431	432
PTA	[g]	0.20	0.30	0.39	0.19	0.23	0.33
PTD	[cm]	1.20	1.98	2.76	0.91	1.49	2.07
Arias intensity I_A	[m/s]	0.245	0.610	1.149	0.337	0.760	1.392
Housner Intensity HI	[cm]	33.64	55.60	77.33	27.56	44.32	61.00
ASI modified	[g·s]	0.319	0.516	0.714	0.290	0.458	0.629

3. Response of base isolation system

The performance of the DCCSSs under Y-directional seismic excitation is assessed by comparing the acceleration time histories on the shake table with those recorded on the isolated platform. Fig. 4 shows these accelerations for 411Y_EM (PTA 0.39g) and 432Y-FF_EM (PTA 0.33g) tests, which exhibit the highest value of PTA for input motions Emilia Y at ground level and Emilia Y-FF at floor level, respectively.

Fig. 5 displays the corresponding Fourier amplitudes (FFT), where beneficial effects of the DCCSSs are evident. As anticipated in Section 2, the frequency content of the signal at floor level is more significant in the range 4-6 Hz than the counterpart for ground level 411Y_EM test.

To gain further insight into the behaviour of the DCCSS isolation system, the integral response quantities introduced in Sect. 2 were computed. Fig. 6 illustrates the ratios of these quantities for the isolated steel platform and the shake-table for (a) the three tests of Emilia Y and (b) the three tests of Emilia Y-FF. Additionally, the Figure presents the ratio of the peak acceleration on the isolated platform PIA to PTA to quantify the effects of the isolation system. It is worth mentioning that the smaller the values, below unity, the higher the efficiency of the isolator.

The results show that the efficiency of the isolator increases as the PTA values increase, since all computed parameters exhibit a decreasing trend of the ratio isolated platform-to-table. Furthermore, in all but one case (test 408_EM, with a low value of PTA), the integral parameters are less than 1. Similarly to the outcomes obtained for multiple records along X-direction as reported by Berto et al. (2025), Arias Intensity (IA) is the parameter most effectively reduced by the isolator system. As far as PIA/PTA is concerned, a reduction of peak accelerations up to 60% (for PTA= 0.39g) is computed.

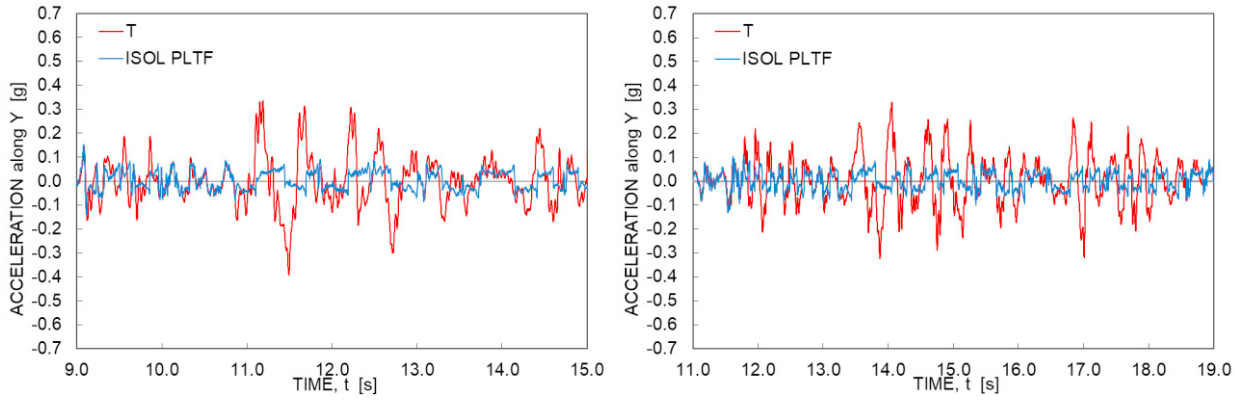
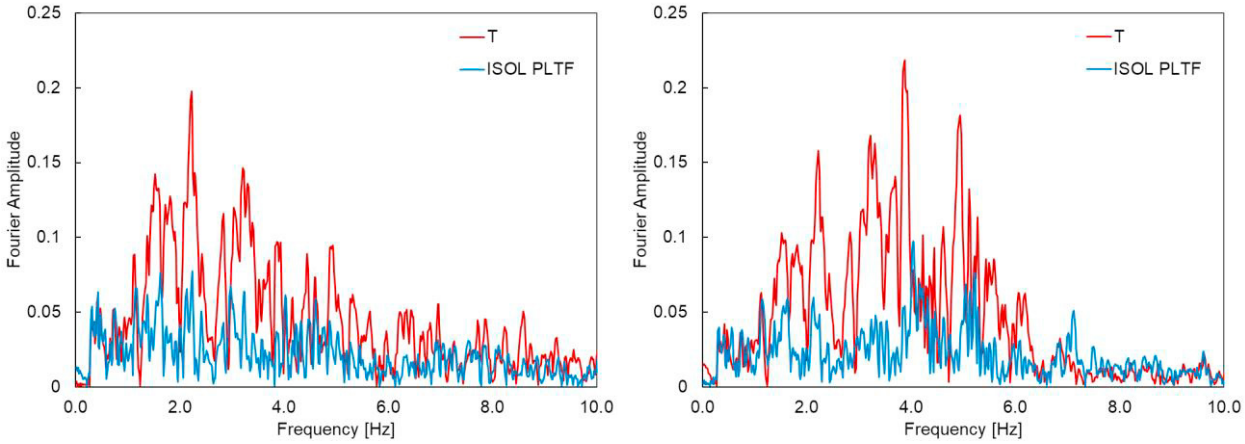
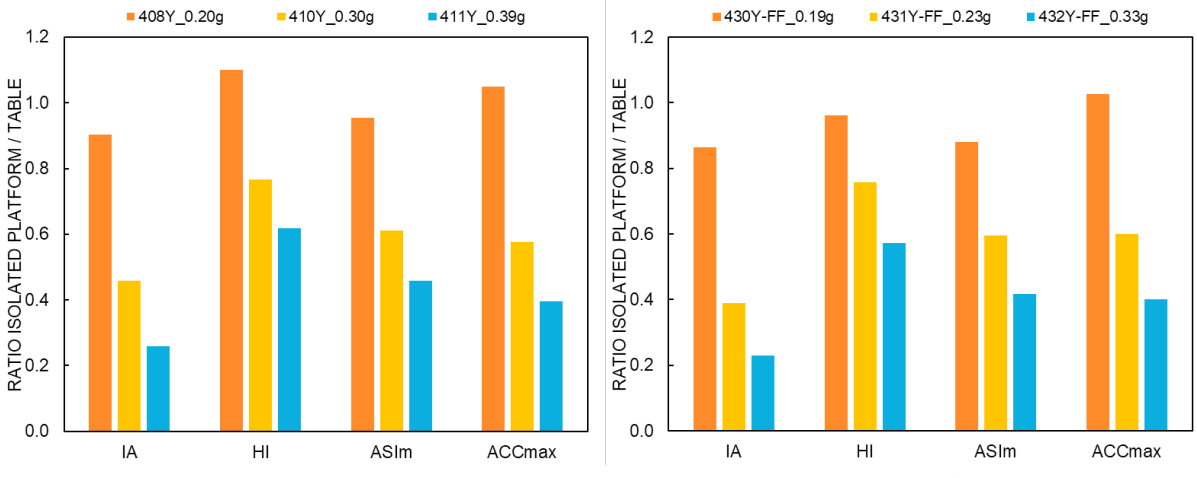


Fig. 4. Comparison between table (T) and isolated platform (ISOL PLTF) accelerations in Y direction for (a) 411Y_EM test (PTA 0.39g), (b) 432Y-FF_EM (PTA 0.33g) test.



(a) (b)

Fig. 5. Comparison between table (T) and isolated platform (ISOL PLTF) accelerations FFT in Y direction for (a) 411Y_EM (PTA 0.39g), (b) 432Y-FF_EM (PTA 0.33g).



(a) (b)

Fig. 6. Ratio between isolated platform and table behaviour in terms of integral parameters and maximum acceleration, for (a) Emilia Y tests, (b) Emilia Y-FF tests.

4. Response of Bust and Pedestals with and without base isolation

The response of the non-isolated artifacts and the isolated counterparts for the tests with the highest values of PTA are compared hereafter. Fig. 7 displays the accelerations in Y direction of hollow pedestal for (a) 411Y_EM (0.39g) test and for (b) 432Y-FF_EM (0.33g) test.

The computed results show that the isolator mitigates the seismic response of the hollow pedestals for both signals, reducing significantly the acceleration (reduction is five-folds). Such results are further supported by visual inspection, where rocking is clearly observed for non-isolated artifacts, both for 411Y_EM and for 432Y-FF_EM. The isolated counterpart tends to exhibit wobbling motions for 432Y-FF_EM test.

The beneficial effect of the isolator is even more evident when observing the response of the bust on hollow pedestal in Fig. 8 for the most demanding input signal. The acceleration time history and visual inspection confirm that the non isolated bust starts a rocking motion, leading to overturning, while the isolated counterpart remains at rest.

To further investigate the different seismic responses of isolated and non-isolated artifacts, 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 ratio corresponds to the component amplification factors (CAF) whilst for the isolated case to the dynamic modification factor (DMF) since it also includes the effect of the isolator, Berto et al. (2023, 2025). The findings demonstrated a relevant reduction of these ratios for the isolated elements with respect to the non-isolated counterparts. For the hollow pedestal this ratio reduces from 5 to 8 times, for 432Y-FF_EM (0.33g) and 411Y_EM (0.39g), respectively, and is higher than 4 for the bust in both tests.

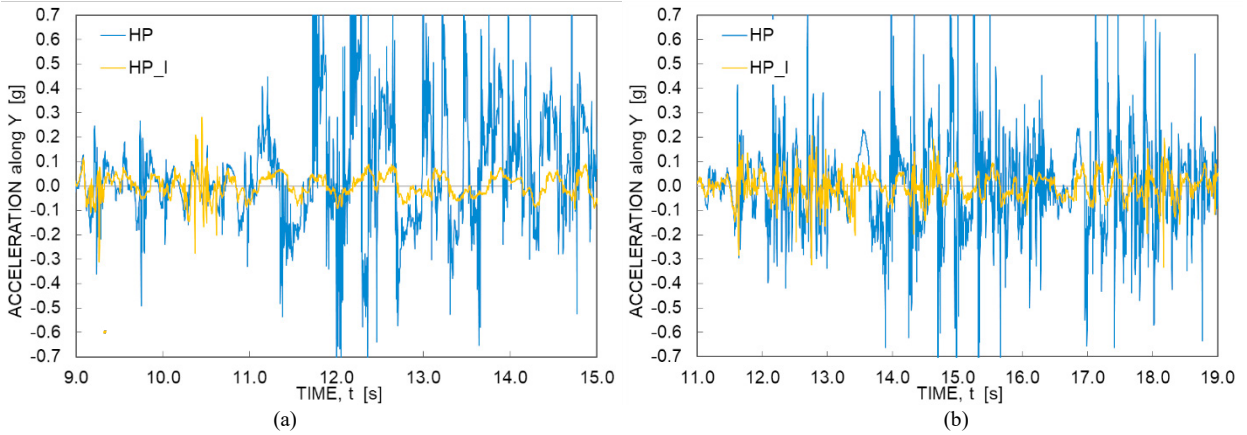


Fig. 7. Comparison between non isolated and isolated hollow pedestal in terms of accelerations in Y direction for: (a) 411Y_EM test (PTA 0.39g), (b) 432Y-FF_EM.

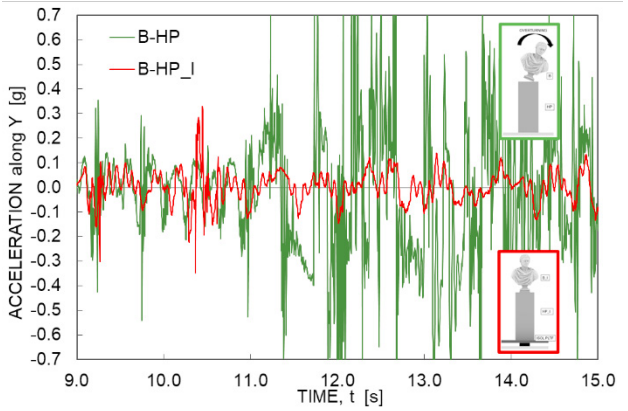


Fig. 8. 411Y_EM test: Comparison between non isolated and isolated bust on hollow pedestal in terms of accelerations in Y direction and evidence of the outcomes of the visual inspection

5. Conclusions

The present work illustrates experimental results from the EU-funded SEREME campaign, concerning shake-table tests of both isolated and non-isolated busts and pedestals. Specifically, this paper presents the outcomes from tests conducted in the Y-direction, which represents the weakest axis for the rocking of busts, including also floor input signals.

The computed results confirm the outcomes of the numerous tests along X direction reported by Berto et al. (2025). It is confirmed the adequate performance of the DCCSS isolators also in Y direction, even when subjected to floor signal accounting for the filtering effect of the building. The isolators led to a significant cut of peak accelerations on the isolated platform with a reduction of the acceleration up to 60% (for PTA= 0.39g) is found. The isolator performance has been also evaluated throw the reduction of integral response parameters of the signals measured on the isolated platform with respect to the counterpart in the shaking table. Similarly to the results of the tests in X

direction, Arias Intensity (IA) is the parameter most effectively reduced by the isolator system. As expected, for all examined integral parameters a decreasing trend is visible as PTA increased.

The present study confirms the importance of protecting artistic assets through base isolations systems and stress the relevance of using adequate pedestals to further damp the earthquake-induced vibrations. The use of DCCSS isolators was found effective to reduce seismic acceleration amplification, preventing rocking and overturning, if any.

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