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Seismic response assessment and protection of statues and busts

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Abstract

Recent post-earthquake surveys carried out in Europe have shown that earthquake actions pose an immense threat to museums and their contents. For example, during the earthquake on 21 July 2017 in the island of Kos (Greece), severe and widespread damage on the city's archaeological museum was reported (Figure 1). The earthquake extensively damaged the

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sculpture exhibition, where many pieces were dislocated, leaned against the walls, or overturned. Fortunately, the earthquake occurred when human visitors were not in the museum, since the damage to the exhibits varied from very light (minor fracturing) to severe (complete overturning and fracture of artefacts). In the case of heavy and slender sculptures, the overturning mechanism, apart from damaging the sculptures themselves, is a serious threat to other standing exhibits in the gallery and the visitors. It is, therefore, of paramount importance to have at our disposal methods and tools for characterising the seismic risk of museum artefacts and, where necessary, proposing cost-efficient protective measures.

Figure 1. Seismic damage on the statue collection of the Archaeological museum of Kos island on 21 July 2017.

The study of the seismic vulnerability of museum artefacts, especially of slender, human-formed statues, is related to the research on the dynamic response of rocking rigid blocks. The dynamic characteristics of the hosting structures are also important. This is evident from the fact that, on many occasions, damage to the structure was reported leaving the exhibits intact and vice-versa. Although the problem is coupled, it can be studied looking separately at the structure and its contents, provided that the contents are not attached to the building. The seismic response of building contents is a topic of growing interest, since it is directly related to seismic loss assessment and earthquake community resilience. Building contents can be either attached to the structure, or may consist of objects that are simply standing. Museum exhibits belong to the latter category, while free-standing components are often studied as rocking objects and hence their response is sensitive to acceleration and velocity-based quantities and also to their geometry. Today, there is lack of standards, while the existing approaches are general in concept and do not sufficiently address the variety of rocking objects. The problem becomes more complicated when it comes to priceless objects such as museum artefacts where more refined and targeted studies are required for understanding their seismic response and also for proposing rapid tools for assessing their seismic risk.

The paper presents an extensive experimental campaign on the seismic response of artefacts, with emphasis on statues and busts. The tests took place in the framework of SEREME project (Seismic Resilience of Museum Contents) at the AZALEE seismic simulator of CEA in Saclay, Paris under the auspices of the SERA project. The aim is to understand the seismic response of statues and busts and then develop novel and cost-effective risk mitigation schemes for improving the seismic resilience of museum valuable contents. The study is focused on the investigation of the seismic response of two real-scale marble roman statues and three busts of three roman emperors standing on pedestals of different types and size. Both isolated and non-isolated artefacts are considered, while two new and highly efficient base isolation systems, tailored to art objects, will be tested. The first isolator is a pendulum-based system, while the second utilizes Shape Memory Alloy wires. Furthermore, the paper examines the importance of the hosting building, i.e. building type and story. Specifically tailored, numerical models of varying complexity, for single and two-block rocking systems, were developed for the needs of this study and are also assessed against the experimental results.

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1. Introduction

Earthquakes are a major threat to museums worldwide, while European museums host significant assets of the world’s cultural heritage. The protection of museums and their treasures against earthquakes is, therefore, a priority, especially for resilient communities. Generally speaking, the study of the seismic behaviour of museum assets and the investigation of novel and cost-effective risk mitigation schemes for improving the seismic resilience of European museums has received little attention in the literature. SEREME project intends to cover this gap through a big number of tests in an extensive experimental campaign.

The seismic response of building contents is a topic of growing interest, since it is directly related to seismic loss assessment and earthquake community resilience and also to the three-dimensional rocking response that has not received the interest it deserves. Common structural analysis and design methods require the assessment of stress resultants and displacement-based quantities. On the other hand, building contents can be attached to the structure but in most cases consist of objects that are freestanding. There are recent works in which the seismic response of freestanding contents is investigated, e.g. Berto et al. (2013), Chiozzi et al. (2015) and DiSarno et al. (2017) among others. Museum exhibits belong to the latter category and the free-standing components are often studied as rocking objects and hence their response is sensitive to acceleration and velocity-based quantities and also to their geometry. Recent studies (e.g. Yang et al. (2009), Adam et al. (2013) Porter et al. (2015) and Fragiadakis et al. (2017) just to name a few) and guidelines (FEMA P-58 (2012), FEMA E-74 (2012)) are focusing on the study of building contents, but the approaches proposed are general in concept and do not sufficiently address the variety of rocking objects. Museum artefacts are priceless objects and, therefore, the problem becomes more significant. In order to understand the seismic response of museum artefacts and propose quick tools for assessing their seismic risk more refined and targeted studies in non-structural components are required.

Exhibits of large size, e.g. sculptures, typically stand on the floor, while exhibits of smaller size are somewhere placed, e.g. on a pedestal (Figure 2). Thus, the former can be modelled assuming equivalent single rocking blocks, while two-block assemblies are required for the latter. Modelling is not always straightforward, since often statues are "glued" to the pedestal with mortar and/or adhesives of unknown strength, thus statue and pedestal may respond as a single block.

For the seismic response of rocking objects, the early study of Housner (1963) set the framework for many later efforts which presented analytical or numerical solutions (Zhang and Makris (2001), Voyagaki et al. (2013), Dimitrakopoulos and Fung (2016), Diamantopoulos and Fragiadakis (2019)) and also experimental approaches. Among the more recent studies, Purvance et al. (2008) carried out extensive experimental and numerical studies to investigate the overturning response of symmetric and asymmetric blocks with both simple and complex basal contact conditions and also proposed block overturning fragilities. Similarly, ready-to-use fragility curves were proposed by Konstantinidis and Makris (2009) through a comprehensive experimental program on full-scale freestanding laboratory equipment located on several floor levels. Generally, these studies considered the behaviour of a single block and only few analyzed dual-body systems. The dual block problem was first studied analytically by Psycharis (1990), while the recent experimental work of Wittich and Hutchinson (2017) studied asymmetric free-standing component configurations. Note that for rocking problems the response is size-dependent, thus the scaling of the specimens is not possible and tests are usually carried out on unscaled specimens. For multi-block assemblies, Psycharis et al. (2013) proposed a performance-based and fragility analysis framework.

A range of viable retrofitting measures for protecting museum artefacts is discussed by Podany (2015), where the practices followed by the J. Paul Getty Museum in Los Angeles, in California, are summarized. Most of the suggested retrofitting measures are applicable on statues, while a novel base isolation system for the artefacts of the Getty museum was developed. Past research on the seismic protection of art objects using isolators, includes primarily several analytical and numerical investigations (e.g. Calio and Marletta (2003) and Contento and Di Egidio (2014)), while to our knowledge only few experimental studies can be found in literature, such as the work of Berto et al. (2013), which reports the results of shake table experiments on rigid blocks simulating the geometrical and inertial properties of a set of statues placed on sliding isolators.

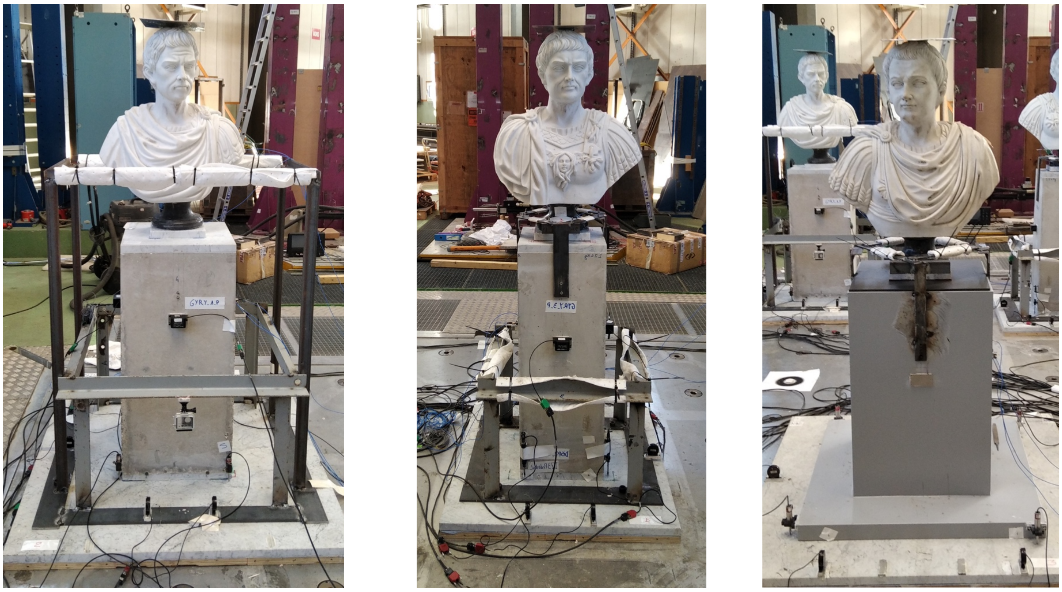
The SEREME project initially studies the seismic behaviour of museum assets that are freestanding on a marble floor or on a pedestal aiming to improve the seismic resilience of European museums and of the hosted exhibits. Concerning the seismic isolation, two pioneering isolation systems (ISOLART® PENDULUM &ISOLART® SMA) for museum exhibits are today available from FIP Industriale. The two systems are extensively tested in low mass objects during the SEREME project. The first system is a specifically-designed pendulum isolator, e.g. Castellano et al. (2016), while the latter is a novel isolator based on a Shape Memory

Alloy wires. The resilience of the seismically protected artefacts is compared towards artefacts without any special protection.

2. Description of experimental campaign

2.1. Busts and pedestals

SEREME project is focused on the investigation of the seismic behaviour of two real-scale marble roman statues (two copies for each) and three busts of roman emperors standing on pedestals (Figure 2a) of different types and size. The busts are always on a pedestal which is used in order to bring the specimen to the eye-level of the visitor. Three different pedestal types were considered: (i) solid pedestal, with dimensions 45×45×100 cm, (ii) hollow pedestal, with dimensions 35×35×100 cm, and (iii) modern type metallic pedestals. The old style, hollow and solid, pedestals were made of concrete that has a specific weight close to that of marble, while at the upper and the lower face of the pedestals marble plates with thickness equal to 3 cm were installed. The difference between these two pedestals lies on the fact that the solid pedestal is massive with a large base and hence it is difficult to uplift, while the hollow pedestal is slenderer since its center of gravity is higher and also it has a small base. The metallic pedestal had a large square base with side equal to 85 cm but it weighs only 85 kgr.



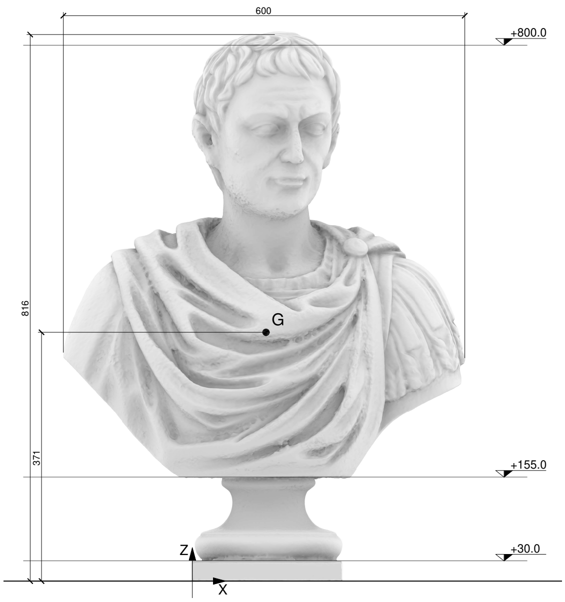
(a) (b) (c)

Figure 2. Busts on (a) a solid/large and hollow/small pedestal; (b) a hollow/small pedestal; (c) a metallic/modern pedestal.

The geometric characteristics of all the specimens were obtained with the aid of laser scanning (Figure 3). Statues, busts and artefacts are usually laser scanned in order to estimate their geometrical and inertial characteristics. Laser scanning has two-fold purpose: first it provides a fine mesh of the artefact's geometry that can be then introduced in a Finite Element software and second it gives useful information such as the center of mass, the total mass, the rotational moments of inertia and the distance of the CM from the pivot points. An example of laser scanning from the current work is shown in Figure 3.

2.2. Base isolation

Base isolation can be a very efficient approach for the seismic protection of building contents. Such systems should be tailored to “low” mass structures. Therefore, for art objects as well as other non-structural components with small mass, there are particularities and the classic isolators cannot be used. Several low-mass seismic isolation systems have been proposed in the literature, but most of them are either under construction or have not been tested in real ground motion records. A range of viable retrofitting measures for protecting museum artefacts is discussed by Podany (2015), where the practices followed by the J. Paul Getty Museum in Los Angeles in California. Other systems, e.g. friction-pendulum systems (Castellano et al. (2016)) and systems based on Shape Memory Alloy (SMA) wires have been successfully tested, while the wire-rope technology has been addressed for the seismic isolation of statues. For the latter case, most works are based on analytical solutions or Finite Element models (Calio and Marletta (2003) and Contento and Di Egidio (2014)) while in the paper of Berto et al. (2013) a number of experimental results has been presented. They simulated the geometric characteristics of a big number of seismically isolated specimens. Chiozzi et al. (2015) also have experimentally investigated the response of heavy non-structural monolithic objects while Wittich and Hutchinson (2017) studied the behavior of asymmetric statues without seismic isolation system.



(a)

(b)

Figure 3. (a) Geometric properties of the bust, (b) laser scanning.

Under the auspices of the SEREMA project two new base isolation systems, pertinent for art objects will be extensively tested on a shake table for the first time. The two systems are commercially available by FIP Industriale and are known as ISOLART® PENDULUM and ISOLART® SMA, respectively. The former system, is a specifically-designed pendulum isolator, while the latter is a novel isolator based on Shape Memory Alloy (SMA) wires that is still under testing. ISOLART® PENDULUM, is similar to the well-known pendulum isolators used for structures, but it consists of different materials and it has been designed specifically for low-mass structures such as objects of art. ISOLART® SMA is a patented isolation system which takes advantage of the super-elastic properties of SMA wires, i.e. their capacity to have a stress-induced non-linear behaviour similar to elasto-plastic behaviour up to high deformations (about 7%) and unload to zero displacement. The main difference between the two isolation devices is the range of mass of the objects to be isolated. The SMA-based system is more suitable for very small mass objects, while for larger mass objects the pendulum system is preferable. Moreover, the SMA-based system is able to resist tension as opposed to the pendulum isolators that obviously cannot.

2.3. Hosting structure

Today most museums are located in historical buildings at the centres of European cities. Typically, museums are low-storey buildings. The statues are usually hosted on the ground floor but artefacts can be found in all stories of the structure either as freestanding or elevated on a concrete, hollow or solid, pedestal or on a metallic pedestal (modern designed). The SEREME project considered a case-study museum, a typical reinforced concrete museum building. Strong ground motion records of different amplitudes are applied on the numerical models of the structures and the acceleration response histories at different locations along the plan/height of the building are calculated numerically and used as acceleration input for the shake table tests. The case-study building is very stiff with first eigenperiod T_1=0.18sec. The models created both in Seismostruct and OpenSees for comparison reasons.

In case of museum exhibits, the dynamic response of the structure that hosts the exhibits is very significant. There are cases, e.g. big statues that are hosted in the ground level and their response in not affected by the structure. When the artefacts ate placed on a floor of a building their response is coupled with the building's behaviour. Fragiadakis and Diamantopoulos (2018) have investigated the response of rigid blocks when they are on different stories of a plane frame while they have proposed the framework for the fragility assessment of objects that can rock and their motion is described by Housner's (1963) theory.

2.4. Testing configurations

Eight different configurations were tested on the AZALEE shake table at TAMARIS/CEA in Paris. The tests were carried out on January-February 2020 and lasted approximately one month and a half. Each configuration compared the response of different pedestal and isolator types. The most populated configurations, in terms of the number of statues tested, are shown in Figure 4. Ten different ground motion records, each scaled to different levels of seismic intensity were resulting to more than 400 seismic simulations in total. Furthermore, a very detailed monitoring scheme was adopted. The monitoring considered of measurements of the acceleration and of the uplift of the statues and the pedestals. Regarding the monitoring of the rocking motion, the bodies were assumed rigid and gyroscopic measurements of the rotational velocity were obtained. Furthermore, for the upper body, i.e. the bust/statue, videometric measurements of the displacement were obtained with the aid of a camera positioned right above the shake table.

3. Seismic response assessment

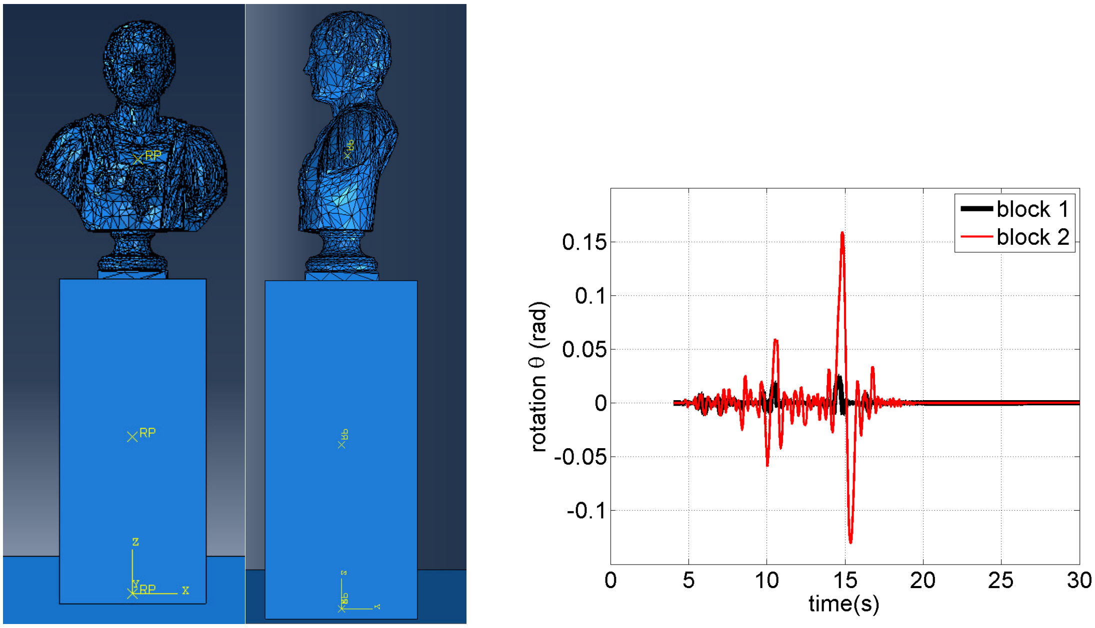
As it has already been discussed laser scanning was adopted for determining the geometric characteristics of the busts and the statues that examined in this campaign. The accuracy of the scanning provides the information for the elements, nodes and surfaces that are then simulated on a Finite Element software. However, because of the high precision of the procedure, the required analysis time in a Finite Element model is considerably increased. Hence, simple models should be also adopted for the seismic response prediction. The models consider either two-block assemblies (pedestal-bust) or freestanding, symmetric or asymmetric, rocking blocks (a freestanding statue or a bust that rocks on a pedestal in rest). Simple models are typically limited to one-direction simulations and hence the procedure should be repeated for both longitudinal and transverse direction due to the asymmetry of the specimens. A simplified approach is offered using the equation of motion proposed by Housner (1963). A possible solution approach based on the theory of Housner is that proposed by Diamantopoulos and Fragiadakis (2019). For the two-block case and for simplicity reasons the work of Psycharis (1990) can be adopted. The equations of motions in every case should be solved using methods from the literature (Runge-Kutta, Newmark etc) and considering that energy dissipation takes place when an impact occurs. Vlachos et al. (2019) presented a first attempt to extend the two-block problem in case of asymmetric upper block when the pedestal is symmetric.

The simulation of the problem using the Finite Element Method (Figure 5a) has advantages concerning the accuracy but there are also difficulties. The surface-to-surface interaction between the upper surface of the pedestal and the lower surface of the bust requires knowledge of the friction coefficient and the damping ratio, while damping of the motion due to rocking impacts cannot be introduced in a straightforward manner. Also, the FE method is a more realistic assuming either rigid or flexible bodies. Introducing the flexibility and the real modulus of elasticity of the artefacts will increase the CPU time, thus making prohibitive a large number of simulations. On the other hand, the Discrete Element Method (DEM) assumes that the objects are rigid and consequently can be adopted with reduced computing cost. For the interaction between the surfaces, springs can be introduced but they should be appropriately calibrated. Psycharis et al. (2013) have described the numerical model for the simulation of a multi-drum ancient columns which is subjected to natural ground motion records. The column consists of eight rigid bodies, the upper placed on the top of the lower. In this work the 3DEC software has been used for the simulation of the problem.

Figure 4. Two different testing configurations considered. The busts on the right-hand side of the photo are placed on friction pendulum isolators.

4. Conclusions

The paper presents an extensive experimental campaign on the seismic response of artefacts, with emphasis on statues and busts. The tests took place in the framework of SEREME project (Seismic Resilience of Museum Contents) at the AZALEE seismic simulator of CEA in Saclay, Paris under the auspices of the SERA project. The campaign aims to help us understand the seismic behavior of the selected statues and busts and then to develop novel and cost-effective risk mitigation schemes for improving the seismic resilience of valuable objects hosted in European museums. Two real-scale marble (replicas are usually made from gypsum) roman statues and three busts of three roman emperors standing on three pedestals of different types and size are investigated concerning their response under seismic loading. The artefacts are considered either isolated or non-isolated. In the latter case, two new and highly efficient base isolation systems, tailored to art objects, are tested. The efficient and the effectiveness of the isolators are of the main interest of the authors. The first isolator is a pendulum-based system, while the second utilizes Shape Memory Alloy wires. Different configurations were considered for examining all cases. The importance of the hosting building is also examined, i.e. building type, stiffness and story that hosts the artefacts. Specifically tailored, numerical models of varying complexity and Finite Element models for single and two-block rocking systems, were developed for the needs of this study and are also assessed against the experimental results.



(a) (b)

Figure 5: (a) Finite Element model (pedestal-bust), (b) response time history (Loma Prieta 1989).

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