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Eccomas Proceedia COMPDYN (2025) 303-314

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COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

SEISMIC PERFORMANCE OF THE STATUE "MARZOCCO" EXHIBITED AT THE NATIONAL MUSEUM OF BARGELLO (FLORENCE, ITALY)

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Abstract

The assessment of the seismic vulnerability of artifacts has been collecting many experimental and theoretical contributions. Numerical analysis through FEM models has been extensively adopted to represent the dynamic response of complex systems - such as sculptures and objects of art - subjected to seismic excitation. Due to the on-going increase of the computational capacity of software, FEM modeling has been becoming more and more effective, allowing to represent many of the most relevant behaviors of the dynamic response of complex systems. The current work investigates one of the most representative pieces of Florence's Renaissance: the stone statue "Marzocco" by Donatello, currently exhibited at the National Museum of Bargello, in Florence. The dynamic response of the statue has been represented through a FEM model set on the basis of a detailed photogrammetric survey, and it has been studied accounting for the dynamic properties of the building.
The seismic acceleration experience by the statue has been checked accounting for the seismic hazard of the area and for the dynamic propagation of the building, opportunely checked through an experimental investigation. The seismic response of the case-study has been found with reference to the seismic excitation of the foundation soil of the building and to the one at the floor where Marzocco is exhibited, in order to check the role plaid by the building propagation. The results provided by the analysis have been compared to the threshold for the overturning mechanism of the statue, which resulted to be safe.

Keywords: Instructions, ECCOMAS Thematic Conference, Structural Dynamics, Earthquake Engineering, Proceedings.

Peer-review under responsibility of the organizing committee of COMPDYN 2025.
doi: 10.7712/120125.12410.25075

1 INTRODUCTION

The seismic safety of artworks is an important issue that is gathering a lot of attention by researchers. Due to their vulnerability, indeed, artworks can easily be damaged by earthquakes, even when their seismic intensity is not strong enough to threaten the buildings' integrity [1-4].

Art collections exhibited within Museums can be even more vulnerable to seismic excitations, since the buildings can represent a threat for their contents [5], besides increasing the seismic input affecting each artifact [6].

One of the most crucial aspects of the artworks' safety assessment is determining the intensity of the seismic input. Indeed, the seismic acceleration experienced by the manufact is the results of the filtering effect plaid: by the soil, by the building and – if present – by the displayer utility [7].

This work is focused on the seismic vulnerability of the stone statue "Marzocco", representing the famous lion, which is the symbol of Florence, currently exposed in Florence, at the National Museum of Bargello. Former investigations carried out by the Authors [8] found the dynamic behavior of the building hosting the National Museum of Bargello due to ground acceleration. Such analysis was based on experimental data performed through seismic stations placed along the building's heigh, which provided the acceleration's time histories at various levels due to the ordinary noise excitation. The recorded waveforms were analyzed in the frequency and time domain; the comparison between the excitation peaks of the various levels to the one at the ground, provided the amplification plaid by the structure. These results were compared to the floors response spectra provided by Italian Technical Code [9].

In this work the results of the monitoring campaign have been used to determine an ensemble of ground motions representing the seismic excitation at the level where the statue "Marzocco" is exhibited. A Finite Element (FE) model has been made to perform the analysis, based on a detailed geometrical model provided by a photogrammetric survey. The seismic response of the model has been found with reference to an ensemble of three ground motions compatible, respectively, with the ground excitation and the floor excitation, in order to check the effect of the dynamic response of the building. The lateral displacement of the artwork due to the seismic excitation has been compared to the threshold displacement activating the overturning. The propagation effect of the building proved to play a fundamental role on the seismic response of Marzocco. Its seismic performance, however, largely comply the safety requirements for rocking.

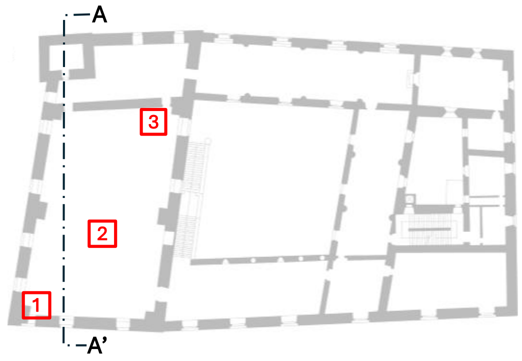
2 CASE-STUDY: THE MARZOCCO AND THE INTERNATIONAL MUSEUM OF BARGELLLO

2.1 National Museum of Bargello and "Sala Donatello"

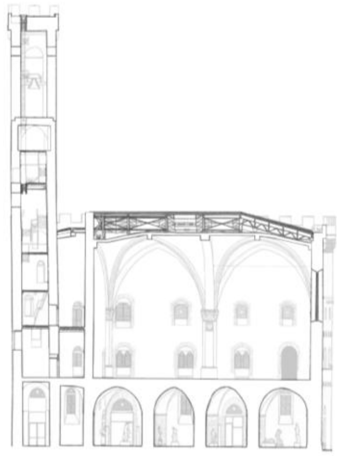
The National Museum of Bargello is placed in the Bargello palace: a historical building dating back to the XIII century, which ever plaid a special role for the town of Florence: it was, in the time, public building, police headquarter, and prison. Only in 1865, after a comprehensive restoration, it hosted the current museum, which was the first National Museum in Italy.

The building, shown in Figure 1, has a rectangular plan, with a masonry structure very massive and quite irregular, a central courtyard and the Volognana Tower at one of the plan's corners: a masonry tower with a height of 57m.

As evidenced in Figure 1, the "Marzocco" statue is placed in "Sala Donatello", at the first floor of the palace. The dynamic response of the building, and, more specifically, of the floor of Sala Donatello, has been checked through an experimental investigation, by placing three seismic stations on the room's floor (see [6,10]), and three further stations in the same position at the lower floor. By comparing the results provided by each couple of stations, the dynamic amplification has been found as a function of the frequency. Figure 2 shows the amplification found for the three couples of seismic stations. As can be noticed, the dynamic propagation of the three seismic stations evidences a peak for 1 Hz, corresponding to the first vibrational mode of the Tower [8], and two further peaks for frequencies around 2.6Hz and 3Hz, respectively, which correspond to the two first vibrational modes of the building, respectively equal to T_1 = 0.38s and T_2 = 0.33s. Further information on the dynamic response of Bargello building can be found in [8].



1st floor plan



Section A-A'

Figure 1. Bargello building: horizontal and vertical sections.

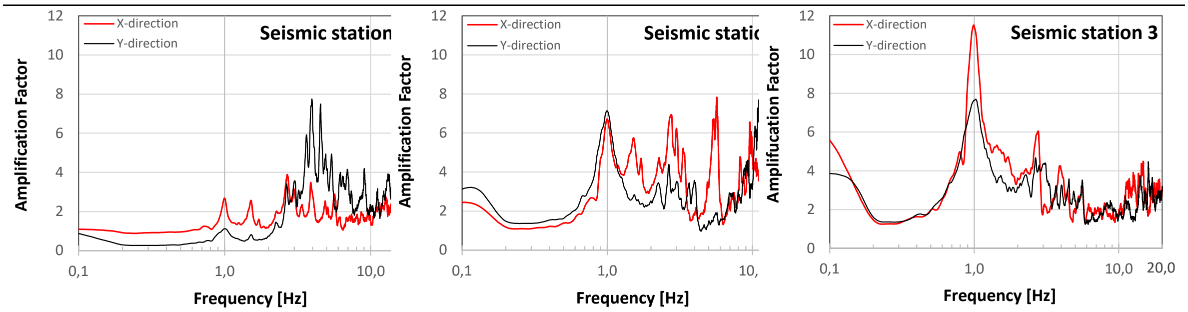


Figure 2. Amplification Factors of the three couple of seismic stations (from [10]).

2.2 The statue "Marzocco"

The "Marzocco", shown in Figure 2, is the heraldic lion which is the symbol of Florence from the Middle Ages [11-12]. It was made by the famous artist Donatello after the requirement of the Republic of Florence in 1418, for the visit of Pope Martino V: the statue had to decorate the stairway of Santa Maria Novella' cloister, leading to the papal rooms. It was removed at the beginning of the XVI century, with the dismantle of the stairway. There is not information regarding Marzocco from the removal until 1812, when it was placed in front of *Palazzo Vecchio*, Florence's city hall. This external location induced a decay of the statue; therefore, it was moved to the Uffizi Museum first (1847), and finally to the National Museum of Bargello (1865).

The "Marzocco", made by boulder stone, is a lion, in a sit position, with a paw on the shield showing the red lilium which id the symbol of Florence. It is placed over a marble base, lying, in turn, over a magnificent marble pedestal (see Figure 3), which is part of the piece-of-art. The pedestal was made by Benedetto da Maiano in the years 1480-83 to support another sculpture, and it was successively used as Marzocco's pedestal, arriving to Bargello Museum only in 1999 [13]. It is a parallelepiped element consisting of a molded foot, a central body completed by four banisters and an entablature composed of architrave, frieze and frame, all enriched with heraldic symbols.

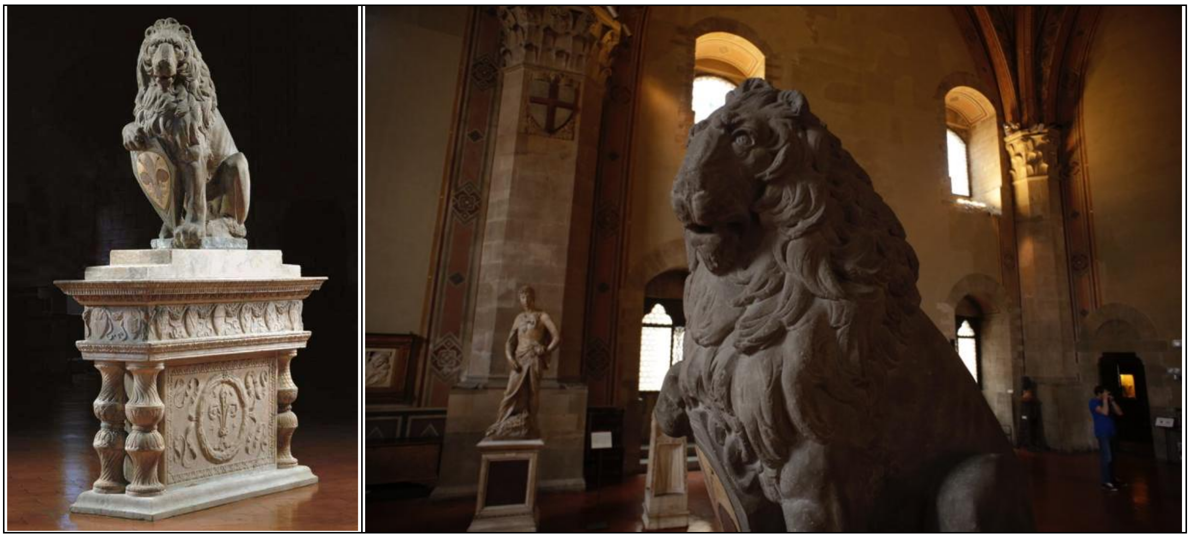
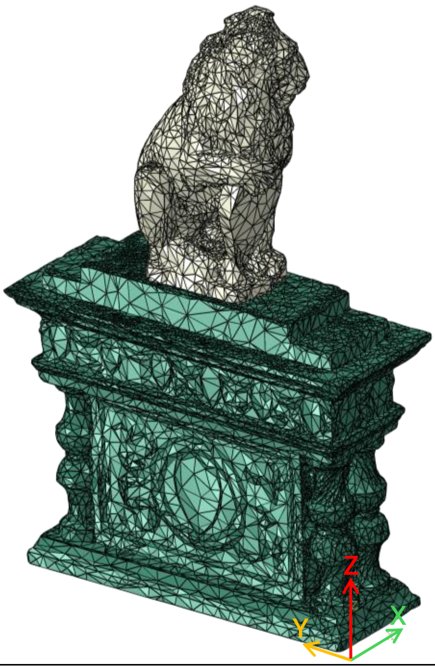


Figure 3. Views of the statue of "Marzocco" by Donatello on the pedestal by Benedetto da Maiano.

2.3 The structural model

The geometrical model of Marzocco, its base and its pedestal has been found on the basis of a detailed photogrammetric survey.



Geometrical model

	Statue	Pedestal	Base
Nodes	7060	17472	2845
Tetrahedrons	31040	77618	12083

Mechanical properties of materials

	Statue	Pedestal	Base
Material	stone	marble	
Strength [MPa]			
Density [kg/m^3]	2650	2700	
Young [MPa]	60000	35000	
Poisson [-]	0.2	0.2	

Figure 4. The model.

The structural model has been made from the geometrical one by reducing the number of points representing the "skin" of the artifact and changing the "surface" model to a "volume" one i.e. considering the volume inside the artifact's skin and using 4-nodes tetrahedrons instead 3-node polygons [14,15]. Figure 4 describes the main properties of the structural model.

A preliminary modal analysis has been performed to check the dynamic response of the artifact; in the modal analysis, the three components of the artwork, i.e. statue, base and pedestal, have been assumed as perfectly fixed to each other, and a linear elastic behavior has been assumed for both materials. In Table 1 the main results provided by the modal analysis are listed. As can be noticed, the first modes of the artworks are along the X-direction.

Table 1. Results of the modal analysis.

Mode	Frequency	Period	Participating mass		
			X	Y	Z
Mode 1	44.57 Hz	0,022 s	49%	0%	0%
Mode 2	123.82 Hz	0,008 s	0%	37%	0%
Mode 3	150.43 Hz	0,007 s	17%	0%	0%
Mode 4	176.13 Hz	0,006 s	3%	0%	0%
Mode 5	261.47 Hz	0,004 s	0%	32%	2%

The modal analysis led to quantify the Reyleigh' coefficients (α, β). In this work they have been found by considering the first two modes, assuming a friction equal to 2%. The coefficients result, respectively: α=8.2367711, β=0.0000378.

The time-history analysis has been performed through the software ABAQUS [16], by introducing an interaction relationship between the contact surfaces (i.e. between the statue and the base and between the base and the pedestal), which has been simulated through the surface-to-surface method. The properties of the contact laws consist of two components, respectively normal and tangential to the surfaces. For the normal behavior, a "hard" contact has been adopted: the two correspondent points belonging to the two contact surfaces separate from each other, i.e. the constraint is removed, when the contact pressure becomes zero or negative. As regards tangential behavior, the Coulomb friction model with a linear and isotropic behavior has been employed, with a friction coefficient equal to 0.8, according with the results presented in [17].

3 THE SEISMIC INPUT

The seismic input used for analysis is the acceleration at the first floor, where the artwork is located. The seismic excitation at the ground level has been defined according to the Italian Code NTC 2018, on the basis of the seismic hazard of Florence and the soil class of the Museum's foundation. According to the Italian Code NTC 2018 [9] and to the detailed information collected on Florence's soil by the recent detailed analysis [18], the area of the Museum can be classified as "class B". The PGA corresponding to the Life Safety (LS) limit state (return period equal to 712 years), is equal to 0.1764g. The seismic input at the ground level of the Museum has been represented through an ensemble of 3 ground motions selected by the software Rexel [19], whose mean spectrum closely approaches the Code one (see Figure 5a), especially for low periods (see Figure 5b), such as the one of the assumed case-study. Table 2 shows the main information of the assumed ground motions.

The dynamic response of the statue has been checked with reference both to the acceleration time histories of the ground and the ones acting at the first level, where the statue is located. In order to find the floor acceleration, each ground motion has been filtered through the software Seismosignal [https://seismosignal.software.informer.com/5.0/], assuming a simplified single degree of freedom system. The period of the SDOF has been assumed 0.35s, which is the average value between the periods of the first and the second dynamic modes of the building, found through the experimental survey. The friction has been assumed to be equal to 5%.

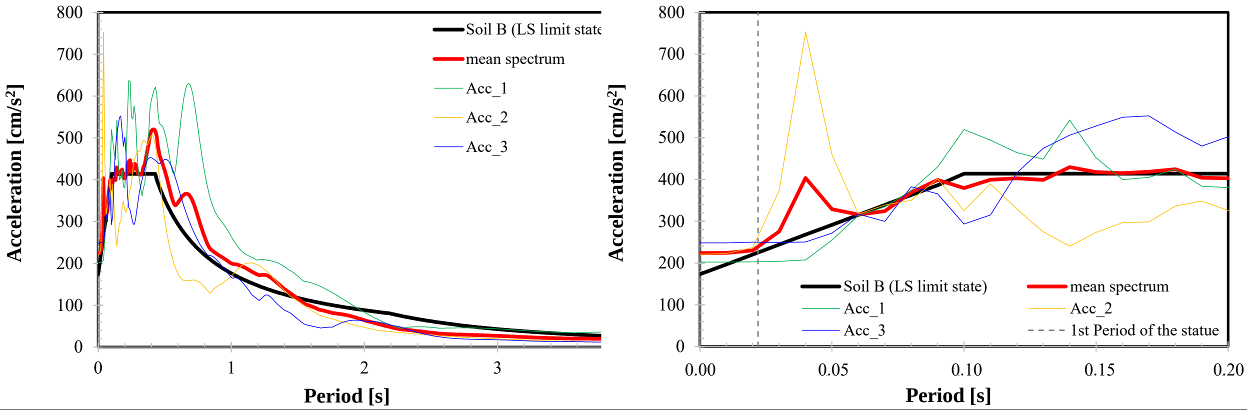
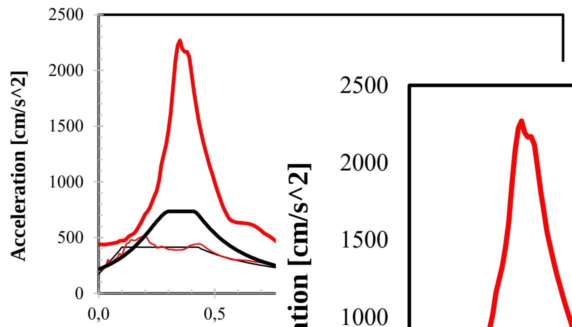


Figure 5. Spectra of the seismic input assumed in the analysis.

Table 2. Ground motions assumed in the analysis.

ID	Code	Date	Time	Magnitude	Distance	PGA
		yyyy-mm-dd	hh:mm:ss	W	[km]	[cm/s^2]
Acc_1	3A_MZ27_HNN	2016-10-30	06:40:18	6.6	28.8	202.2
Acc_2	IT_MSCT_00_HGE	2017-01-18	10:25:24	5.4	4.8	221.24
Acc_3	IT_NRC_00_HGE	2016-10-26	19:18:06	5.9	13.6	248.28

Figure 6 shows the comparison between the acceleration time history found for the first floor and the one provided by the Italian Technical Code.



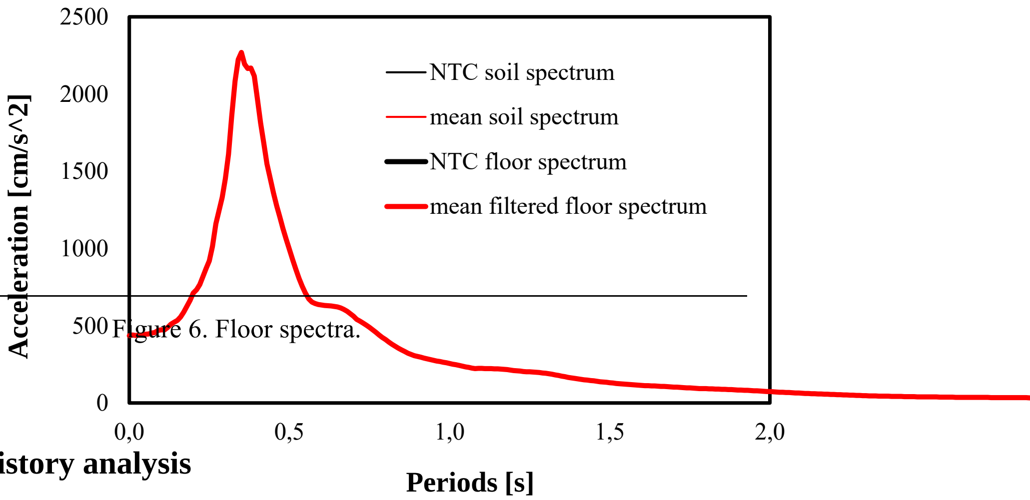


Figure 6. Floor spectra.

4 THE ANALYSIS

4.1 Results of the time-history analysis

The dynamic response of the statue “Marzocco” has been found by assuming both the ground motions spectrum-compatible to the Code spectrum, and the corresponding seismic input acting to the first floor, where the statue is located. Figure 7 and 8 show the displacement of the upper point of the model along the three directions found by considering the ensemble of ground motions at the ground and at the floor.

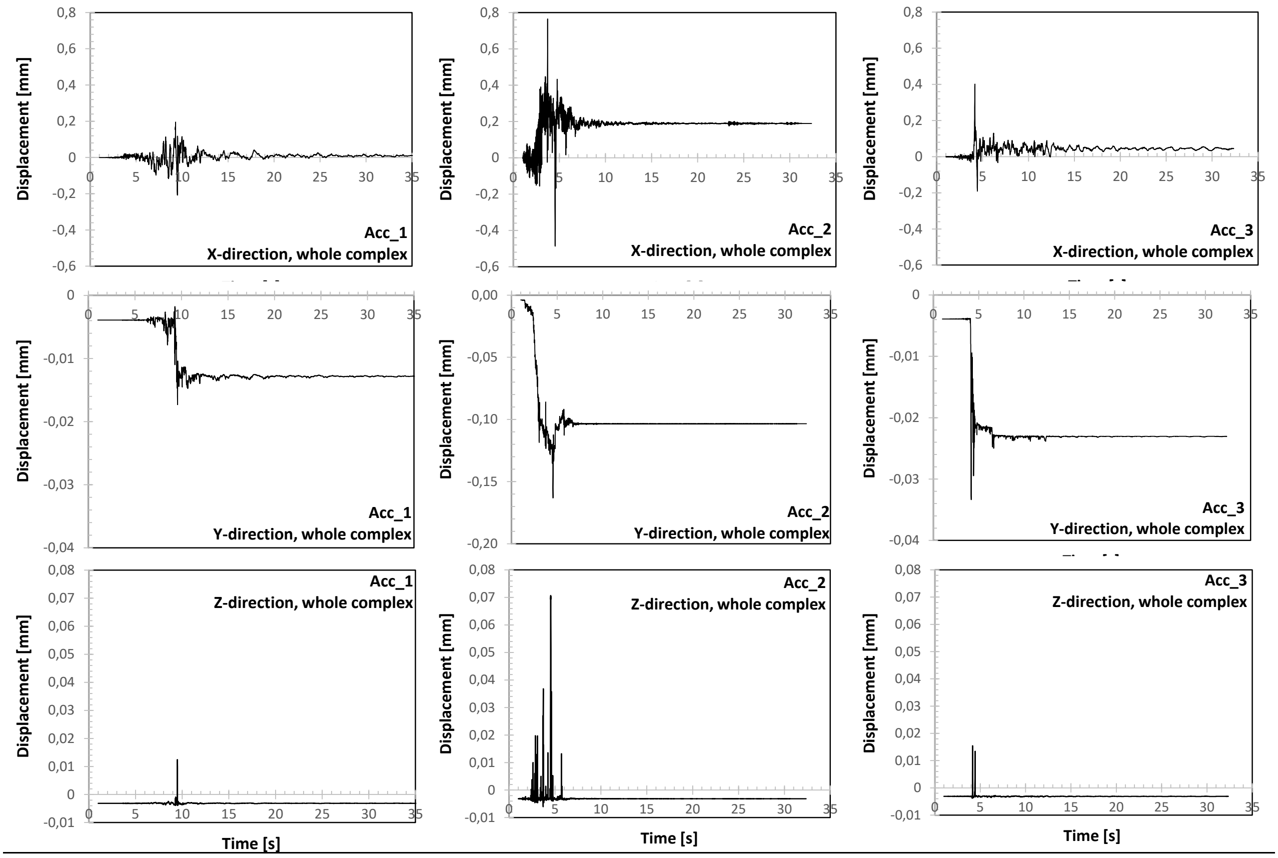


Figure 7. Top displacement of the complex “statue+base+pedestal” provided by the ground excitation.

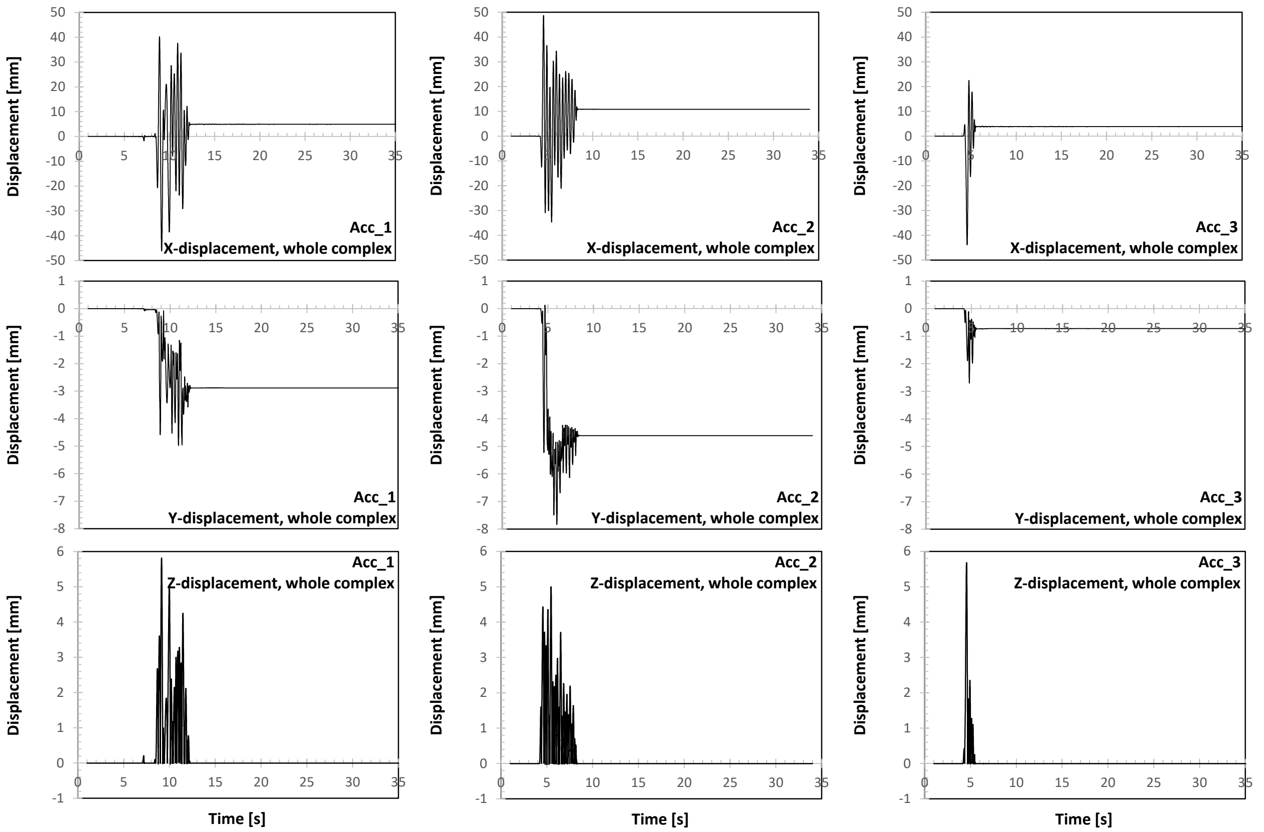
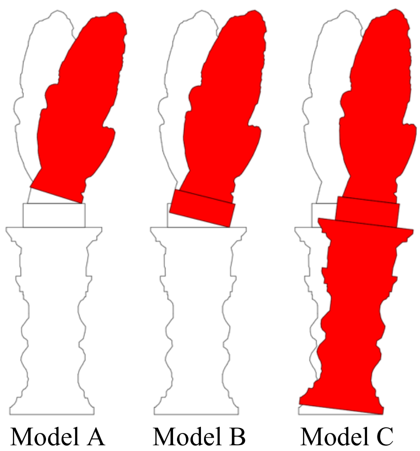


Figure 8. Top displacement of the complex “statue+base+pedestal” provided by the 1st floor excitation.

The response of the system along the three directions is very different, therefore it has not been possible to use the same scale of representation for alle the diagrams. As can be noticed, the maximum response of the artwork occurs along the X-direction, which is its slenderer direction: along the X-direction, the statue experiences a lateral displacement of almost 5cm (acc_01, acc_01). The maximum displacement along the Y-direction, instead, does not achieve 8mm (acc_02). Even the vertical response (Z-direction) is negligible compared to the one experienced along the X-direction; however, it can be noticed that the positive peaks - which represent the detachment of the system form the ground – correspond to the activation of the torsional response, evidenced by the lateral response along the Y-direction.

As can be noticed, the displacement found by considering the seismic excitation at the floor is much higher (over 200 times larger) than the one provided by the seismic excitation at the ground.

In order to check the safety of the artworks, the most significant collapse mechanism of the system is the rocking, represented in Figure 9. It can occur for the overturning of the statue over its base (model A), for the overturning of the system "statue+base" over the pedestal (model B) or for the overturning of the system "statue+base+pedestal" over the floor (model C). This paper investigates the model A, which is consistent with the assumed structural model.



Limit lateral displacements (mm)

	X-direction	Y-direction
Model A	381	467
Model B	515	1400
Model C	977	2243

Figure 9. Limit lateral displacement of the possible rocking models.

Figures 10 and 11 shows the lateral displacement of the statue only. The plots represent only the first 20s of the seismic response of the statue, since it is the most meaningful. Even the dynamic response of the statue is largely affected by the amplification of the seismic input plaid by the building. The seismic performance of the statue has been checked only with reference to the results provided by the floor excitation, since the ground excitation induces to the case-study a dynamic response almost negligible. Even when the floor excitation is considered, however, the lateral displacement experienced by the statue is well below the rocking threshold.

Table 3 shows the values of the maximum lateral displacement experienced by the statue, the limit value for the rocking activation and the consequent safety index (SI) of the statue with regards to the rocking, defined as the ratio between the overturning displacement and the maximum displacement. The SI to overturning has been checked along the X-direction only, since the ground motions have been considered along such direction.

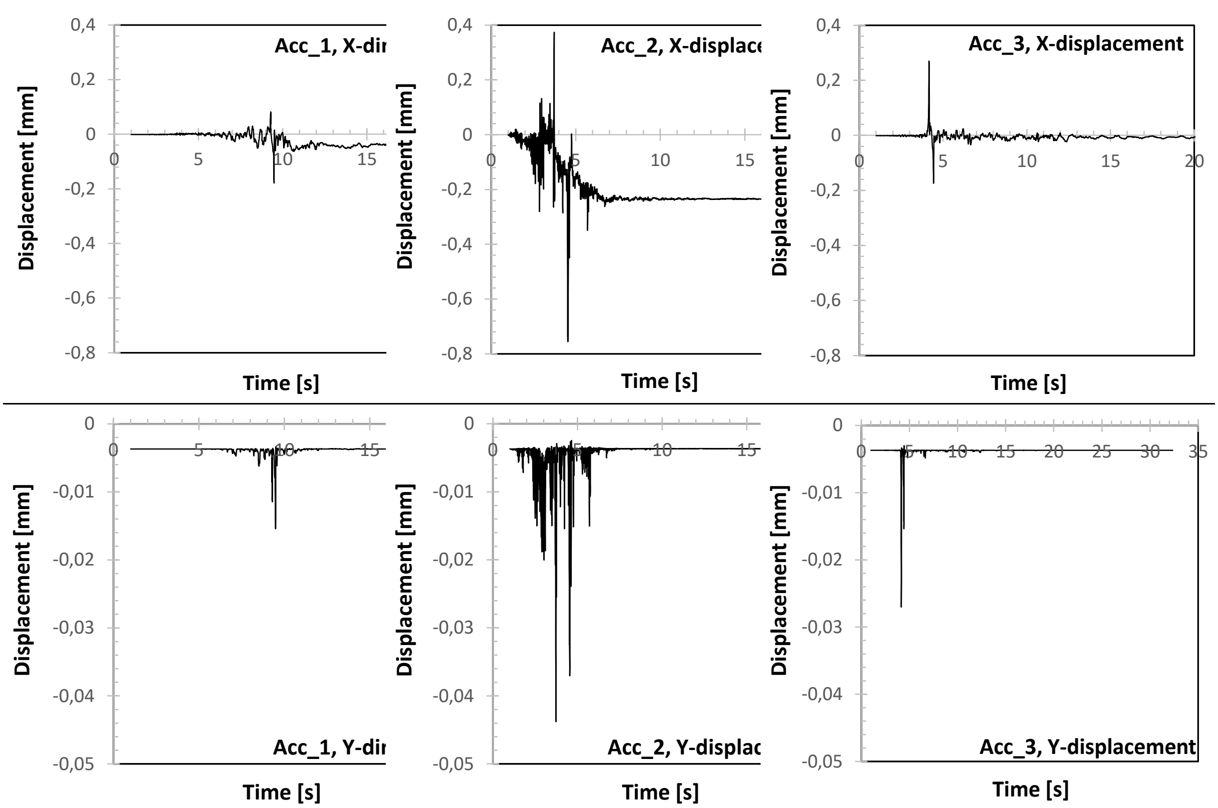


Figure 10. Top displacement of the statue provided by the ground excitation.

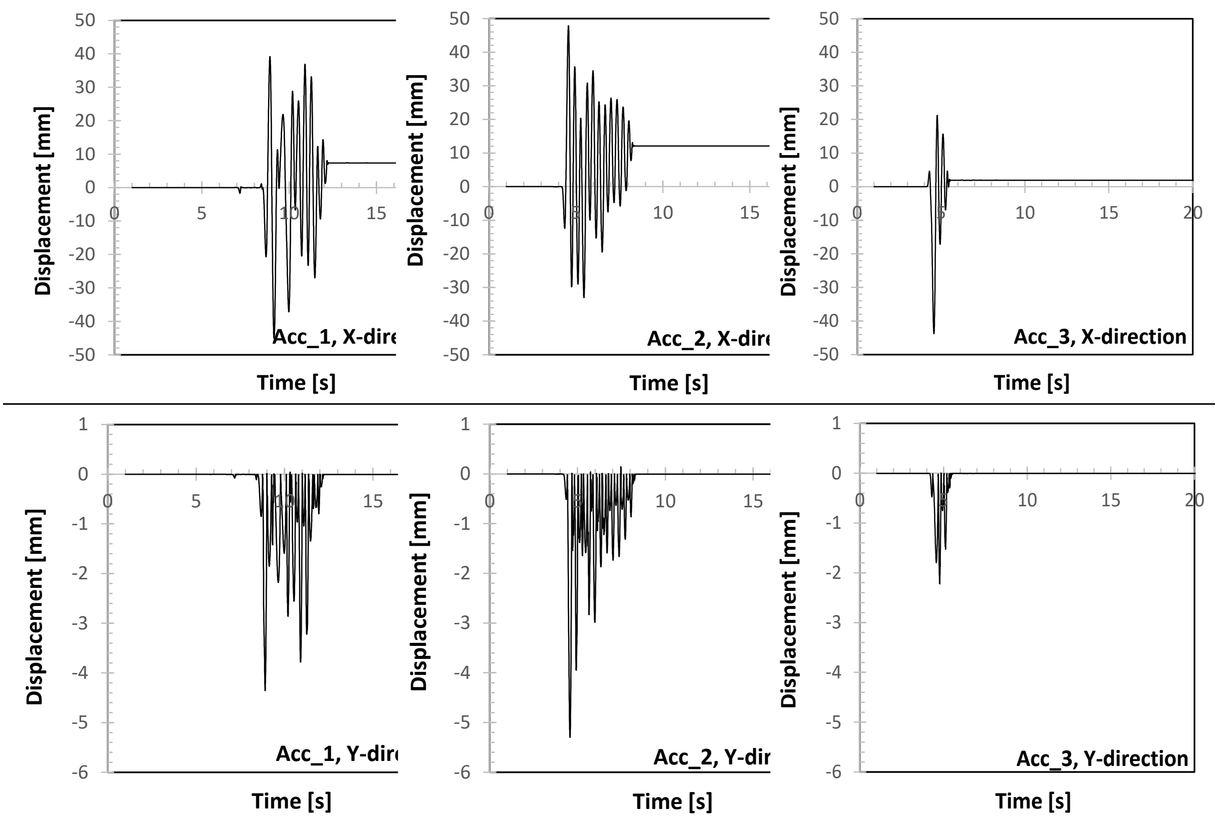


Figure 11. Top displacement of the statue provided by the floor excitation.

The obtained SI is equal to 8.3: the statue results to fully comply the safety requirement to seismic hazard, since the overturning corresponds to SI below the unity. It should be reminded that the analysis refers to the overturning model "A", according to the schemes shown in Figure 9; the further two overturning mechanisms have not been checked.

Table 3. Threshold displacement for rocking activation, absolute value of the maximum displacement of the statue and corresponding safety factor.

	threshold	Acc_1	Acc_2	Acc_3	mean	Safety Index
	mm	mm	mm	mm	mm	
X-direction	381	45.1	47.9	43.8	45.6	8.3

5 CONCLUSIONS

In this paper the dynamic response of the Renaissance masterpiece "Marzocco", exhibited at the Museum of Bargello, has been found by performing a time-history analysis on a detailed FE model through the software ABACUS. The FE model presents a nonlinear behavior, with a proper interface link between the pedestal and the statue and the base, and between the base and the pedestal. The seismic input has been represented by assuming a return period equal to 712 years, which represents the Life Safety limit state, through an ensemble of three ground motions, spectrum compatible with the elastic spectrum provided by the Italian Technical Code for the soil type of the Museum of Bargello. The three ground motions have been filtered through a SDOF model having the same period of the building hosting the Museum, found by performing a proper dynamic monitoring.

The dynamic response of the case-study has been checked in terms of maximum displacement, and compared to the threshold displacement which activates the overturning mechanism.

The analysis provided the following findings:

- The ground excitation provides a dynamic response over 200 times lower than the floor excitation; it can be stated that the safety assessment of artworks exhibited within Museums must be checked with reference to the effective acceleration at their location.
- The floor excitation should be found after a careful analysis of the dynamic properties of the building, which can largely differ from the Code one.
- The safety level of the artwork should be found by considering all the possible collapse mechanisms; as regards rocking, the lateral displacement induced by the assumed excitation should be found by assuming proper structural model, i.e. by introducing interface behaviors compatible with the assumed mechanism.

ACKNOWLEDGMENTS

We are grateful to the National Museum of Bargello of Florence for the kind availability and the opportunity to conduct the experimental survey.

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