Modeling Marble Artworks: The Statue “Oceanus” by Giambologna

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Abstract. The assessment of the structural safety of art works requires the availability of proper models to represent their behavior after the expected excitations. Marble artworks, such as sculptures made in Florence during the Renaissance, are especially sensitive to seismic actions, due to their slenderness, weight, and shape irregularity. The reliable modeling of marble artworks, therefore, is very important for their protection. In these years, many experiences have been made aimed at representing the dynamic response of sculptures after seismic excitations. In this work, a high-fidelity Finite Element model has been compared to a new simple one, consisting of concentrated mass placed in the barycenter of the statue and connected to the soil through two "equivalent" trusses. The comparison has been made on the marble statue "Oceanus", made by Giambologna in 1570. The sculpture, currently exhibited at the courtyard of the Museo del Bargello in Florence, has a mass of about 2 tons, and a height of over three meters, and it is the only giant statue made by Giambologna. The geometrical modeling of the case-study has been made based on a detailed laser-scanner survey, which provided a comprehensive knowledge of its geometry. The paper provides the first results obtained through the proposed simplified model and a more detailed FE representation.

Keywords: Seismic performance of art works; numerical analysis of marble sculptures; safety assessment of sculptures.

1 Introduction

Art works represent the core of the artistic and cultural identity of communities, and their value is unanimously recognized [1-4]. Marble sculptures result to be even more vulnerable than other works of art, due to their slenderness, their irregular shape and the fragility of the material [5]. In case of horizontal actions, such as earthquakes, marble sculptures, depending on their setting and their base fixing, may suffer serious damage because of stress increase, overturning or sliding.

The safety of marble sculptures under seismic excitations has been widely investigated in these last years; such assessment requires to represent their response to horizontal actions. The representation of the response of art works, sculptures and statues to horizontal actions have been investigated through different approaches. The simplest methods adopted for these problems are based on the rigid blocks analysis, introduced by Housner in 1963 [6], and successively developed by many other researchers [7-10]. Another popular approach is based on the Finite Element (FE) analysis. This method has been extensively applied to art works [11-14] because can be applied to complex geometrical models, which can be easily recreated through laser scanner survey. The approaches based on the FE analysis can be adopted to perform time-history analyses, and can provide accurate results, taking into account the specific interface behavior between the base of the object and its support. Lately, some further simplified methods have been proposed [15]; some of them combine a simplified representation of the system with the possibility to investigate its dynamic response. In particular, the system can be represented through a truss-model with a concentrated mass, placed at the barycenter of the system. The truss can be symmetric or not, and its mechanical properties are determined based on equivalence conditions [16,17].

In this work, two models have been adopted to represent the response to seismic excitation of a case study, i.e. the Oceanus by Giambologna, represented in Fig. 1.

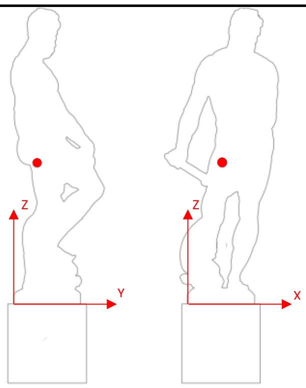
Fig. 1. Views of Oceanus.

Oceanus is a marble statue, currently located in the courtyard of the Museum of Bargello in Florence. It is the only giant sculpture made by Giambologna: it has an heigh equal to 3.31 m, a weight of about 2 tons, and it is made of Carrara's marble. Its geometry has been represented after a comprehensive laser-scanner survey, which provided a rich and detailed points cloud. The assumed horizontal action has been found on the basis of the seismicity of the area and the type of foundation soil of the Museum. The response of the case-study to the assumed horizontal action has been found by adopting a simplified SDOF model and a more detailed FE representation. The effect of the friction between the base of the sculpture and its pedestal has been also considered.

2 The case-study: “Oceanus” by Giambologna

The statue of Oceano was commissioned by Cosimo I de’ Medici in 1567. He got a basin granite by Elba Isle to make a giant Fountain in the Boboli gardens. The original plan of the Fountain is not certain; there is a drawn of the project at the Ashmolean Museum of Oxford. In 1572 a plaster model of Oceanus was placed in the basin, and in the same year the marble sculpture was started. Oceanus was completed in 1576, and it was placed in the hexagonal basin (whose diameter was about 7 m) together with three smaller sculptures in the bottom part.

Today the Fountain looks very different; in 1618 it was moved from its initial location; it was placed close to Grotta Madama first, and after (in 1637) in the western side of the Garden, “The Garden of the Little Island”. In 1907 the statue was moved to the Bargello Museum – its current location – and it was replaced in the Fountain with a copy made by Raffaello Romanelli. The geometry of the statue has been defined after a comprehensive laser-scanner survey, providing the points cloud which was used to define the geometrical model. In Fig. 2, the main information on the case-study is shown, including the position of the barycenter, with reference to the statue only and to the system made of the statue and the pedestal together.



Statue
Material: marble
Height: 331 cm
Base print (XxY): (76.9 x 77.4) cm
● Center of Mass (MC)
MC position: X = 40.2 cm
Y = 26.9 cm
Z = 162.2 cm

Pedestal
Material: concrete
Sides (XxYxZ): (90x90x91) cm

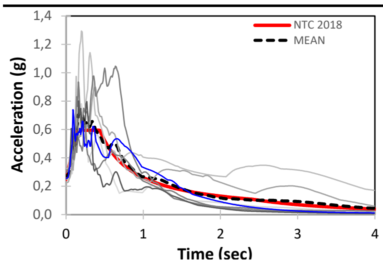
Fig. 2. Geometry of the statue and its pedestal.

Oceanus is made of Carrara’s marble; the mechanical properties of the marble have been found after proper experimental investigations [18,19] made on marble samples taken from the Carrara’s quarries. The compressive and tensile strength have been assumed, respectively equal to 50 and 5 MPa, whilst the Young Modulus has been taken equal to 50000 MPa. A special attention has been paid to the assessment of the friction coefficient (*CF*), which plays a special role in the dynamic response of sculptures subjected to horizontal actions [20-23]. The pedestal of the statue was made in the occasion of the last staging of the sculpture. It is made of concrete, but there is not information regarding the fixing between the statue and the pedestal. In this work, therefore, a *CF* equal to 0.8 has been assumed, in the hypothesis of lack of specific fixing devices, but assuming a layer of mortar between the statue and the pedestal.

3 The seismic excitation

The seismic excitation has been defined according to the Italian Code NTC 2008 [24], on the basis of the seismic hazard of the area and the foundation soil of the Museum. The Museum area, such as the rest of the Florence basin, consists of plio-pleistocene palustrine and alluvial deposits, followed by two sedimentary cycles related to the paleo-Arno River and the holocene geomorphic evolution. According to the information currently available on the Museum area [25,26], therefore, the soil has been classified as "class B" according to NTC 2018.

The considered seismic intensity refers to a Return Period of 949 years, i.e. the *Collapse Prevention* limit state, with a class of use (c_u) equal to 2 (strategic buildings). Figure 3 shows the elastic spectrum provided by NTC 2018 for the case-study with those of an ensemble of seven ground motions selected by the database Itaca [27] through the software Rexel [28]. In this work, for sake of brevity, only one ground motion of such ensemble has been used for the analyses. The spectrum of the selected record, represented in blue in Fig. 3, presents a good agreement to that stipulated by the code.



Name	Station	Magnitude	PGA (g)
SRCO_HNE	S.Rocco	6.0	0.250
STR_HNE	Sturno	6.9	0.316
STR_HNN	Sturno	6.9	0.225
TLM1_HNE	Tolmezzo	6.4	0.315
GMN_HNE	Gemona	5.8	0.298
GMN_HNN_01	Gemona	6.0	0.252
GMN_HNE_01	Gemona	6.0	0.255

Fig. 3. The selected ground motions.

4 The numerical models

In this work two different models have been used to represent the dynamic behavior of the statue, respectively represented in Fig.4:

Finite Element model (FE) (see Fig. 4a), developed within ABAQUS [29]; it represents the real geometry of the statue. It has been defined on the basis of the geometrical model, by reducing the number of the "surface" polygons (representing the "skin" of the sculpture), and changing the model from a "surface" to a solid one, i.e. including the volume inscribed in its lateral surface. The mesh consists of 4-nodes tetrahedron elements, and the model has 24230 nodes and 105890 tetrahedrons. When the statue has been considered as simply supported with the contact friction, a thin plate has been introduced, having a high stiffness and a negligible mass, so that it does not affect the dynamic response of the statue. The sliding between the contact surfaces has been limited to linear relationship assumed for the slip, with a tolerance equal to 0.005.

Truss Triangular model (TT), developed within OpenSEES platform [30]; it represents the statue as a SDOF system, consisting of three trusses (see Fig. 4b) which connect as many nodes. The first node is located at the center of mass (MC) of the system, and the other two ones are placed, respectively, at the intersection between the cross section of the statue and its support. The mass is assumed as concentrated in the MC node. The trusses are modeled as "*elasticBeamColumn*", and the hinges as "*zeroLenght*" elements, with rotational stiffness equal to zero. The rotational inertia has been neglected. The three trusses have the same cross section, which has been set in order to achieve the same Fundamental Period provided by the modal analysis (performed through the FE model). The TT model is a plane one, and it can represent the dynamic behavior of the system in one horizontal direction only. When the statue has been assumed to be simply supported over the pedestal, two further "*flatSliderBearing*" elements have been added between the hinges and the soil. They have no tension stiffness and strength along the vertical direction, in order to simulate the one-directional restraint of the support. A Coulomb friction behavior has been assigned to the horizontal cyclic response of the *flatSliderBearing* elements, which leads the sliding at the overcoming of the friction limit.

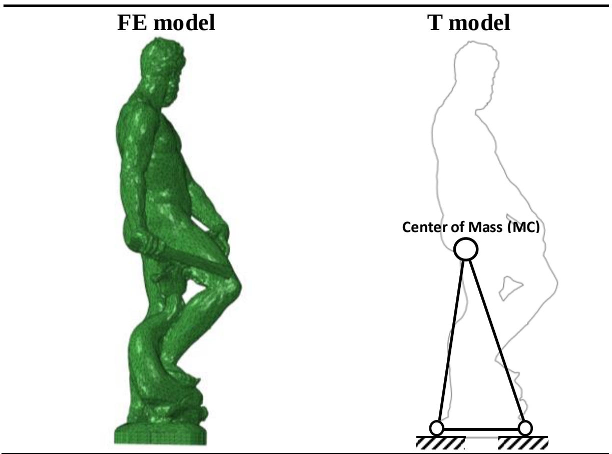


Fig. 4. The structural models.

In both the models, the damping has been assumed through the Rayleigh model [31,32], where the needed α and β coefficients have been found by assuming a damping equal to 3%, whilst the first vibrational periods refer to the first two modes of the system along the selected direction.

In order to set the α and β coefficients, and to set the TT-model, a preliminary modal analysis has been performed with the FE-model, which provided the vibrational Periods of the case-study. The First mode occurs along the *Y*-direction; therefore, the *Y*-direction has been assumed to perform the time-history analysis, and the second Period considered for determining the α and β coefficients has been assumed along such direction (it refers to the 4th vibrational mode of the statue, which is the 2nd mode along the Y-direction).

Table 1. First vibrational Periods along the *Y*-direction and coefficients for the Rayleigh damping matrix

Quantities	1st period	2nd period*	α	β
Unit	sec	sec	Hz	sec
Modal response of the statue	0.0741	0.0110	4.42999	0.0000915
2D modal response of the statue	0.0545	0.0083	6.00018	0.000069

Since the TT-model represents the dynamic response of the system along one-direction only, even the one-dimensional dynamic response of the FE model has been investigated, by introducing lateral restraints to the nodes placed along the front side of the statue. In Table 1 the main information regarding the modal analysis is provided, whilst further results provided by the modal analysis can be found in [33].

5 Results

The dynamic response of the statue has been checked in terms of displacement of the center of mass. Fig. 5 shows the displacement time history of the statue assumed to be fixed at its base, respectively restrained in the Y-Z plane (2D-behavior) or not. The time-histories are plotted in diagrams having different scale, since the dynamic response of the system with lateral restraint is much lower than the one without. It can be noted that the time-histories provided by the two models have a very similar trend; however, the one provided by the TT-model looks shifted compared to the other one; this difference is due to the lack of equivalence between the axial stiffness of the two models; since the system is not symmetrical, indeed, the TT-model presents an initial horizontal displacement due to the gravitational loads.

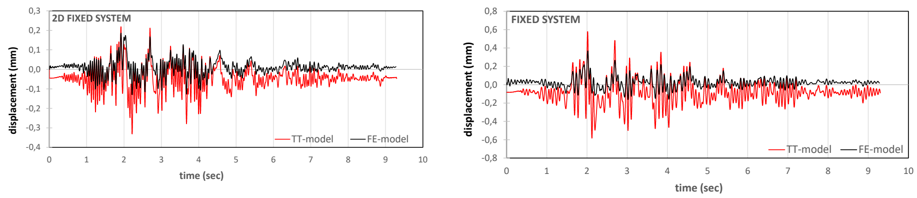


Fig. 5. Displacement time-histories provided by the considered models for the fixed system.

In order to compare the two time-histories without this initial gap, the response provided by the TT-model has been shifted; Fig. 6 shows the comparison between the time-histories after such correction; the comparison is limited to the range of time between 1 and 4 sec, where the dynamic response is higher.

Fig. 7 shows the comparison between the dynamic response of the system found through the two models when the base restraint is assumed to be a simple support with friction between the contact surfaces. It should be noted that removing the fixing restraint at the base, the system experiences higher displacements, since there is some sliding at the base of the statue. In this case, the difference between the two models is higher with respect to the fixed system.

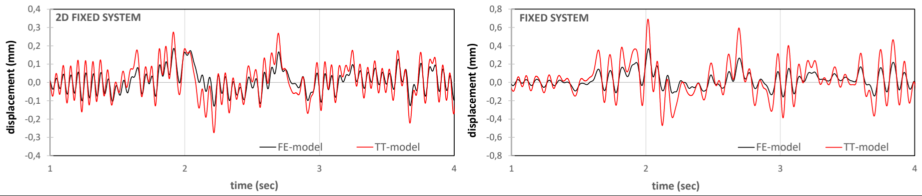


Fig. 6. Details of the displacement time-histories provided by the considered models for the fixed system (after the shift of the TT results).

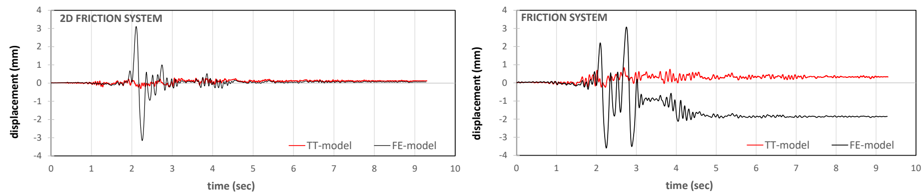


Fig. 7. Displacement time-histories provided by the considered models for the simply supported system with friction.

The maximum displacement provided by the simplified TT-model does not exceed 1 mm, while the one provided by the FE-model exceeds 3 mm both in the 2D and in the 3D systems. The response of the FE-model, when the 3D system is considered, evidences some peaks between 2 and 3 seconds, settling around a horizontal displacement equal to 2 mm for a time over 5 sec.

In order to better understand the dynamic response of the simply supported system, Figure 8 shows both the horizontal responses provided by the FE model. The plot is focused on the range of time between 1 sec and 6 sec, when the most significant response occurs. It can be noted that the response of the system along the *X*-direction plays an important role in its global response. Along the *X*-direction, indeed, the system experiences a displacement up to 1 mm, changing its fundamental configuration after the first 3 sec of vibration.

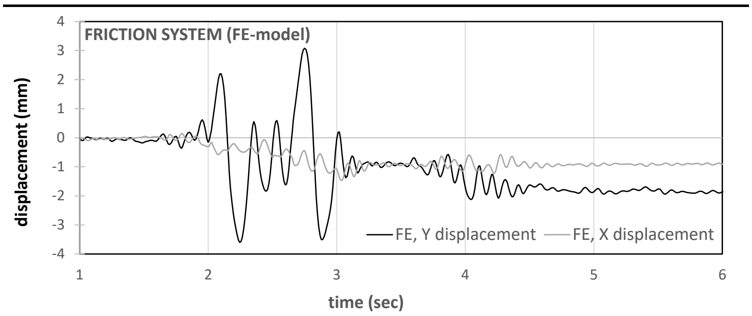


Fig. 8. Details of the displacement time-histories along the *X* and *Y* directions provided by the FE model for the simply supported system with friction.

6 Final remarks

The paper presents the first results of a numerical investigation made on the marble sculpture Oceanus, currently located in the courtyard of the International Museum of Bargello in Florence. The dynamic response of the system has been checked with reference to a ground motion compatible to the seismic hazard of the area.

Two different numerical models, involving different computational effort, have been adopted in the analysis: a FE model, and a simplified Truss Triangular model, consisting of three truss members, where the mass of the system is concentrated in the mass center. The TT model represents the dynamic response of the system in one plane only, and its stiffness is set on the dynamic properties of the system.

The dynamic analysis has been performed along one direction only, i.e. the direction of the first vibrational mode of the statue. Two different base restraints have been considered; the statue has been assumed to be fixed and simply supported with the introduction of a proper friction coefficient. Furthermore, the statue has been assumed both as having a spatial and a 2D response, by introducing proper lateral constraints to limit its response in the X-Z plane.

When the statue has been assumed as fixed at the base, the two models have provided a quite similar dynamic response, both for the spatial and for the 2D cases. The simplified model provided the same dynamic trend, with displacements slightly higher than the FE model.

When the statue has assumed to be simply supported, and the friction has been introduced, the simplified TT-model provided horizontal displacements much smaller than the FE-model, especially for the free (3D) system. In this case, indeed, the dynamic response of the system along the X-direction (orthogonal to the direction of the analysis) has played a crucial role in the spatial response of the system.

The study is currently limited to one case-study only, and only one response quantity has been processed; furthermore, the performed analyses refer to one ground motion only. Anyway, the study has evidenced that the simplified TT-model provides a quite satisfactory representation of the dynamic response of the system when a fixed restraint is assumed at the base. When the system is assumed to be simply standing over the pedestal, and the friction is introduced at the base, the response provided by the TT-model differs considerably from the one provided by the FE model. In order to better understand the properties of each model, the numerical responses should be compared to the results provided by an experimental test. Moreover, further analyses should be done, considering a larger number of response quantities, case studies and ground motions.

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