European Community on Computational Methods in Applied Sciences

ECCOMAS Thematic Conference

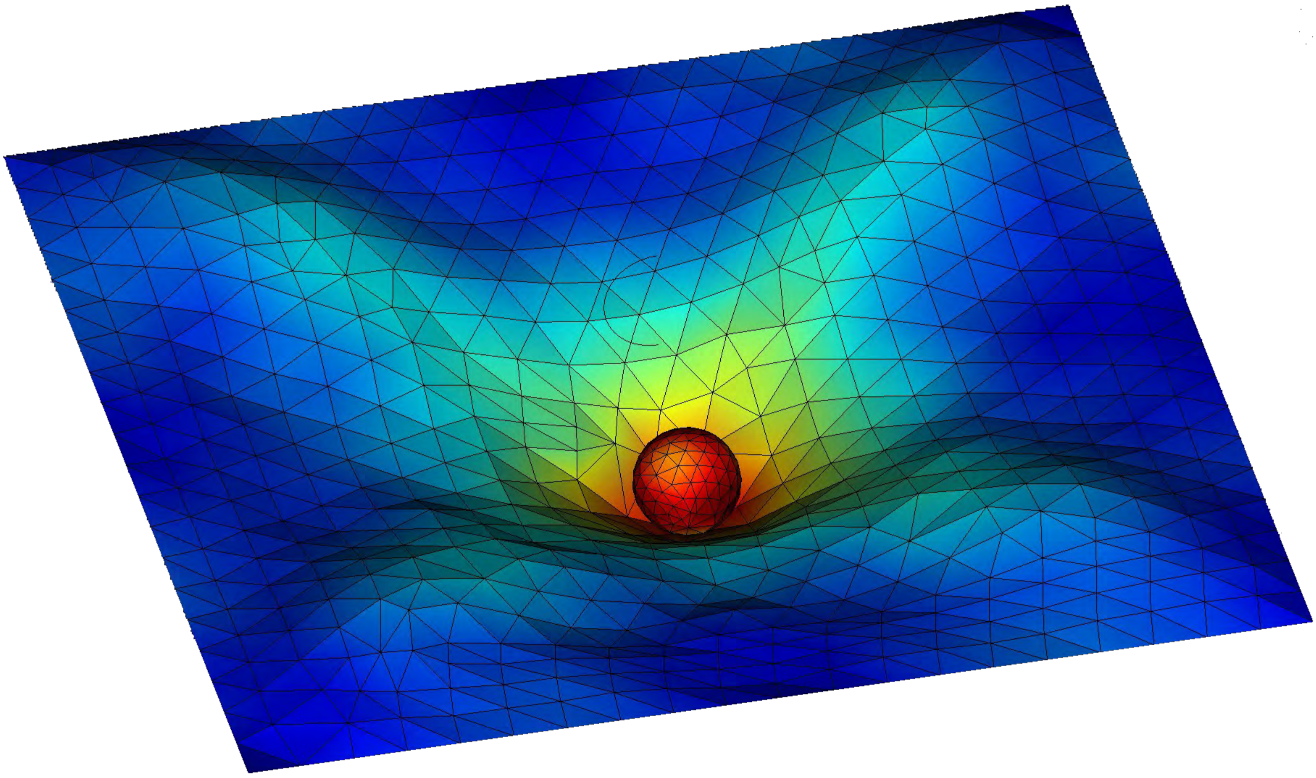
COMPDYN 2025

10th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering

PROCEEDINGS

Volume I

M. Papadrakakis, M. Fragiadakis (Eds.)



An IACM Special Interest Conference

COMPDYN 2025

Computational Methods in Structural Dynamics and Earthquake Engineering

Proceedings of the 10th International Conference on Computational
Methods in Structural Dynamics and Earthquake Engineering
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15-18 June 2025

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Computational Methods in Structural Dynamics and Earthquake Engineering

M. Papadrakakis, M. Fragiadakis (Eds.)

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PREFACE

This volume contains the full-length papers presented in the 10th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2025) that was held in Rhodes Island, Greece on June 15-18, 2025.

COMPDYN 2025 is one of the 32 Thematic Conferences of the European Community on Computational Methods in Applied Sciences (ECCOMAS) which were held in 2025 and is also a Special Interest Conference of the International Association for Computational Mechanics (IACM). The purpose of this Conference series is to bring together the scientific communities of Computational Mechanics, Structural Dynamics and Earthquake Engineering, to act as a forum for exchanging ideas in topics of mutual interests and to enhance the links between research groups with complementary activities. We believe that the communities of Structural Dynamics and Earthquake Engineering will benefit from their exposure to advanced computational methods and software tools which can highly assist in tackling complex problems in dynamic and seismic analysis and design of structures, while also giving the opportunity to the Computational Mechanics community to be exposed to very important engineering problems of great social interest.

The COMPDYN 2025 Conference is supported by the National Technical University of Athens (NTUA), the European Association for Structural Dynamics (EASD), the European Association for Earthquake Engineering (EAEE), the Greek Association for Computational Mechanics (GRACM) and the Hellenic Society of Earthquake Engineering (HSEE).

The editors of this volume would like to thank all authors for their contributions. Special thanks go to the colleagues who contributed to the organization of the Minisymposia and to the reviewers who, with their work, contributed to the scientific quality of this e-book.

Editors

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- European Community on Computational Methods in Applied Sciences (ECCOMAS)
- International Association for Computational Mechanics (IACM)
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- Hellenic Society for Earthquake Engineering (HSEE)
- School of Civil Engineering, National University of Athens (NTUA)

Plenary Speakers and Invited Session Organizers

We would also like to thank the Plenary and Semi-Plenary Speakers and the Minisymposia Organizers for their help in the setting up of a high standard Scientific Programme.

Plenary and Semi-Plenary Speakers: Manfred Bischoff, Ludovic Chamoin, Eleni Chatzi, Laura De Lorenzis, Geert Degrande, Matthew DeJong, Alireza Doostan, De-Cheng Feng, Roger Ghanem, Muneo Hori, Boris Jeremic, Marc P. Mignolet, Giuseppe Muscolino, Udo Nackenhorst, Martin Ostoja-Starzewski, Costas Papadimitriou, Iason Papaioannou, K. C. Park, Alessandro Reali, Gianluigi Rozza, Alexandros Taflanidis, Enrico Tubaldi, Marcos Valdebenito, Wolfgang Wall.

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SUMMARY

VOLUME I

Minisymposia

MS 7: DYNAMIC MONITORING OF MONUMENTAL BUILDINGS AND ARTISTIC GOODS

COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
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SEISMIC ANALYSIS OF A MODERN ARTWORK THROUGH DETAILED FE MODELING

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Abstract

Cultural heritage artworks constitute significant traces of human actions throughout history, underlying the importance of their preservation and transmission to future generations. Nevertheless, due to environmental, anthropogenic and natural actions, they are subject to deterioration, decay and potential loss. Cultural heritage artifacts, such as statues, are vulnerable to strong impacts due to their fragile behavior. For these reasons, although protected in museums, these artworks are characterized by a notable risk towards seismic actions, especially considering their potential overturning. The expected behaviour of statues depends on the peculiarity of each good, the type of connection to the support, the mass centre's position, the stress flow along the static configuration. Given the exceptional context of these artworks, structural analysis requires detailed surveys and accurate modelling, limiting the uncertainties normally acknowledged in civil construction works.

In this research, a detailed finite-element (FE) model has been carried out to investigate the seismic response of a modern statue. The artwork is part of the Marino Marini Museum collection, a museum situated in the centre of Florence (IT) hosting a variety of artistic goods created in the 20th century by the Italian artist and sculptor Marino Marini. A photogrammetric survey of the statue was conducted, and a complete three-dimensional mesh was obtained. The model of the statue, imported in a FE environment, has accounted for unilateral constraints to simulate the interaction between the statue and the floor. The seismic analysis has considered a seismic input compatible with the soil underlying the museum. The outcomes of the research, evaluated in terms of stress and displacements of the statue, permitted estimating the risk affecting the artwork towards seismic actions, providing useful information for stakeholders aimed at its conservation.

Keywords: Modern Statues, Sculptures, FE Model, Seismic performance of artifacts, Step-by-step dynamic analysis.

1 INTRODUCTION

Artworks are important manifestations of mankind on earth, representing the capacity of human beings to overcome their natural instincts towards transcending ideas, concepts and beauty. For these reasons, artistic goods are invaluable pieces that require protection and conservation throughout the centuries. Natural risks are serious threats to artworks; fires, floods, earthquakes, have demonstrated their destroying capacity, leading to significant artistic losses [1]. Given a natural hazard, not every artwork's typology is the same vulnerable to each threat. For instance, paintings are particularly vulnerable to fires, less vulnerable (but still significant) to floods, and less vulnerable towards seismic actions, if not for indirect effects. While the issue of indirect effects opens towards the challenging evaluation of museum content together with its content [2], it is worth noting that explicit multi-risk evaluations for artworks are not fully developed [3-4]. In the field of seismic risk, standing goods, e.g. statues, are the most affected pieces [5]; according to their geometric and structural features, the collapse can be caused by: overturning, sliding (e.g. out of a pedestal), stress-failure. Since the first research on the collections of the Paul Getty Museum in California [6], different in-depth studies have been carried out, from very specific case studies up to generalized evaluations [7-10]. Recent advances include detailed geometrical acquisition, involving laser scanner or photogrammetry, with interesting attempts identifying the dynamic behavior of artefacts and their supports [11-13].

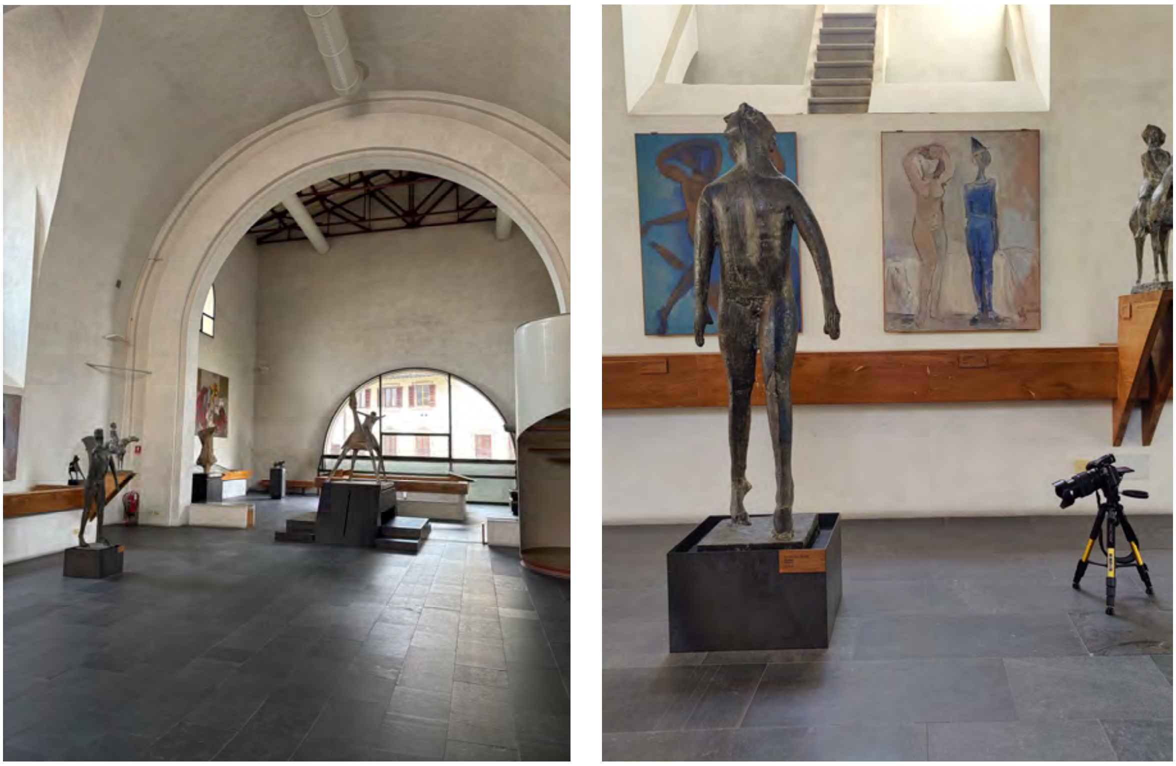
While advanced research has been devoted to ancient art goods, such as roman marble statues, modern and contemporary artworks have not been addressed for specific studies. In this paper, a detailed FE modeling of a modern statue of the artist Marino Marini is carried out. The artwork is part of the Museum Marino Marini, a permanent collection located in the center of Florence and gathering the works of the artist during the XX century. The museal building is object of interdisciplinary research targeted at evaluating the multi-risk of cultural heritage buildings [14]. The on-going research on the museal building has become the pretext to pursue some detailed evaluation of the art goods, starting from a pilot case. The manuscript presented is structured as it follows: in Section 2 an overview of the museal collection is shown; Section 3 reports the geometrical acquisition of the statue and the details of the restitution process; in Section 4 the seismic analysis is carried out; finally, Section 5 reports the conclusions of the work and its conclusive remarks.

2 MARINO MARINI COLLECTION

Marino Marini Museum is host inside the former San Pancrazio Church, in the historical center of Florence (IT). The building, erected during the Middle Age, has undergone several interventions. After several years serving as an ecclesiastic building, in 1808, the church was deconsecrated and it started serving as Napoleonic Lottery before, and as a tobacco manufacturer and military warehouse later. In 1988, the building space was restored, and the first museum of contemporary art of Florence was inaugurated. The museum hosts the works of artist Marino Marini, one of the main Italian artists of the XX century. As the restorations followed the idea of realizing a museum dedicated to Marini, the inner space is conceived as a promenade along the works of the artist. The treatment of the inner space through mezzanines and visual connections is meant to appreciate the tridimensionality of the sculptures from different perspectives, leading to a unique experience. The collection is made of statues, drawings, engravings and paintings, gathering artwork from the '20s to the '70s. Concerning the statues, there is a big variety of dimensions, from small objects to monumental goods. The materials adopted by Marino Marini are mostly bronze and chalk, with minor cases of marble or wood.

3 GEOMETRICAL ACQUISITION

The selected statue is named “The Juggler” and was realized in 1954. The dimensions of the statue are 166 x 58.5 x 38.4 cm and it is located at the last floor of the Museum (Fig 1a). The statue is made of bronze and characterized by welded parts within them. The Juggler is represented by a stylize man, standing with the face oriented towards the right side (Fig. 1b). Although the figure has the bust right oriented, the legs present a misalignment configuring a stabler position.



(a) (b)

Figure 1: a) View of the upper level of the Museum; b) The Juggler statue, by Marino Marini.

Acquisitions have been carried out through photogrammetric survey. The campaign was conducted using a digital medium format camera, the Fujifilm GFX-50s capable of taking shots at the resolution of 50 Mp on a sensor of 43.8 × 32.9 mm, mounting a Fujinon Zoom lens with a focal length of 32-64mm and a maximal aperture of F4.

3.1 Photogrammetry

The options for having a successful SfM_IM (Structure from Motion, Image Matching) photogrammetry mostly depends on the quality of the shots (free from shaking blur, with minimal digital noise and well positioned so to cover all the corners of the subject, reducing the occlusion spaces). In the case of the statue “the Juggler” one possible additional issue was the material in itself, the bronze surface may turn to be too much reflective and interfering with the proper productions of the various steps of the digital model generation. The lens was setup at 64mm focal length (equivalent to a 51mm length on a full frame sensor) and stop-down at F8/F11. The quite intense natural light on the statue allowed a sequence of images well flooded by light, with a proper depth of field on the statue and with a minimal amount of reflections. The intensity of natural light made preferable to operate with the camera on a tripod and then with minimal issues about shaking blur effects, the ISO setting of the sensor was placed at 400, with no significant digital noise production. In all the parts where the reflections started to appear, the shooting was intensified with a denser coverage and with sensible variations in the position of the camera, so to gradually reduce the influence of these strong lights on the modelling process. The overall number of shots was 2057, taken moving around the statue and taking images in circle and then moving up the camera to an upper level and creating a new circle of images. In this way, when the position of the camera reached the height of the statue, a final series of shots were taken placing the camera on an extensible pole, so to cover completely all the top parts of the sculpture. The photogrammetry work at the museum was then finished taking some direct measurement on the base of the statue for further scaling of the resulting model. The following processing was brought on using EG Reality Capture software, with the classic process starting from the alignment and then passing to the polygonal mesh generation (creating a 108,9 million triangles model), the optimization/simplification of the mesh (creating a surface reduced to four million tringles) and finishing with the application of the texture and the extraction of high resolution orthophotos.

3.2 3D modeling

The resulting model was then exported in its simplified version, at four million triangles, using the OBJ format- This version was used to upload the model into Sketchfab.com allowing an easy streaming of the result to any user of that community. The model can be viewed and inspected at the URL: https://skfb.ly/p9sNY on the Sketchfab platform. The model was then imported into Autodesk 3D Studio Max 2025, where the surface was processed to add a thickness of about one centimeter and then to receive a specific and very practical modifier, the “multires”, it allows to calculate a multi-resolution value for the polygonal surface and then regulate the number of triangles at any reduced value. This solution speeds up the creation of a version compliant with the following needs for FR modelling and seismic analysis allowing multiple versions to be created from the same base model and then tested in the final part of the process. After the correct number of triangles was found the model was processed in Instant Mesh, a freeware/BSD software dedicated to polygonal simplification and retopology, the optimized and simplified version of the Juggler was then ready to be moved to the following steps.

4 FE MODELING AND SEISMIC ANALYSIS

4.1 FE modeling

The geometric model has been converted in the *.iges* format and imported into a FE environment. The imported geometry consisted of 8142 faces configuring the statue’s shape. Strand7 © was used to realize the mesh of the statue, while Abaqus CAE © has been adopted to execute numerical analyses. The model consists of 43124 nodes and 38504 elements divided between 8271 linear quadrilateral elements of type S4R and 11328 quadratic triangular elements of type STRI65 (Statue) and 18905 linear tetrahedral elements of type C3D4 (Basement) (Figure 2). A linear elastic material was assumed, with a density of 8500 kg/m^3 and an Elastic Young’s Modulus of 113000 MPa. Based on a rough estimation of the weight of the statue, the thickness of the shell elements was assigned 0.005 m, leading to a weight of 70 kg.

The statue was modeled as rested on a pedestal. In this first evaluation, the pedestal has been modeled in a simplified manner, considering it as a rigid body fixed to the ground. To simulate the interaction between the Artwork and the Pedestal, a contact between the surfaces was modelled through a normal behavior (defined in Abaqus through a “hard contact”) and a tangential behavior (defined through a friction coefficient).

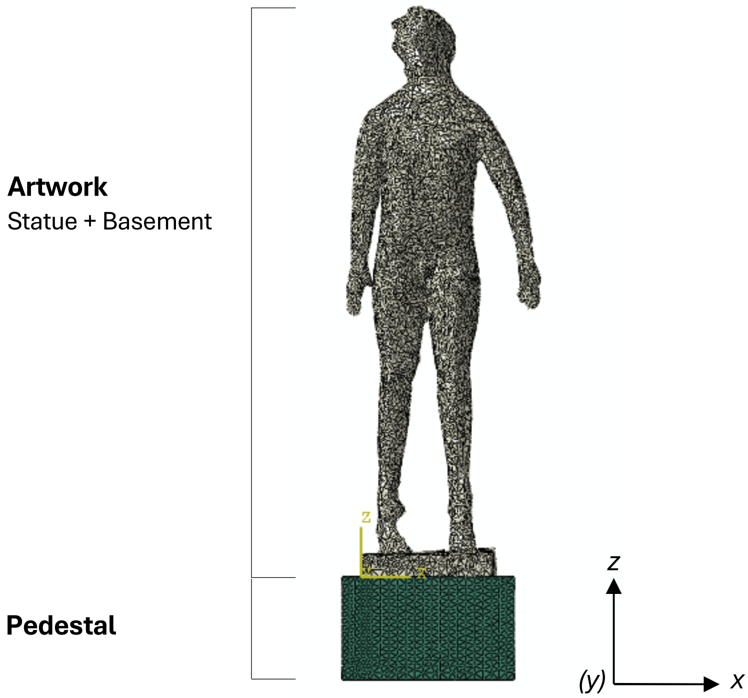


Figure 2: Meshed model of The Juggler with its pedestal.

Preliminary to the seismic assessment, gravity analysis and modal analysis were executed. In terms of gravity loads, the mass of the statue leads to the maximum tensions at the feet and ankles of the model, with maximum stress values in the order of 2.8 MPa.

According to the modal analysis, a first mode of 12.06 Hz was found, with a slight diagonal mode shape given by the geometrical position of the legs. The other principal modes correspond to 43.25 Hz (translational) and 72.92 Hz (torsional).

4.2 Seismic assessment

4.2.1. Definition of seismic input

The seismic input has been defined in accordance with the Italian Building Code (NTC2018). The demand spectrum was considered assuming a nominal life of 50 years and an important factor of 1.5, leading to a reference life of 75 years. Based on the soil characteristics of the historical center of Florence where the Museum is located, a soil class B was assumed. The elastic spectrum for the Life Safety Limit State (SLV) defined for a seismic action with a return period of 712 years has been adopted to select spectrum-compatible accelerograms for dynamic analyses. The selection of the records was done through Rexelweb [15]. In this work, the record SM.103.00.HN.IS-2000-0048, scaled according to the reference PGA has been applied to the statue (Figure 3); further steps of the work will regard the application of the entire sample to overcome the record-to-record variability of the signals.

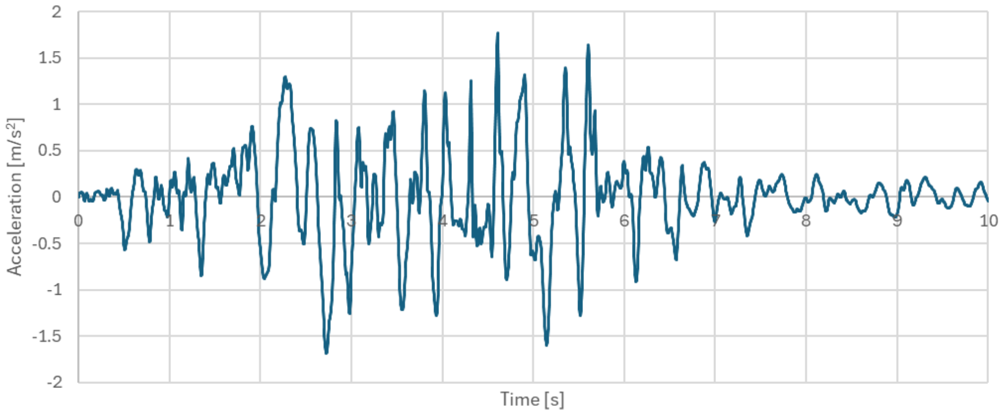


Figure 3: Acceleration input.

4.2.2. Dynamic analyses

A simplified scheme based on the mass of the statue and its center of mass to assess the possibility of sliding was considered. The center of mass is at 0.705 m (*z* direction), and at 0.20 m from the edges of the pedestal (*x, y* directions), thus obtaining a horizontal multiplier for activating the overturning equal to 0.283. The sliding condition occurs when the applied force is greater than the static friction force. Considering the surface of the Statue (bronze) and the one of the Pedestal (steel), the available literature indicates a static friction coefficient of 0.16 which brings to an expected sliding mechanism of the statue before overturning.

The numerical analysis has been conducted considering two steps: firstly, the gravity load has been applied, secondly, the accelerogram was assigned to the pedestal. The excitation was given according to the *y* direction, with a scaled action of 30% in the *x* direction. In Figure 4 the acceleration time-history graphs for different control points are reported. From the Basis, it is worth noting the amplification of the seismic signal along the statue, reaching peak values of 3.26 m/s^2.

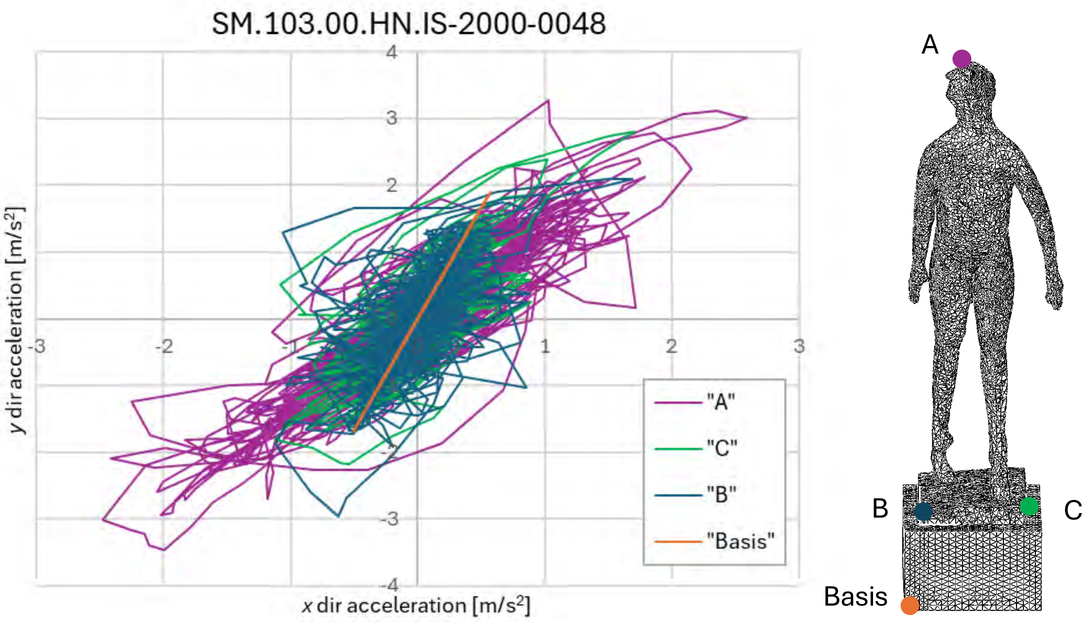


Figure 4: Acceleration time-history for different monitored points.

In terms of displacements, as expected, the statue exhibits a sliding mechanism. In absence of vertical component, excluded from this study, the artwork tends to rotate over its vertical axis, pointing out displacements from the initial position. Along the *y* direction, the scatter between points B and C during the time-history reaches a maximum value of 0.51 mm, with a residual scatter at the end of the analysis of 0.39 mm (Figure 5). Concerning the total displacement, a maximum value of 0.8 mm was found during the analysis at the time of 4.56 s.

Observing the maximum tension in the model, a tensile value of 88.22 MPa is exhibited at the right foot of the statue for a step time of 6.15 s.

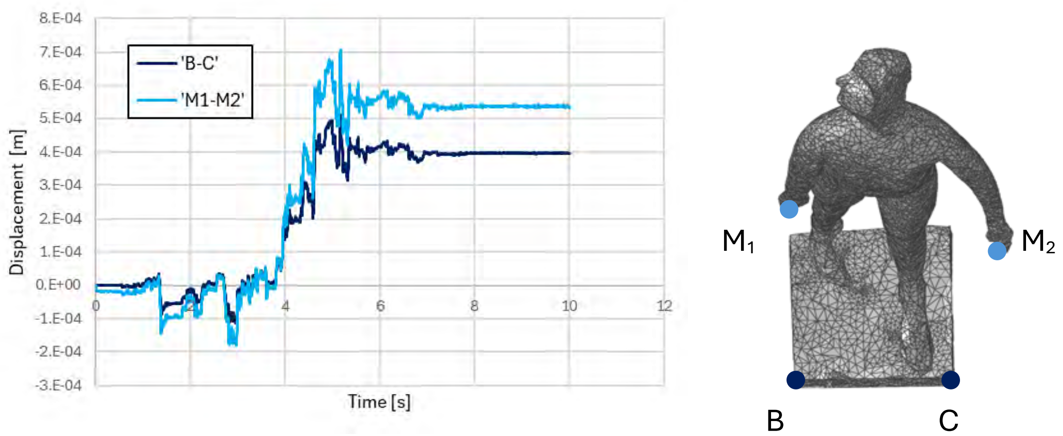


Figure 5: Time-history for the relative displacement between the basement and the hands of the statue.

5 CONCLUSIVE REMARKS

The manuscript presents preliminary research aimed at investigating the risk of art goods inside the Marino Marini Museum. The work has regarded the initial seismic analyses of “The Juggler” statue by contemporary artist Marino Marini through FE modeling. The research took advantage of a detailed photogrammetry campaign, which permitted defining the geometry of the artwork. The FE modeling considered a simplified configuration of the pedestal, without accounting for additional interactions within pedestal and pavement.

The outcomes of this study provide partial results, offering initial insights into the seismic assessment of the statue. Further analyses are required to comprehensively evaluate its behavior under ground motions. Future steps of the work will include analyses considering additional accelerogram records, the account of vertical component, as additional interactions involving the possible sliding of the pedestal on the pavement.

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