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A SEISMIC ASSESSMENT AND PROTECTION PROPOSAL OF A BASE ISOLATION SYSTEM FOR MICHELANGELO'S DAVID

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Abstract

Michelangelo's David is a masterpiece that belongs to the world community and needs to be preserved. Actually David stands in Accademia Gallery, Florence (Italy). This site is characterized by a medium seismicity. Therefore many studies have been produced throughout last decades to assess its static behaviour and to find a proper solution able to provide adequate seismic protection. In this regard, base isolation application to statues is a relatively new technique. Several devices have been already applied to important structures all over the world. This study focuses on the application of sliders between Michelangelo's David and its basement. These devices consist of two sliding plates arranged in an array of movable top plates and fixed bottom plates. This paper mainly aims at reproducing the interaction statue – sliders – basement taking into consideration seismic protection devices currently named as sliders. Isolation system behaviour has been reproduced by employing a Bouc and Wen hysteretic model whose parameters have been calibrated by shaking table tests performed at the Pacific Earthquake Engineering Research (PEER) Center, in California. The study aims at numerically reproducing the sliders with OpenSees, to simulate the high non linearities of the interface and reproduce the large displacements predicted by the analytical model.

Keywords: Michelangelo's David, base isolation, Bouc and Wen, numerical simulations, OpenSees

1. Introduction

Michelangelo's David is one of the most iconic artefact of the Italian Renaissance. This masterpiece is a world heritage that has to be protected. It actually stands inside Accademia Gallery in Firenze, Italy, which is considered by the Italian Seismic Code [1] to have a medium seismicity. David's stability is critical because its static configuration and its intrinsic weakness. For these reasons, David's seismic protection is of fundamental importance and this paper aims at presenting an original contribution. The actual state of the statue shows the presence of a diffused system of cracks especially in correspondence with the legs. Many studies have been performed in the past in order to analyze the static and seismic behaviour of the statue ([2], [3], [4]), and they offer valuable information.

In this regard, the actual state of mechanical computations allows to investigate the statue with high potential tools. The Finite Element (FE) code ANSYS was employed to build a numerical model of Michelangelo's David. Geometry of the model was created according to the laser scanner relief performed within the "Digital Michelangelo Project" coordinated by Marc Levoy (Stanford University) and developed between 1997 and 1999.

Moreover, base isolation is considered one of the most effective techniques to minimize seismic risk for structures. Many additional applications - such as artefacts and statues - have been recently proposed. Several devices such as laminated rubber bearings, sliding bearings and marble devices have been used in the world. This paper investigates a base isolation system that employs sliders between the basement and the floor. The seismic risk reduction of Michelangelo's David is analyzed as an applicative case study. The device herein considered consists of two sliding plates arranged in an array of movable top plates and fixed bottom plates. The goal is to decouple seismic motions between the basement and the floor

The study aims to reproduce the interaction statue – sliders – base support taking into consideration EQX global (http://www.eqxglobal.net) seismic protection devices. Isolation system behaviour has been reproduced by employing a Bouc and Wen hysteretic model whose parameters have been calibrated by shaking table tests performed at the Pacific Earthquake Engineering Research (PEER) Center laboratories, University of California, Berkeley.

This study presents a numerical model aimed at reproducing a detailed insight into the sliding behaviour by applying a versatile constitutive approach in conjunction with an advanced interface. In particular, the paper applies the open-source computational interface OpenSeesPL [5] implemented within the finite element (FE) code OpenSees [6]. Thanks to its potentialities, OpenSees is able to simulate high non-linearities of the devices and reproduce the large displacements that have been predicted by the analytical model and lab tests.

2. David

Michelangelo (1475-1564) created David (Fig. 1) between 1501 and 1504 immediately after the success obtained with Pietà (Roma, 1499-1500) when he was twenty-six year old. David was originally conceived as one of the statues to be positioned along the roof-line of the Cathedral of Firenze, but this plan was abandoned when it became clear that raising of the six-ton five-meter statue was not practicable. Alternatively, the main entrance of Florence town hall ("Palazzo Vecchio") was chosen and Michelangelo's David was unveiled there on 8 September 1504. It remained in this location until 1873. Between 1852 and 1872, a growing concern arose about the deterioration and stability of David due to a series of visible cracks. Some of these were found in the tree trunk that supports the right leg, and others in the lower part of the left leg. Three Committees were established and the conclusive decision was to move Michelangelo's David inside Accademia Gallery ([2], [3], [4]).

As a result of Michelangelo's conception, David stands with one leg holding its full weight (the right) and the other leg (the left) forward. Such a static position, with the right leg bearing most of the weight, caused Michelangelo to reinforce the right leg with the tree trunk. Nevertheless, cracks arose more than three centuries (nineteenth century) after the statue had been unveiled. In this regard, the intrinsic weakness of the statue cannot be considered as the main cause of these observed cracks. A conclusive explanation of the damage was offered by [4] showing, for the first time, that the cracks in the legs were likely caused by an acquired slight forward inclination of the statue. When David was moved to the Accademia Gallery in 1873, the tilt was corrected and the cracks have not worsened ever since.

David has recently been investigated by [2], [3], [7]. Consequently, a great number of data and results are now available, making the statue a representative case study. Geometric characteristics of the statue such as its volume have been obtained thanks to a laser scanner relief performed within the "Digital Michelangelo Project" (coordinated by Marc Levoy, Stanford University and developed between 1997 and 1999). Marble material properties have been evaluated according to [4]. This case study is particularly interesting since, as explicitly suggested by [4], to find a proper solution able to provide adequate seismic protection for David, is a challenging issue.

Fig. 1 – Michelangelo's David.

3. Numerical model

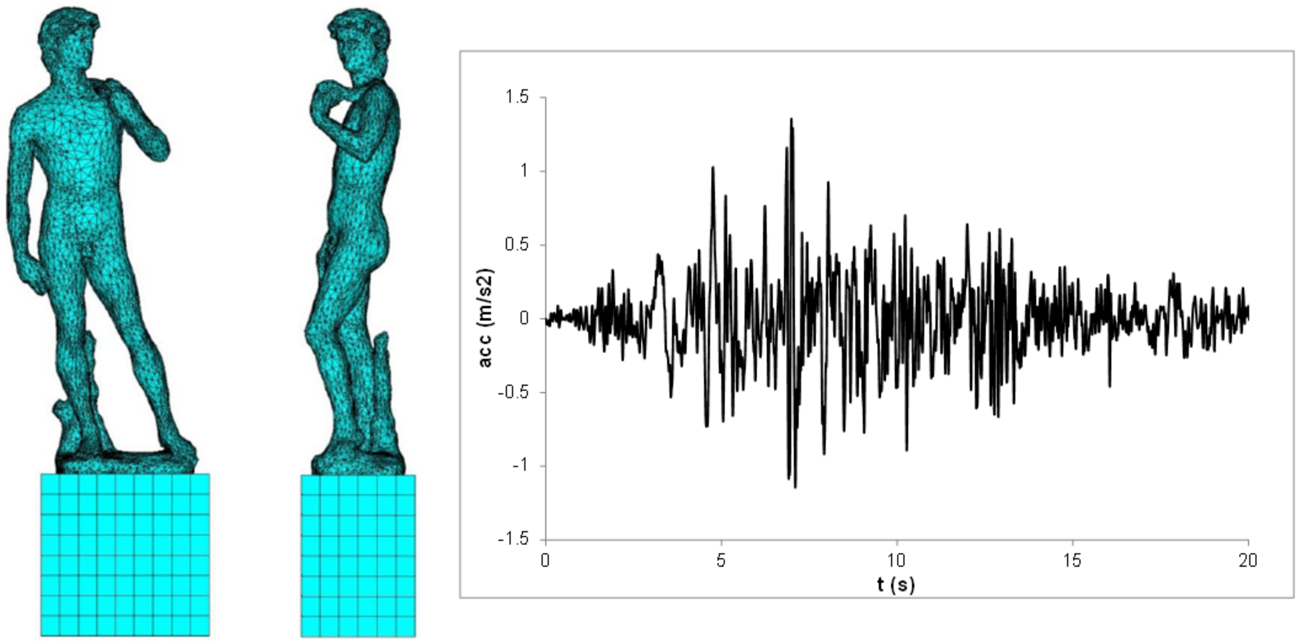
Finite element (FE) code ANSYS [8] was employed to build the numerical model of Michelangelo's David. Model geometry was created according to the laser scanner relief performed within the "Digital Michelangelo Project" coordinated by Marc Levoy (Stanford University) and developed between 1997 and 1999.

FE model (see Fig. 2 (a)) was built with 40.205 iso-parametric three-dimensional (3D) elements and 10.297 nodes. Despite the possibility to implement a nonlinear behaviour to account for the marble tensile and compressive strength, ANSYS model has been employed to perform linear time-history analyses. Marble material properties have been evaluated according to [4]. The boundary conditions between David's basement and the pedestal were set as fixed at the base of David, neglecting the realistic discontinuity that connects the two materials.

In order to take into account the seismicity of Florence, Italian Seismic Code (NTC 2008 [1]) has been considered with following assumptions: soil type B and Topographic classification T1. The limit state of life safety (SLV) has been considered (characterized by a return period of 475 years, associated with a reference period of 50 years). The corresponding peak ground acceleration (a_g) resulted equal to 0.16g.

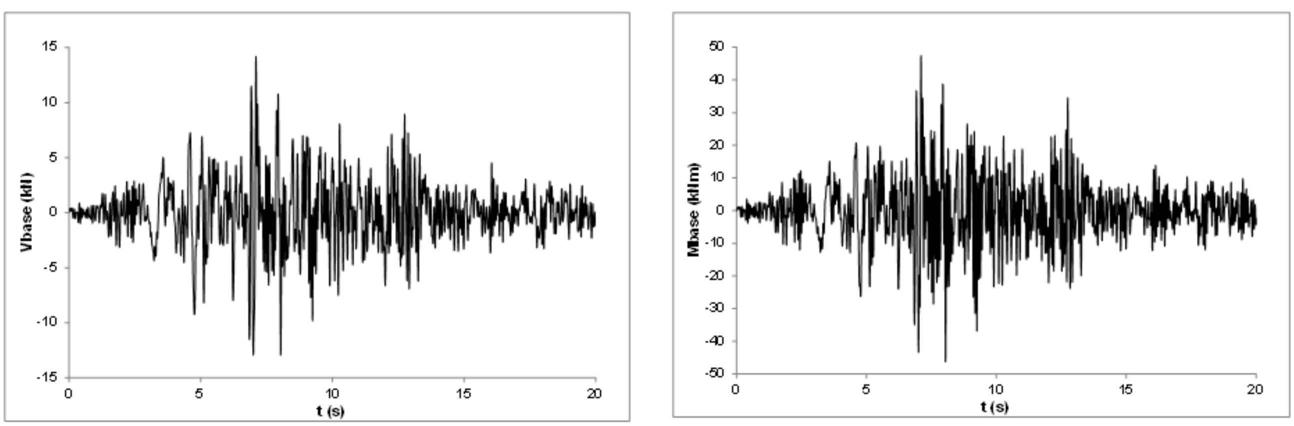
To perform the analyses seven input motions have been accordingly determined with REXEL [9]. One of these, obtained with REXEL, is shown in Fig. 2(b). In particular the input motion has been assigned at the base of the pedestal of the statue without taking into consideration any possible amplifications caused by the pedestal and the interface between the pedestal and the statue itself. It is noteworthy to observe that only the horizontal component of the seismic records has been considered.

In order to assess several possibilities of failure, such as the overturning, support shear failure and cracking of David's lower parts, base shear and bending moment at the base of the statue have been calculated. Fig. 3 shows these time histories and the obtained maximum values that are 15 kN and 40 kNm for the base shear and the bending moment, respectively (time histories reported in Fig. 3 refer to the acceleration time history reported in Fig. 2(b); similar values are obtained if remaining seismic records are considered).



(a) (b)

Fig. 2 – (a) Views of the FE model (ANSYS); (b) Acceleration time history.



(a) (b)

Fig. 3 – (a): Base shear time history; (b) Bending moment time history.

4. Seismic protection with isolation

Nowadays isolation technique is a widely recognized solution aimed at minimizing seismic effects providing effective solutions for seismic risk mitigation. Originally, first applications were proposed mainly on large structures like public buildings, nuclear plants, bridges, etc. In the last few decades, applications of seismic protection for artefacts have been studied and designed all over the world. In this regard, [10] was one of the first attempt in this field and developed analytical and experimental procedures for seismic assessment of several museum pieces. The response of an isolated statue, modelled as a single-degree-of-freedom system (SDOF), was analyzed through a parametric study by [11] while, a passive control system for art objects employing the rigid block equations of motion, was proposed by [12].

Several applications and demonstrative case studies dealing with artefacts showed the benefits of this technique. In the case of the statues, different typologies of devices have been employed, such as double concave curved surface sliders, marble devices, etc. An isolation technique that proposes a marble (and/or granite) anti-seismic base was developed at CNR-ENEA Research Center (Rome, Italy) and adopted for the seismic protection of the Bronzes of Riace (Archeological Museum of Reggio Calabria, Italy, [13]). The effectiveness of the results allowed the author to propose the same technique for Michelangelo's David. [14] investigates an isolation application based on small-size double concave curved surface sliders. The authors propose the use of traditional devices (usually adopted for civil applications) in order to take advantage of existing industrial knowhow and technical background. A proper calibration of the device frictional parameters is discussed through the analysis of experimental tests. As exemplary applications, several numerical simulations on a group of statues at the ground floor of the Accademia Gallery in Firenze were performed. The results, after proper redesign of the devices, show the effectiveness of the proposed isolation technique. Other recent applications have been discussed by [15].

Taking into account this background, the presented study focuses on the application of sliders between Michelangelo's David and its basement. These devices consist of two sliding plates arranged in an array of movable top plates and fixed bottom plates. The paper mainly aims at reproducing the interaction statue – sliders – basement taking into consideration seismic protection devices, by EQX global. The physical behaviour of the system statue – sliders – basement is reproduced by employing a Bouc and Wen hysteretic model ([16], [17]). Parameters have been calibrated by considering several shake table tests. After calibration, the efficiency of the proposed SDOF Bouc and Wen approach has been compared with numerical simulations developed with OpenSees.

In the following paragraphs, the Bouc and Wen model employed to reproduce the experimental results is briefly introduced. The procedure adopted to identify the parameters is described and several sliders have been compared. OpenSees Finite element model is described in section 6 and the materials have been implemented in order to represent the lab test behaviour. Section 7 discusses the obtained results comparing the finite element model and the simplified SDOF (single-degree-of-freedom) Bouc and Wen model.

5. SDOF Bouc and Wen Model

Bouc [16] and Wen [17] model (B&W in the following) is widely employed to represent hysteretic behaviour of various materials. Herein it was applied to reproduce the relation between the applied shear force and displacement of the tested sliding plate systems denoted as TPL02 and TPL10.

B&W model describes the nonlinear restoring force of the examined system as the linear combination of a linear and a nonlinear term. If x denotes the displacement of a SDOF system and F the restoring force, then:

$$F = k\left[\alpha x + (1-\alpha)\cdot z\right] \tag{1}$$

The additional parameter z, the so-called hysteretic displacement, is described by means of a differential equation which models its evolution during the loading process. In particular, its increment δ_z is proportional to an increment δ_x of the displacement by the following nonlinear term:

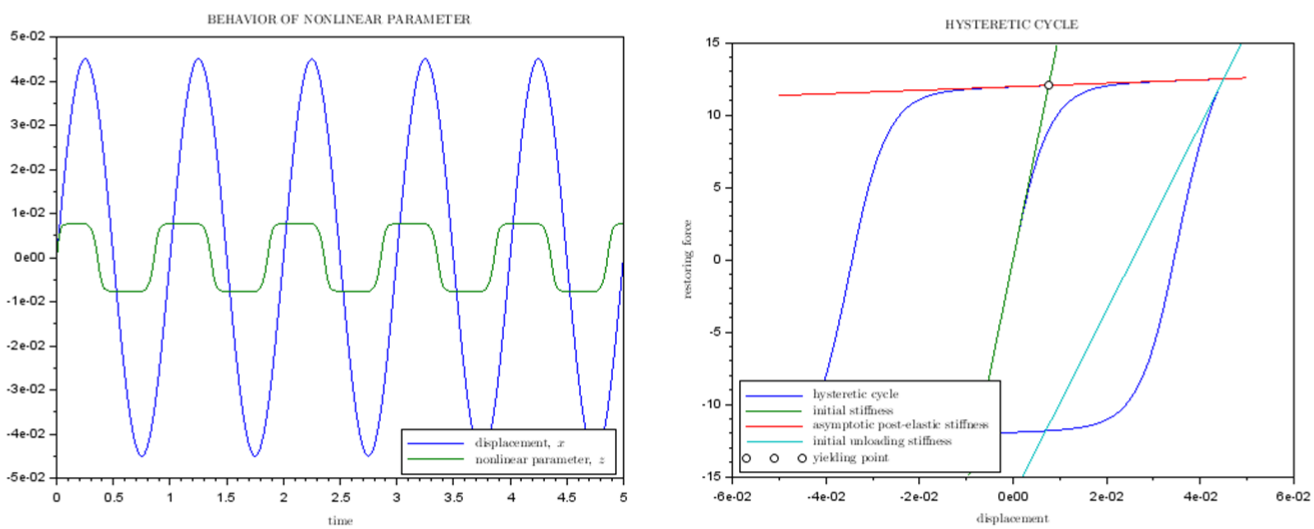
$$\delta_z = \delta_x \cdot \left[A - |z|^n \cdot \left(\beta + \gamma \cdot sign(z) \cdot sign(\delta_x)\right)\right] \tag{2}$$

It can be shown that parameter A is redundant and therefore in the following it will be set to 1.0. B&W model imposes a decreasing increment δ_z for increasing amplitudes of the nonlinear parameter z: this ensures that, starting from zero, reaches an asymptotic value and decreases when the increment δ_x changes sign, as shown in Fig. 4 (a).

When a generic hysteretic relation between displacement and applied force of a given system is taken into consideration, it is possible to relate the B&W parameters α, β, γ, n and k to the physical characteristics of the examined system. Referring to Fig. 4(b), it can be shown ([18], [19]) that the initial stiffness k_i, the asymptotic post-elastic stiffness k_f, the initial unloading stiffness k_u and the ideal yielding point x_Y are related to the B&W parameters by the following relations:

$$k = k_i\ ; \alpha k = k_f ; \frac{\beta - \chi}{\beta + \gamma} = \frac{k_i - k_u}{k_i - k_f} ; \beta + \gamma = x_Y^{-n} \tag{3}$$

A total of four relations have been obtained for the calibration of five parameters; the fifth parameter, n, governs the transition from the initial elastic behaviour to the post-elastic behaviour of the system and is usually determined by means of a least-squares procedure.

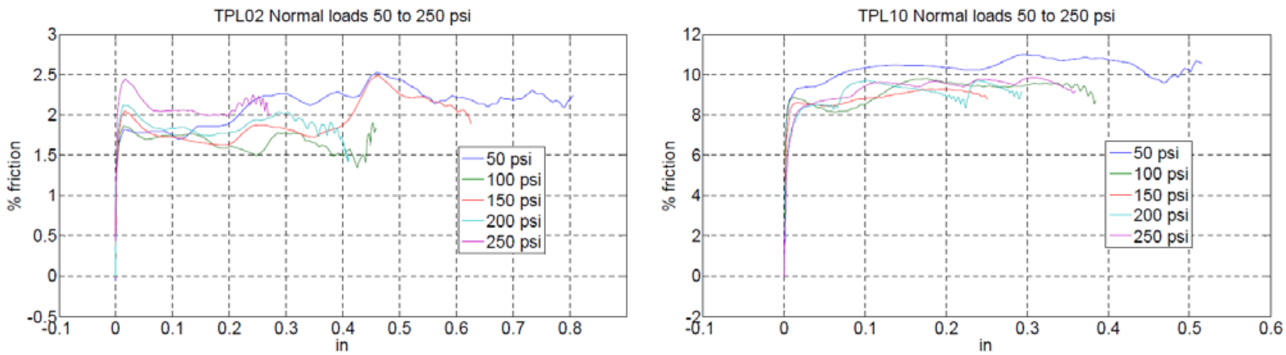


(a) (b)

Fig. 4. (a) Behaviour of nonlinear parameter z(t) (green line) for an imposed harmonic displacement x(t) (blue line); (b) Definition of initial, asymptotic and unloading stiffness of B&W model and of the ideal yielding point.

5.1 Seismic floor system

The study analyzes a base isolation system that foresees the application of sliders between the statue and the basement, by EQX global. More details are reported in [20]. The sliders are arranged in an array of thin plates that slide over each other. The bottom plates are polished stainless steel with a deformed pattern while the top plates are coated with a special polymer that controls the friction to either 2% (named TPL02) or 10% (named TPL10) depending on the application. Tests on specimens were carried out at the Pacific Earthquake Engineering Research (PEER) Center, University of California, Berkeley under the supervision of Prof. James Kelly and Dr. Davide Forcellini. Single objects with a high aspect ratio and relatively lower mass require a higher degree of isolation to prevent tipping. In this paper both the 2% (TPL02) and 10% (TPL10) friction devices were considered. Coupon tests of materials for breakaway friction properties were performed by a double shear test using two sets of plates. The normal loads were applied in increments of 0.34 MPa (50 psi) until noticeable scarring or significant increases in the coefficient occurred. The results of tests are shown in Fig. 5(a): TPL02 and (b): TPL10.



(a) (b)

Fig. 5 – Test results (a): TPL02; (b): TPL10.

5.2 Parameter identification

Available data on the plates didn't allow a description of the unloading behaviour of the system, therefore it was assumed that the initial unloading stiffness k_u was equal to the initial stiffness k_i, implying that $\beta=\gamma$. Initial values for parameters α, β and k were determined by regressions performed on the experimental data, and n was initially set to unity. Subsequently, a least-squares procedure was performed to calibrate all the parameters.

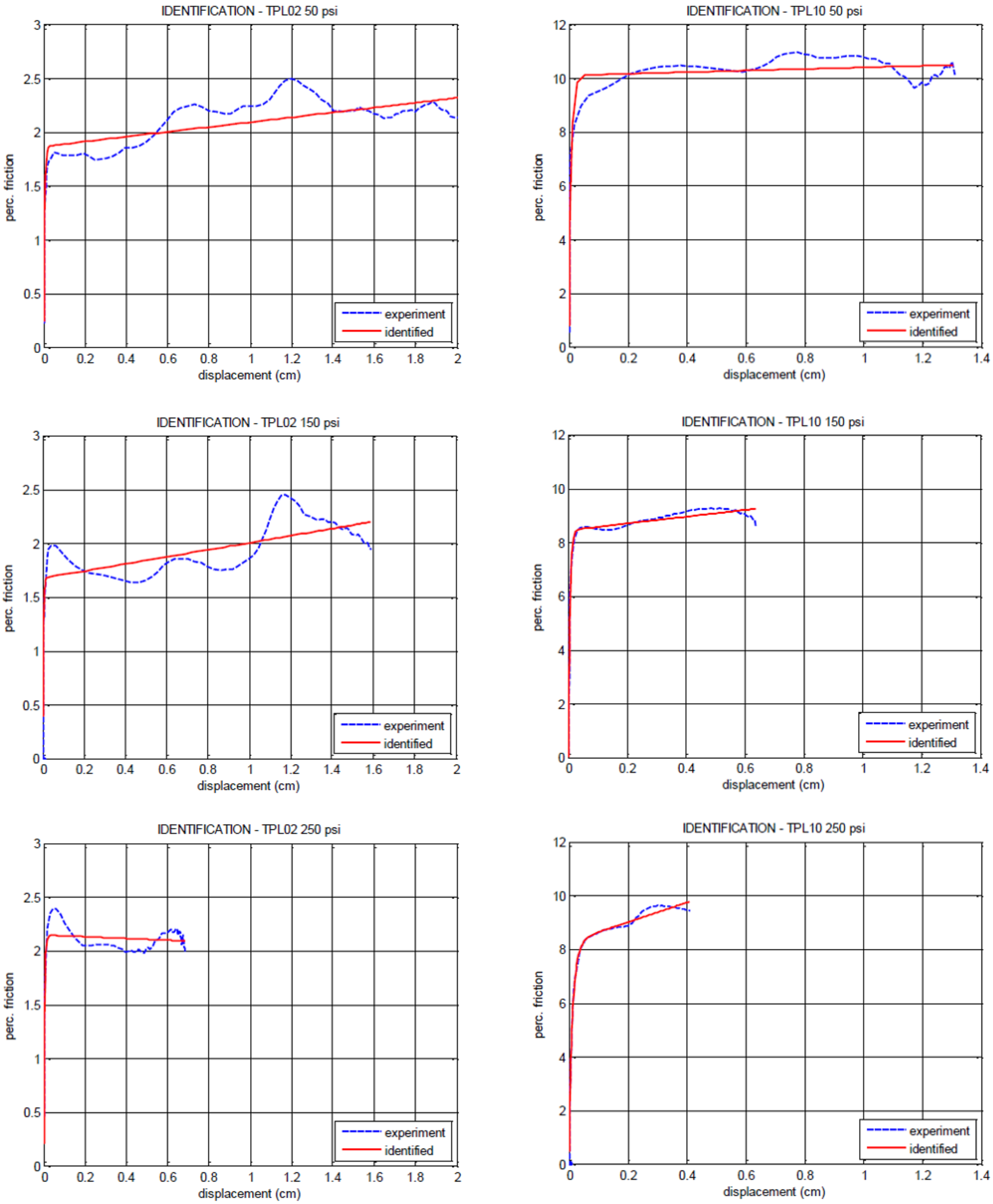
Fig. 6 compares the B&W model results with experimental results respectively for TPL02 and TPL10 devices (plate loaded at 50, 150 and 250 psi). Table 1 and Table 2 report the identified parameters of the B&W model for TPL02 and TPL10, respectively.

Table 1 – TPL02: B&W model identified parameters.

	50 psi	**150 psi**	**250 psi**
k_i	1.10e+004	4.55e+002	9.04e+004
α	2.03e-005	7.19e-004	-8.80e-007
n	3.36e-002	1.28e+000	5.60e-003
β	6.69e-001	6.79e+002	5.30e-001
γ	6.69e-001	6.79e+002	5.30e-001

Table 2 – TPL10: B&W model identified parameters.

	50 psi	**150 psi**	**250 psi**
k_i	2.23e+004	1.29e+003	3.16e+003
α	1.30e-005	9.66e-004	1.15e-003
n	5.01e-002	1.26e+000	1.76e-001
β	7.35e-001	2.90e+002	1.42e+000
γ	7.35e-001	2.90e+002	1.42e+000



(a) (b)

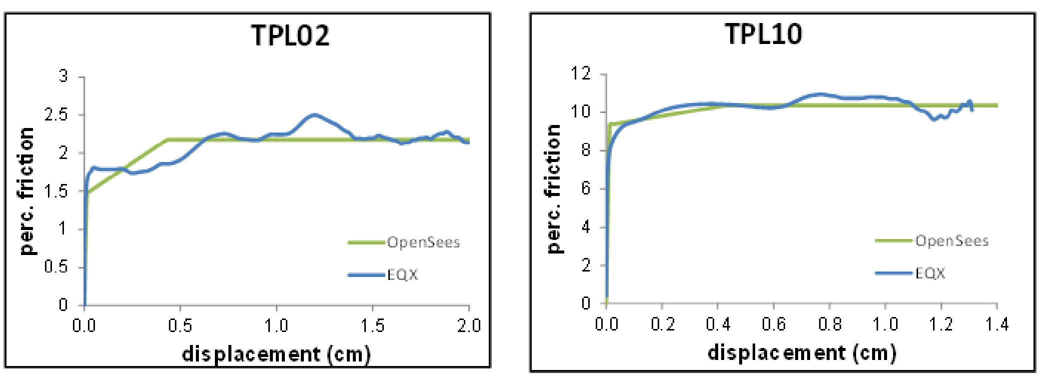
Fig. 6 – Experimental data compared with the identified B&W model. (a): TPL02 and (b): TPL10.

6. Slider FEM model

Numerical model aims at reproducing a detailed insight into the sliding behaviour by applying a versatile constitutive approach in conjunction with a well advanced interface. In particular, the paper applies the open-source computational interface OpenSeesPL [5] implemented within the FE code OpenSees [6]. The model here presented is a first attempt in order to calibrate the platform. In this regard, the statue has been represented as a cantilever with distributed mass and equivalent stiffness. The platform, originally for soil applications has been here modified in order to study slider behaviours. The 3D domain is represented by 8 nodes brick elements [6] as to describe the solid translational degrees of freedom in longitudinal direction. Fig. 7 shows the adopted 3D FE (original and deformed) mesh, composed of 736 brickUP (isoparametric 8 node elements with 1.003 nodes). OpenSees ability to model the boundary conditions is of particular importance in order to reproduce the slider behaviour. In particular, the base has been set with rigid conditions. The lateral boundaries has been modelled with a shear type behavior, in order to reproduce the sliding effect of the plates. The seismic excitation was defined along the base in the longitudinal direction, as shown in Fig. 3. The characterization of the sliding material was carried out in order to calibrate the frictional behaviour with the defined material, called Pressure Independ MultiYield. This model consists of a nonlinear hysteretic material [21] with a Von Mises multi-surface ([22], [23]) kinematic plasticity model, focused on reproduction of the hysteretic elasto-plastic shear response. Plasticity is formulated based on the multi-surface (nested surfaces) concept, with an associative flow rule, according to the well-known formulation by [24]. In this model, the nonlinear shear stress-strain back-bone curve is represented by the hyperbolic relation, defined by the two material constants, low-strain shear modulus and ultimate shear strength. The values are considered constant and detailed in Table 3 for TPL02 and TPL10. The letter C represents the shear stress peak value that is reached in correspondence with the shear strain named p, while n is the number of yield surfaces considered. Fig. 7 shows the shear stress-strain backbone curves adopted for the sliding materials (considering plate loaded at 50 psi). Fig. 8 shows the undeformed and deformed 3D mesh. Fig. 8 verifies that the deformations are concentrate in the sliding material, which shows a shear type behaviour, as expected.

Table 3 – Characteristics of the material.

	C [kPa]	p [%]	N
TPL02	650	0.7	3
TPL10	3100	0.7	10



(a) (b)

Fig. 7 – OpenSees behaviour compared with the esperimental data (a): TPL02; (b): TPL10.

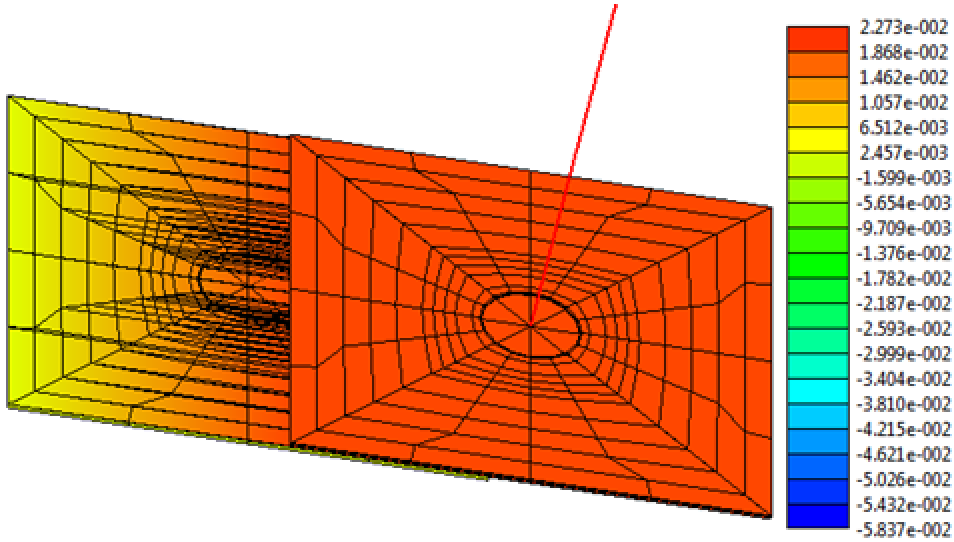
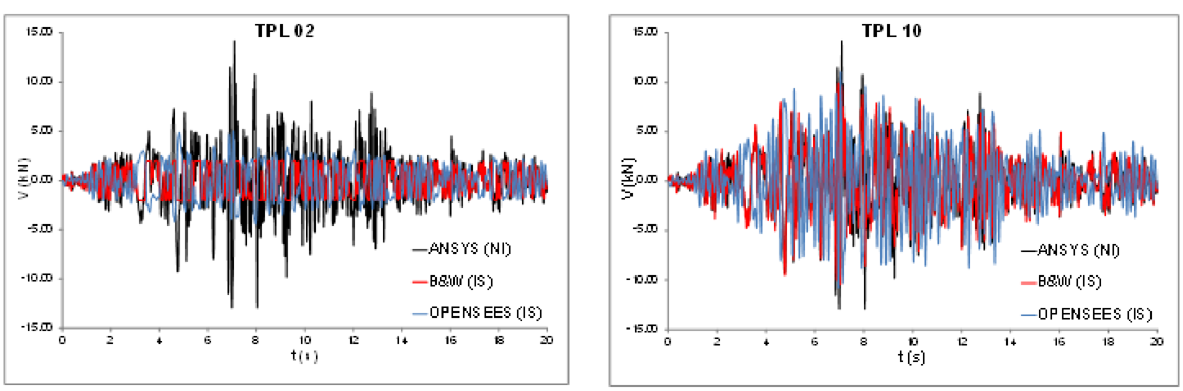


Fig. 8 – OpenSees model (deformated 3D mesh)

7. Discussion

Fig. 9 compares base shear forces obtained in the NI configuration with the one obtained through the B&W model and the one resulted from OpenSees simulations for the case of TPL02 (a), TPL10 (b), (plate loaded at 50 psi). In particular, comparing NI and SI results, it is possible to evaluate benefits of each typology of sliders. Considering TPL02 system, the maximum base shear varies as follows: from 14.20 kN (NI) to 2.12 kN (around 15%) for B&W model and to 5.03 kN (around 35%) for OpenSees model. For TCL10 these values result: from 12.95 kN (NI) to 10.50 kN (around 81%) for B&W model and to 10.76 kN (around 83%) for OpenSees model.

It is possible to assess the benefits of applying the sliders in terms of reducing the shear applied to the statue. In particular, OpenSees values are bigger than those resulted from Bouc and Wen theoretical model because the numerical simulation is able to take into account many sources of non-linear effects such as p-delta effects, large displacements and plastic deformations. Therefore, both devices (especially TPL02) are able to reduce significantly the levels of forces (and consequently stresses) that can potentially induce failures, such as the overturning, support shear failure and cracking of David's lower parts.



(a) (b)

Fig. 9 – Base Shear time histories (comparison between the NI configurations and B&W and OpenSees SI configurations) for (a) TPL02; (b) TPL10.

Fig. 10 shows longitudinal displacement time histories in correspondence with the top plate resulted by OpenSees. It is possible to understand that the values are small (maximum values: 5.76 cm for TPL02 and 3.66 cm for TPL10). In particular, the entity of such displacements, induces several considerations. First of all, these results are important in order to design the free space around David that allows it to move in case of a seismic event. The dimension of such space is relatively small, even for TPL02. Secondly, the entity of such displacements is so small that avoids the design of re-centering devices.

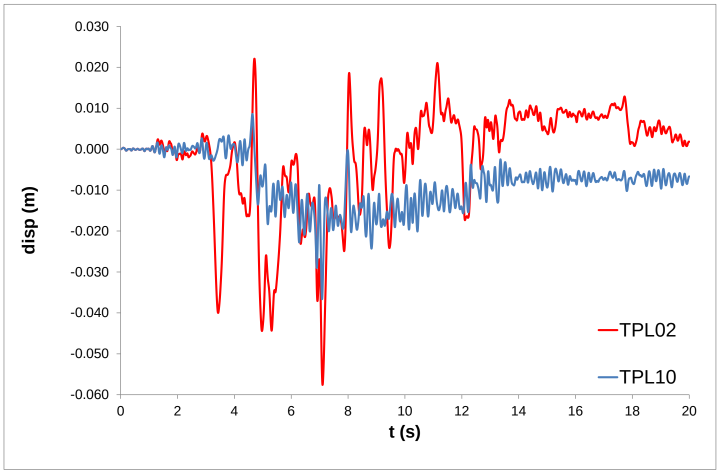


Fig. 10 – Longitudinal displacement time histories for the top plate (OpenSees).

6. Conclusions

The paper focuses on base isolation techniques to minimize seismic effects on statues, with an application to Michelangelo's David. In particular, the applied system consists of two sliding plates between the statue basement and the floor. The devices have been performed firstly with a SDOF Bouc & Wen hysteretic model calibrated as to reproduce the physical behaviour of sliding devices. Secondly, the same case study has been performed with OpenSees. In particular, both the approaches show the isolation technique effectiveness in Michelangelo's David seismic protection. The comparison between the non-isolated (NI) and isolated (SI) configuration allows to assess slider ability in reducing maximum values of shear forces at the David basement. In this regard, this reduction is significant to protect the statue from several failures, such as the overturning, support shear failure and cracking of David's lower parts. The presented study does not take into account the uplift phenomenon that can significantly modify the response of the statue. Further work is necessary in order to investigate this behaviour and many other aspects.

7. Acknowledgements

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