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# Damage risk assessment of historical asset using laser scan and finite element approach

Gian Paolo Cimellaro[a], Marco Tanganelli[b], Marco Domaneschi[a]*, Stefania Viti[b]

[a]*Dipartimento di Ingegneria Strutturale, Edile e Geotecnica (DISEG), Politecnico di Torino*
[b]*Dipartimento di Architettura (DIDA), Università di Firenze*

**Abstract**

Most part of valuable art goods are conserved in the Museums, which are in charge of their maintenance and their exposure; some of them, however, have an outdoor location, enriching the artistic and touristic worth of the towns which host them. The art works have an intrinsic vulnerability, due to their irregular shape, slenderness, fragility and – as concerns some sculptures of historical centers – to their oldness. The outdoor artifacts, however, have further hazard sources, since they can hardly be guarded, and they are subjected to possible vandalism actions and lunatic or terrorist attacks.

In this work the dynamic response of artifacts to blasts of assigned intensity are investigated on a case-study, i.e. the Fountain of Neptune, located in "*Piazza della Signoria*", in Florence. The Fountain of Neptune is a marble and bronze opus made by *Bartolomeo Ammannati* between 1560 and 1565. The main character of the Fountain, Neptune, is a marble statue 5.7 meters tall, with a weight equal to 11.5 ton. A preliminary laser scanner survey has been made to achieve the geometrical representation of the statue. The considered load condition consists of an explosion caused by 10 kg of TNT placed at 8 meters from the Fountain. The dynamic behavior of the complex under the assumed load has been represented through a numerical analysis, by considering the main statue only - since it is the slenderest element of the complex – and by assuming it as simply supported on the pedestal, without any connector. The obtained results showed the vulnerability of the statue to the assumed blast, and pointed out the role plaid by the contact assumption on its dynamic response.


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*Keywords:* Artifacts; safety of artifacts; blast hazard; vulnerability of case-studies; FE analysis.

* Corresponding author. Tel.: +39-011-0904835
*E-mail address:* marco.domeneschi@polito.it


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## 1. Introduction

The art goods are most Cultural assets, to which individuals and communities attribute different historical, artistic, symbolic and economic values, with level of concern and sensitivity that can change over the time, run the risk of being defaced, damaged, stolen, illegally exported or dispersed, in some cases forever. Focusing on historical assets such as statues, they are subjected to multiple hazards such as environmental and catastrophic terrorism that are not predictable. The need of protect them and to allow present and future generations to enjoy them means that the owners and those responsible for their keeping must assess the ideal conditions for their preservation, whenever possible in those places (churches, buildings, archeological sites, squares, etc.) and setting where they were created or to which they were brought by historical circumstances or, if necessary, transferring them to places that are more suited to their conservation and display. Therefore, developing effective strategies for disaster preparedness and risk management is essential to deal with cultural heritage emergencies. In this paper, a numerical procedure is developed to predict risks of damage arising from blast.

As a case study, the Fountain of Neptune, placed in Florence, in *Piazza della Signoria*, has been selected. The Fountain has been commissioned by *Cosimo I de' Medici* to celebrate the new aqueduct of the town and the military achievements of Florence. The Fountain is made in marble and bronze form Bartolomeo Ammannati, one of the most important artists of Renaissance. The main sculpture (Neptune) is made of marble, and it is placed in the middle of the octagonal pedestal decorated with representations of the mythical figures of Scylla and Charybdis, which contains the water. All around some minor marble and bronze sculptures were added, representing river gods, satyrs and sea-horses.

Figure 1. Views of the Fountain of Neptune.

The sculptures constituting the current Fountain, however, are copies made in the *XVII* century, to preserve the original artifacts from vandalism. The first documented damages date back to 1580, and they went on until nowadays; the last event occurred in 2005, when three vandals climbed Neptune, damaging one hand and the trident of the sculpture. Currently, the measures taken to secure the Fountain consist of some cameras and a railing all around.

In this work, a numerical simulation has been made representing a blast due to the explosion of 10 kg of TNT placed at 8 meters from the Fountain. The effect of the blast on the Fountain has been checked through a Finite Elements analysis. The Fountain has been represented through a simplified model, by fixing the following assumptions: *i)* the main statue (Neptune) has been considered instead the entire complex, neglecting the contribution of the side sculptures and of the fountain itself, and *ii)* the statue has been considered as simply supported on the pedestal, without specific connection between the two contact surfaces.

The FE model of the statue has been made after a laser scanner survey, which provided the geometrical model. In § 2 the geometric model has been described, and the changes needed to obtain the structural model used for the FEM analysis have been reported. In § 3 the preliminary analyses made on the case-study have been shown, while § 4 presents the results provided by the dynamic analysis. The dynamic response of the system is a precious information even for setting the possible mitigation strategies for the considered hazard, such as shock absorption pads, special cases containing the statue, screens to protect the object from critical environmental conditions or malicious actions, or methods of tying and stabilizing the object.

## 2. The model and the preliminary analyses

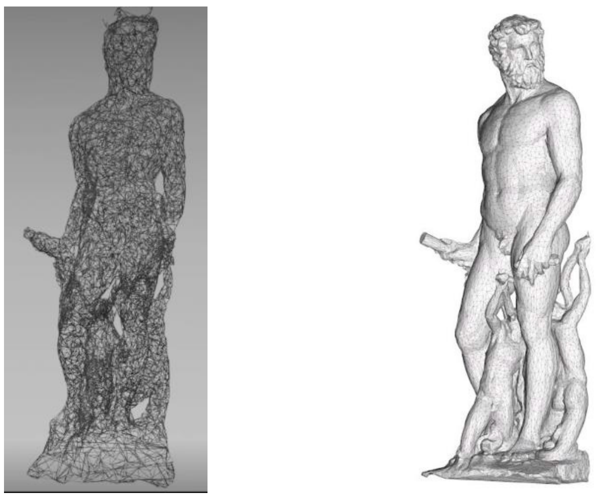
### *2.1. FE Mesh, boundary conditions and adopted parameters*

The analysis of the dynamic response of the sculpture requires to represent the artifact through a numerical model. The geometry of Neptune has been made through a laser-scanner survey (Verdiani and Fantini 2012, Cerri *et al.* 2018a), using a Cam/2 Faro Photon unit, based on phase shift measurement technology.

The survey provided a very detailed geometrical model (see Figure 2), consisting of 1,234,492 polygons. Such numerical representation of the object is too detailed to be used for structural purposes, and it is limited to the "skin" only of the statue. In order to perform a structural analysis, such model has been changed, to obtain a volume model with a lower number of brick-elements. The simplification procedure adopted to set the structural model starting from the points-cloud provided by a laser-scanner survey can be found in Cerri *et al.* (2018) and Pintucchi *et al.* (2019). In this work the finite element mesh of the statue has been developed in MARC & MENTAT (2014) and consists of about 150k linear isoparametric (4-nodes) constant-strain tetrahedral solid elements and about 33k nodes. Boundary conditions have been implemented in terms of base contact friction support and gravity load.

In Figure 2 the two models are shown, together with the main information regarding the geometry of the sculpture, the mechanical properties of the marble and the main data regarding the models.

*geometrical model* *structural model*



| *Main geometric data of the statue* | |
|---|---|
| *Height [m]* | *5.68* |
| *Volume [mc]* | *4.27* |
| *Weight [ton]* | *11.5* |
| *Footprint [cm]* | *100x134* |
| *Mechanical properties of the marble* | |
| *Density [kg/m³]* | *2,700* |
| *Young Modulus [MPa]* | *50,000* |
| *Poisson coefficient [MPa]* | *0.2* |
| *Compressive strength [MPa]* | *50* |
| *Tensile strength [MPa]* | *5* |
| *Friction coefficient* | *0.8* |
| *Models information* | |
| *Number of polygons of the geometric surface model* | *1,234,492* |
| *Number of polygons of the simplified surface model* | *29,000* |
| *Number of tetragons of the simplified volume model* | *152,000* |

Figure 2. Geometric and structural models of Neptune and main information

The model setting is not limited to the geometric representation of the sculpture, but it includes even the assumptions related to the material behavior. In this work different assumptions have been considered, such the introduction on nonlinearities both in the material constitutive law and the contact surfaces. Indeed, the structural response of a statue and the possible damage conditions are both related to the pressure wave arising on the surfaces due the blast, but also to the impact with the ground. Besides hazard conditions, the capacity of the statue includes the characterization of the nonlinear characteristics of the material that should be able to withstand to the external loads.

The FE analyses have been performed on the marble statue assuming the parameters reported in Figure 2, that have been previously adopted in literature (Viti and Tanganelli 2019, Tanganelli *et al.* 2019, Viti *et al.* 2020) to reproduce the dynamic behavior of a different Carrara's marble statues. For the preliminary analyses (presented in § 2.2) some further assumptions, such as the fixed restraint at the statue base, have been considered, in addition to those described above.

## *2.2. Static and modal analyses*

Preliminary linear and contact-non-linear static analyses, and a subsequent modal analysis, have been performed through the software MARC & MENTAT (2014) to assess the structural and dynamic properties of the artifact.

Figure 3 depicts the contour bands results in terms of gravity load considering *(a)* a FE static analysis of the statue with contact conditions at the base; *(b)* full constrains at the contact surface, and finally *(c)* the contact analysis has been performed in transient conditions (implicit analysis, small displacements).

As it can be observed, the results are in good agreement with each other, and the resulting vertical stresses at the base due to self-loading conditions are compatible with those physically estimated (about 0.1 MPa) by considering the axial load representing the marble weight and the cross section of the statue. The agreement of results provided by the three models is quite expectable, since for low level of strain and stress, the different assumptions proper of each model should not affect the structural response of the system.

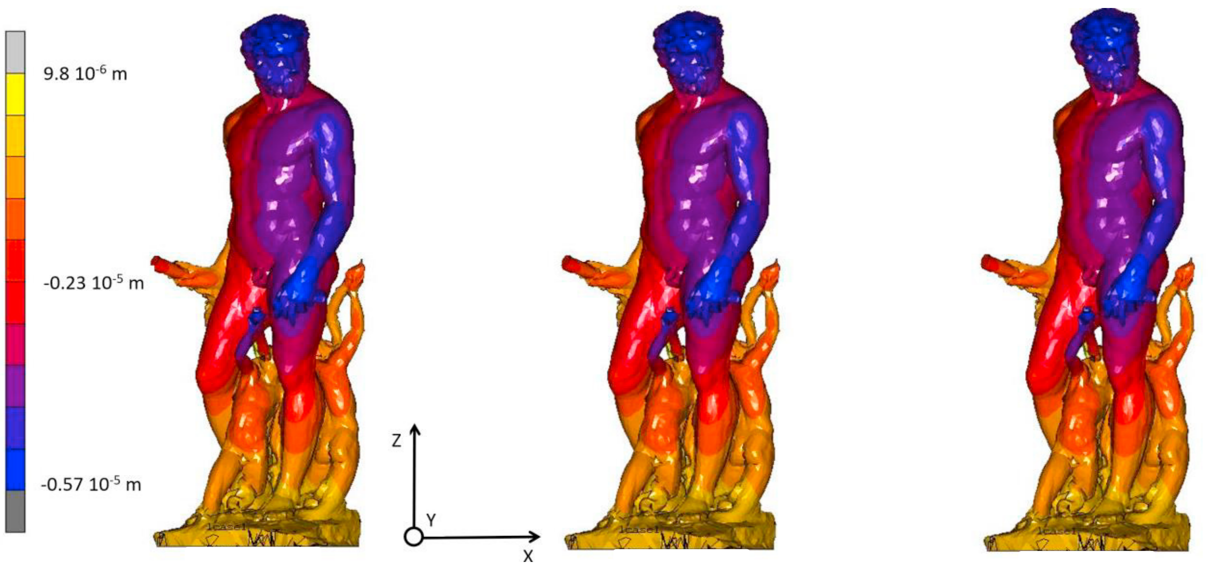



Fig. 3. Gravity load - vertical displacements: (a) static analysis with contact conditions, (b) static analysis with fixed constrains, (c) contact analysis in transient conditions.

Before checking the dynamic response of the system, a modal analysis has been performed, to find its main vibrational modes. The modal shapes and main vibration frequencies have been computed considering the FE mesh fully restrained at the base.

Figure 4 depicts the mode shapes and the corresponding frequencies. They are reasonably comparable to similar statues as that one analyzed in Viti *et al.* (2020).

As can be seen, the first two modes are mostly translational, along the *Y* and the *X* directions respectively, whilst the following ones are mostly rotational.

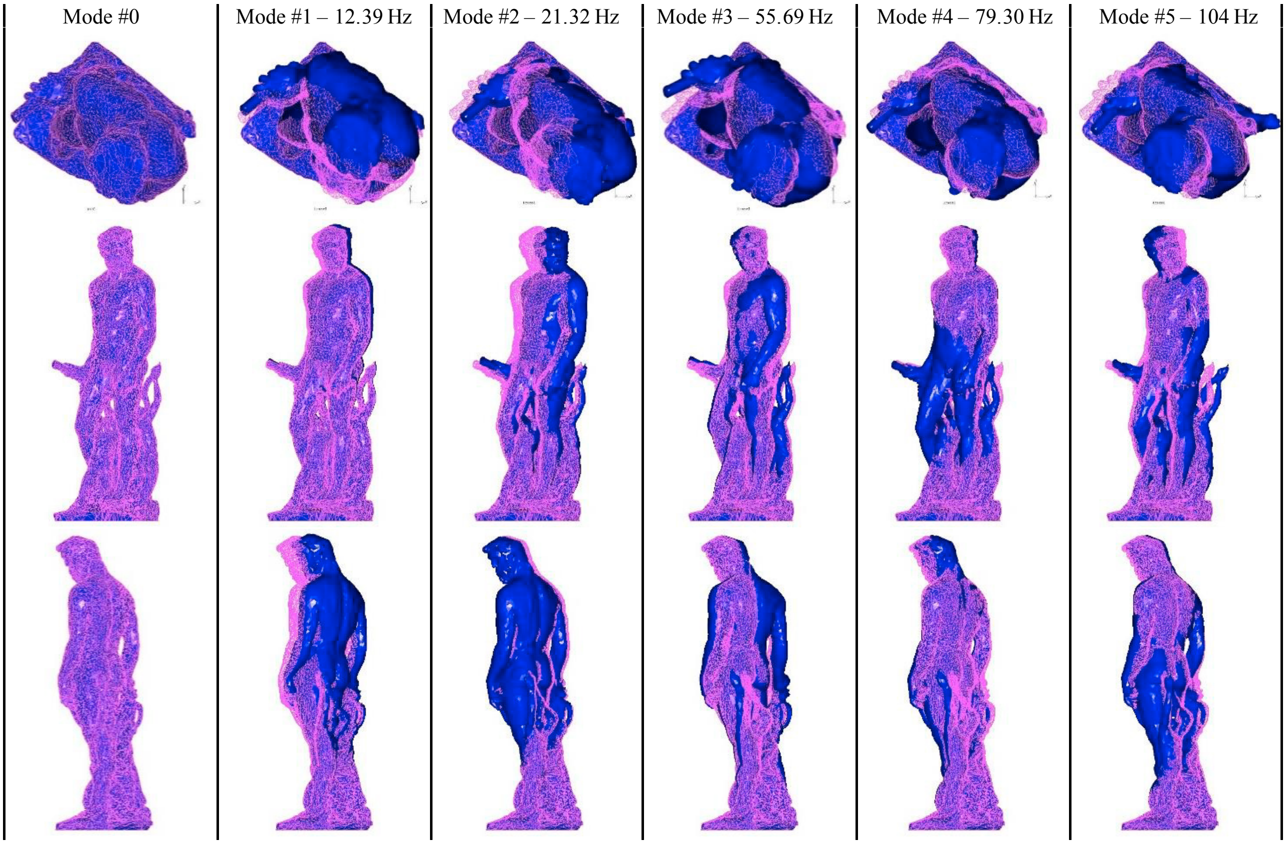



Fig. 4. Mode shapes (planes *XY*, *ZX* and *ZY*, respectively) and associated frequencies. Purple grid is equivalent to the undeformed shape, while the solid blue to the deformed one. From left to right: Y, X and Z views.

## 3. The dynamic analysis

The dynamic analysis is aimed at representing the response of the sculpture to an explosive attack. The loading condition, therefore, consists of the explosion of 10 kg of TNT, i.e. a quantity compatible to the volume of a suitcase. The simplification of the model, i.e. the choice of considering the central statue only instead the entire Fountain, seems to be consistent, since the Fountain/pedestal, made of marble, has a high stiffness, and it can be assumed to transfer consequently the stress to the central statue. In the following paragraphs the assumed load condition and the performed analysis are described.

### 3.1. The blast-loading

The loading condition has been quantified according to the contribution of Karlos and Solomos (2013). The blast has been assumed to be caused by the explosion of 10 kg TNT laying on the ground (surface burst condition) at 8 m from the statue (Karlos and Solomos 2013, TM5-1300 1990). Under this assumptions, the peak overpressure in bars PSO can be computed following the formula proposed by Newmark and reported in Karlos and Solomos (2013).

$$P_{SO} = 6784\frac{W}{R^3} + 93\sqrt{\frac{W}{R^3}} = 6784\frac{0.01t}{(8m)^3} + 93\sqrt{\frac{0.01t}{(8m)^3}} = 0.134bar = 13400Pa \quad (1)$$

where $W$ is the charge mass in metric tons (=1000kg) of TNT, $R$ is the distance of the surface from the center of a spherical explosion in m. The impinging wave is considered as plane and the idealized blast overpressure time history was assumed triangular (Figure 5).

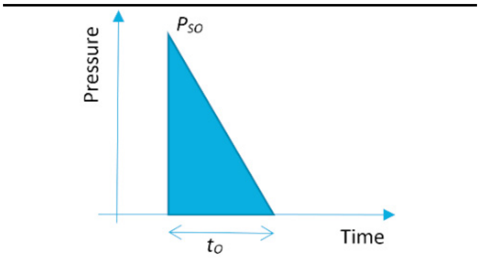


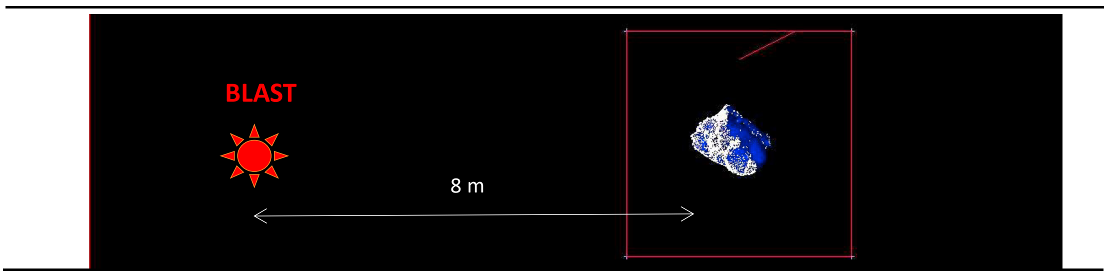

Fig. 5. Triangular blast overpressure time history.

The same idealized blast overpressure time history has been used to perform dynamic analyses assuming an overpressure linear decay and a fictitious duration ($t_o$) from literature (Karlos and Solomos 2013).

$$t_0 = C\sqrt[3]{W} = 7.0\ \text{s} \quad (2)$$

where $C=C(Z)$=3.25 has been obtained by reference to Karlos and Solomos (2013) assuming a dimensional scaled distance $Z$ as follows:

$$Z = \frac{R}{W^{1/3}} = 3.71 \quad (3)$$



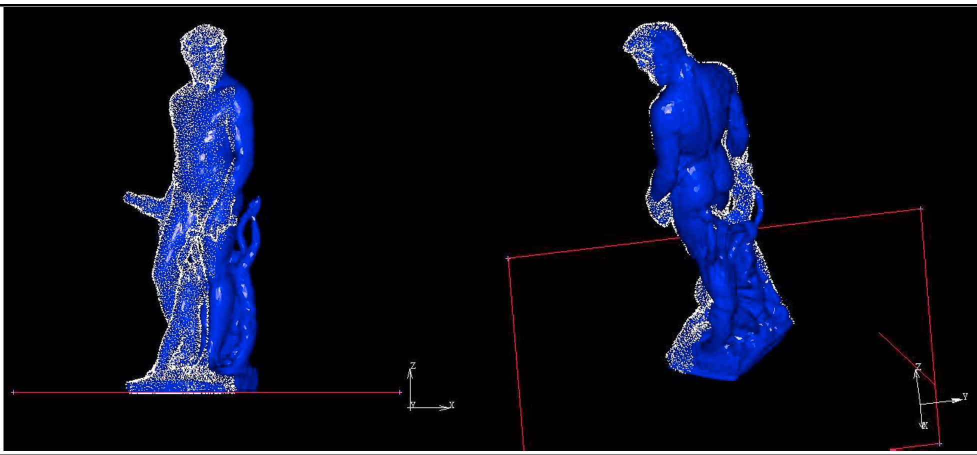


Fig. 6. Pressure boundary condition, normal to the external surface (MARC & MENTAT 2014).

Blast pressure in *x* direction, as a new boundary condition, is applied subsequently to the gravity load in the transient implicit dynamic analysis, normal to the external surface, considering the screening effect (see Figure 6).

It should be reminded that the assumed loading condition should be considered as a first attempt to define the effective impact of an explosion. This assumption is affected by several assumptions and approximations, regarding: *i)* the distance of the blast to the sculpture, *ii)* the amount of explosive and *iii)* the model assumptions made for determining the stress distribution.

As regards the distance, the limit distance could be assumed to vary between the one from the statue and the protecting parapet of the Fountain and the one from the statue and the farthest corner of the square. As regards the amount of explosive, the assumed one can be considered as consistent to represent a standard condition, since the crowding of the place, together with the active cameras, leads the adoption of larger quantities of explosive not too easy to manage. Finally, the distribution of the stress due to the blast has been assumed in a very simplified way in the current analysis, by assuming a uniform pressure on all the surfaces exposed to the blast, and neglecting both tangential components and the depression effects.

### *3.2. Results of the dynamic analysis*

The analysis outcomes highlight how, under the blast condition of 10 kg TNT at 8 m distance, the statue overturns, and the maximum value of maximum principal stress is about 2.8 MPa (Figure 7). The marble tensile strength consists of 5 MPa, as reported in Figure 2. In the considered case-study the overturning comes out to be the collapse mechanism activated as a consequence of the blast. Such occurring, however, is strictly related the assumed restraint conditions and to the amount of excitation acting on the sculpture, which, in turn, is affected by the distance from the explosion source and the amount of explosive.

In order to have a more suitable knowledge of the dynamic behavior of the system, a more comprehensive analysis should be made, considering a wider range of situations as regards the loading condition and the effective restraint of the sculpture.

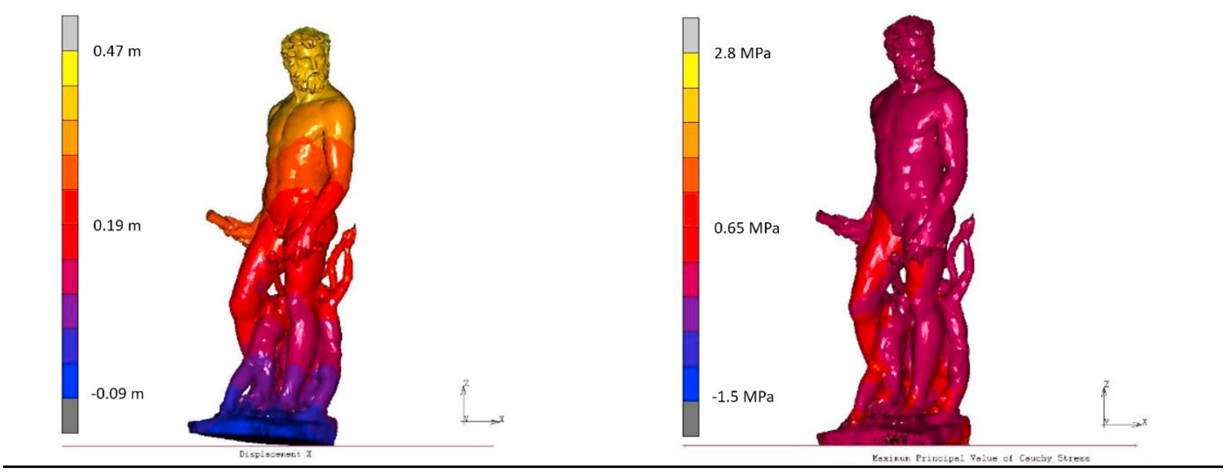



Fig. 7. Transient analyses results. Deformed shape (incipient overturning – 0.49 s) and displacement *x* (left). Maximum principal stress (peak 0.12 s – right).

## 4. Conclusive remarks

This paper presents the first results found on the numerical simulation of a blast effects on a case-study, i.e. the main sculpture of the Fountain of Neptune in Florence, a marble statue 5.7 meter tall. In order to perform the analysis, a structural model has been made on the basis of a detailed laser-scanner survey, which provided a points-cloud of the sculpture. The mechanical properties of the marble have been assumed according to studies made on sculptures similar for period, features and provenience quarry.

The loading condition has been found by determining the intensity of the explosion on the basis of the assumed amount of explosive (equal to 10 kg TNT) and the distance to the statue (8 meters). The pressure distribution arising on the sculpture surface as a consequence of the blast has been found according to the Karlos and Solomos (2013) contribution.

The dynamic analysis has induced the overturning of the statue, whilst the stress level of the material has kept well below its elastic limit.

The study has evidenced the importance of some assumptions, which can largely affect the structural response of the system under observation. Special attention should be paid to the boundary conditions, such as the restraint assumptions, which – in the work – has been assumed as simply laying on the pedestal. At the current moment, indeed, it has not been possible to know the technological solution adopted for fixing the base of the statue. The quality of the base restraint, however, can affect the collapse mechanism of the artifact.

Further analyses, moreover, should be needed to check the safety level of the statue as a function of the distance from the blast and the statue and the amount of explosive, in order to achieve more general results on the safety of art works regards this type of hazards.

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