Engineer Education and Research With Code Aster

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***Abstract* — The paper reports some recent experiences of the authors about the use of the Open Source finite element software Code Aster in the field on civil engineering. Two illustrative examples, a historic masonry building and a statue, are presented and discussed.**

Keywords* — *Engineering Reseacrh; Opern Sofware; Nonlinear Modelling; Damage Models.

I. Introduction

Last decades have seen an increasing interest of the scientific community toward the use of Open Source finite element codes. The free software proposes a developmental model totally antithetical to that of the commercial world. Raymond, in a book of 1997 [1], now generally regarded as the manifest of the Open Source movement, describes and compares two styles of development introducing the two categories of "cathedral model" and "bazaar model". In the cathedral model, the program is implemented by a limited number of experts who shall write the code in almost total "isolation"; the project has a strict hierarchical subdivision and each developer takes care of his little piece of code. In contrast with this model is the bazaar model (substantially the Linux world), in which the source codes are freely available to the users that can interact with developers and amend and/or supplement the code. In this case the development is decentralized, and there is not a strict division of the activities. The difference between the two developmental models can be also exemplified by the terms *copyright*, for the commercial world, and *copyleft* for the Open Source world; the GNU General Public License, created by Richard Stallman, is a typical example of *copyleft* licence.

The GNU license (GPL, General Public License), based on the principles of *copyleft*, ensures four "fundamental freedoms" (as defined by Stallman): i) freedom to run a program for any purpose; ii) freedom to study how the program works, and adapt it to own needs; iii) freedom of redistribution to others; iv) freedom to improve the program, and redistribute the improvement to others. A program is free software if the license enables all of these freedoms (and, of course, in order to have these freedoms is necessary to have free access to the source code). As part of the GNU Project have been, and are, written many Free Software programs. Free Software and Open Source use the same medium (free movement of the code) for different purposes: the free flow of information the first and the development of good software second. To be Open Source a software must meet the criteria: a) the free redistribution; b) availability of source code; c) ability to create derivative works under the same license; d) integrity of the code we source; e) no discrimination to persons or groups; f) no discrimination towards application domains; g) the terms of the license automatically apply to those who receive the software; h) the license must not be specific to a certain product (set of programs); i) license must not impose restrictions on software distributed together with open source software; l) the license must be independent of the technology platform.

Under this license, and in parallel to what is now available for many other areas, the last few decades have seen the development and release of a number of computer codes (for FEM analyses) in the traditional fields of engineering and computational mechanics. Among these it is possible to quote Elmer, OOFEM, OpenSees and Code Aster (http://www.code-aster.org). The last one, in particular, is a free finite element code (distributed under the GNU GPL license) for the numerical simulation of materials and mechanical structures, developed by EDF (Électricité de France). The paper discusses on some recent experiences of the authors in the field of civil engineering through the presentation of two illustrative case studies: the damage assessment of a historic masonry building and the dynamic analysis of a statue.

II. Open Source Software in Engineering Education and Research

The structural section of the Department of Civil and Environmental Engineering (DICEA) has started, in the last years, to employ Code Aster, a free and open source finite element code, as a foundation to teach software engineering and to analyse engineering problems in the field of seismic assessment of historic masonry buildings and artefacts. The aim of the use of the software are: to provide students with a real-world software engineering experience (that can be freely employed after their study); to introduce students to the Open Source developmental model; to attract a wider variety of students into computing due to the real-world and the ethical nature of the project. In addition the code has been employed in several research projects and, in this respect, the paper aims to show some recent experience in the numerical modelling field carried out with Code Aster (the code has been employed in combination with the platform Salome-Meca).

Next, the results obtained in numerical modelling of two case studies are reported. In particular (together with the description of the damage model adopted to account for the non-linear behaviour of the masonry material) two specific illustrative examples are presented and discussed. The first is the identification of the damage of a historic masonry building, and the second is the finite element modelling of a statue.

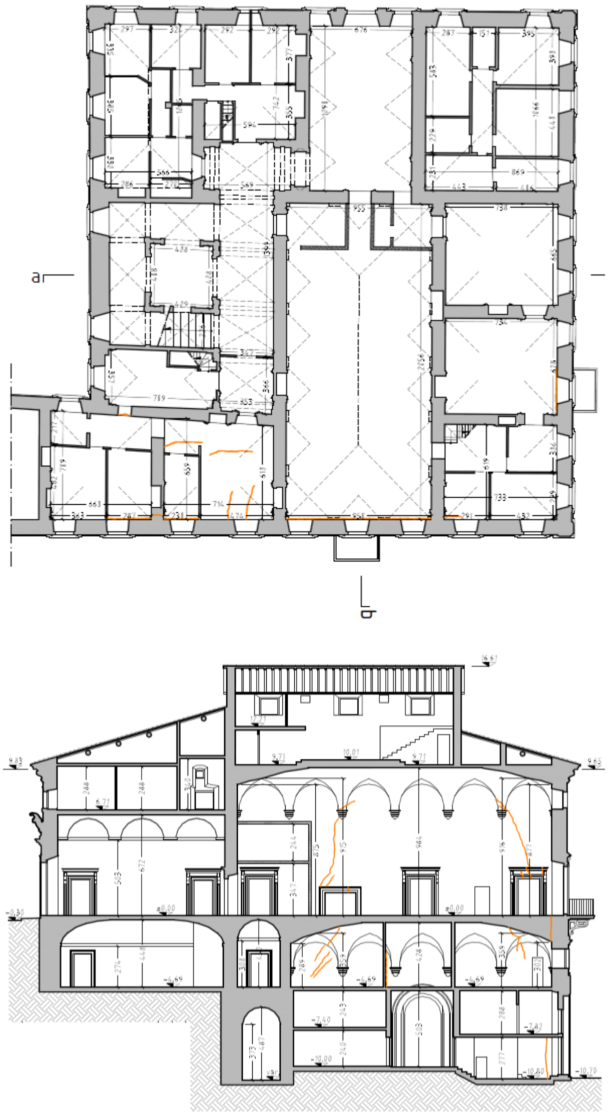

Fig. 1. Masonry palace plan layput (up) and section (down).

III. DAMAGE ASSESSMENT OF A HISTORIC PALACE

The first case is a historic Italian Palace which dates back to the seventeenth century. The Palace is a masonry building with a rectangular plan section (Fig. 1) located in Piancastagnaio (South Tuscany, Italy). The Palace exhibits a severe and variegated vertical and horizontal cracking pattern mainly affecting two façades: the southern and eastern ones. Due to the severe damage (Fig. 2), the palace was evacuated by the Public Authorities during the 1980s and a series of provisional remedies (mainly steel chains) were added.

From a geometrical point of view, the building is a rectangular three-story masonry construction, with a length of about 34 m and a width of about 31 m and an external masonry wall thickness of about 1.2 m. At the level of the first floor (the so-called “piano nobile”) there is a large monumental room ((Fig. 1). A stone stair connects each level of the palace. The foundations of the palace are not at the same level and an underground level (a storage basement) is present in the southern area, as part of the building (the northern part) was partially built over the old city walls. The floor levels are made by several types of masonry vaults, depending on the dimension and importance of the room. Smaller rooms are usually covered by cross vaults, while the monumental room is roofed by a cloister vault. Noteworthy is the regularity of the geometrical configuration of the building characterized by well-connected orthogonal masonry walls. The only geometrical irregularities are vertical and affect the walls perpendicular to the eastern façade. These walls in particular, having a thickness of about 0.7 m, do not reach the foundation level, as they end at ground floor and their vertical load is transferred to the ground by two big arches.

Fig. 2. Cracks detail (monumental room)

Code Aster was employed to provide an interpretation of the origin of the manifested damage, and to identify the damage state the following models have been analysed: i) model A is the model of the building with fixed base assumption; ii) model B is the model that accounts for the soil-structure interaction. The soil-structure interaction was analysed considering, due to the unknowns about ground properties, several scenarios with variable stiffness (or local underground collapses). To reproduce the masonry nonlinear behaviour a damage criterion was employed. This model is next discussed.

A. The damage isotropic model

Code Aster has a wide library of non-linear material models, and to reproduce the masonry non-linear behaviour the continuum damage model of Mazars [2] [3] was adopted. This model, originally proposed for the analysis of the concrete, requires for its definition a reduced number of parameters with clear physical meaning. In addition it has already been employed for the analysis masonry buildings, and therefore the scientific literature presents some illustrating examples in the modelling of a masonry material. In its original formulation the model of Mazars [2] is a homogeneous and isotropic scalar parameters model, employed in the continuum damage mechanics (CDM). Typically the damage mechanic aims at modelling the evolution of the degradation phenomena on the microscale from the initial (undamaged or pre-damaged) state up to creation of a crack on the mesoscale (material element). To shortly recall the basis of CMD, it is possible to consider a cylindrical sample with cross-section S subjected to the uniaxial tension F. For the undamaged material the uniaxial stress is F/S. As the sample begins to get damaged only a part of the original sections (the effective area), denoted with $\hat{S}$, will contribute to transferring the load. It is then possible to define a damage variable, D, a continuous positive function in the range $D\in[0, 1]$, so that $\hat{S} = S \cdot (1-D)$. The damage may grow from D=0 (undamaged material) to the critical value D=1 which corresponds to entirely damaged material (the effective area reduced to 0). According to this scheme instead of the standard uniaxial stress, it is convenient to introduce (for the simple considered cylindrical sample) the actual stress for the damaged material expressed as follows:

$$\hat{\sigma} = \frac{F}{\hat{S}} = \frac{F}{S \cdot (1 - t \cdot D)} = \frac{\sigma}{(1 - t \cdot D)} \tag{1}$$

where t is a parameter that accounts for crack reclosing (a function of the loading history and of the material properties). In case of first crack it assumes a unitary value; in case of crack reclosing it assumes a value between 0 and 1. In eq. (1) it is implicitly assumed that the effective area (i.e. the not damaged section) is still characterized by a linear elastic behaviour. Conversely the damaged area is assumed not to contribute to the loads transfer.

Maintaining for the damaged sample the same definition of deformation formulated in the absence of damage, it is possible to formulate the damage through a variation of stress. This stress is the nominal for the sample without damage but is the net for the sample with damage. In so doing the constitutive law of the material, formally, assumes the same expression both in the absence or the presence of damage. Hence, still referring to the uniaxial cylindrical sample, the deformation can be expressed by the following expression:

$$\hat{\varepsilon} = \frac{\hat{\sigma}}{E_0} = \frac{\sigma}{(1 - D) \cdot E_0} = \frac{\sigma}{\hat{E}} \tag{2}$$

where E_0 denotes the modulus of Elasticity of the undamaged material, while $\hat{E} = (1 - D) \cdot E_0$ represents a secant modulus associated to the damaged material.

The approach of the damage according to the above scheme allows to analyse the behaviour of the medium as a continuum, through an isotropic damage model with damage independent variables in tension and compression. Basic assumption can be summarized as follows: a) the mechanical properties of the continuous medium are changed after the attainment of a certain damage threshold; b) the medium has a different behaviour in traction compared to compression; c) the medium develops permanent deformations. Given the assumption of isotropic behaviour the model is not fully applicable to masonry material which, given the particular texture that characterizes them, should be more effectively represented by orthotropic behaviour (if not anisotropic). Although this assumption is not fully respectful of the actual material texture, it can still be considered acceptable.

To complete the uniaxial model formulation, eq. (2) must be accomplished with a damage evolution law which can be considered, f.i., in the form of a dependence between the damage variable and the applied load. Usually, instead of considering such a function, a limit state function is introduced as follows:

$$f(\hat{\varepsilon}, D) = \hat{\varepsilon} - \kappa \tag{3}$$

where the variable κ characterizes the maximum level of strain reached in the material before the damage arise (eq. (3) is completed by the classical Kuhn-Tucker condition).

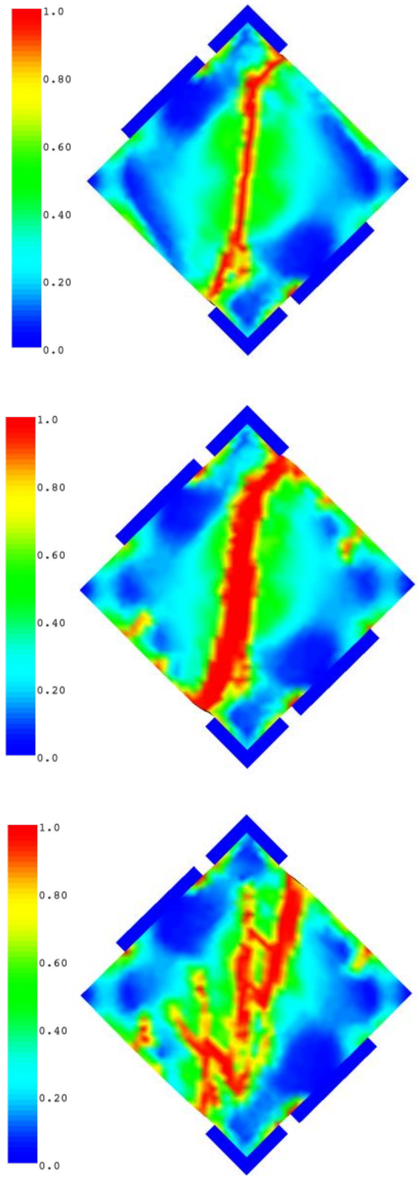

Fig. 3. Collapse damage map (β = 1.04, β = 1.00 and β = 1.07)

The initial value of this threshold (first damage occurrence) can be put in relation with the tensile strength of the material, denoted with f_t, through the following: expression: $\kappa_0 = \varepsilon_{D0} = f_t / E_0$. The damage begins when the equivalent strain reaches the threshold, hence: $f(\hat{\varepsilon}, D) = \hat{\varepsilon} - \kappa = 0$, $D = D(\kappa)$ and $\kappa = \hat{\varepsilon}$. After the activation of the first damage, with the increasing external loads, the activation threshold moves and κ assumes the value attained by the equivalent strain. The Mazars model introduces two damage parameters, D_t associated to a tension mechanism and D_c associated to the damage under compression, to account for the dissymmetric damage surface that characterizes the behaviour of geo-material (yield value in compression several times the value in tension). These two parameters are evaluated from two evolution functions which are assumed to depend both on a unique definition of the equivalent strain. Consequently in the FE code the damage variable is defined as follows:

$$D = (1-\alpha_t)^{\beta} D_c + {\alpha_t}^{\beta} D_t;\ \textit{with:}$$

$$D_c = 1 - \frac{\kappa_0(1-A_c)}{\kappa} - \frac{A_c}{e^{[B_c(\kappa-\kappa_0)]}} \tag{4}$$

$$D_t = 1 - \frac{\kappa_0(1-A_t)}{\kappa} - \frac{A_t}{e^{[B_t(\kappa-\kappa_0)]}}$$

where A_c, A_t, B_c e B_t are scalar parameters that modulate the shape of the curve after post-peak, and β is a corrective factor that accounts for damage coupling.

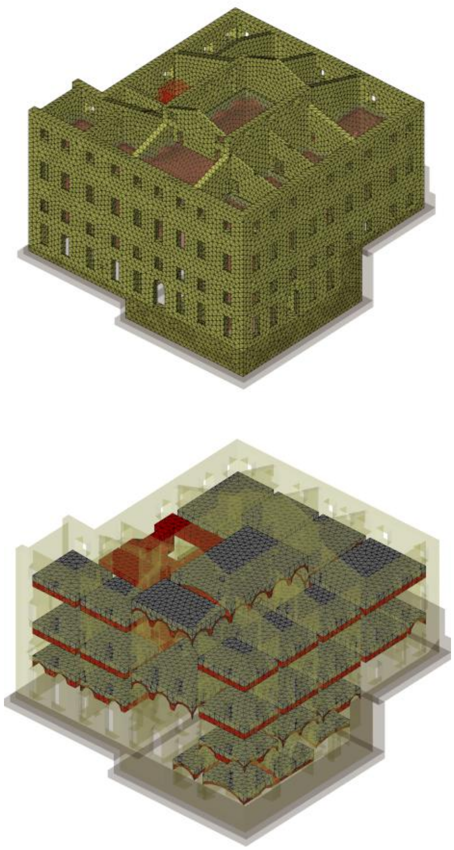

Fig. 4. FE model of the palace (mesh discretiazion)

The damage model of Mazars is implemented in Code Aster in two versions [3]: local (where the stress in a point only depends on the deformation at the same point) and nonlocal (the stress in a point depends on an average deformation around the point). In case of the local version the numerical solution can depend on the mesh size, and hence it is necessary to first investigate the mesh dependence of the solution. In the nonlocal case (expressed through a nonlocal strain tensor) such dependence is eliminated since the stress is function of an average strain tensor regularized over a representative volume element (RVE).

The total number of the parameters required by the Mazars's model is 8: the two elastic coefficients E_0 and ν_0, the scalars k_0, A_t, B_t, A_c, B_c that are material parameters which can be easily derived from compressive and tensile tests and the constant β whose determination should requires a shear test. To analyse the nonlinear behaviour of masonry, preliminary sensitivity analyses on the Mazar's parameter have been performed. In particular results of available diagonal compression tests carried out on masonry wallets have been considered. Fig. 3 reports the collapse damage map obtained assuming three different values of the constant β (whose determination would require a shear test).

B. The Palace FE model

To build the FE model of the palace, a preliminary detailed reconstruction of the structural geometry was performed. The final mesh is reported in Fig. 4. The discretization of the geometry into finite elements was carried out by adopting the algorithm *netgen* with one-dimensional input and generating a tetrahedral mesh reasonably uniform and regular.

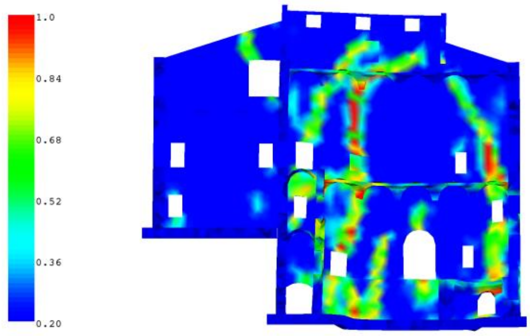

Fig. 5. Damage maps (internal section)

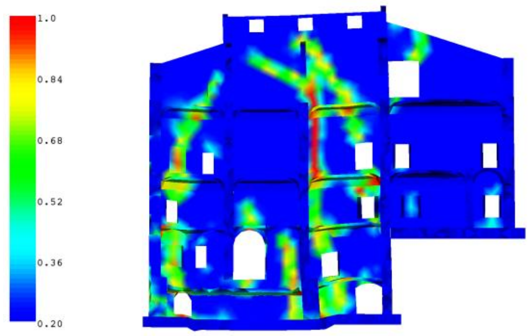

Fig. 6. Damage maps (internal section)

Having employed the model of Mazars in its local version, preliminary parametric tests were carried out to verify the dependence of the solution from the discretization thus verifying that the adopted discretization leads to stable results.

The effects of differential ground settlements (model B) were considered by means of different parametric analyses. The results allowed to identify that the damage in the palace was due to a local failure of the ground under the middle part of the eastern façade of the palace. The activation of an arch-type cracking pattern on this wall can be responsible for a sequence of mechanisms that might account for the present damage (Fig. 5, Fig. 6).

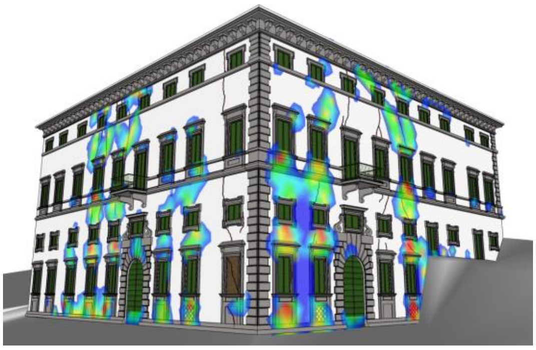

Fig. 7. Damage maps (South-Eastern façade)

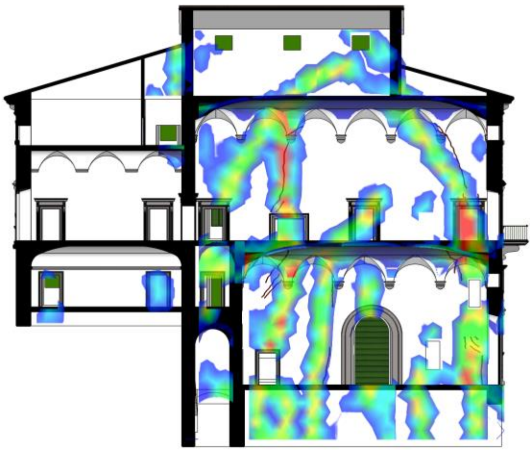

Fig. 8. Damage maps (section)

Fig. 7 and Fig. 8 show a superimposition of the damage map obtained with Code Aster and the relief of the damage both in the external façades and in an internal section.

IV. NUMERICAL MODELLING OF ARTIFACT

As a second case study, Code Aster was employed to build the numerical model of Michelangelo's David (Fig. 9). Michelangelo built the David between 1501 and 1504 when he was twenty-six year old (immediately after the success obtained with the Rome Pieta of 1499-1500). The statue is an interesting case study due to the Michelangelo's conception: the David stands with one leg holding its full weight (the right) and the other leg (the left) forward. The statue is hence characterized by a significant eccentricity between the center of mass and the center of the supporting base. Such a static behavior, with the right leg which bears most of the David weight was also clear to Michelangelo that decided to reinforce the right leg with the tree trunk.

The Michelangelo's David was unveiled on 8 September 1504 and it remained in front of the main entrance of Florence town hall until 1873. Between 1852 and 1872 a growing concern arouses about the David deterioration and stability due to a series of visible cracks: the first in the tree trunk that supports the right leg, and another in the lower part of the left leg. These cracks arose more than three centuries (nineteenth century) after the statue had been unveiled, than the original David's conception with its intrinsic weakness cannot be considered as the main cause of the observed cracks.

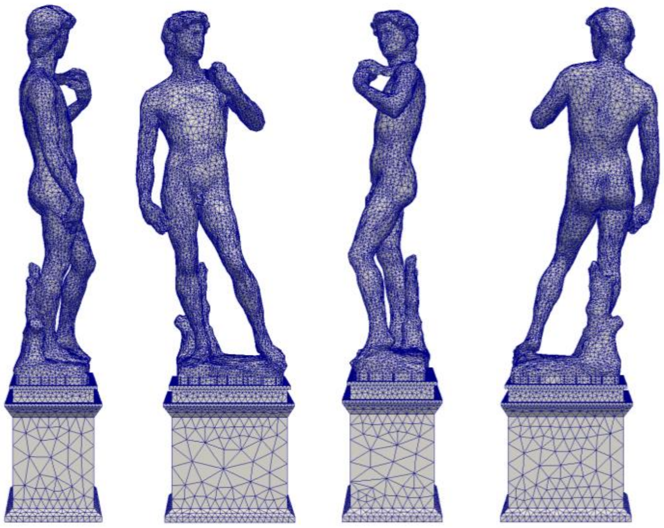

Fig. 9. Numerical model of Michelangelo's David.

The David has been deeply investigated in the past [4] [5] [6], and consequently a great number of data and results are now available that allow to consider the statue a representative case study.

Fig. 10. Von Mises stresses (gravity loads).

A conclusive explanation of the damage, for instance, was offered by Borri and Grazini [4] that showed, for the first time, that the cracks in the legs were likely caused by a slight forward inclination of the statue due to a shifting of the ground underneath it subsequent a flood in 1844 (or due to the additional weight that was placed on the David by Clemente Papi in 1847 to makes a plaster cast). When the David was moved to the Accademia Gallery in 1873 the tilting was corrected and the cracks have not worsened since.

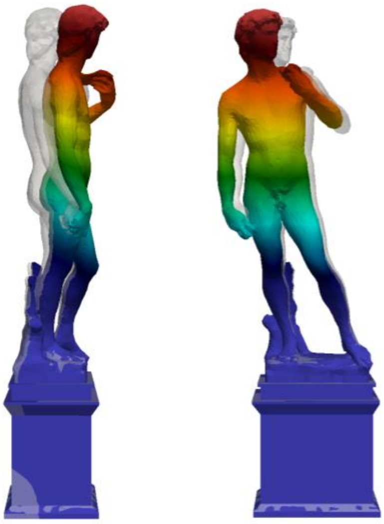

Fig. 11. First mode shape (3.5 Hz)

Fig. 12. Second mode shape (8.4 Hz)

To build the numerical model, the geometric characteristics of the statue (and its volume) have been obtained according to the results of the laser scanner relief performed within the "Digital Michelangelo Project" (coordinated by Marc Levoy - Stanford University - and developed between 1997 and 1999). The numerical model was created according to this laser scanner relief. The material properties of the marble have been evaluated according the results of previous researches [4].

The stress concentration on the legs is visible in Fig. 10 where the Von Mises stresses obtained with a static linear analysis are plotted. The Code Aster numerical model of the statue has been also employed to evaluate the dynamic behavior of the statue and Fig. 11 and Fig. 12 report the first two mode shapes of the statue.

V. Conclusive Remarks

The paper, through the discussion of two representative case studies, reports some recent experience of the authors about the use of the Open Source Finite Element Software Code Aster in the field on civil engineering. The first case study is the numerical modelling of a historic masonry building. The analyses were aimed to identify the origin of the actual damage pattern. The nonlinear behaviour of the masonry elements was modelled through the continuous damage model of Mazars. The second case study was the numerical modelling of a statue, the Michelangelo's David. The numerical model was a linear one and it was employed to identify the static dynamic behaviour of the artefact.

Acknowledgment

The authors wish to acknowledge Prof. Marc Levoy (Stanford University), coordinator of the "Digital Michelangelo Project" - http://graphics.stanford.edu/projects/mich/ -, for the release of the 3D laser scan of the Michelangelo's David here employed to build the FE model.

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