Safety Assessment of Masonry Constructions via Numerical Tools: The NOSA-ITACA Code

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Abstract

This paper describes the main features of the NOSA-ITACA code, software for the structural analysis of masonry buildings of historical interest resulting from integration of the finite element code NOSA and the open-source platform SALOME. After a short description of the constitutive equation used to model the mechanical behaviour of masonry constructions, some details are given concerning the code's implementation. Then, the result of a static analysis of the "Voltone" in Livorno, performed via the NOSA-ITACA code, is presented with the aim of highlighting the important role of mathematical models and numerical tools in assessing the safety of historical masonry buildings.

Keywords*: Masonry Buildings; Nonlinear Elasticity; Numerical Methods; Safety Assessment*

1. Introduction

In order to numerically describe the structural behaviour of ancient masonry buildings, it is crucial to realistically model masonry materials, whose response to tension is fundamentally different from that to compression, and whose mechanical properties depend on their constituent elements and the building techniques used. The numerous techniques proposed for modelling masonry structures can be grouped into the following main classes: micro–mechanical approaches [34], [37], rigid block modelling for limit analysis [27], [19] and dynamic analysis [10], homogenisation techniques [8], [18] and continuum models [26], [38], [33], [4], [31]. The most common constitutive models used are the linear elastic [26], [38], [33] and the elastic-plastic model [34], [37], [18] and [4]. The former provides only qualitative information on the global behaviour of masonry structures without however considering their inability to withstand tension, while the latter instead takes into account the strong nonlinearities of such structures' static and dynamic responses.
The studies described in [32], devoted to the development of numerical models for the structural analysis and maintenance of historical masonry buildings, are a contribution in the direction prescribed by article 2 of the Venice Charter [25], which reads "The conservation and restoration of monuments must have recourse to all the sciences and techniques which can contribute to the study and safeguarding of the architectural heritage". These studies have led to the implementation of the finite element code NOSA [15] developed by the laboratory of Mechanics of Materials and Structures (MMS lab) of ISTI-CNR, in which masonry is described as a nonlinear elastic material with zero tensile strength and bounded compressive strength. The code has been successfully applied to a number of studies, commissioned by both private and public bodies, on important historic buildings, such as the Medici Arsenal [32] and the church of San Pietro in Vinculis in Pisa [32], the bell tower of Buti [3], the church of Santa Maria Maddalena in Morano Calabro [32], and the Rognosa tower in San Gimignano [9], [20].
With the aim of improving the performance of the NOSA code and equipping it with an interactive graphic tool for pre- and post-processing, the project "Tools for the modelling and assessment of the structural behaviour of ancient constructions" has been conducted by the MMS lab and a research team from the Department of Civil and Environmental Engineering of the University of Florence. The project [23], funded by the Region of Tuscany (2011-2013), has led to the development of the NOSA-ITACA code, resulting from integration of the NOSA code and the open source graphic platform SALOME [24].
The present paper describes the main features of the NOSA-ITACA code and reports the results of a study of the "Voltone" − a large vaulted masonry structure located beneath Piazza della Repubblica in Livorno, Italy.

2. The NOSA-ITACA code

The constitutive equation for masonry materials proposed in [32] models masonry as a nonlinear hyperelastic material with Young's modulus $E > 0$, Poisson's ratio ν (where $0 \leq \nu < 1/2$), zero tensile strength and maximum compressive stress $\sigma_0 < 0$ and generalizes the constitutive equation of masonry-like materials introduced in [16] and [17]. The total strain tensor is the sum of an elastic term, which depends linearly and isotropically on the Cauchy stress tensor, and two orthogonal inelastic strains: the crushing strain, negative semidefinite, and the fracture strain, positive semidefinite. Constraints on the stress tensor, whose eigenvalues must be negative and greater than or equal to σ_0, and the orthogonality properties between the stress tensor and the inelastic strains complete the set of equations describing the constitutive behaviour of masonry. The coaxiality of the stress, total strain, fracture strain and crushing strain tensors − valid for isotropic materials − allows for solving the constitutive equation explicitly. Moreover, it is possible to explicitly calculate the derivative of the stress with respect to the total strain, necessary to calculate the tangent stiffness matrix adopted in the Newton-Raphson method for solving the nonlinear equilibrium problem of masonry structures. More details on the constitutive equation and algorithms implemented in the NOSA code for nonlinear static analyses can be found in [32] and [15].
As far as numerical solution of dynamic problems is concerned, the equations of motion are integrated directly, and the Newmark method has been implemented within NOSA in order to perform the integration with respect to time of the system of ordinary differential equations obtained by discretising the structure into finite elements [14]. Moreover, the Newton-Raphson scheme, needed to solve the nonlinear algebraic system obtained at each time step, has been adapted to the dynamic case.
Within the framework of the project "Tools for modelling and assessing the structural behaviour of ancient constructions" [23], a new integrated tool, the NOSA-ITACA code, has been developed based on the finite element code NOSA and SALOME [24], an open-source integration platform for numerical simulation.

The NOSA code has been substantially modified and improved in light of FORTRAN 90 specifications and equipped with new finite elements, thus enhancing its application capabilities. The subroutines devoted to solving linear systems via modified LU factorization have been optimized, thus significantly improving the code's performance.

Moreover, a procedure for the modal analysis of linear elastic structures has been implemented. This procedure, aimed at solving the generalised eigenvalue problem obtained by discretising the structure into finite elements and assembling the stiffness and mass matrices, takes into account both the sparsity of the matrices and the features of master-slave constraints (multipoint constraints). The implementation, described in [35], is based on open-source packages embedded in NOSA: SPARSKIT [36], for managing matrices in sparse format (storage, matrix-vector products), and ARPACK [29], which implements a method based on Lanczos factorization combined with spectral techniques that improve convergence. In particular, ARPACK requires the user to supply an external routine to solve linear systems with the coefficient matrix given by the stiffness or mass matrix. To this end, the ICFS package has been adopted, as it provides an advanced implementation of the conjugate gradient method, accelerated with a preconditioner based on Incomplete Cholesky Factorization with limited memory [30].

Implementation of the NOSA-ITACA code was then completed by integrating the finite element code NOSA within the open source graphic interactive code SALOME [24], used both to define the geometry of the structure under examination and to visualise the results of the structural analysis. Specifically, the NOSA code has been implemented within the SALOME architecture (developed mostly in the C/C++ and Python languages) as an additional module on a par with those already existing (MESH, GEOM, POST-PRO), and called the Nosa module. Through such integration the Nosa module thus allows the user to define the physical quantities to associate to a mesh (materials, element thickness, boundary conditions, loads, analysis type, etc.), display the load applied to the structure, generate the input file for running and monitoring the finite element analysis, etc. The module includes the executable file "nosan" and several CORBA interfaces (with ".idl") for data exchange between the Nosa module and the MESH and/or POST-PRO modules. The Nosa module executes the numerical analysis using as input the card (".crd") created by the Nosa module itself, via the MESH module, and allows the user to monitor the analysis. Finally, the ".t19" output file containing the results of the numerical study is transmitted to the POST-PRO module via conversion into a ".med" output file (fig. 1).

NOSA-ITACA, which enables solving static and dynamic problems of masonry constructions even in the presence of thermal loads, can also be used to model restoration and strengthening operations, such as the application of metal chains and rods, as well as to assess the mechanical behaviour of historical masonry constructions subjected to earthquakes (in light of Italian regulations [11], [12] and [13]). In particular, when a seismic analysis is required, the modal analysis allows determining the conventional loads to be applied to the model in order to simulate the effects of an earthquake in accordance with such regulations [12].

Shell structures, such as vaults, domes, walls or towers can be modelled by using quadrilateral eight-node shell elements based on the Love-Kirchhoff hypothesis [32] or four-node shell element based on Mindlin plate theory [28]. Furthermore, solid elements, such as eight- or twelve-node brick elements, can be used to describe more complex geometries. A detailed description of the NOSA-ITACA code, including the SALOME Nosa module user's guide, the element library, the NOSA keywords reference and user subroutine guides is provided in [6].

Applications of the NOSA-ITACA code are described in [5], [7], [21], [1] and [2]. In particular, [5] and [7] provide detailed descriptions of the study of the "Voltone", whose static safety assessment is outlined in the present paper. Moreover, the code has also been used to study the church of San Francesco in Lucca [21] and the Dome of San Cerbone Cathedral in Massa Marittima [1] and [2].

NOSA-ITACA is a freeware/open-source software for computational mechanics, as is the Salome-Meca - Code_Aster package [22], and is distributed with the aim of disseminating the use of mathematical models and numerical tools in the field of Cultural Heritage.

3. An example application: non linear static analysis of the "Voltone" in Livorno

The "Voltone" (i.e., the great vault), built in 1845 after the design of Bettarini, is a 220-meter long, tunnel-like masonry structure located beneath Piazza della Repubblica in Livorno (fig. 2). It is constituted by a segmental vault, through which the "Fosso Reale" canal flows. The vault is set on two lateral walls and strengthened by buttresses placed at intervals of about 5.8 meters one from the other.

The vault, made of lime mortar and bricks, is about 0.41÷0.43 m thick, with constant thickness along the section and length of the vault, except for the tunnel's ends (in correspondence to the roadways), where the thickness increases to about 0.7 m. The vault's structure, which is segmental (quite 'lowered' with respect to a semicircle), spans 12.4 m and has a rise of about 1.65 m.

The lateral walls, made up by external layers of a local chalky stone and an inner cohesive mortar core layer, are variable in height above the surface of the canal, decreasing from 5.27 m to 2.65 m. The walls' maximum overall height is 9.3 m with a thickness of about 2.3 m. The walls have been strengthened by some buttresses, whose thickness has been set to 1.6 m for the purposes of the modelling.

In order to realistically model the structural behaviour of this monument via the NOSA-ITACA code, the geometry, the mechanical properties of the constituent materials and the characteristics of the soil and surrounding structures must be known. To this end, some non-destructive tests were conducted (laser scan digital geometry acquisition and georadar scan of the surface of the tunnel and overlying square), and four vertical core samples extracted, two from the wall and surrounding soil, and two from the vault (at the crown and haunch), with the aim of accurately measuring the thickness of the vault and walls and determining the stratigraphy and mechanical properties of their constituent materials. In addition, two horizontal core samples were extracted from the lateral walls, starting from the intrados. The results of these tests were then supplemented by data gathered from historical and archaeological reports. The information collected allowed us to build a three-dimensional finite element model of the structure (fig. 3). The model was built by using 43,228 thick shell and beam elements and 45,379 nodes; the connections between the vault and the lateral wall elements were guaranteed by multipoint constraints able to model the geometrical misalignment between the vault and the wall, and specified by expressly developed user routines. The analyses have been conducted adopting the constitutive equation of masonry-like material with bounded compressive strength, under the assumption that the structure is subjected to permanent and accidental loads, calculated on the basis of the structure's usage class [11], [12]. More precisely, besides the permanent loads, such as the weight of the structure and filling material, and the soil pressure acting on the walls, two different types of accidental loads were considered: a load that models the presence of a tight crowd (of 6 kN/m^2) in the central region of the square, and a traffic load for bridges of category II on the square's ends, where roadways are located.

The analyses have enabled calculating the stress field and then assessing the structure's safety. The results are also reported in terms of the line of thrust, a diagram which allows evaluating the static safety of a masonry vault graphically (Figure 4). Indeed, a line of thrust that is well contained within the arch's ring is an index of static safety [27], [32]. Safety checks aimed at studying the structure's behaviour at its ultimate limit states are being implemented in the NOSA-ITACA code. They are based on the partial safety factors method [12] expressed by the inequality $E_d / R_d \leq 1$, where E_d is the design effect calculated by applying the design loads to the model, while R_d is the design strength, which depends on the materials' mechanical characteristics, the section's geometry and appropriate safety coefficients (Figure 5 shows the ratio between the design value of the applied moment M_{Ed} and the design value of the moment of resistance M_{Rd}, both calculated per unit length).

4. Conclusion

A new software tool for assessing the static and seismic vulnerability of age-old masonry structures, the NOSA-ITACA code, has been presented. This software stems from integration of the finite element code for nonlinear analyses, NOSA, and the open-source graphical user interface platform SALOME. The NOSA-ITACA code models masonry by means of a nonlinear elastic constitutive equation that takes into account masonry's different behaviour in tension and compression. The SALOME tools for pre – post processing operations allow users to easily define the model geometry and loads and visualize the results of the analysis. An application of the code to the "Voltone" in Livorno has been presented, and the structure's mechanical response to permanent and accidental actions assessed. This case study, conducted in collaboration with the Municipality of Livorno, provides an opportunity to validate both the models proposed and the calculation tool developed and highlights the important role played by mathematical models and numerical tools in assessing the mechanical behaviour of historical masonry constructions.

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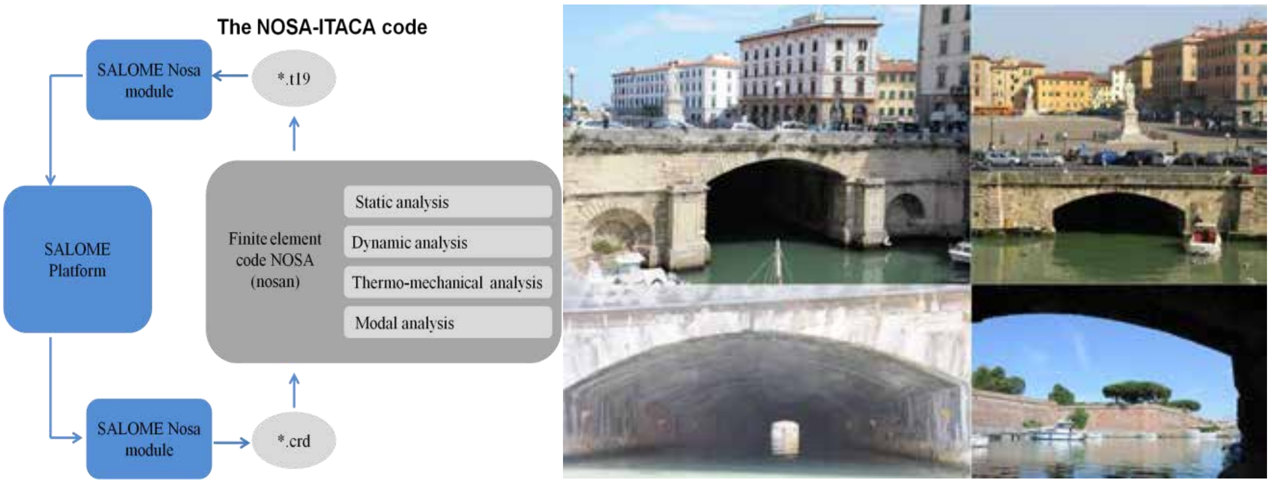

Figure 1: The NOSA-ITACA code.

Figure 2: The "Voltone" in Livorno.

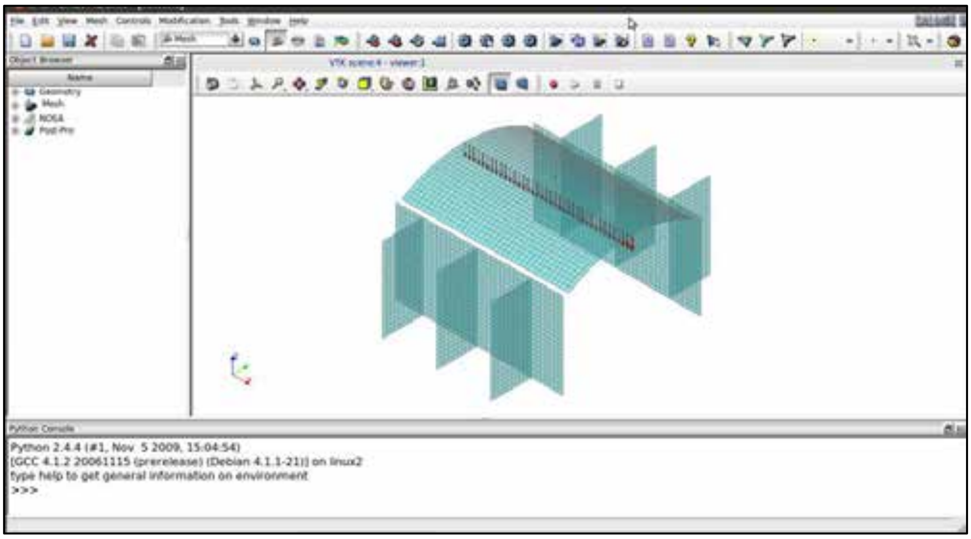

Figure 3: Mesh generation via NOSA-ITACA.

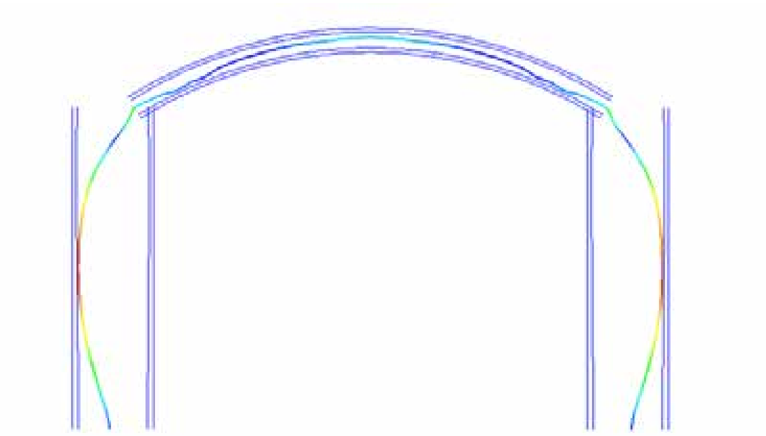

Figure 4: Line of thrust in a transverse section of the "Voltone".

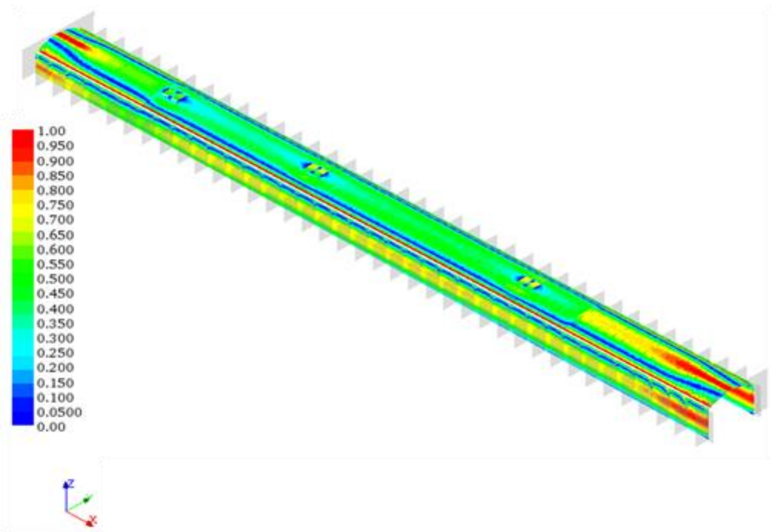

Figure 5: Example safety check: ratios M_{Ed} / M_{Rd} in the vault and lateral walls.