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Nonlinear seismic behavior of historical masonry towers by means of different numerical models

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Abstract

Historical masonry towers constitute a great part of Italian built heritage: wonderful towers and bell-towers can be observed all over the territory. Such structures exhibit many aspects which are difficult to describe from a numerical point of view. Among the most common: *i*) the restraint condition at their base is not exactly clear as they are often embedded in other buildings (such as church bell-towers); *ii*) the material behavior is not very clear as the masonry is often made of three layers, each one with different mechanical characteristics. Simplified models can be set up for these structures in order to assess their relative seismic risk, i.e. such models may be applied to a set of nearby towers in order to identify the most prone towers to earthquakes. A deeper insight into their behavior, nevertheless, requires reliable nonlinear numerical models.

In the paper, in this respect, some constitutive models already implemented in a finite element software (Code Aster) are employed to perform static nonlinear analyses on a prototype of masonry tower (a cantilever beam), and the obtained results are then compared. The parameters required by each constitutive model have been tuned to obtain comparable values of compressive and tensile strengths, and subsequent comparison is presented. Eventually, a fiber continuous simplified numerical model is also presented; it takes into account several degrees of freedom, chosen as the displacements of the vertical axis of the tower. Nonlinear behavior and damage of the material, along with the efficiency of cross sections, are taken into consideration. The model compares satisfactorily with more complex analyses performed with Code_Aster. The comparison shows both the main advantage and the main limitations of the simplified fiber model.

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Keywords: Built heritage; Masonry towers; Nonlinear systems; Seismic behaviour; Damage models

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1. Introduction

The assessment of the structural behavior of existing constructions under earthquake loads requires reliable and expedite tools of analysis. Focusing on slender masonry structures, whose vulnerability has been shown once again during recent Italian earthquakes [1] [2], several simplified numerical approaches have been recently proposed to assess their structural response under seismic loading. In fact, the high vulnerability of such a typology of structures highlights the need of expeditious and effective tools of analysis in order to assess their seismic safety and to allow proper retrofiting strategies. Such tools must take into account the nonlinear mechanical behavior of the masonry components, usually characterized by a small tensile strength and a limited compressive strength. In the field of structural engineering, the use of proper mechanical models and numerical codes is frequently required to perform a broad range of tasks, whose results constitute an important support input for decision looking for structural problem solving. Usually solutions offered by the various models are affected by a certain degree of uncertainty, which asks for a proper quantification by means of reliability analyses. Uncertainties affecting the physical systems can be grouped in two main categories: aleatory and epistemic uncertainties [3] [4]. The first group collects the uncertainties that are typically due to the randomness of the natural phenomena. The second group considers the inaccuracy due to the lack-of-knowledge. Several sources of inaccuracy can occur and, generally, epistemic uncertainties collect a wide range of potential incomplete knowledge. While aleatory uncertainties are typically irreducible and non-subjective, the epistemic uncertainties are potentially reducible since they are substantially due to ignorance or roughness in modeling the overall physical environment. In addition, numerical models are usually tuned through comparison with available experimental results but, at the same time, they are employed to predict the structural behavior under exceptional loads, and predictions for new extreme load cases may be inaccurate. This is true in general, but in case of the modeling of masonry constructions the problem is amplified by the great, and growing, number of approaches and numerical models proposed by the research community [5] [6] [7] [8].

Discussion of these aspects, and their effects, is herein approached through the results of a benchmark on the seismic assessment of cantilever masonry beams. The comparison between the results obtained by different constitutive models has the purpose of the estimation of the effects of the epistemic uncertainties (which are herein mainly related to the different analytical models). Eventually, with the aim to create a simplified and expeditious instrument, a fiber continuous numerical model is presented. The model takes into account several degrees of freedom, chosen as the displacements of the vertical axis of the tower. Nonlinear behavior and damage of the material, along with the efficiency of cross sections, are taken into consideration.

2. The reference nonlinear masonry beam

The reference structure was a 10 m wide (B), 40 m high (H) and 2 m thick cantilever masonry beam (Fig. 1). The nonlinear response of the beam under seismic loading was numerically evaluated employing a finite element (FE) code. The loads were applied in the plane of the structure, and the behavior of the reference masonry tower under seismic loads was analyzed by means of static nonlinear pushover analysis.

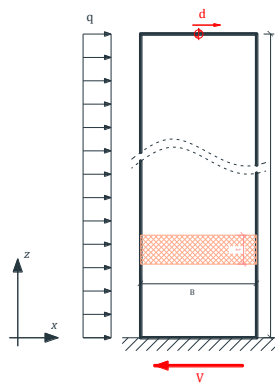


Fig. 1 The reference masonry cantilever beam.

The paper, analyzing the clarifying example of the masonry cantilever beam, investigates the employability and the efficiency of several constitutive models to reproduce the nonlinear behavior of the masonry in order to account for the nonlinear damage phenomena that develop in slender masonry towers during seismic loading.

3. Numerical modeling and results

The numerical model of the cantilever masonry beam was built by means of the open source software CODE_ASTER, a free finite element code for the numerical simulation of materials and mechanical structures, developed by EDF (Électricité de France). The code was employed to build numerical model with 8-node three-dimensional (3D) elements having the dimensions of $0.5 \times 0.5 \times 0.5$ m, employed for the nonlinear static analyses. The model was characterized by 3,200 elements and about 15,120 degrees of freedom (dofs).

In order to take into account the nonlinear behavior of the masonry, four types of mechanical damage models were considered: a) ENDO_ISOT_BETON; b) the ENDO_ORTH_BETON [9] damage behavior; c) the damage model of MAZARS [10]; d) the BETON_DOUBLE_DP model. Among the considered constitutive models, the MAZARS damage model is an isotropic scalar damage model, quite simple and robust (from a computational point of view), which has the limit of not taking into consideration the stiffness restoring due to the cracks closing. The ENDO_ORTH_BETON is an anisotropic model which is able to take into account the cracks closing. Both mechanical models were originally introduced for the numerical modeling of concrete. Their effectiveness in order to reproduce the masonry nonlinear behavior was evaluated by comparing the numerical results obtained. The models need different parameters to identify the damage threshold but, in general, they require a reduced number of independent parameters to define the nonlinear behavior (Mazars 1984; Godard 2005). The parameters required by each model were identified in order to fit a common set of mechanical strength values (uniaxial compressive strength of 5 MPa and uniaxial tensile strength of 0.1 MPa).

Additional information about the identification of the Mazars model parameters can be found in [11].

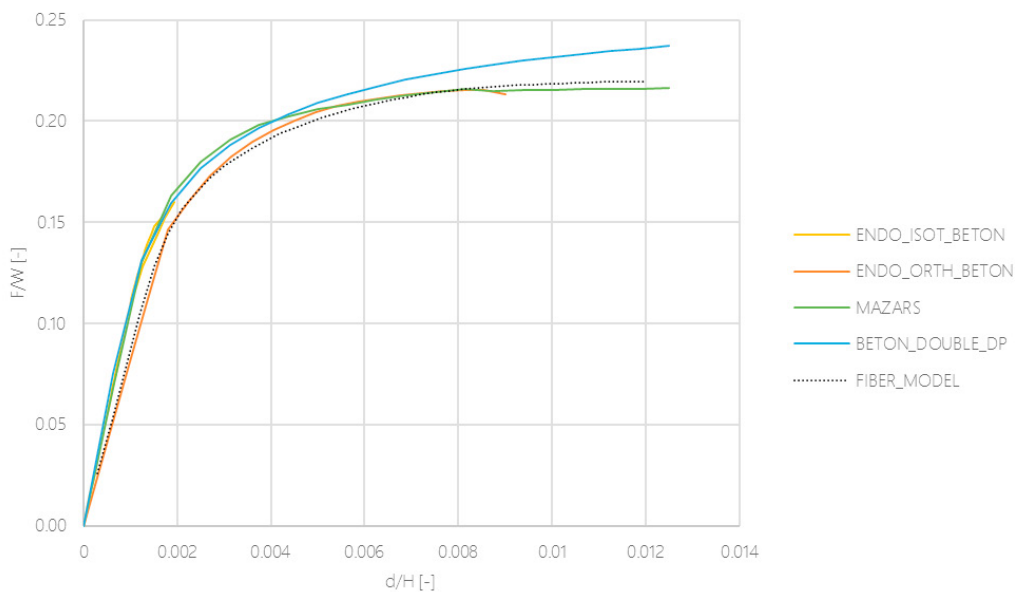


Fig. 2 Pushover curves.

As a comparison among the different constitutive models static nonlinear pushover analyses were performed assuming a uniform distribution of horizontal loads along the height of the cantilever beam. The results were consequently compared analyzing the collapse damage patterns and the corresponding capacity curves.

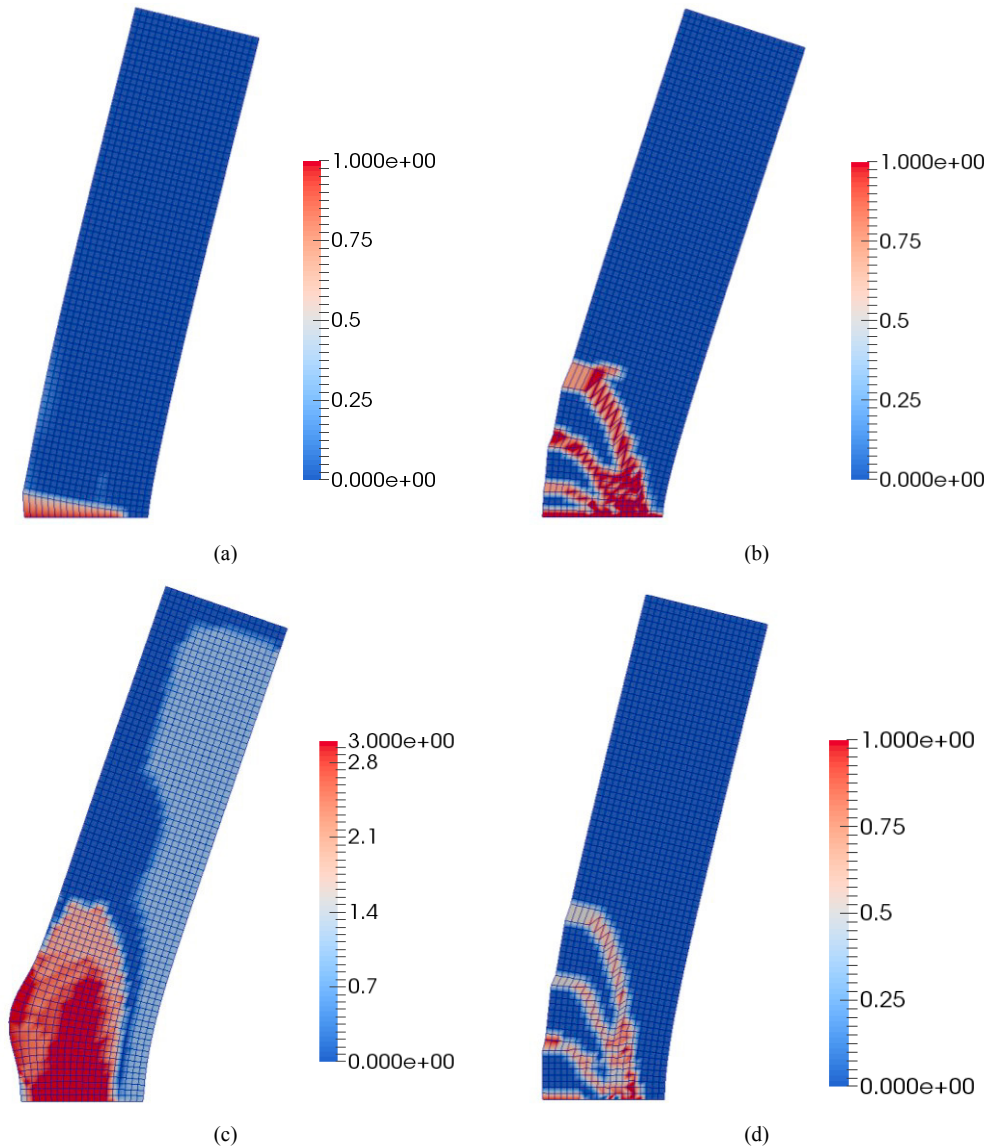


Fig. 3 Collapse damage patterns: (a) ENDO_ORTH_BETON, (b) MAZARS, (c) BETON_DOUBLE_DP; (d) MAZARS adaptive pushover.

Fig. 2 compares the capacity curves (base shear vs. top displacement). It is noteworthy to observe that, despite the different mechanical constitutive laws adopted to account for the nonlinear modeling of masonry, all the constitutive laws offered a reliable estimation of the collapse load (about 22-24% of the weight of the beam). A minor difference is instead observable in the maximum displacement (the horizontal displacement of the center of mass of the beam's top section). Higher displacements are obtained with the MAZARS and the BETON_DOUBLE_DP laws. Fig. 3 compares the damage maps obtained at the end of the analyses with the four models. It is interesting to observe that the ENDO_ORTH_BETON tends to concentrate the damage at the base. An opposite behavior is obtained with the BETON_DOUBLE_DP constitutive law which on the contrary spreads the damage over all the base area. The Mazars model was employed to perform an adaptive pushover (Fig. 3d), and the results are quite similar to the one obtained with the classic pushover approach. The damage pattern obtained with the Mazars law is similar to the one obtained by other authors.

4. Simplified fiber model

A simplified fiber model was implemented, according to the theoretical framework of the Eulero-Bernoulli (EB) beam (Fig. 4a), with the code OCTAVE. The EB eqsn. were considered for each single fiber of the section of the beam, together with proper nonlinear assumption. The nonlinear static analysis is performed by imposing the initial shape of the load, which is increased under displacement control. The nonlinearity is taken into account through an index of efficiency (i_E) of the section, which is increasingly reduced as the fibers undergo damage (according to the masonry constitutive law).

Due to the discretization of the beam along its axis, the efficiency index can vary along the height itself. It is noteworthy that, additionally, it is possible to take into account a variability of the cross-section of the beam through a proper discretization. Finally, taking into account the specific typology of tower under consideration, the shear deformability has not been accounted for.

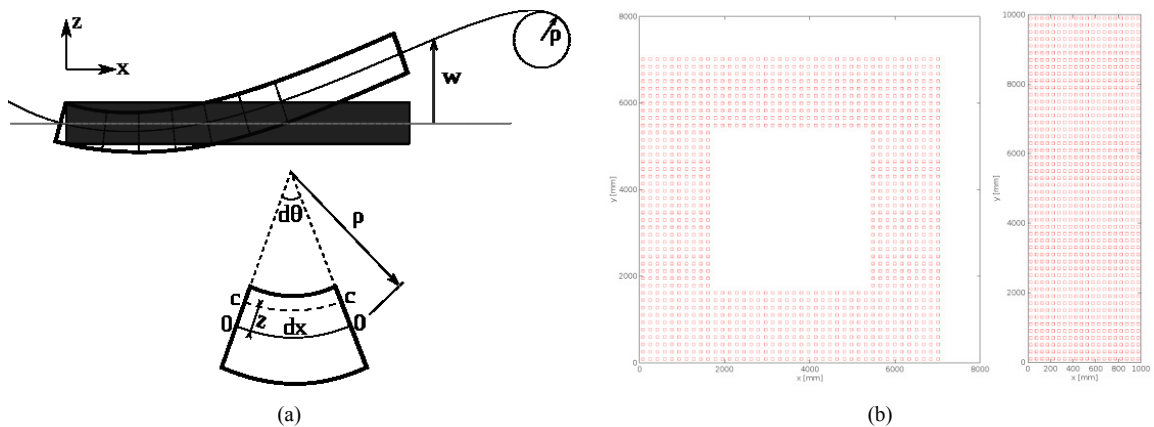


Fig. 4 (a) Eulero-Bernoulli beam; (b) Fiber section.

Taking advantage of the relative simplicity of the eqsn (especially when a prismatic section assumed), the beam is discretized in sections of finite length, and the elastic line differential equation is solved for each sections. For simple load conditions, it is possible to obtain a closed-form expression. The congruence is imposed at the ends of each discretized section:

$$EJ \frac{d^4 v}{dz^4} = q(z); v_i(z_i) = v_{i+1}(z_i); v'_i(z_i) = v'_{i+1}(z_i) \quad (1)$$

The fiber model assumes the discretization of the section in a number of polygons to which are associated geometric features such as center of gravity position and area. It is obtained a set of mono-axial elements to which a constitutive law can be associated (Fig. 4b). The load shape is imposed *a priori*. It may be defined point-by-point, in discrete form, or may be imposed through the choice of one of the predefined shapes. The results obtained assuming a uniform load distribution are reported in Fig. 5 in terms of displacement, rotation, curvature and index of efficiency (i_E). It is possible to observe a coherence between the i_E and the damage pattern obtained with the BETON_DOUBLE_DP model (Fig. 3c).

5. Conclusive remarks

In the paper some constitutive models implemented in a finite element software (Code Aster) are employed to perform static nonlinear analyses on a cantilever beam. The obtained results are compared by analyzing the pushover curves and the collapse damage maps. After the parameters required by each constitutive model have been tuned to obtain comparable values of compressive and tensile strengths, the results show that even if a quite good comparison

is obtained with respect to the pushover curves, a certain variability is on the contrary obtained with respect to the collapse damage. As a second step, a simplified fiber continuous numerical model based on the Eulero-Bernoulli beam theory is presented; the model takes into account several degrees of freedom, chosen as the displacements of the vertical axis of the tower. Nonlinear behavior and damage of the material, along with the efficiency of cross sections, are taken into consideration. The model compares quite satisfactorily with more complex analyses performed with Code_Aster and has the advantage of relative simplicity and reduced computational costs.

Further development could be addressed towards an adaptive pushover, which was partially used in this study, and an IDA approach, to assess the reliability of static methods for different types of cantilever tower-like beams, especially in treating slender structures.

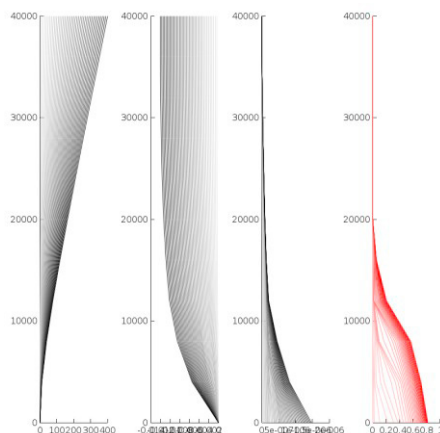


Fig. 5 Results obtained with the fiber model in terms of: displacement, rotation, curvature and index of efficiency ($1-i_E$), respectively.

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