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Dynamic response of a damaging masonry wall

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Abstract

A nonlocal damage-plastic model is adopted to describe the nonlinear structural response of masonry structures. The model, based on a macromechanical approach, accounts for strength and stiffness degradation with hysteretic dissipation typically characterizing the masonry response, when it is subjected to horizontal loads. The stiffness recovery due to the crack closure, under cyclic loading, is also introduced by defining two different scalar damage variables for prevailing tensile and compressive states. To explore the effect of such nonlinear phenomena on the masonry structural response, the behavior of an unreinforced slender wall is investigated in the dynamic field. Special attention is devoted to the analysis of the wall frequency response curves (FRCs), obtained by imposing base harmonic accelerations with slowly time-variable frequency. These curves highlight the complexity of the dynamic phenomenon: due to the stiffness decay exhibited by the wall, a continuous variation of its natural frequencies occurs, which in turn modifies the resonance conditions. Finally, the wall response results strongly path-dependent and the characteristics of the wall restoring force lead to multi-valued FRCs.

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Keywords: Masonry; damage; plasticity; unilateral effect; cyclic response; frequency response curves.

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1. Introduction

Masonry buildings represent a significant part of the historical and architectural heritage in many countries. The development of efficient numerical procedures to study their structural response especially under seismic loading conditions is a challenging and significant task for researchers and practitioners. Masonry material shows a very complex behavior due to the heterogeneous and composite nature of the medium and to the strongly nonlinear behavior of the constituents. The overall response is influenced by shape, sizes and arrangement of blocks and mortar, by the cohesion and friction between them, and by their mechanical properties. During the loading process, onset, growth and coalescence of microcracks occur and plastic irreversible strains are accumulated. Different modeling approaches, based on different scales of the analysis [1–6], have been proposed, that is micromechanical, macromechanical and multi-scale. All contain damage and plasticity constitutive laws to describe the mechanical response of each

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constituents or the overall response of the masonry modeled as an equivalent homogenized medium. Macromechanical approaches represent a fair compromise between accuracy of results and computational burden and are able to take into account the main mechanisms characterizing masonry response under cyclic loads: strength and stiffness degradation, unilateral effect and hysteretic dissipation. All these nonlinear mechanisms significantly affect both the static and dynamic masonry structural response, as shown both by experimental evidences and by the observation of the masonry real response under seismic events.

A number of studies have been dedicated to investigate the effects of the degrading and plasticity phenomena on the nonlinear cyclic static response of masonry walls. But the presence of damage and irreversible strains substantially modifies the dynamic structural response too, under seismic actions [4,6] and harmonic excitations [4,7]. In particular, the frequency response curves (FRCs) are relevant for the structural dynamic characterization and permit to highlight and distinguish the effects of the different nonlinear mechanisms. Several studies on nonlinear oscillators, characterized by geometrical and/or material nonlinearities, have clarified that the FRCs features are referable to the restoring force shape: hardening or softening behavior, multi-valued curves with jump phenomenon or single-valued curves can be occured [8–10].

This study adopts the damage-plastic model and the finite element formulation presented in [5] to numerically investigate the nonlinear response of an unreinforced masonry wall. The masonry constitutive model introduces two different scalar damage variables, governing the degrading processes for prevailing tensile and compressive states, to account for the unilateral effect. Moreover, a classical $J2$ formulation governs the flow of the irreversible plastic strains. First, the nonlinear static response of the wall is investigated under horizontal loads. Then, the wall dynamic response is explored by deriving the frequency response curves of the structure, exhibiting degrading and plastic mechanisms and framing the influence of the peculiar masonry constitutive relationship within the large amount of the available data devoted to systems characterized by invariant restoring forces.

2. Model and equilibrium equations

A 2D plane stress formulation under the hypothesis of small displacements and strains is adopted. The stress-strain constitutive relationship, based on the damage-plastic model presented in [5], is expressed as:

$$\boldsymbol{\sigma} = [(1 - D_t)\,\alpha_t + (1 - D_c)\,\alpha_c]^2\,\mathbf{C}\,(\varepsilon - \varepsilon^p) \tag{1}$$

where $\boldsymbol{\sigma}$, ε and ε^p are the stress, total strain and plastic strain vectors, respectively, while $\mathbf{C}$ is the elastic constitutive matrix of the undamaged material under plane stress conditions. D_t and D_c are two distinct damage variables, measuring the material degradation for prevailing tensile and compressive states, respectively, while $\alpha_{t/c}$ are weighting coefficients defined below. The definition of two distinct damage variables in tension and compression permits to account for the unilateral effect, related to the closure in compression of the tensile cracks. According to their definition [11], D_t and D_c range in $[0, 1]$, the lower bound corresponding to the initial undamaged material state, the upper one attained when the material is completely damaged. The thermodynamic irreversible constraint is imposed, such that $\dot{D}_{t/c} \geq 0$, together with the condition $D_t \geq D_c$.

The evolution processes of the two damage variables are driven by two equivalent strain measures, Y_t and Y_c, defined as:

$$Y_t = \sqrt{\sum_{i=1}^{3} \langle e_i \rangle_+^2} \qquad Y_c = \sqrt{\sum_{i=1}^{3} \langle e_i \rangle_-^2 + \kappa \sum_{i=1}^{3} \sum_{j \neq i} \langle e_i \rangle_- \left\langle e_j \right\rangle_-} \tag{2}$$

where the Mac'Auley brackets $\langle \bullet \rangle_{+/-}$ compute the positive/negative part of a quantity, κ is a material parameter influencing the shape of the damage limit function in compression and e_i results as:

$$e_i = (1 - 2\nu)\,\hat{\varepsilon}_i + \nu \textstyle\sum_{j=1}^{3} \hat{\varepsilon}_j \tag{3}$$