Finite element modeling and shake-table testing of unidirectional infill masonry walls under out-of-plane dynamic loads

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A B S T R A C T

The dynamic out-of-plane response of unreinforced masonry walls is investigated. The study combines analytical, numerical, and experimental methodologies. The paper focuses on structural schemes that involve supporting at the base and the top and yield a unidirectional (one-way) flexural action. First, the modeling concepts for the nonlinear dynamic analysis are discussed and used as a basis for a finite element formulation. The element is based on a first-order shear deformation theory with large displacements, moderate rotations, small strains, material nonlinearity, and a Rayleigh type of viscoelastic damping. The nonlinearities due to cracking and the inelastic response under cyclic compression are introduced through the constitutive model for the mortar. The experimental part includes shake-table testing under different levels of out-of-plane excitation and compressive loading. The experimental results and the numerical model quantify a range of physical phenomena, including the dynamic arching and rocking effects, the coupling of the axial (in the height direction) and the out-of-plane responses, the role of axial loading, and the vulnerability of the masonry construction to dynamic loads. The comparison between the numerical results and the experimental results examines the capabilities of the model and gains insight into the nonlinear dynamics of the masonry wall.

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1. Introduction

Masonry construction is one of the oldest building techniques. Masonry structures are found in almost every built environment around the world and in many historic buildings that are still in use today. In modern structures, it is mostly found in the form of external or internal infill walls. Such walls are usually not considered as major load carrying members. Yet, extensive seismic excitation, seismic inter-story drift, wind loads, or sudden loading of the peripheral structural system may yield significant dynamic out-of-plane loading of the masonry wall. These loads may end up with severe damage to the wall itself or even with collapse and potential injury of occupants [1–3]. In that sense, the dynamic response becomes a factor affecting the safety of the structure and dictating the need for a dynamic structural upgrade.

The dynamic out-of-plane response of masonry walls is usually characterized by nonlinear effects and a chaotic type of response [3–6]. The main contributors to this response are the cracking and the physical nonlinearity at the joints, the evolution of dynamic “arching” forces, the coupling of the axial (in the height direction) and the out-of-plane dynamic effects, and the geometrical nonlinearity [7–10]. The time and amplitude dependency of the dynamic characteristics [11,12], the interaction with the adjacent structural components [13], and the dependency on the level of gravity load [3] also contribute to the complexity of the dynamic response.

An analytical or computational model for the dynamic analysis of the masonry wall has to face the challenges that stem from the above physical (material), interfacial (contact), and geometrical nonlinearities. Among the reported analytical and computational approaches, one can list equivalent static loading simulations (e.g. [14]); stability analyses [15], single degree of freedom idealizations (e.g. [12–13]); analysis of rigid bodies connected through cracked joints (e.g. [16–18]), and sequential linear analysis methods (e.g. [19]). The application of piecewise linear acceleration profiles [3] and the assessment of macroscopic moment curvature curves [20] are also reported. Many other approaches for the analysis of the wall use the finite element (FE) method (e.g. [14,2]) and take advantage of its generality and universality. On the other hand, the combination of different length scales, the presence of joints, and the combination of materials with significantly different elastic, mass, and mechanical properties critically impact the FE analysis and usually end up with a complicated and computationally demanding problem.

Another approach, which is also based on an FE analysis, is the homogenization technique (see, for example, the review paper by Lourenço et al. [21]). This approach uses a multi-scale concept and models the wall as a macro-scale continuum with