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

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ABSTRACT

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.

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

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macroscopic stress and strain tensors and macroscopic inelastic and nonlinear properties. The macroscopic properties are defined through analysis at a unit-cell level (micro-scale). Then, the relationships and the information paths between the different scales are established. The homogenization method shifts much of the efforts to the analysis of the unit-cell scale [22,23] and ends up with a scheme that it is usually more efficient than standard FE analysis of the wall. Yet, it still requires significant computational efforts for the solution of the two series of detailed 2D or 3D nonlinear problems, one for the micro-scale and one for the macro-scale (also see [21]). This aspect becomes even more critical when out-of-plane flexure and 3D analyses are of interest.

An analytical approach for the dynamic analysis of unidirectional masonry walls (i.e. walls that transfer loads to two opposite supporting elements only, usually at the base and at the top, and that are governed by a one-way flexural action) is presented in [8]. Yet, this presentation is limited to analytical handling, it does not include the effect of damping, and it is not supported by direct dynamic experiments. Models for the static nonlinear and dynamic analyses of masonry walls that are strengthened with externally bonded composite materials are presented in [7,9]. Experiments focusing on the static out-of-plane response are presented in [24,25]. In [26,27] the analytical models for the dynamic behavior of walls strengthened with composite materials are converted into an FE form and examined through comparison with dynamic shake-table tests of the strengthened wall. The model presented in [8] for the un-strengthened wall accounts for the cracking of the joints, the arching and rocking effects, the coupled axial (in the height direction) and out-of-plane responses, and the nonlinear behavior of the mortar material. The modeling approach of [8] combines the different physical components and all structural scales to a unified model. The distinction between the masonry units and the mortar bed joints allows for the direct implementation of the material properties of each component, eliminates the need to calibrate the properties of a unit cell, and allows for the detection of some localized effects. On the other hand, the convergence characteristics of the model, in which the material nonlinearity and the implicit nonlinear form of the constitutive equations are handled using a secant moduli and direct iteration approach, and the corresponding computation efforts, are designated as drawbacks. The complicated implementation of the model presented in [8] in a broader structural analysis platform, the limited possibility to expand the iterative scheme to more general cases like bidirectional (two-way) response or dynamic/seismic in-plane shear analysis, the limited experimental data, and the limited comparison with direct dynamic experimental results are additional drawbacks of [8].

In this paper, the dynamic response of unreinforced (one-way) masonry walls to out-of-plane dynamic loads is studied. The objective of the paper is to gain insight into the dynamic behavior of the wall and to address the modeling and analysis of this behavior. The paper combines analytical and numerical methodologies with shake-table experiments. Both the modeling and the experiments are more oriented toward modern infill walls but the modeling concepts and the some of the experimental observations are also relevant to load bearing walls under unidirectional loading and supporting conditions. The analytical phase adopts some of the modeling concepts of Hamed and Rabinovitch [7–9] and derives an FE based computational and modeling tool. The FE approach, which is also used in [26,27] for walls strengthened with composite materials, aims to support its potential implementation in broader analysis platforms, to set a basis for potential extension to more complicated cases such as bidirectional action, and to take advantage of the handling of the implicit nonlinear form of the constitutive model through Newton's method. The experimental phase aims at generating a range of experimental reference results for the dynamically loaded wall, at identifying some of the important physical and modeling aspects, and at validating the analysis capabilities. The conversion of the general modeling concept into a FE formulation and the experimental study of bare masonry walls that are not reinforced of strengthened and yet subjected to direct dynamic out-of-plane load are not presented or addressed in [7–9,24–27]. In that sense, the present paper aims to takes a step toward the conversion of the modeling concept into standard and accessible computational tools, toward the generation of experimental reference results for the examination and validation of the modeling concepts, and toward gaining insight into the structural response of dynamically loaded un-strengthened and unreinforced masonry walls. It should be emphasized that opposed to [7–9,24–27], which applied analytical, numerical, and experimental techniques, respectively, to study masonry walls strengthened with composite materials, this paper focuses on the bare un-strengthened and unreinforced masonry wall. As such, it has to face a range of analytical, numerical, and experimental challenges that stem from the absence of any tensile resisting component or mechanism.

For simplicity, the analytical and experimental efforts focus on unidirectional (one-way) flexural and axial action (in the height direction) of the masonry walls. In that sense, it is assumed that the wall is supported at two opposite edges (usually at the base and at the top) and that the structural scheme yields a one-way (beam-like) flexure. It is recognized that under certain combinations of boundary conditions, infill masonry walls can develop a bidirectional type of response [1]. In other cases, the construction method, the boundary conditions, the formation of gaps between the wall and the surrounding elements, and the accumulation of damage yield a unidirectional type of response (also see [16,17,11,20]. The present paper is limited to unidirectional out-of-plane response only and it focuses more on infill walls.

2. Modeling and finite element formulation

2.1. Modeling and assumptions

The notations and sign conventions for the modeling appear in Fig. 1. The modeling assumptions follow Hamed and Rabinovitch [8] and assume that the boundary conditions, the construction method, the width to height ratio, and the loading pattern yield a unidirectional (beam-like) flexural action through the height of the wall. It is also assumed that the vertical loads acting on the wall due to interaction with adjacent components are uniform through the width. Particularly in case of infills, the determination of such a vertical load can be very difficult. In addition, since the vertical load is usually transferred by a horizontal beam, it could vary along the width of the wall. The model derived here does not consider these effects. Based on the above assumptions, the model adopts a beam theory, assumes that the stresses are uniform through the width, and accounts for flexural and axial actions in one direction only. In addition, the model assumes that the pattern of the masonry construction of the wall repeats itself in the width direction and therefore defines a "periodic" or "repeating" pattern. Under these conditions, and by neglecting the effect of the head joints, the wall can be divided into vertical strips that are similar one to another in terms of construction patterns and structural behavior. All of these strips are represented by a single "characteristic strip" that periodically repeats itself through the width. The width of each strip (and thus the width of the characteristic strip) may vary from half the width of a single masonry unit to the width of the entire wall. For example, it is usually convenient to define the width of the characteristic strip as the width of a single block. By neglecting the effect of the head joints and the difference between voussoirs that are made of a single block and those made of two