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Influence of load history on the force-displacement response of in-plane loaded unreinforced masonry walls

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Empirical drift capacity models for in-plane loaded unreinforced masonry (URM) walls are derived from results of quasi-static cyclic shear-compression tests. The experimentally determined drift capacities are, however, dependent on the applied demand, i.e., on the loading protocol that is used in the test. These loading protocols differ between test campaigns. The loading protocols applied in tests are also different from the displacement histories to which URM walls are subjected in real earthquakes. In the absence of experimental studies on the effect of loading histories on the wall response, this article presents numerical simulations of modern unreinforced clay block masonry walls that are subjected to different loading protocols. The study shows that the force capacity is not very sensitive to the loading protocol. The drift capacity of walls failing in shear is, however, rather sensitive to the loading history while the drift capacity of walls failing in flexure is not. The largest difference in drift capacity of up to 100% is observed between monotonic and cyclic loading for shear controlled walls under double-fixed boundary conditions and low axial load ratios.

1. Introduction

Displacement-based seismic assessment of unreinforced masonry (URM) buildings requires as input—among other parameters—the nonlinear force-displacement response of the in-plane loaded URM walls. The latter is often approximated by a bilinear curve, which is described by the effective stiffness, the peak shear strength and the drift capacity of the wall, drift being the horizontal displacement divided by the wall height. In many codes [1–4], drift capacities are determined with empirical models that have been fitted to data of quasi-static cyclic shear-compression tests of URM walls. Yet, the drift capacities of URM walls seem to depend on the load history to which the walls are subjected during the test. To the author's knowledge, the only pairs of URM walls tested using different loading protocols (monotonic vs. reversed-cyclic) stem from campaigns by Ganz & Thürlimann [5] and Magenes & Calvi [6]. As mentioned in [7], the cyclic tests led to a slightly greater effective stiffness and a slightly smaller shear force capacity when compared to the monotonic tests. The most significant effect was observed for the drift capacity, for which the one obtained from the cyclic test was only about half that from the monotonic test.

In a test campaign on reinforced masonry walls by Tomazevic et al. [8] multiple identical specimens were subjected to different loading protocols: monotonic loading, reversed-cyclic loading and reversed-cyclic loading superimposed with an additional sine function as well as a load history corresponding to a simulated earthquake. While the two cyclic loading protocols led to similar force and drift capacities as the simulated earthquake, the shear force and drift capacities obtained from the monotonic tests were significantly greater. Therefore, the loading protocol used in shear-compression tests appears to influence the outcome of those tests [9,10]. However, loading protocols differ between test campaigns (e.g. [5,11–14]). The most common loading protocols comprise cycles of zero mean with increasing amplitudes but both the applied drift limits and the number of cycles per drift limit vary; examples of loading protocols are given in [10,15–23]. Moreover, the loading caused by a real seismic event might be rather different from the loading histories applied in laboratory tests.

The cumulative drifts $\Sigma abs(\delta_i)$ up to a reference drift capacity of 1% that result from loading protocols designed for test campaigns on full-scale masonry walls loaded in-plane are compared in Fig. 1a. The plot shows that the cumulative drifts of the various protocols differ by as much as a factor of four. All loading protocols

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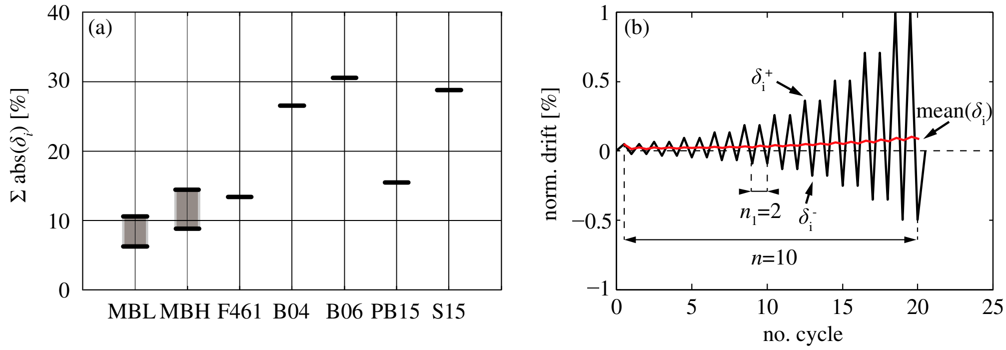

Fig. 1. (a) comparison of the cumulative drift up to a reference drift capacity of 1% (MBL – Mergos & Beyer [10] full range of considered periods of structures for regions of low to moderate seismicity, MBH – Mergos & Beyer [10] full range of considered periods of structures for high seismicity regions, F461 – FEMA461 [22], B04 – protocol used in test campaign by [11], B06 – protocol used in test campaign by [12], PB15 – protocol used in test campaign by [14], S15 – protocol used in test campaign by [13]; (b) loading protocol with non-zero mean of drift limits introducing number of drift limits n, number of cycles per drift limit n_1 and drift limit mean.

that were effectively used in test campaigns on masonry walls (B04, B06, PB15, S15) imposed a higher cumulative demand than the loading protocols that were derived to represent the demand in regions of low to moderate seismicity (protocol MBL by Mergos & Beyer [10]). As a result, the drift capacity obtained from these tests might be smaller than that of a corresponding wall when subjected to the demand of a design level earthquake from a region of low to moderate seismicity. Note that the protocols MBL and MBH depend on the fundamental period T of the structure and yield therefore a range of values as T was assumed to vary between 0.1 and ≥ 0.5 s.

The load histories to which URM walls are subjected during real earthquakes or laboratory tests might differ with regard to (i) the applied drift limits δ_i, (ii) the sequence of those drift limits, (iii) the number n_1 of cycles per drift limit and (iv) the mean of the drift cycles (Fig. 1b). This paper investigates through numerical studies the influence of these parameters on the force-displacement response of URM walls. The effect of the strain rate on the force-displacement response, which is a further parameter that differs between typical laboratory and real loading conditions, is not investigated here.

In the following, a numerical study is carried out simulating quasi-static cyclic tests on URM walls for different loading protocols. The numerical model is explained and validated in Section 2. In Sections 3–4, the parametric study is outlined and the results are presented, interpreted and conclusions on the effect of the load history on the URM wall response are drawn. A first simple formulation that accounts for load history effects on the drift capacity of walls failing in shear is proposed in Section 5.

2. Analysis procedure

A numerical study is performed to assess the influence of the load history on stiffness, strength and deformation capacity of URM walls. The simulated walls are modern clay block masonry walls with joints of normal thickness (∼1 cm). First, the wall configurations are presented, which correspond to walls that have been tested experimentally for a reversed-cyclic loading protocol. Second, the numerical modeling approach, the material laws and parameters are introduced. Finally, the numerical model is validated against the experimental results.

2.1. Wall configurations

The analysed wall configurations stem from two experimental studies on the same masonry typology: walls made of vertically perforated clay blocks with normal thickness bed-joints and normal strength mortar. All tests are quasi-static cyclic shear-compression tests in which the axial load was kept constant and the wall was subjected to cycles of horizontal drifts of increasing amplitude. From each experimental study, two walls are analysed, which have identical dimensions but are subjected to different static boundary conditions. They were chosen to cover various types of failure modes. The two walls of the first study, T1 and T3 [13], failed due to diagonal shear cracking. They were both subjected to fixed-fixed support conditions but differed with regard to the applied axial load. The walls of the second study are PUP3 and PUP4 [14], which developed a flexure controlled behaviour including rocking and toe crushing. The two walls differed again with regard to the axial load ratio. Both walls were tested applying a constant shear span of 1.5 times the wall height (see Table 1).

2.2. Numerical model

The masonry walls are simulated in Abaqus 6.14 [24] using the modelling approach and a material subroutine developed by Aref and Dolatshahi [25]. The simulation is conducted as a dynamic analysis with an explicit solution method.

2.2.1. Modelling approach

The modelling strategy is presented in more detail in [25] and is based on the works of Lourenço [26] and Oliviera et al. [27]. The model is a simplified micro-model in 3D. In this model, the bricks are modelled by solid elements (C3D8R) and the joints as interface elements (COH3D8). Since the interface elements have zero thickness, the bricks are expanded on four sides by half the mortar joint width. The interface elements placed between the bricks represent the bed- and head-joints and will be referred to as horizontal and vertical joints, respectively. Further interface elements (COH3D8) are introduced vertically in the middle of each brick representing a possible fracture plane through the brick. These elements will be referred to as middle joints.

2.2.2. Solid elements

The bricks are modelled as solid elements with a size of $l_{mesh} \sim 7.5$ cm and $h_{mesh} \sim 10$ cm varying slightly between the two chosen walls due to their different brick sizes. The 'Concrete Damaged Plasticity' model, which is available in the material model library of Abaqus, is assigned to the solid elements. The elastic modulus of the brick is estimated based on the brick compressive strength ($E_b = 400 f_{B,c}$); it differs for the two test campaigns (T1, T3: $E_b = 10'520$ MPa, PUP3, PUP4: $E_b = 14'000$ MPa) The inelastic stress-strain relationship in compression follows a formulation by Kaushik et al. [28]. In tension, the pre-peak response is linear