SIZE EFFECTS IN DRIFT CAPACITIES OF URM WALLS

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Abstract

Examining the results of a large set of quasi-static cyclic tests on unreinforced masonry (URM) walls showed that the drift capacity of URM walls reduces with increasing wall size. Such a size effect is of concern since most wall tests were carried out on test specimens with heights much smaller than actual story heights. In modern URM buildings the wall height is, however, often equal to the story height. Current drift capacity models implemented in structural design codes do not account for this size effect, thereby they tend to overestimate the drift capacity of URM walls with heights equal to the story height.

The objective of this paper is to review existing evidence for size effects on the drift capacity of URM walls and discuss possible reasons for this effect. The paper starts with a general review of size effects in quasi-brittle structures and a review on existing numerical and experimental evidence for size effects in the seismic response of URM walls. It puts forward the notion that for walls failing in flexure the size effect is largely caused by the confining effect of the foundation, which diminishes with increasing height, while for walls failing in shear the size effect stems mainly from the post-peak response and the formation of a crushing band of the height of a brick. It concludes with an outlook on future research needs for quantifying the size effect on the drift capacity of URM walls in flexure and shear.

Keywords: Unreinforced masonry walls, size effect, drift capacity

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Introduction

With the term “size effects” structural engineers refer typically to the decrease in nominal strength of quasi-brittle structural elements with increasing size. The topic has been a subject of research for several decades [Bažant 2000] and studies have focused mainly on concrete structures [e.g., Bažant 1983; Elkadi 2006]. The study of size effects for unreinforced masonry (URM) structures is still at the very beginning. The aim of this paper is to provide a review on previous findings, to discuss the choice of test unit size in experimental testing and to illustrate possible reasons for size effects of URM walls failing in flexure by means of a newly developed mechanical model. The paper focuses on URM walls subjected to seismic loading, which in laboratory tests is applied in the form of quasi-static cyclic horizontal loading. From a seismic engineering point of view, the deformation capacity is of particular interest when understanding the seismic response of buildings. For this reason, the influence of the test unit size not only on the wall’s strength but also on its deformation capacity will be discussed.

The deformation capacity of URM walls is typically expressed in terms of interstory drift $\delta$ (in the following shortened to drift). The drift is defined as the horizontal displacement $u_{\text{hor}}$ at the top of the wall divided by the height $H$ of the wall (Figure 1a). The drift capacity is typically defined as the drift at which the strength dropped to 80% of the peak strength. At present, empirical drift capacity models are used to predict the drift capacity of URM walls. The possible presence of a size effect is therefore of concern since most wall tests were carried out on test specimens with heights much smaller than actual story heights (see Section “Experimental studies on URM walls”). In modern URM buildings, the wall height $H$ is, however, often equal to the story height $H_s$ since the window units span from floor to floor (Figure 1b and c). With the exception of the model proposed by Petry and Beyer [Petry 2014a], empirical models do not account for the size effect, thereby they tend to overestimate the drift capacity of URM walls with heights $H=H_s$ (Figure 1).

Size effects can have two reasons [Bažant 2000]: First, assuming that the failure of brittle structures can be represented by the weakest link model, the normalized strength and displacement capacity of brittle structures decreases with increasing size. This follows from statistical considerations assuming that the strength of the links follows a probability distribution. The larger the structure and hence the sample size of links, the greater is the probability of a particular weak link. The second effect is a mechanistic size effect in quasi-brittle materials where the crack propagation is controlled by the fracture energy of the material and the material strength. While the energy release rate increases with the square of the structure size, the energy consumption increases only linearly with the structure size. Hence, the larger the structure, the lesser is the strength of the structure. Related to this effect is a size effect on the post-peak deflections. The zone where damage and therefore inelastic deformations concentrate was shown to scale not linearly with the size of the structure. As a result, the post-peak deformation capacity reduces with increasing size of the structure.

For URM walls the second effect is most likely the more important one but the study of size effects is yet at its beginning. The objective of this paper is to review existing evidence for size effects on the drift capacity of URM walls and discuss the possible reasons for this effect. The paper starts with a review on existing numerical and experimental evidence on the
size effect in URM walls. It then uses a recently developed analytical model for the drift capacity of URM walls failing in flexure to illustrate the size effect and to discuss the confinement of the wall foundation on the size effect. For walls failing in shear, such an analytical model is not yet available. For these walls, hypothesis on the reasons for the size effect are formulated, which might help developing an analytical model for drift capacities failing in shear.

![Figure 1](image)

**Figure 1.** Modern URM buildings with RC slabs: Deformed shape and moment profile of a URM wall (a). Façade layout of a standard URM building (b) and layout of an internal wall or a modern façade where window units reach from the top to the bottom (c).

### Literature review on size effects in masonry structures

#### Numerical studies on URM walls

The first study that addressed size effects in URM elements was the numerical study by Lourenço [1997], who analyzed URM walls of different sizes by means of simplified micro-models. Lourenço found that with increasing size of the wall, the maximum lateral strength of the wall reduced. The numerical results also showed that the slope of the post-peak branch became steeper and therefore the drift capacity of the URM walls decreased with increasing size if failure occurred due to tensile failure of bricks or due to crushing of the masonry. For sliding failure, the strength and deformation capacity was independent of the size as sliding is generally a ductile mechanism. Lourenço acknowledged that the adopted modelling approach might not be adequate for capturing compression failure correctly and recommended further research on this topic.

#### Experimental studies on URM walls

Lourenço’s results were confirmed qualitatively by the experimental data in [Petry 2014a]. The analysis of a group of 64 URM wall tests revealed for walls developing a shear, flexural or hybrid failure mode a size effect on the horizontal drift capacity (**Figure 2**), i.e., the larger the test unit the lesser its drift capacity. The database contains walls constructed with full-size clay bricks and normal cement mortar for joints of normal thickness. The drift capacity was defined as the drift capacity at a 20% drop in strength [Frumento 2009]. Most walls failed due to crushing of the compression zone and the failure along a diagonal crack passing through
bricks. For such failure modes, size effects are expected to play a role [Lourenço 1997]. A failure mechanism involving only bed joint sliding would not be affected by size effects [Lourenço 1997], but such a mechanism is rarely observed in URM walls with modern bricks that are vertically perforated [Petry 2014a].

Figure 2. Drift capacities in function of the wall height $H$ for walls failing in shear, flexure and a hybrid mode [Petry 2014a].

The large majority of the tests were carried out on walls with a height smaller than typical story heights: Hence, if empirical models are fitted to the entire data set without accounting for size effects, the resulting drift estimates are unconservative for walls with $H = H_s$. Such tall walls are rather frequent in URM buildings: Internal walls span typically over the entire story height $H_s$. In new URM buildings, also the outer walls are often equal to the story height since the window units span from floor to floor. To account for the size effect, Petry and Beyer [Petry 2014a] proposed an empirical drift capacity model that includes the height of the wall as one input parameter. The model builds on the model proposed by Lang [2002], who proposed a drift capacity model that accounts for the axial stress ratio $\sigma_0/f_m$.

\[
\delta_{CT} = 1.3\% \cdot \left(1 - 2.2 \frac{\sigma_0}{f_m}\right) \cdot \frac{H_0}{H} \cdot \left(\frac{2400mm}{H}\right)^{0.5}
\]  

(1)

On the choice of the size of URM walls for experimental testing

The experimental data presented in the previous section showed that many wall tests were carried out on test units with heights smaller than the story height. URM walls with dimensions smaller than common story heights might be tested for three reasons: First, the test stand might not be large enough to accommodate full-scale specimens requiring therefore the testing of a reduced-size specimen. Second, to reduce the complexity of the test setup, a wall subjected to a top moment might be transformed into a cantilever wall test.
by reducing the wall height from $H_s$ to $H_0$. Third, test specimens might represent walls that are supported on spandrels (Figure 1b). The free height $H$ of the wall is therefore smaller than the story height $H_s$. In all three cases testing walls with heights different to $H_s$ has some implications on the obtained results. This will be discussed in the following sections.

Note that the discussion focuses on URM walls in buildings with RC slabs. In modern URM buildings with RC slabs the walls are bounded at the top and bottom by RC slabs, which are rather stiff elements and therefore define clearly the boundary conditions. In the laboratory, the slabs are replicated by a very stiff foundation and top beam, which are used to fix the test unit to the strong floor and connect the actuators to the test unit respectively. For masonry walls in buildings with timber slabs the boundary conditions are less clearly defined and particular considerations need to be given on how the boundary conditions of a wall in a real building can be best replicated in the laboratory. These considerations touch on similar aspects as those discussed for walls with free heights smaller than $H_s$ (Section “Testing specimens with $H < H_s$ to account for the actual free height”).

Testing reduced scale specimens due to test stand limitations

Due to limitations of the test stand—this could be the size of the test stand or the capacity of the available actuators—it is sometimes necessary to test specimens that are smaller than the actual wall size. To this purpose, URM walls can be scaled in two different ways (Figure 3): In the first approach the bricks are not scaled and the reduced-scale test unit is constructed using full-scale bricks. Hence, if the wall size is scaled down, the number of bricks required for the construction of the wall reduces (Figure 3b). In the second approach the brick number is maintained and therefore the brick size needs to be scaled down (Figure 3c). In particular when hollow brick units are used, the production of reduced-scale brick units entails significant preparation and also costs [Petry 2014b]. For this reason, this second scaling approach is typically only applied to shake table testing (e.g. [Beyer 2014]) and not to quasi-static cyclic testing.

The common approach of testing masonry walls under quasi-static cyclic testing at reduced size uses therefore full-size bricks to construct the small-scale test unit (Figure 3b). This puts naturally some bounds on the scaling factor and typically scaling factors of 2-3 are the maximum scaling factors that can be applied with this method. This paper discusses size effects that are introduced by this scaling method, i.e., all specimens are constructed using full-scale bricks.

Figure 3. Full-scale test unit of masonry wall (a). Half-scale test unit with full-size bricks (b). Half-scale test unit with half-size bricks (c).
Testing specimens with \( H < H_s \) to transform the boundary conditions

In general the height of zero moment \( H_0 \) of a masonry wall does not correspond to the wall height \( H \) (Figure 1a). When testing a wall of height \( H \) whose shear span \( H_0 \) is different to \( H \), the two vertical actuators need to introduce—next to the axial load \( N \)—also a top moment \( M_{\text{top}} \) (Figure 4a). With today’s control systems such boundary conditions can be applied without much difficulties and the test setup with three fully coupled actuators became the standard test setup for URM wall tests. An alternative setup with one servo-controlled actuator and one hydraulic jack, which simplifies the setup of the control system to that of a cantilever wall test but results in a somewhat more complex loading beam structure, is shown in Figure 4a. In the past, however, such setups were not frequently used but a cantilever wall with height \( H_0 \) was tested instead (Figure 4b). Using test setup in Figure 4b instead of the test setup in Figure 4b or Figure 4a will affect the drift capacity estimates that are obtained from the test. This is for two reasons: First, the test setup in Figure 4b might lead to a different crack pattern; this applies only to walls failing in shear. Second, the drift definitions that result from the two tests are not coherent.

![Figure 4. Different test setups for testing walls with \( H_0 < H_s \) with one servo-controlled actuator and one hydraulic jack: Test setup for test unit with \( H = H_s \) (a) and test setup for test unit with \( H = H_0 \) (b).](image)

For walls failing in diagonal shear, the top beam at height \( H_0 \) acts like a very strong horizontal reinforcement and prevents the opening of a diagonal crack at the height of the top beam. At failure the diagonal crack typically follows the geometric diagonal (Figure 4, [Petry 2014a]). Testing a specimen with \( H = H_0 \ (H_0 < H_s) \) will therefore lead to a less inclined crack than testing a specimen with \( H = H_0 \). The wall test on a specimen with \( H = H_0 \) does therefore not reproduce the behaviour of a wall with \( H = H_s \). For walls failing in flexure where the damage concentrates at the base of the wall, the effect of this beam on the failure mode is likely to be relatively small.

Independent of the failure mode, the test setup in Figure 4b leads to incoherence in the drift capacity definition: At present, the deformation capacity of URM walls is defined in terms of interstory drift. The definition requires that a panel is tested that comprises the entire deformable part of the story-high wall. This is not the case for the test setup in Figure 4b, which yields the chord rotation and not the interstory drift. The two measures are identical for cantilever walls and—in case of symmetric failure—also for walls subjected to double-bending but not for general loading conditions [Petry 2014c]. Experimental results showed, however, that the differences in drift capacities that are obtained for the two definitions are typically rather small (in the order of 10-15%, [Petry 2014c]).
Testing specimens with \( H < H_s \) to account for the actual free height

The most shear critical walls are often those that are framing at the left and right into spandrels—for these walls the free height \( H \) is smaller than the story height \( H_s \) (Figure 1b). To the knowledge of the authors, these walls were always tested applying the same type of boundary conditions as story-high walls, i.e., the walls were supported on a stiff foundation beam at the base and a stiff top beam was used to connect the actuators to the test unit (Figure 5b). For the wall base, the boundary condition of a stiff beam is not representative of the boundary condition in the real building where the wall is supported by the masonry panel into which the wall and the spandrel elements frame (Figure 5a). Replacing the masonry by a stiff foundation beam confines the masonry at the base of the foundation. Unlike for concrete, this confinement effect has not yet been well studied. However, several observations and numerical investigations suggest that it has a significant effect on the behaviour of the masonry. This is discussed further in the following section. When testing walls with \( H < H_s \), it might therefore be more representative to include a small URM pedestal in the test unit (Figure 5c). Note that similar considerations might apply to the bottom and top boundary conditions for testing of URM walls that are representative of buildings with timber slabs or in buildings with lintels above window and door openings.

![Figure 5. Testing of walls that are supported on spandrels: Wall supported on spandrels (a, detail of Figure 1a); common test setup (b) and proposed test setup (c) for such walls.](image)

Confinement of masonry by RC slabs

A masonry panel under vertical compression fails typically due to vertical splitting of the central brick rows, i.e., of those bricks rows for which the confinement provided by the top and bottom beam has either vanished or is at least smaller than for the brick rows in direct vicinity of these beams. This is illustrated by the photos in Figure 5a and b, which show a masonry wallette subjected to uniaxial compression. To eliminate the confining effect on the masonry strength, testing standards prescribe minimum numbers of brick rows for such compression specimens. The confinement effect is also evident in the crack pattern of walls subjected to horizontal loading (Figure 5c, [Petry 2014d]): Splitting cracks at the wall toe tend to initiate at the second joint above the base, i.e., at a height \( h = h_B \) above the wall base [Petry 2014e]. The confinement by the foundation reduces the lateral tensile stresses in the bricks, which result from the different Poisson’s ratios of mortar and brick and therefore the strength of the bottom brick row is increased. At present, models that predict this increase in strength...
are missing. The brick strength obtained from compression tests on single bricks may serve as a first estimate of an upper bound strength estimate at the wall base. These observations were used as failure criteria in a mechanical model for the prediction of the drift capacity of masonry walls with hollow clay bricks failing in flexure [Petry 2014e]. The mechanical model will be used in the following section to predict the effect of the confinement on the drift capacity. It will be shown that the size effect in drift capacities depends largely on this confinement effect.

Figure 6. URM Wallette subjected to axial compression (a, b; [Beyer 2010]). URM wall failing in flexure (c; [Petry 2014c]).

Figure 7. Confinement effect in numerical analyses with VecTor 2: Comparison of experimental results to numerical results for a wall failing in shear (PUP1) and a wall failing in flexure (PUP3). [Zhang 2014]

Error! Reference source not found. shows the results of a finite element analysis of two URM walls that were tested experimentally [Zhang 2014]. The analyses were carried out using the masonry model that was recently put forward by Facconi, Plizzari and Vecchio [Facconi 2013] and which is implemented in the software VecTor2 [Wong 2013]. The model does not account for a confinement effect (“VecTor 2” in Figure 7). For this reason, the confinement effect was considered artificially by increasing the strength of the elements that correspond to the bottom brick row to the brick strength (“VecTor 2 (M)”). The comparison of numerical to experimental results shows that, for a wall failing in shear (PUP1), the confinement effect at the base has only a small influence on maximum strength and deformation capacity. For a
wall failing in flexure (PUP3), however, the model whose bottom brick row was assigned an increased strength ("VecTor 2 (M)") predicts the strength and deformation capacity of the walls significantly better than the original model ("VecTor 2") where confinement effects had not been considered.

**Size effect predicted by a new mechanical model for drift capacities of URM walls failing in flexure**

Drift capacity models for URM walls implemented in current design codes and guidelines [e.g. ASCE 2013, CEN 2005] are empirical drift capacity models that were derived from test results of quasi-static cyclic tests (Section “Experimental studies on URM walls”). For walls failing in flexure exist, however, mechanical models for predicting the monotonic force-displacement response and drift capacity of URM walls [Petry 2014f]. The following discussion of size effects on drift capacities of URM walls is based on the mechanical model put forward in [Petry 2014e], which is the only mechanical model that captures the size effect on drift and force capacity. In [Petry 2014e] the confinement by the foundation is accounted through the following assumptions: The peak stress that can be reached at the extreme fibre of the wall base is equal to the compressive strength of the brick rather than the masonry. Reaching of the unconfined masonry strength $f_m$ might initiate splitting of bricks at the second joint (i.e., a brick above the wall base). This assumption, which is based on observations from experimental test [Petry 2014a, c], introduces the size effect in the predicted drift capacities. This is shown in Figure 8 where the drift capacity is plotted as a function of the wall height. Up to $H=2.1$ m, for walls seated on a very stiff foundation (“with confinement”), the failure is controlled by crushing at the wall toe, i.e., the brick strength governed the behaviour. For larger walls, the failure is controlled by crushing in the second bed joint ($h=h_b$), where the masonry strength governs the behaviour.

![Figure 8. Drift capacity $\delta_u$ of URM walls failing in flexure as a function of the height of the wall and the confinement conditions at the base of the wall.](image)

If the confining effect of the foundation is neglected (“without confinement”), all walls fail due to crushing at the wall toe reaching at the toe a peak strength equal to the masonry strength. For these walls, there is no size effect on the drift capacity. Hence, assuming that test units
with $H<H_s$ were tested to represent walls seated on URM spandrels, these results suggest that we only observe a size effect in URM walls failing in flexure, because walls with $H<H_s$ were tested with inadequate boundary conditions, i.e., using test setup of Figure 5a instead of Figure 5b. This hypothesis needs, however, to be verified through experimental tests comparing results from the two aforementioned test setups.

**Size effects in walls failing in shear – some reflections**

For walls failing in shear a mechanical model for predicting the drift capacity is not yet available. Therefore it is only possible to formulate some hypotheses on the causes of the size effects in URM walls failing in shear. Figure 9a shows a wall failing in shear (PUP1, [Petry 2014d]). The wall failed by developing a crushing band along the diagonal of the wall. The height of this crushing band was equal to the brick height. Assuming that this crushing band is the origin of the post-peak deformations, Figure 9b shows the schematized force-displacement response of a large and a small URM wall failing in shear. It postulates that the size of the test unit has little to no influence up to the peak response but only becomes evident in the post-peak response. It is further assumed that the deformations in the post-peak response are controlled by the crushing band that forms along the diagonal. If the shear displacement capacity of this crushing band is just a function of the brick height and type, it is independent of the wall size. Therefore, the drift capacity that results from the deformations of this crushing band is inversely proportional to the wall height leading therefore to a lesser post-peak drift capacity of larger walls. Since the drift capacity is defined as the drift at a 20% drop in strength (e.g. [Frumento 2009]), the drift capacity $\delta_u$ of larger walls is lesser than for small walls.

**Figure 9.** Wall failing in shear (a, [Petry 2014d]) and schematized force-displacement response for a large and small wall failing in shear.

**Conclusions and Outlook**

The paper investigates the effect of the test unit size on the drift capacity of URM walls when all walls are constructed with full-size bricks. A reduction in drift capacity with increasing wall size had been observed in the past from numerical analyses [Lourenço 1997] and experimental evidence [Petry 2014a]. When analyzing the experimental data base comprising quasi-static cyclic tests on clay brick masonry walls it became evident that many tests have
been carried out on test units that are smaller than walls in modern URM buildings. Empirical models that do not account for a size effect might therefore lead to unconservative drift capacity predictions of walls in modern URM buildings. The objective of this paper was to review and discuss the evidence and possible reasons for size effects in the drift capacity of URM walls.

The paper puts forward the notion that size effects in URM walls failing in flexure are mainly caused by the confining effect of the foundation. The confinement increases the strength of the bottom brick row and crushing failure therefore often initiates at the second joint rather than the base joint. The fact that the second rather than the bottom joint is critical leads to a size effect in the predicted drift capacities, which is captured by a recently proposed analytical model for URM walls failing in flexure. In the past, reduced-scale specimens were often tested with reference to walls that are supported on masonry spandrels, i.e., walls whose free height is less than a story height. However, it is argued here that these walls should include a small masonry pedestal and not be placed directly onto a stiff foundation beam. If this would be done, the mechanical model predicts that the drift capacity of the small walls should in fact not be larger than that of story-high walls.

For URM walls failing in shear an analytical model that predicts the drift capacity is not yet available. Numerical analyses have shown that the confinement effect does not seem to have a major effect on the drift capacity of URM walls failing in shear. Hence another phenomenon must be at the origin of the size effect observed for drift capacities of these walls. Based on the failure pattern, it is considered likely that the post-peak response causes the size effect for these walls: In the post-peak response a crushing band of the height of one brick row forms and the drift capacity that results from the deformations of this crushing band is inversely proportional to the wall height leading therefore to smaller drift capacities of larger walls. Ongoing research aims at developing a mechanical model for the drift capacity of URM walls failing in shear that accounts for this size effect. Such a model would—similarly as the one for walls failing in flexure—allow to identify the parameters that control the drift capacity of URM walls.

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References


