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SENSITIVITY OF DRIFT CAPACITIES OF URM WALLS TO CUMULATIVE DAMAGE DEMANDS AND IMPLICATIONS ON LOADING PROTOCOLS FOR QUASI-STATIC CYCLIC TESTS

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Abstract

Displacement-based seismic design and assessment procedures require as key input parameter estimates of displacement capacities of the critical elements. The displacement capacities of unreinforced masonry (URM) walls are typically determined by means of quasi-static cyclic tests. This paper shows that for URM walls failing in shear the number of applied cycles in quasi-static cyclic tests influences the drift capacities obtained from these tests. It is therefore important that loading protocols are used that reflect the expected cumulative damage demand. The latter will depend on the structural properties and the seismicity of the region. Existing loading protocols for quasi-static cyclic testing were derived to reflect the cumulative cyclic demands in regions of high seismicity and where derived for structural systems other than masonry buildings. For regions of moderate seismicity, these protocols are likely to underestimate the actual drift capacities. Based on statistical analysis of the displacement response of SDOF systems representative for URM buildings, the paper proposes new loading protocols for quasi-static cyclic tests on URM walls.

Keywords: Unreinforced masonry walls, uncertainties, drift capacity, quasi-static cyclic tests, loading protocols

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Introduction

Displacement-based design or assessment methods require as input estimates of the displacement demand and the displacement capacity. Studies on the prediction of the displacement demand on unreinforced masonry (URM) structures have been conducted in recent years [e.g., Norda 2011; Graziotti 2013], but analytical displacement capacity models are at present missing. The displacement capacities of URM walls are therefore typically determined by means of quasi-static cyclic tests. The results of these tests are then used to derive empirical drift capacity models [e.g., Pfyl-Lang 2011, Petry 2014].

At present, these empirical drift capacity models are affected by large uncertainties, which can be linked to two sources: The first is the natural variability of the construction materials mortar and bricks and of the brick-mortar interface (aleatory variability). The second group of uncertainties comprises uncertainties that result from differences that could be considered through drift capacity models if the drift capacity models could account, for example, for the different masonry typologies, the applied loading histories and velocities (epistemic uncertainties). While the aleatory variability cannot be reduced, it seems pertinent to work towards reducing the epistemic uncertainties in order to guarantee an effective implementation of displacement-based design and assessment procedures in modern structural design and assessment codes. The objective of this paper is to contribute towards this effort by (i) assessing the effect of cumulative cyclic demand on the obtained drift capacities and (ii) by proposing loading protocols that are representative of actual cumulative demands on URM structures:

- First, it is shown that the cumulative damage demand imposed in quasi-static cyclic tests influences the obtained drift capacities if the walls fail in shear. Hence, the fact that different laboratories use different loading protocols introduces a variability, which is reflected in the epistemic uncertainty. At the moment, there is not yet a model available that can account for the effect of cumulative damage demand in URM walls on the obtained drift capacities. It is therefore important that loading protocols are applied that are representative of the actual cumulative damage demand, since the results of quasi-static cyclic tests will be used as input to drift capacity models that do not account for cumulative damage demands.

- Second, loading protocols are developed that are representative for the cumulative damage demand on URM buildings. These demands will strongly depend on the seismicity of the region where the buildings are located. New URM buildings will largely be constructed in regions of low-moderate seismicity while existing URM buildings are located also in regions of high seismicity. The paper will therefore derive cumulative demands for both types of regions. The paper builds on the methodology developed in a study on loading protocols for reinforced concrete, reinforced masonry and steel buildings [Mergos, 2014] and extends it to unreinforced masonry buildings.

The influence of loading protocols on the obtained drift capacities

Force and deformation capacities of structural members that are susceptible to cumulative damage demands are not independent of the imposed seismic demand but are related to it [Krawinkler 2001]. The drift capacities that are obtained from quasi-static cyclic tests are therefore dependent on the loading protocol that is applied in the test. The significance of the loading protocol will depend on the sensitivity of the tested member to cumulative damage demands.

Masonry walls are generally known to be susceptible to cumulative damage but mechanical models that are able to account for this effect on the force and displacement capacity are at present not available. The effect of the cumulative seismic demand has hence not been quantified for masonry walls. The objective of this section is to review the available experimental evidence for the effect of cumulative damage on the drift capacity of clay brick masonry walls. The drift capacity δ_u is defined as the drift at which the force dropped to 80% of the peak force.

Comparison of monotonic and cyclic response

A systematic study that compares the response of URM walls for different loading protocols is missing. In the literature, tests on three pairs of URM walls with vertically perforated clay bricks are documented where one wall had been subjected to monotonic loading while the other was tested under cyclic loading [Beyer 2014]. The first two pairs stem from the experimental campaign by Ganz and Thürlimann [1984], the third from Magenes and Calvi [1992]. Ganz and Thürlimann applied always 10 cycles per amplitude level. The total number of cycles applied until failure was 58 for W6 and 61 for W7, which from today's point of view is certainly not representative of the loading history imposed by an earthquake. Magenes and Calvi applied a loading history which corresponds in many respects already to today's standard for URM wall testing. Until failure approximately six cycles were applied (the small cycles are difficult to identify since only a figure with the force-displacement response was available). The largest influence of the loading history is observed for the drift capacity, which is in average twice as large for monotonic tests as for quasi-static cyclic tests. The force capacity is approximately the same for monotonic and cyclic tests while the effective stiffness is somewhat larger for cyclic tests than for monotonic tests [Beyer 2014]. Despite the admittedly very limited data set, this comparison of monotonic vs. cyclic test results suggests that the loading history is not important if one is only interested in the force capacity of the URM wall. It becomes, however, significant if the displacement capacity is of interest.

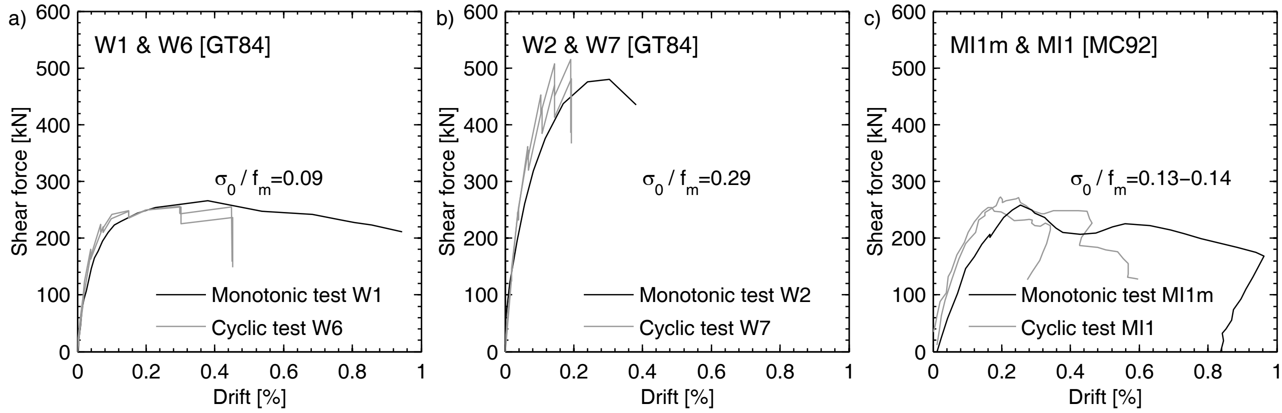

Figure 1. Monotonic vs. cyclic loading: Comparison of force-displacement envelopes [Beyer 2014].

The six walls that are compared in **Figure 1** developed shear or hybrid failure modes. For URM walls that failed in flexure such a wall pair that was tested under monotonic and cyclic loading could not be identified. Further, the comparison of monotonic and one cyclic test does not show the influence of the number of cycles applied in the test on the drift capacity.

Influence of the number of cycles applied in quasi-static tests

To investigate the influence of failure mode and the number of cycles applied up to horizontal load failure, the number of applied cycles was estimated for the 64 walls in the database by Petry [2014], which is based to a large extent on the database by Frumento [2008]. It is clear that the number of cycles is only a relatively weak indicator for the cumulative damage demand as also the amplitude and order of the applied cycles should be considered. However, for most of these tests only printed copies of the force-displacement relationships were available and in particular for the smaller cycles it was difficult to identify the individual cycles and therefore already the number of cycles is attributed with a relatively large uncertainty. Due to the relatively poor data quality it was therefore considered unwarranted to refine the analysis further and only the estimated number of applied cycles at horizontal load failure will be used as indicator of the cumulative demand that was applied.

Figure 2 shows the obtained drift capacities as a function of the failure mode and the number of applied cycles. **Figure 2**a shows the walls that failed in flexure and a very clear trend of increasing drift capacity with increasing number of cycles is obtained. This seems at first very perplexing as one would expect that the drift decreases with increasing number of applied cycles or is at best insensitive to the number of applied cycles. The origin of this observation lies in the way how loading protocols are designed in practice: The loading protocols should be designed by estimating the expected displacement capacity and then determining the amplitudes of the cycles as a function of the total number of cycles that are to be applied and the number of cycles that are applied per drift level. Often this is not done and rather constant intervals of increases in drift capacity chosen. The applied number of cycles is therefore not representative of the expected cumulative damage demand. If the wall did not fail at the expected value, the loading protocol is extrapolated and more and more cycles added. For this reason, walls that reach larger drift capacities are subjected to more cycles. Since the relationship between number of applied cycles and drift capacity is approximately linear, one can conclude that the drift capacity of walls developing a flexural failure mode is not significantly affected by the applied loading protocol.

Walls developing a shear or flexural failure mode show very different trends (**Figure 2**b and c): Here the drift capacity obtained from quasi-static tests decreases or remains approximately constant with increasing number of applied cycles. This suggests that the drift capacities of such walls is sensitive to the applied number of cycles and supports therefore the finding from the comparison of monotonic and cyclic tests in **Figure 1**.

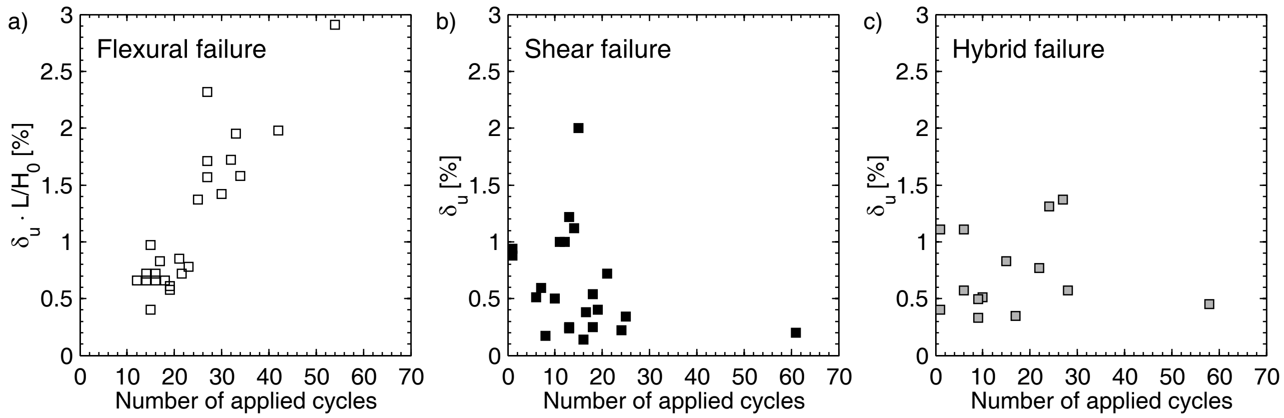

Figure 2. Drift capacities obtained from quasi-static monotonic and cyclic tests as a function of the number of applied cycles until failure.

Review of existing loading protocols for quasi-static cyclic tests on masonry walls

Krawinkler [2009] reviewed existing protocols for quasi-static cyclic tests. As examples, the SPD protocol [Porter 1987] and the SAC protocol [Clark 1997] are shown in **Figure 3**. The SPD protocol might not be that well known. However, previous to this study, it was the only protocol that had been deliberately derived for masonry structures. It had been developed for the US-Japan TCCMAR Testing program for masonry research and aimed at representing the seismic demand on very rigid and short period structures [Krawinkler 2009]. It was, however, later recognised that the cumulative demand imposed by this protocol is even for regions of high seismicity too high [Krawinkler 2009]. Furthermore, the loading history is normalized with regard to the displacement demand in the “first major event” (FME) but the definition of this event remained very ambiguous leading hence to very large differences in application between laboratories [Krawinkler 2009].

The ATC-24 protocol [ATC 1992] is probably one of the most known and most frequently applied loading protocols. Although it was originally derived for steel structures, it found also wide application when testing other structural members. The original protocol applies three cycles per amplitude for smaller amplitudes and two cycles for larger amplitudes (**Figure 3**b). In practice often three cycles up to failure were applied. The protocol is defined in function of the yield displacement δ_y—which is here the source of ambiguity. In particular for structural elements such as URM walls, the definition of a yield displacement is often rather difficult.

Other and more recent protocols are the protocols in [CEN 2001, Krawinkler 2001, FEMA 2007, ISO 2010, Hutchinson 2011]. All of these protocols have been developed for regions of high seismicity. Large magnitude earthquakes typically impose higher cumulative damage demands than small magnitude earthquakes [Kramer 1996]. Hence, existing loading protocols may overestimate the cumulative cyclic demand in regions of low to moderate seismicity. Tests on URM walls with these protocols might therefore underestimate the actual drift capacity that URM walls exhibit when subjected to cumulative cyclic demands representative of those in regions of low-moderate seismicity.

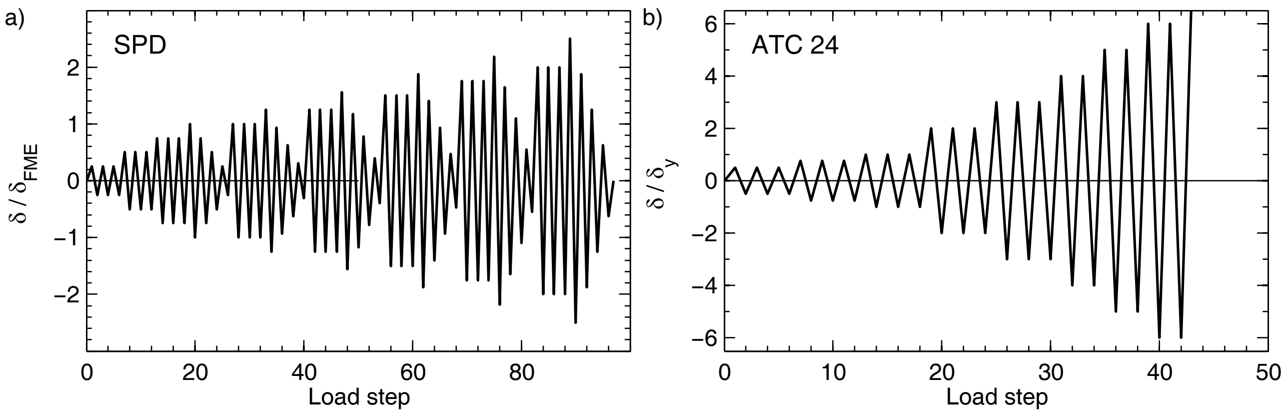

Figure 3. Two examples of existing loading protocols: The SPD protocol (a) and the ATC-24 protocol (b).

Procedure for the definition of loading protocols

The objective of the loading protocols that are derived here is to represent the median cumulative cyclic demand that a particular structure is subjected to. To obtain this demand a large number of dynamic analyses are carried out and then evaluated statistically. The procedure for the derivation of the loading protocol is outlined in detail in Mergos [2014]. The response of the URM walls is simulated using the macro-element for URM walls that is implemented in the program Tremuri [Penna 2013; Lagomarsino 2013]. For the sake of simplicity the structures are represented by SDOF systems. Each model consists of one macro-element subjected to a vertical compression load N at the top. The base node is fixed and the top node of the macro-element connected in horizontal direction to a mass M. The connection is rigid axially but completely flexible in flexure and shear. The mass was supported on an elastic column that is also rigid axially but very flexible under horizontal loads.

The analyses were based on a wall with a length of L=12 m, a width of b=0.3 m and a height of 8 m. The compressive strength of the masonry was assumed as f_m= 6 MPa. The E-modulus and G-modulus of the masonry were estimated as:

$$E_m = 1000\, f_m \; and \; G_m = 0.25\, E_m$$

The initial stiffness of the cantilever wall was hence:

$$k_{tot} = \left(\frac{1}{k_s} + \frac{1}{k_f}\right)^{-1} \; where \; k_s = \frac{G_m A_{gross}}{H} \; and \; k_f = \frac{2E_m\, I_{gross}}{H^3}$$

where A_{gross} and I_{gross} are the area and inertia moment of the gross section of the wall. Note that the flexural stiffness of the macro-element is not equal to the flexural stiffness of Bernoulli beam. The effective stiffness was assumed as 50% of the gross sectional stiffness. To obtain a certain effective period T, the horizontal mass of the system had to be set to:

$$M = \left(\frac{T}{2\pi}\right)^2 \cdot \frac{k_{tot}}{2}$$

The loading protocols were developed for structures designed for a particular force reduction factor q[3] [Mergos 2014] and for the masonry structures investigated here q-factors of 1.5. The shear force capacity was determined from the spectral design acceleration at T assuming an overstrength factor OSR=1.5:

$$V_r = S_{pa}(T,q) \cdot M \cdot OSR$$

The spectral acceleration S_{pa}(T,q) is taken as the design accelerations of the 475 year design spectrum. As URM walls failing in shear proved to be the most sensitive to the cumulative cyclic demands, the analysis focused on these. Note also that loading protocols for rocking walls are included in Mergos [2014]. For walls failing in shear, a friction coefficient and cohesion of 0.7 and 0.25 MPa respectively were assumed and a brick height h_b of 0.2 m and length l_b of 0.3 m. The shear capacity can then be computed as:

$$V_s = \hat{\mu} \cdot N + \hat{c} \cdot A_{gross} \; where \; \hat{\mu} \coloneqq \mu \cdot \frac{1}{1 + \frac{2h_b}{l_b}} \; and \; \hat{c} \coloneqq c \cdot \frac{1}{1 + \frac{2h_b}{l_b}}$$

The applied axial force N was determined such that the capacity corresponded to the pre-determined V_r:

$$N = \frac{1}{\hat{\mu}} \cdot (V_r - \hat{c} \cdot A_{gross})$$

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[3] Here the European notation is used as the design approach is consistent with the Eurocode EC 8. In the American terminology the force reduction factor is annotated with R.

To represent the demand of low-moderate seismicity regions, 60 records were selected from the European Strong Motion Database [Ambraseys 2004]. These records are representative for the 2/50 seismic hazard level of the city Sion in Switzerland, which was used as a reference location. To determine the equivalent demand for regions of high seismicity, the same 20 records were used that had been employed in several studies on loading protocols for high-seismicity regions [Krawinkler 2001]. The dynamic analyses are carried out with 2% Ralyeigh damping [Graziotti 2013] at the initial period T_i (computed from gross sectional properties) and three times the effective period T. The parameters G_c and b, which describe the pre-peak and post-peak softening of the shear response of the macro element are set to 1.0 and 0.4 respectively, following hence the recommendations by Penna [2013].

From the results of the dynamic analyses the median cumulative cyclic demand is constructed and a loading history designed that envelopes this demand. The amplitudes of the loading protocol are smoothed to follow the following exponential function:

$$f(x) = \delta_u \cdot \left(0.55 \cdot \exp\left[\left(\frac{x}{n}\right)^{\alpha}\right] - 0.50\right)$$

where α and n are parameters that depend on the structural system, its effective period, the force-reduction factor and the seismicity (see following section).

Loading protocols for quasi-static cyclic tests on masonry walls

Table 2 summarises the parameters that describe the loading protocols for URM walls failing in shear. The number n1 indicates the number of cycles per amplitude and n the number of amplitude levels. The total number of cycles that should be applied up to failure is therefore $n_{tot}=n*n_1$. To design the loading protocol an estimate of the drift capacity is required. For a URM shear wall, δ_u can be estimated as 4/3*0.4%=0.53% [CEN 2004]. The number of cycles per amplitude level can be chosen between 1 and 3. If the structure has, for example, an effective period of 0.3 s and is situated in a region of low-moderate seismicity, the loading protocols should have the following amplitudes:

- One cycle per load step (n_1=1): 0.03, 0.03, 0.03, 0.03, 0.04, 0.05, 0.07, 0.09, 0.12, 0.16, 0.21, 0.28, 0.38, 0.53 [%]
- Two cycles per load step (n_1=2): 0.03, 0.04, 0.07, 0.13, 0.26, 0.53 [%]
- Three cycles per load step (n_1=3): 0.05, 0.15, 0.53 [%]

As example, **Figure 4**a shows the loading protocol for n1=2 and compares it to the corresponding protocol that is representative of regions of high seismicity (**Figure 4**b).

Table 2. Parameters for loading protocols for URM walls failing in shear

Force-reduction factor	Effective period	Low-moderate seismicity						High seismicity					
		n_1=1		n_1=2		n_1=3		n_1=1		n_1=2		n_1=3	
q=1.5		n	α	n	α	n	α	n	α	n	α	n	α
	T=0.1s	26	6.56	12	6.22	6	5.54	11	6.7	3	5.33	2	4.07
	T=0.3s	14	2.98	6	2.85	3	2.52	25	3.4	12	3.39	7	3.26
	T=0.5s	9	2.73	4	2.66	2	2.23	16	2.19	7	2.12	4	1.94

The table shows that the longer the fundamental period of the structure, the smaller the number of cycles the structure is subjected to. It also demonstrates the difference in cyclic demands in regions of low-moderate seismicity and high seismicity. If the building is designed for a higher q-factor, cumulative damage demands tend to be slightly lower [Mergos 2014].

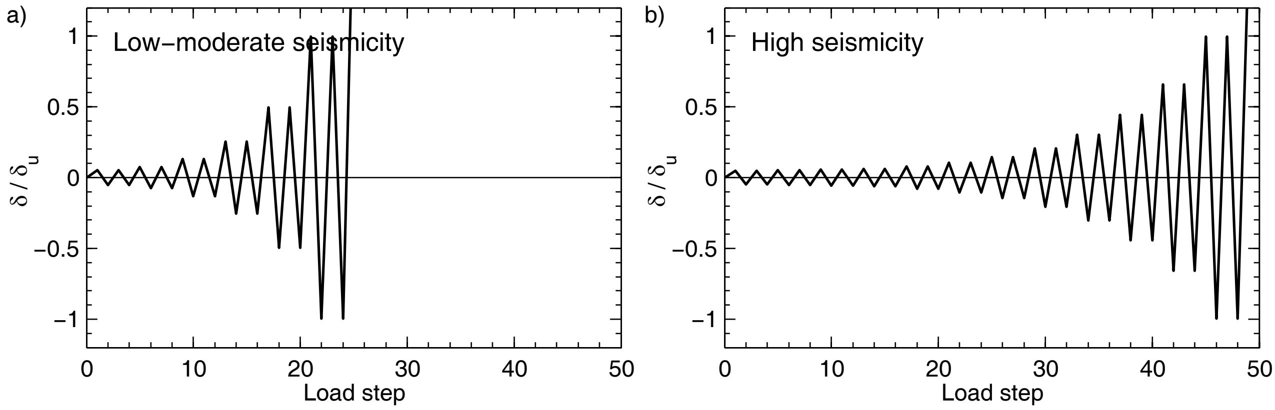

Figure 4. New loading protocols for URM walls: Protocols for a structure with T=0.3s in a region of low-moderate seismicity (a) and a region of high seismicity (b). Both protocols have two cycles per amplitude level.

Conclusions and Outlook

The paper shows that URM walls failing in shear are susceptible to cumulative damage demands. Since the drift capacities obtained through quasi-static cyclic testing are therefore dependent on the applied loading protocol, care needs to be taken when choosing the loading protocol. Existing protocols were derived for high-seismic regions and mostly for structural typologies other than unreinforced masonry structures. This paper proposes two new sets of loading protocols for unreinforced masonry buildings failing in shear that are representative of regions of low-moderate seismicity and high seismicity respectively. It is hoped that these protocols will contribute to apply more realistic cumulative cyclic demands in quasi-static cyclic tests. In particular for regions of low-moderate seismicity where most of the new URM buildings are constructed, these protocols can help to derive more realistic and less conservative drift estimates than existing protocols that were derived for high-seismicity regions.

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