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Displacement capacity of contemporary unreinforced masonry walls: An experimental study

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ABSTRACT

A research project on the displacement capacity of contemporary unreinforced masonry (URM) walls is underway at the Institute of Structural Engineering of ETH Zurich. The development of the basis for the displacement-based design of URM structures is the prime objective of the present project. In the experimental phase of the project, a total of 10 static-cyclic shear tests on full-scale URM walls made of clay and calcium-silicate blocks were performed to investigate the effects of various factors, i.e. unit type, vertical pre-compression level, aspect ratio, size, and boundary conditions, on the displacement capacity of URM walls. This paper presents and discusses the obtained test results. All the walls (regardless of their failure mode) exhibited limited displacement capacity. The test results show that as the vertical pre-compression level increases, the displacement capacity decreases. Furthermore, they indicate a possible reduction in the displacement capacity of URM walls in the case of an increase in the height or a decrease in the aspect ratio, i.e. the height divided by the length. It is also shown that the values recommended by the current codes of practice for the displacement capacity of URM walls cannot be considered as reliable. Finally, a simple empirical model for the displacement capacity of contemporary URM walls is proposed, based on the results obtained from the tests.

1. Introduction

Although unreinforced masonry is a sustainable and economical construction method, its share of the construction market has decreased in recent decades. This is mainly because current codes of practice severely limit the possibility of construction with unreinforced masonry by requiring over-conservative values for the force-reduction factor (q-factor in Europe or R-factor in the US). However, recent studies show that the performance of structurally designed and detailed low-rise URM buildings should be considered acceptable for the category of ordinary occupancy even in regions of appreciable seismicity. Hence, unreinforced masonry is still a very competitive choice for two- or three-story residential buildings in regions of low to moderate seismicity [1,2]. In conclusion, the potential of unreinforced masonry has not yet been fully exploited and there is a clear need for better utilization.

Based on the positive experience gained in recent years in developing the basis for the displacement-based seismic design of reinforced concrete structures, it appears that the most feasible approach to enhance the rationality of the design of URM structures is to apply the same fundamentals. A more consistent representation of the seismic capacity as well as of the seismic demand leads to a more realistic design. Obviously, the first step towards the development of such an approach for URM structures is to investigate the limits of their displacement capacity.

The displacement capacity is a key parameter in the seismic design and assessment of structures. Unfortunately, our current state of knowledge of the displacement capacity of URM walls is limited. On the one hand, the available experimental data has pronounced variability, so it is not possible to identify rational values for the displacement capacity of URM walls based only on such experimental data and, on the other hand, there are no reliable analytical models for either the displacement capacity or the force–displacement relationship of URM walls [3]. In general, the displacement capacity of URM walls is a very complex value; it is influenced not only by the failure mode but also by many other factors such as the constituent materials, geometry, boundary conditions, and pre-compression level. Currently, we are still not able to take into account properly the influences of all factors affecting the displacement capacity of URM walls due to inhomogeneous experimental data and a lack of reliable analytical models.

A substantial amount of research activities, both experimental and theoretical, has been invested on the in-plane response of

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URM walls. However, these studies have been mainly focused on the strength characteristics of the in-plane response of URM walls. Only recently (after a successful implementation of performance-based earthquake engineering concept for reinforced concrete and steel structures), are the displacement characteristics of the in-plane response of URM walls attracting the attention of researchers. Tomaževič and Weiss [4] performed a series of shaking table tests on 1:5 scale URM building models to assess the force-reduction factor for URM structures. Frumento et al. [5] also evaluated the q-factor for the seismic design of clay masonry buildings based on the results of 75 static-cyclic shear tests on clay masonry walls carried out in various European laboratories. Most recently, Petry and Beyer [6] performed a series of 6 static-cyclic shear tests on unreinforced clay masonry walls to investigate the effects of boundary conditions on the displacement capacity.

A large number of static, pseudo-dynamic, and dynamic shear tests with different test set-ups and testing programs can be found in the literature, e.g. Ganz and Thürlimann [7], Abrams and Shah [8], Tomaževič and Weiss [4], Tomaževič et al. [9], Magenes and Calvi [10], Costa et al. [11], Bosiljkov et al. [12] and Fehling et al. [13,14]. In general, mainly two types of failure modes have been reported: diagonal cracking (shear mode) and initial rocking followed by toe crushing (flexural mode). The displacement capacity of walls with shear failure was found to be limited, whereas walls with flexural failure exhibited much larger displacement capacity. The other significant feature of the displacement capacity of URM walls is the large scattering of results obtained from previous experiments.

Regarding theoretical research, although significant progress has been made in the field of modelling the in-plane response of URM walls (see e.g. Lourenço [15], Lourenço et al. [16], Magenes [17], Chen et al. [18], Yi et al. [19] and Penna et al. [20]), there are still no reliable and practical models for the force–displacement relationship of URM walls. Refined finite element models, besides being too complex for everyday engineering practice, suffer from numerical instabilities in the post-peak regime, and available structural macro-elements are still a long way from yielding sufficiently accurate results regarding the displacement capacity, especially in the case of the shear failure mode. A comprehensive review on the previous experimental and theoretical studies on the displacement capacity of URM walls can be found in [3].

Given the above, there is a need for a thorough investigation of the displacement capacity of URM walls. Obviously, to get a clearer picture of the problem, it is essential to carry out further experiments and to develop reliable analytical models to describe the force–displacement behaviour (or the displacement capacity) of URM walls. To meet the aforementioned need, the authors have initiated a research project. The ultimate objective of the research project, which should be seen as the first step of an initiative to investigate the limits of the displacement capacity of URM walls, is the development of the basis for the displacement-based design of URM structures. Prior to our own experimental programme, a thorough survey and assessment of existing experimental and theoretical research in the area of the displacement capacity of URM walls has been carried out [3]. The experimental work was divided into two phases, i.e. the preliminary and main phases, and consisted of 10 static-cyclic tests on full-scale URM walls. The primary goal was to capture the overall structural behaviour of the walls and to investigate the effects of various factors, i.e. unit type, vertical pre-compression level, aspect ratio, as well as size and boundary conditions, on the displacement capacity of URM walls. This paper presents and discusses the obtained test results, and closes with a set of conclusions and recommendations for future work. It should be emphasized once again that the design of new URM buildings is the main concern of the project. Hence, the project is focused on contemporary URM practice, which mainly consists of URM walls made of hollow blocks and reinforced concrete slabs.

2. Test programme and masonry materials

In order to investigate the displacement capacity of contemporary URM walls, 10 static-cyclic shear tests were performed. Firstly, four tests on relatively small (1.5×1.6 m) specimens (preliminary phase) were conducted to determine the most suitable type of units for the main tests, and to verify the test set-up and the measurement system. Subsequently, six tests were performed on full-scale, storey-high (2.6 m), clay masonry walls (main phase) in order to investigate the influences of the pre-compression level, aspect ratio and boundary conditions on the displacement capacity of URM walls. Table 1 gives an overview of the experimental programme, where l_w, h_w and t_w are the length, the height and the thickness of the specimens, σ_0 is the applied pre-compression stress, f_x is the mean compressive strength of the masonry (perpendicular to the bed joints), and V is the applied pre-compression force. Test T1 served as the reference test. Comparison of the other tests results with the results of the reference test enabled us to investigate the influences of the pre-compression level (tests T2 and T3), aspect ratio (tests T5 and T6) and boundary conditions (test T7) on the displacement capacity of URM walls. Since most Swiss contemporary masonry structures consist of clay masonry, and the observed behaviour of both clay and calcium-silicate walls tested in the preliminary phase was acceptable, it was decided to use clay masonry in the main phase. The test specimens were built by skilled masons in the laboratory on reinforced concrete beams. Due to the limited number of reinforced concrete beams, the walls had to be constructed in four stages. The walls were built in running bond and both the bed and head joints were about 10 mm thick and fully filled. All the walls were stored in the laboratory for at least 28 days before testing.

Typical Swiss perforated clay blocks with nominal dimensions of $290 \times 150 \times 190$ mm and a void ratio of 42% were used to build all the specimens of the main phase and specimens P1 and P2 of the preliminary phase (Fig. 1a). For the construction of specimens P3 and P4 of the preliminary phase, calcium-silicate blocks with nominal dimensions of $250 \times 145 \times 190$ mm and void ratio of 25% were used (Fig. 1b). The mean values of the compressive strength of the clay and calcium-silicate blocks, determined according to EN772-1 [21], were 26.3 and 22.2 MPa, respectively.

Dry ready-mixed general-purpose cement mortar was used for the construction of all the specimens. However, two different mortar manufacturers provided the mortar used for the construction of the preliminary and main walls. Mortar samples were taken during the construction of all the walls. The samples were stored in the laboratory together with the walls and tested according to EN 1015-11 [22] almost at the same time as the corresponding walls were tested. The mean values of the flexural and compressive strength of the mortar used in the preliminary phase were 4.1 and 14.1 MPa with coefficient of variation (COV) values of 2.4% and 3.8%, respectively. For the mortar used in the main phase, the mean values of the flexural and compressive strength were 2.8 (COV = 13.2%) and 10.5 MPa (COV = 13%).

In the preliminary phase, only masonry compressive strength perpendicular to the bed joints, f_x, was determined (according to EN 1052-1 [23]), but in the main phase, masonry compressive strength parallel to the bed joints, f_y, (according to SIA 266/1 [24]) and masonry shear bond strength (according to EN 1052-3 [25]) were determined as well. The test results are summarised in Table 2. The obtained mean values of f_x were used to determine the pre-compression stress for the tests.