EXPERIMENTAL STUDY OF THE DEFORMATION CAPACITY OF STRUCTURAL MASONRY

A. Salmanpour[1], N. Mojsilović[2] and J. Schwartz[3]
[1] PhD Student, ETH Zurich, Institute of Structural Engineering, CH-8093 Zurich, Switzerland, salmanpour@ibk.baug.ethz.ch
[2] Senior Scientist, ETH Zurich, Institute of Structural Engineering, CH-8093 Zurich, Switzerland, mojsilovic@ibk.baug.ethz.ch
[3] Professor, ETH Zurich, Institute of Technology in Architecture, CH-8093 Zurich, Switzerland, josephs@ethz.ch

ABSTRACT
A research project on the deformation capacity of unreinforced structural masonry is underway at the Institute of Structural Engineering of ETH Zurich. The development of the basic building blocks for the displacement-based design of masonry structures is the objective of the present research project, which should be seen as a first step in an investigation of the limits of the deformation capacity of structural masonry. After a thorough survey and assessment of existing experimental and analytical research in the area of the deformation capacity of structural masonry, we started our own experimental program. It has been planned in two phases, i.e. preliminary and main phases, and consists of a total of 11 cyclic quasi-static tests on full-scale unreinforced masonry walls made of clay and calcium-silicate blocks to investigate the effects of the various factors, i.e. unit type, vertical pre-compression level, aspect ratio, size effect and boundary conditions on the deformation capacity of structural masonry. This paper presents and discusses the first results obtained from the preliminary phase of the abovementioned experimental program.

KEYWORDS: deformation capacity, experimental study, cyclic-static test, structural masonry, URM

INTRODUCTION
The deformation capacity is a key parameter in the seismic design and evaluation of structures. Unfortunately, our current state of knowledge of the deformation capacity of structural masonry is limited. The available experimental data has pronounced randomness, and it is not possible to identify a rational value for the deformation capacity of masonry structures based only on such experimental data. Furthermore, there are no reliable analytical models for the force-deformation relationship of structural masonry. It should be noted that the values recommended in the literature for the deformation capacity of masonry structures are based primarily on the statistical analysis of the results of past experiments. These values are not always readily applicable because, as mentioned before, the data obtained from tests exhibits a rather large scatter.

In general, the deformation capacity of masonry structures is a very complex parameter; it is influenced not only by the failure mechanism but also by many other factors such as the constituent materials, geometry, pre-compression level, etc. Currently, we are still not able to properly take into account the influence of all factors affecting the deformation capacity of structural masonry due to inhomogeneous experimental data and a lack of reliable mechanical models. Given the above, there is a need for a thorough investigation of the deformation capacity of structural masonry. Obviously, to get a clearer picture on the problem, it is essential to carry out further experiments and also to develop reliable mechanical models to describe the load-deformation behaviour of structural masonry.

To meet the aforementioned need, a research project on the deformation capacity of unreinforced masonry structures has been initiated at the Institute of Structural Engineering of ETH Zurich. The objective of the present research project, which should be seen as the first step of an initiative to investigate the limits of the deformation capacity of structural masonry, is the development of the basic building blocks for the displacement-based design of masonry structures. Before our own experimental program was begun a thorough survey and assessment of existing experimental and analytical research in the area of the deformation capacity of structural masonry [1, 2] was carried out. The experimental work is divided into in two phases, i.e. the preliminary and main phases, and consists of a total of 11 cyclic quasi-static tests on full-scale unreinforced masonry walls to investigate the effects of the various factors, i.e. unit type, vertical pre-compression level, aspect ratio, size effect and boundary conditions on the deformation capacity of structural masonry. A novel approach will be developed and utilized for the purpose of applying experimental evidence collected from our own tests for the development of reliable mechanical models for structural masonry. This paper presents and discusses the results obtained from the first phase of the abovementioned experimental program.

TEST PROGRAM AND MASONRY MATERIALS

In order to investigate the deformation capacity of structural masonry, a total of 11 cyclic quasi-static tests were planned to be performed in two phases. Table 1 summarizes the details of the planned tests, where l_w, h_w and t_w are the length, the height and the thickness of the specimens, σ_0 is the pre-compression stress, and f_x is the mean compressive strength of the masonry (perpendicular to the bed joints). The first phase (preliminary phase) of the experimental program, i.e. tests P1 to P4, has been completed, and its results have been presented and discussed in this paper. The second phase (main phase) of the experiments has been scheduled for the first quarter of 2013.

Table 1: Test Program

Phase	Test	Units	Specimen Dimensions l_wxh_wxt_w [mm]	Boundary Conditions	σ_0/f_x
Preliminary	P1	Clay	1500x1600x150	Fixed Ends	0.10
Preliminary	P2	Clay	1500x1600x150	Fixed Ends	0.15
Preliminary	P3	Calcium-Silicate	1550x1600x150	Fixed Ends	0.10
Preliminary	P4	Calcium-Silicate	1550x1600x150	Fixed Ends	0.15
Main	T1	Clay	2700x2600x150	Fixed Ends	0.10
Main	T2	Clay	2700x2600x150	Fixed Ends	0.05
Main	T3	Clay	2700x2600x150	Fixed Ends	0.15
Main	T4	Clay	900x2600x150	Fixed Ends	0.10
Main	T5	Clay	1800x2600x150	Fixed Ends	0.10
Main	T6	Clay	3600x2600x150	Fixed Ends	0.10
Main	T7	Clay	2700x2600x150	Cantilever	0.10

Since the possible lack of robustness of the hollow clay bricks indicated by previous tests could influence the development of a mechanical model, it was decided to examine the behaviour of specimens made of two different types of masonry unit, hollow clay and calcium-silicate, in the preliminary tests, and to determine the type of masonry unit for the main tests by analysing the tests results. The other objectives of the preliminary tests were to verify the applied vertical pre-compression level, the test set-up and the measurement system. It is also intended to investigate the size effect by comparing the preliminary and main tests results.

As shown in Table 1, in the preliminary phase a total of 4 relatively small (1.5×1.6 m) masonry walls (2 clay and 2 calcium-silicate walls) were tested under two different pre-compression levels, i.e. 10 and 15 percentage of the mean compressive strength of the specimen. For the construction of the clay masonry walls typical Swiss extruded clay bricks with nominal dimensions of 290×150×190 mm were used. The calcium-silicate units had nominal dimensions of 250×145×190 mm. Figure 1 shows the units used for the construction of the specimens. A cement mortar of M15 class (according to the European standard EN 998-2 [3]) was used for the construction of all the specimens and had a mean compressive strength of 14.1 MPa. All walls were made with general purpose mortar, i.e. about 10 mm thick, in bed and head joints.

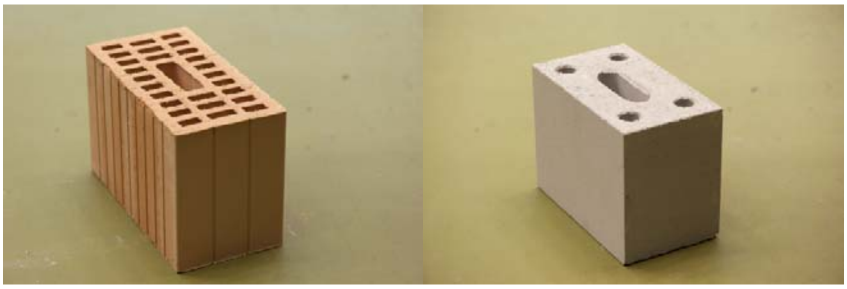


Figure 1: Clay and Calcium-silicate Units Used for the Production of Specimens

For each type of unit, the mean compressive strength of the masonry, f_x, was determined by three compression tests according to the European standard EN 1052-1 [4]. The mean compressive strength (based on the whole section area) obtained for the clay and calcium-silicate masonry was 6.4 MPa and 7.7 MPa, respectively.

In the main phase of the experimental program, 7 tests will be performed on large, storey-high, full-scale walls. Test T1 is intended to serve as the reference test. Comparison of the other tests results with the results of the reference test enables us to investigate the influence of the pre-compression level (tests T2 and T3), aspect ratio (tests T4, T5 and T6) and boundary conditions (test T7) on the deformation capacity of structural masonry. Since most Swiss masonry structures consist of clay masonry, and the observed behaviour of the 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 same units and mortar as used in the preliminary tests will be used in the construction of the main walls.

TEST SET-UP, MEASUREMENT SYSTEM AND TESTING PROCEDURE

Figure 2: Test Set-up

Figure 2 shows a picture of the test set-up. The specimens are built on 350 mm thick reinforced concrete foundations which can be clamped to the strong floor by means of post-tensioned steel bars. The horizontal servo-hydraulic actuator reacting on the strong wall of the laboratory applies a shear force to the top of the walls through a stiff steel beam (loading beam). The loading beam is connected to the walls by a layer of mortar. The vertical load is applied by means of two servo-hydraulic actuators reacting on the reaction frame. To prevent any out-of-plane movement of the loading beam, an auxiliary sliding system is used to guide the web of the loading beam during the tests.

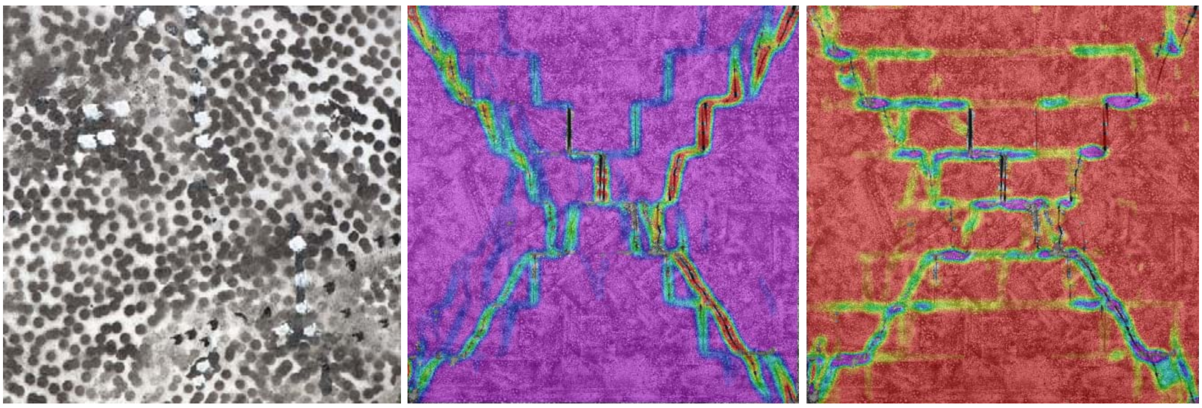


Figure 3: Applied Pattern (left), Major (middle) and Minor (right) Principal Strain Fields in Wall P4

Measurements included all applied forces together with an overall and a local picture of the deformation state of the specimens. In order to achieve this, in addition to the traditional hard-wired instruments, i.e. LVDTs, a 2D Digital Image Correlation (DIC) measurement system was used. DIC is a non-contact, optical measurement technique that provides full-field displacements and strains by comparing the digital images of the test object's surface obtained before and after deformation. The surface of the test object is usually painted with a random pattern. For example, Figure 3 shows the major and minor principal strain fields in specimen P4 just before the collapse of the specimen as well as the details of the applied pattern on an area of 150×150 mm of the wall surface.

The test walls are first subjected to a specific level of pre-compression, which simulates the weight of the upper floors supported by the shear wall under investigation. It is also very important to apply the appropriate level of pre-compression in order to avoid premature (shear) failure of hollow clay block units, due to possible lack of robustness. Secondly, horizontal cyclic quasi-static shear load is applied using computer-controlled displacement steps. Each of the steps is repeated three times in the form of a sinusoidal wave. The loading speed is determined by the corresponding horizontal displacement, i.e. for small displacements the loading speed is slower whereas for larger displacements it is faster. Table 2 shows the loading history used for the preliminary phase tests.

Table 2: Loading History

Story Drift [%]	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.6	0.8	1
Target Displacement [mm]	0.8	1.6	2.4	3.2	4	4.8	5.6	6.4	7.2	8	9.6	12.8	16
Period [sec]	250	250	250	250	250	250	250	275	300	350	400	550	675

As shown in Table 1, the test program envisaged two different boundary conditions: cantilever and fixed ends. In case of cantilever boundary condition, the forces of the vertical actuators are kept constant during the test and hence they are not dependent on the horizontal actuator force and displacement. The fixed ends boundary condition is obtained by a mixed force-displacement control of the vertical actuators which imposes a constant vertical load and maintains the horizontally of the loading beam. The tests are stopped in case of critical damage conditions.

TEST RESULTS

Clay brick wall P1 was tested at the pre-compression level of 10% of the mean masonry compressive strength. Test P1 was characterized by diagonal cracks developed in the units and the bed joints. The wall finally collapsed because of toe-crushing and also of separation of a large part of the wall while applying the third cycle of 6.4 mm displacement. Spalling of the units at the centre of the wall also occurred. The maximum attained horizontal force was 92 kN. Figure 4 presents the hysteretic force-displacement response of the wall with a picture of the wall at the end of the test.

Wall P2 had the same constitutive materials and geometry as wall P1, but was tested at a higher level of pre-compression (15% of the mean masonry compressive strength). Figure 5 shows the hysteretic force-displacement response of the wall. Test P2 was characterized by shear cracks passed through the units and the bed joints followed by shear-compression failure of the toes.

The behaviour of wall P2 was quite similar to that of wall P1, but the shear cracks did not follow the corner-to-corner X-shaped paths, see Figure 5. The maximum attained horizontal force was 107 kN, and the wall failed when applying the second cycle with target displacement of 4.8 mm.

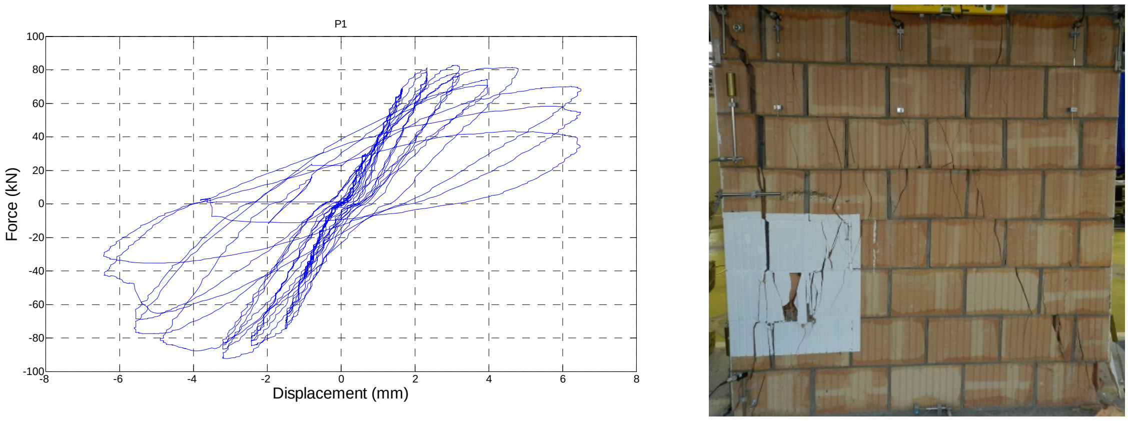


Figure 4: Hysteretic Response of Wall P1

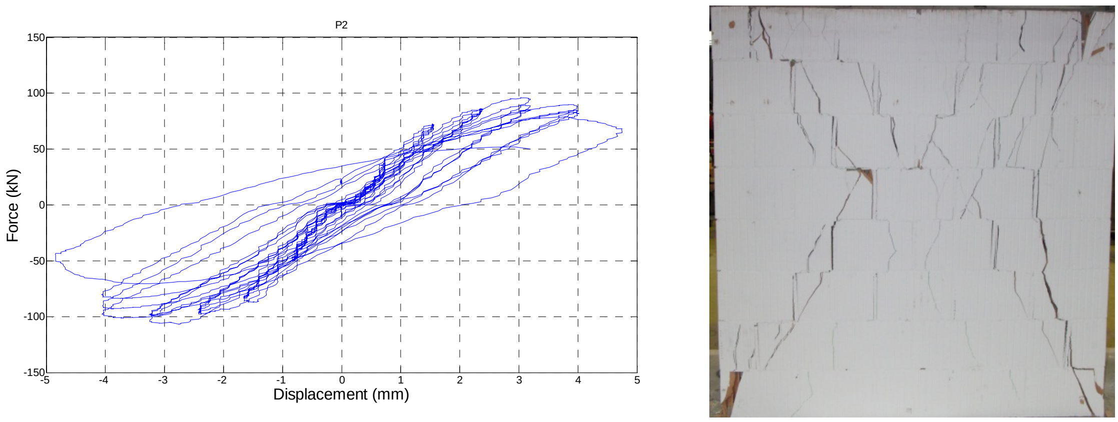


Figure 5: Hysteretic Response of Wall P2

Walls P3 and P4 were made of calcium-silicate units, and tested under the pre-compression levels of 10% and 15% of the mean masonry compressive strength, respectively. Figures 6 and 7 show the hysteretic force-displacement response of these walls. Tests P3 and P4 were characterized by early sliding along diagonal stepwise cracks that passed through the bed and head joints. Secondly, the effective area of the walls was reduced by the formation and development of shear cracks in the units. Finally, the specimens failed due to compression failure at the centre of the walls as well as at the corners, see Figures 6 and 7. The maximum attained horizontal force for tests P3 and P4 was 133 kN and 156 kN, respectively. Wall P3 failed after three cycles of 6.4 mm displacement and when applying the first cycle with a target displacement of 9.6 mm. It should be noted that the applied load steps were slightly different in test P3 (0.8, 1.6, 2.4, 3.2, 4.8, 6.4 and 9.6 mm). Wall P4 failed when applying the first cycle of 6.4 mm displacement.

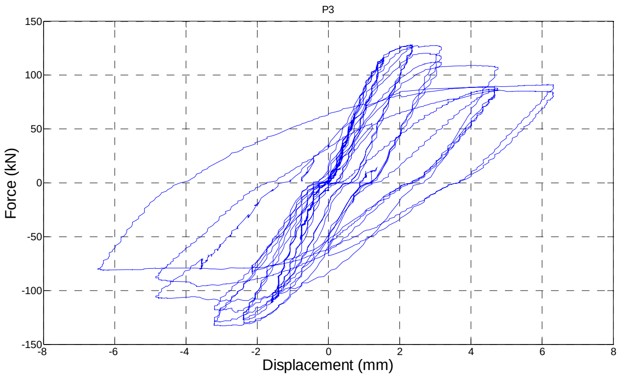
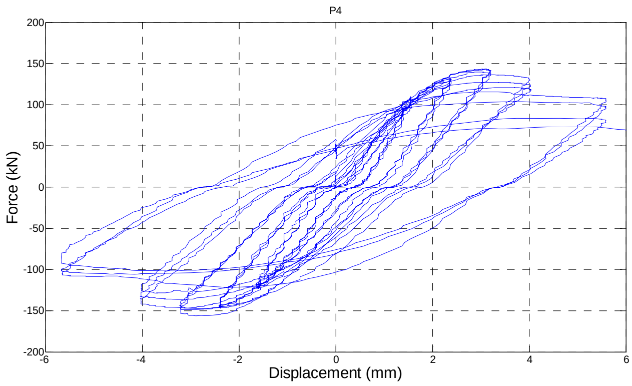


Figure 6: Hysteretic Response of Wall P3



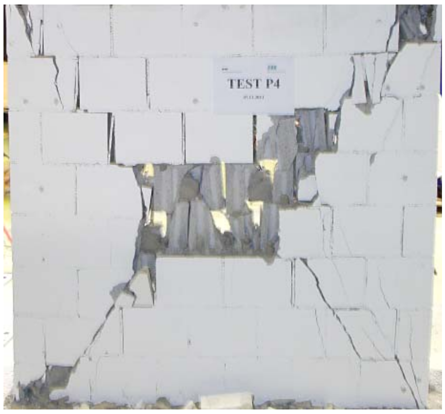


Figure 7: Hysteretic Response of Wall P4

Table 3 presents a summary of the test results, where V_0 is the applied pre-compression load, F_{max} is the maximum attained horizontal force and d_{max} and δ_{max} are the maximum attained deformation and drift, i.e. deformation divided by the height of the specimen. Furthermore, d_u and δ_u represent the ultimate deformation and drift capacity of the specimens. The ultimate deformation capacity values have been taken as the deformation corresponding to a strength degradation of 20%. This criterion has been widely used for the definition of the ultimate deformation capacity by majority of researchers and been adopted by most of the current structural codes.

Table 3: Summary of the Test Results

Test	Units	V_0 [kN]	F_{max} [kN]	d_{max} [mm]	δ_{max} [%]	d_u [mm]	δ_u [%]	Failure Mode
P1	Clay	144	92	6.4	0.4	6	0.375	Shear
P2	Clay	216	107	4.8	0.3	4	0.250	Shear
P3	Calcium-Silicate	179	133	6.4	0.4	5.2	0.325	Shear
P4	Calcium-Silicate	268	156	5.6	0.35	5	0.313	Shear

DISCUSSION

It can be seen from Table 3, that the 20% strength degradation criterion, which is traditionally used for the definition of the ultimate deformation capacity, underestimates the deformation capacity of the specimens, especially in the case of specimens P3 and P4. As an example, wall P3 reached the 20% strength degradation limit at a displacement of 5.2 mm, but it was able to sustain the applied vertical load even after the next 3 cycles of 6.4 mm displacement (wall P3 failed when applying the first cycle of 9.6 mm displacement). In order to take advantage of the complete capacity of masonry structures, it would be necessary to develop more consistent criteria for the ultimate deformation capacity.

The average maximum drift capacity for the clay and calcium-silicate walls was 0.35% and 0.38%, respectively, whereas the ultimate drift capacity provided by Annex 3 of EN 1998-3 for unreinforced masonry walls with the shear failure mode is 0.53% [5]. This shows that the values prescribed by Eurocode could result in an unsafe design.

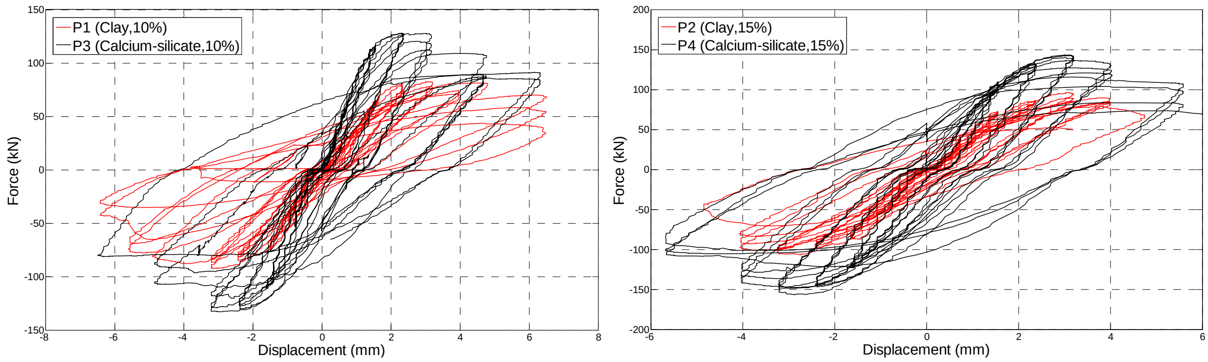


Figure 8: Comparison of Hysteretic Behaviour of the Clay and Calcium-silicate Walls

Figure 8 shows a comparison between the hysteretic response of the clay and calcium-silicate walls. It is clear that the calcium-silicate walls (P3 and P4) exhibit a higher deformation and energy dissipation capacity compared to the clay walls (P1 and P2). It can mainly be related to the formation of the sliding mode along stepped diagonal cracks in the calcium-silicate walls.

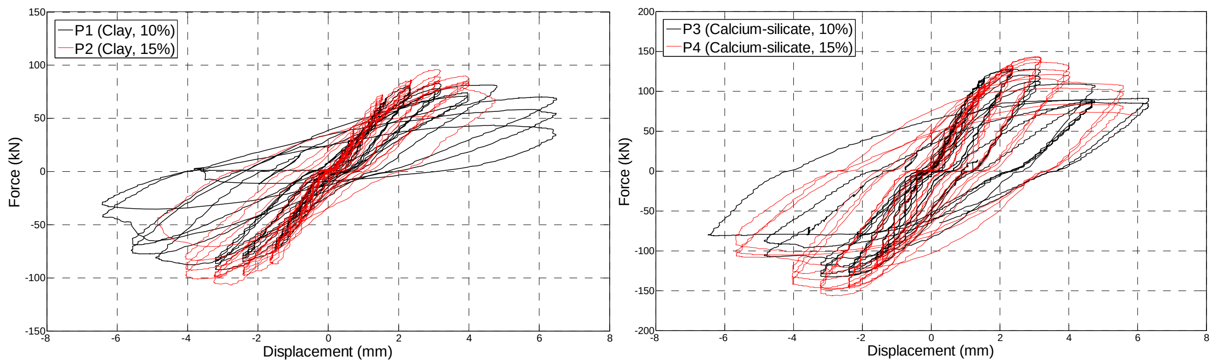


Figure 9: Effects of Pre-compression Level on the Hysteretic Behaviour of the Walls

It is also clear from the test results that the deformation capacity of the walls decreased as the pre-compression force increased, see Figure 9. This is because increasing the pre-compression force accelerates the formation of the mechanisms that correspond to the collapse of the specimens, i.e. shear-compression failure at the toes and centre of the specimen.

CONCLUSIONS

The results of the first phase of an experimental program on the deformation capacity of unreinforced masonry structures have been presented and discussed. A total of four tests were carried out on the walls made of clay and calcium-silicate units with general purpose mortar in the bed and head joints. The specimens were tested with fixed-end boundary conditions at two different levels of pre-compression, i.e. 10% and 15% of the mean masonry compressive strength.

Due to the formation of a sliding mode in the calcium-silicate walls, they were able to exhibit a higher deformation and energy dissipation capacity compared to the clay walls. However, in both cases, the obtained values of the ultimate drift capacity were somewhat below the value given by Annex 3 of EN 1998-3 for the ultimate drift capacity of unreinforced masonry walls failing in shear. Furthermore, as expected the deformation capacity of the walls decreased as the vertical pre-compression load increased. The need to define a more consistent criterion for the ultimate deformation capacity was also discussed.

In the second phase of the experimental program, seven tests will be performed on large, storey-high, full-scale walls made of clay units to investigate the influence of the pre-compression level, aspect ratio, boundary conditions and size effect on the deformation capacity of unreinforced structural masonry. Further attention will also be given to the analysis of the results of the DIC measurement system in order to develop reliable mechanical models for structural masonry.

ACKNOWLEDGEMENTS

Funding from the Swiss National Science Foundation (Grant 200021_131971) is gratefully acknowledged.

REFERENCES

1. Salmanpour, A., Mojsilović, N. and Schwartz, J. (2012) “Deformation Capacity of Structural Masonry: A Review of Experimental Research” 15th International Brick/Block Masonry Conference, Florianopolis, Brazil, Paper No. 4C2.
2. Salmanpour, A., Mojsilović, N. and Schwartz, J. (2012) “Deformation Capacity of Structural Masonry: A Review of Theoretical Research” 15th World Conference on Earthquake Engineering, Lisbon, Portugal, Paper No. WCEE2012-2145.
3. CEN-EN 998-2 (2003) “Specifications for mortar for masonry, Part 2: Masonry mortar”.
4. CEN-EN 1052-1 (1998) “Methods of test for masonry, Part 1: Determination of compressive strength”.
5. CEN-EN 1998-3 (2005) “Eurocode 8: Design of structures for earthquake resistance, Part 3: Strengthening and repair of buildings”.