Focussed on Modelling in Mechanics

Numerical simulations of tests masonry walls from ceramic block using a detailed finite element model

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ABSTRACT. This article deals with an analysis of the behaviour of brick ceramic walls. The behaviour of the walls was analysed experimentally in order to obtain their bearing capacity under static loading and their seismic resistance. Simultaneously, numerical simulations of the experiments were carried out in order to obtain additional information on the behaviour of masonry walls made of ceramic blocks. The results of the geometrically and materially nonlinear computations were compared to the results of the performed tests.

KEYWORDS. Ceramic blocks; Mathematical model of a wall; Finite Element Method; Nonlinear computations.

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INTRODUCTION

Before its introduction to the market, masonry made from innovative clay hollow blocks filled with mineral wool, had to be tested for functionality and reaching the conformity with calculation models according to the Eurocode 6 [1] and/or Eurocode 8 [2], in more complex cases of load, before it was launched on the market. During the years 2011 – 2014, an extensive project [3-6] devoted to the assessment of the product static characteristics as well as the behaviour of the walls lined from these blocks was realized on Technical and Test Institute for Construction Prague, Czech Republic (TZÚS Praha). The basic as well as the extended tests were realized, including the evaluation of its results,

in TZÚS brunch office in Brno. The clay block masonry walls were tested for a load capacity under the short-term and long-term static load on small masonry walls [3, 4], possibly on walls and pillars of an actual size [5, 6].
Seismic resistance testing was carried out according to the instructions of Klouda, J. K. and with his attendance in a testing department of the National Building and Civil Engineering Institute (ZAG) Ljubljana, Slovenia. Shear tests for the cyclic loading of four (2+2) constantly vertically preloaded walls were conducted. The walls were 2750 mm high and 440 mm thick. They differed in the length. Two of the walls were 2500 mm long and the other two 1500 mm, the wall width and height ratio was then ca. 1 : 1 and 1 : 2. The vertical preload was designed at two levels, at a nominal amount of approximately 1/3 or 2/3 of the value of the wall vertical design load capacity. At the same time, numerical simulations of the experiments for obtaining additional information on the clay block masonry wall behaviour were carried out – the same as by eccentric loaded pillars [7]. The mathematical analyses were carried out using the finite element method on the detailed wall models. Block material properties (modulus of elasticity, tensile strength, compression strength, tensile strength in bending, etc.) were determined experimentally before performing the calculations. The models were considered as geometrically and materially nonlinear, including unilateral bonds. The calculation results are further compared with the results of the conducted tests.

THE CLAY BLOCK MASONRY WALLS UNDER THE STATIC LOAD

The load-bearing capacity of brick walls fabricated from ceramic blocks (Fig. 1) under static loading was first tested on small specimens consisting of three rows in the single block format, then on medium-height pillars consisting of seven rows of blocks and finally on high wall pillars consisting of eleven rows of blocks. The test specimens were loaded centrically and eccentrically.

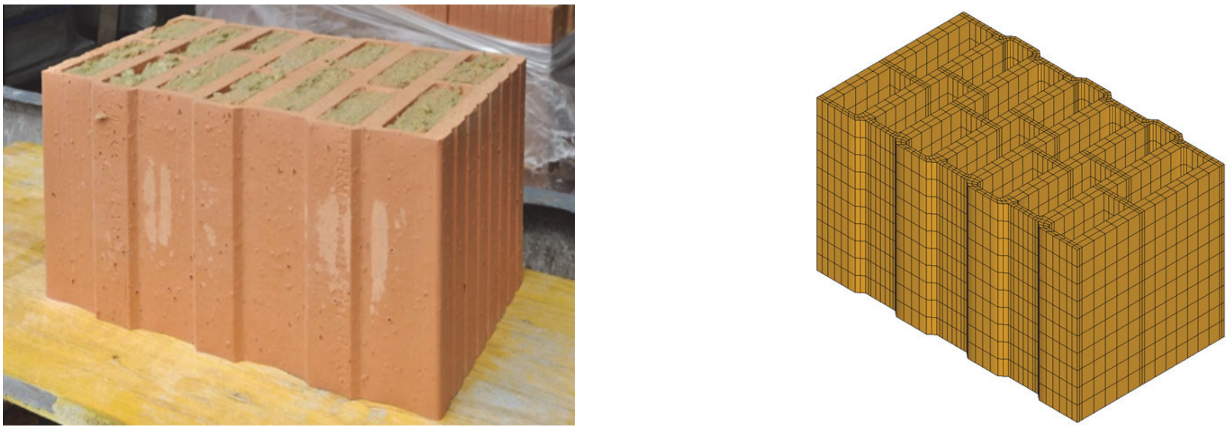
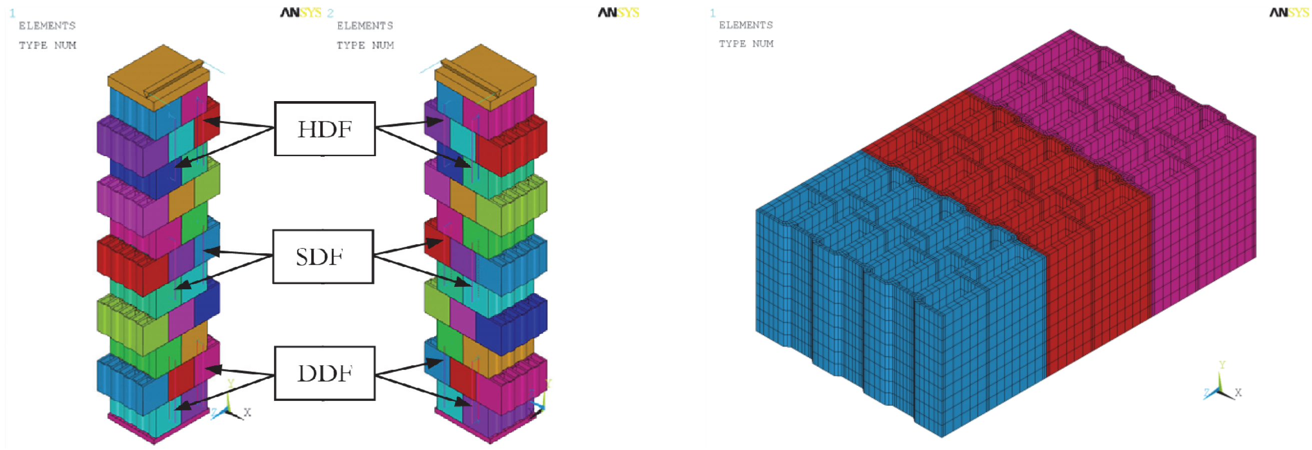


Figure 1: Masonry block used in experimental walls and FEM model of masonry block.

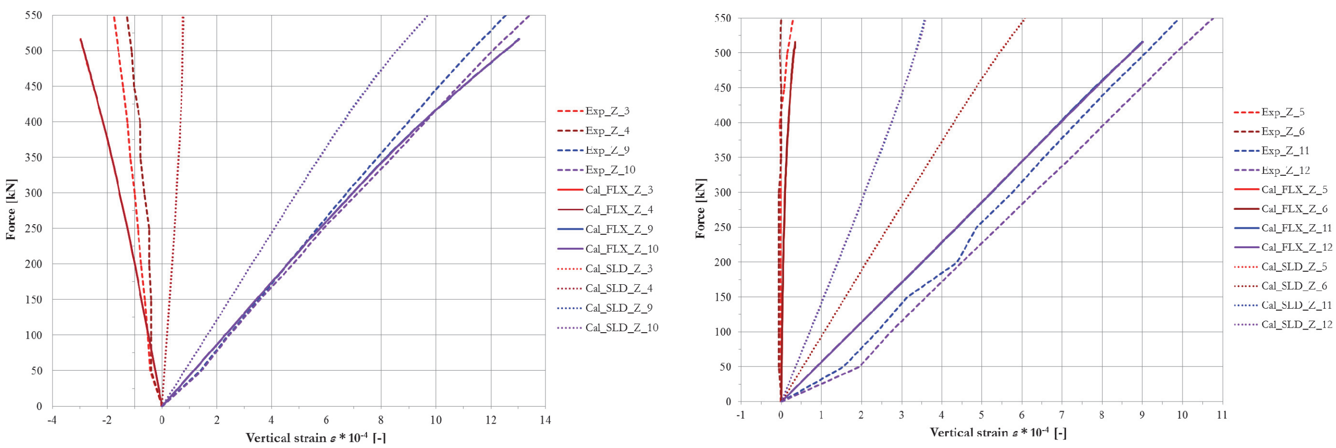
Details regarding the executed tests are shown in [5] and [6]. Detailed models were created using the Finite Element Method for use in the numerical simulation of static tests. The brick blocks were modelled along with the mortar in the bed joints, the steel plates under and above the pillars, and the steel apparatus for imposing load. Planar elements under the bottom plate simulate the possible flexibility of the placement of the steel plate. Contact pairs (elements) for the modelling of interaction between the blocks, mortar and steel plates are inserted between the blocks and the areas adjacent to them. These contact elements transfer only compressive and shear forces. Please see Fig. 2 a) for an example computational model of a wall pillar. Fig. 1 and 2 b) illustrates the division of a block into volumetric finite elements. The loading carried out in accordance with the test was considered to be forced displacement load. Details about the calculations can be found in [7]. Fig. 3 shows the dependence of relative transformation in the vertical direction on load. The dashed lines show the measured results and the full (FLX – flexible support) and dotted (SLD – solid support) curves show the results of the calculations. Calculated values of deformation are identical in various levels. It is apparent that the support of the wall needs to be modelled carefully as the seemingly stiffness of support the test specimen can influence the results of the measurements significantly.



a) Model of a pillar, including deformeters

b) Three neighbouring blocks

Figure 2: Computational model of a high brick pillar.



a) Top area – values from the deformeter.

b) Bottom area – values from the deformeter.

Figure 3: A sample of C 1-1 Specimen – load-dependent vertical strain ε.

ANALYSIS OF BEHAVIOR OF CYCLIC LOADED CLAY BLOCK WALLS

Tests of the structure of the masonry walls built from precise burnt masonry elements of the clay blocks POROTHERM 44 T Profi loaded by a cyclically forced loading correspond to the shear tests of walls of the actual size. Four walls of the different width were tested. The walls of the greater length are marked "L" and the shorter walls are marked "S", (Fig. 4).

The vertical walls were built on a rigid reinforced-concrete beam that was attached firmly to the floor so that the shear displacement along the floor and beam tilting were eliminated. The transmission of the vertical forces was carried out by steel sections and four independent hydraulic cylinders and one program-controlled hydraulic cylinder bringing in the lateral displacement (along the wall) cyclically corresponding to the seismic loading. The controlled lateral displacement was introduced to the beam by the predominating masonry wall. The individual blocks were lined on thin joint mortar of 1 mm thickness. The mortar is only in horizontal joints, vertical indented joints are dry.

Idealized and real lateral displacement time history is shown on the Fig. 5. During the experiment, the vertical and horizontal forces and the displacements at predetermined points were measured (Fig. 6). An optical camera measurement system was used to determine the motion of the wall surfaces. The lateral force (resistance) dependencies on the lateral displacement were the result of the measurement. The measurements provided data regarding dependencies of vertical force (resistance) on transverse displacement. The results of the experiments are arranged in a tabular form.

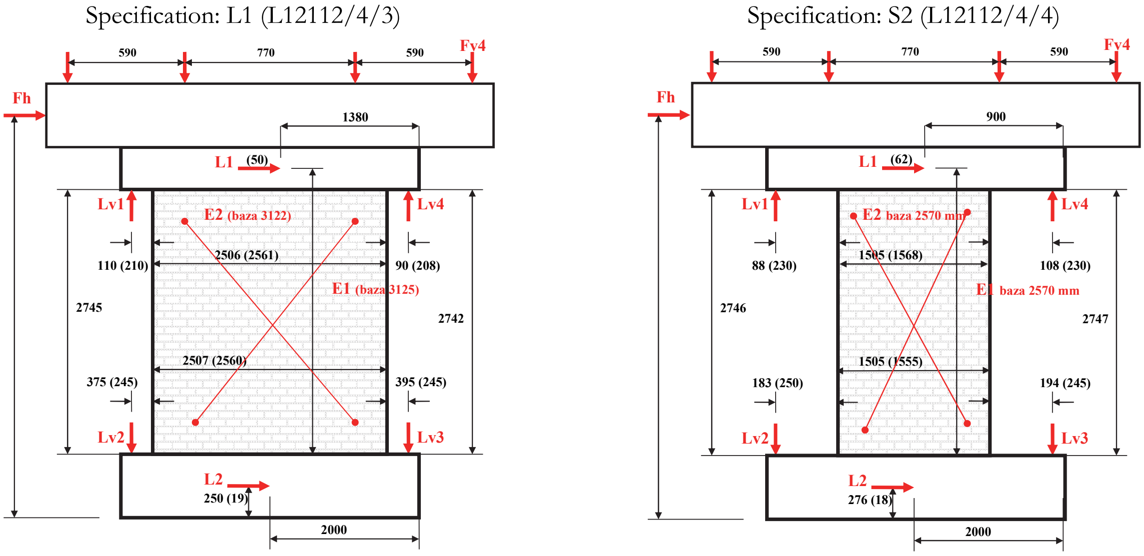


Figure 4: Diagrams of walls "L" and "S".

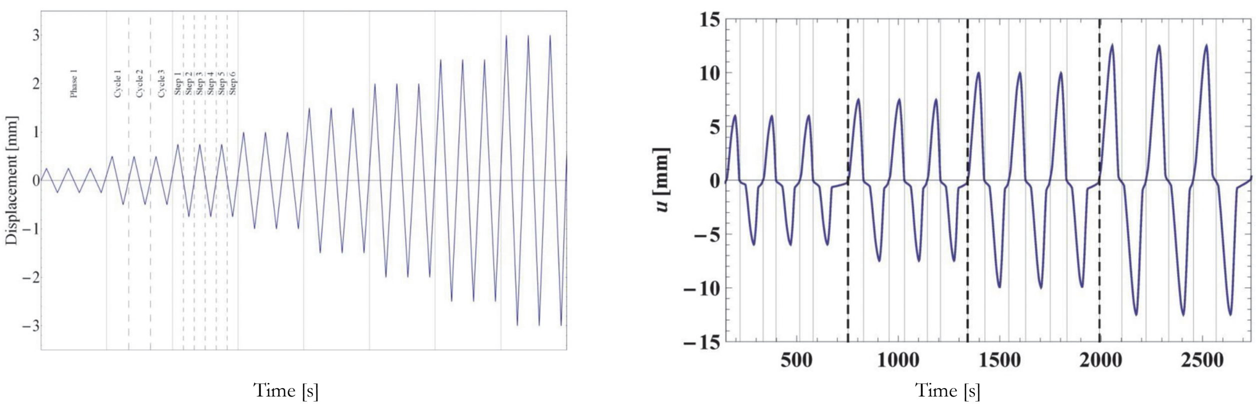


Figure 5: Idealized and real imposed lateral displacement time history.

Wall models

In accordance with the data, numerical models of the walls were created using the finite element method (FEM). Only the fundamental difference in the geometry, that is the difference in the length of the walls, was taken into consideration while modelling by the FEM model. On the basis of this consideration, two computational models were only created: One for the analysis of the long "L" walls and the second one to analyze the short "S" walls. The calculations also differ by vertical preload and excitation functions. The vertical preload values (including the girder and the concrete block) are considered for each model as follows:

L1 - 1/3 f_{cd} - vertical preload 807 kN,
L2 - 2/3 f_{cd} - vertical preload 1613 kN,
S1 - 1/3 f_{cd} - vertical preload 484 kN,
S2 - 2/3 f_{cd} - vertical preload 968 kN.

On the basis of the data, see the diagrams in Fig. 4, models of long "L" on the left and short "S" walls on the right side including underlay and delivering elements over the walls were created in the ANSYS software.

Considering the symmetry of realized complementary structures and walls to the vertical plane in the longitudinal direction and the manner of loading, the computational models were created using this symmetry (the *x*-*z* plane). The graphic representation is including the mirrored part of the model.

The computational models are mainly created from the 3-D finite elements of the SOLID45 type, see (fig. 7). They are the blocks, the mortar, the concrete base beam, the concrete beam and the main steel girders and two additional beams directly under the pressure cylinders at the "S" type walls (Fig. 8). The concrete base beam of the dimensions

3980x500x500 of the "L" model, or 2074x500x500 the "S" model, is considered as elastically placed in the calculations, because the floor showed to be yielding. Relatively rigid beam placing is modelled by the COMBIN14 and SHELL181 elements. The clay blocks are bound by the mortar at the horizontal direction and they are without filling in the vertical joints.

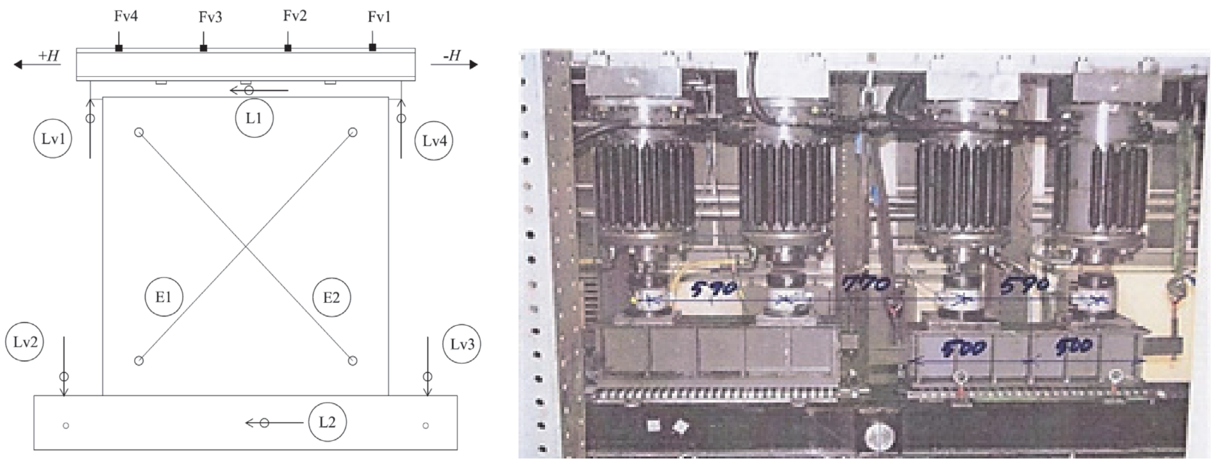
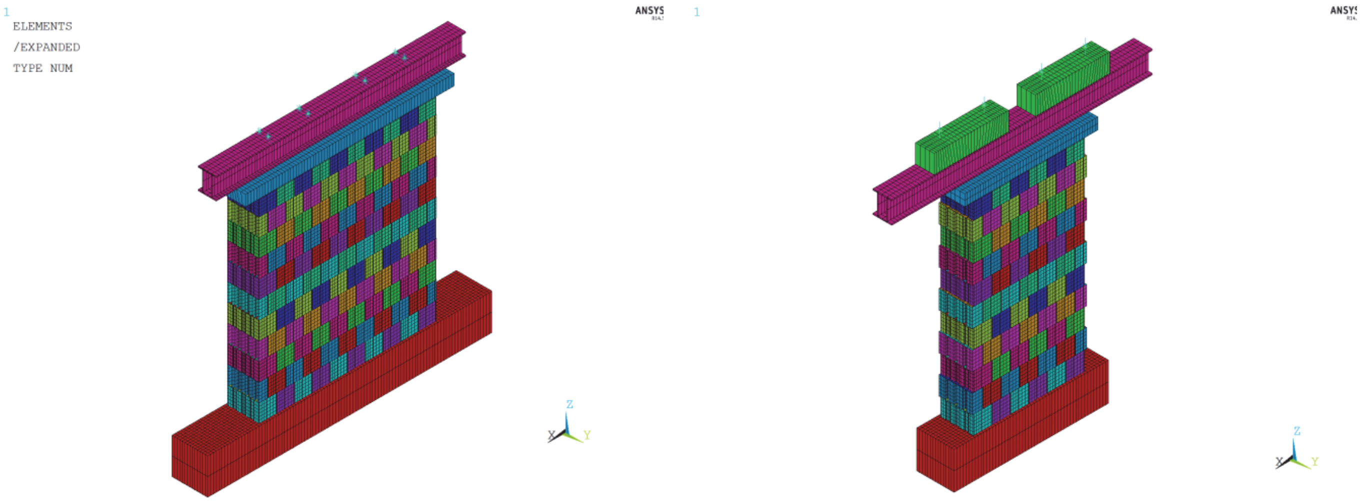


Figure 6: Scheme of locations of indicators – walls L and arrangement of device for vertical loading.



a) "L" type model

b) "S" type model

Figure 7: Axonometric view on models – finite elements mesh.

The interaction between the blocks, possibly the mortar is modelled using contact pairs – the elements of CONTA173 and TARG170 type (Fig. 8). Similarly, these elements are put between the mortar and the concrete beams. The wall height including the mortar is 2,749 mm. The upper concrete beam is 2,928 mm long (1,789 mm "S" type), 150 mm high and 500 mm wide. The steel girder is bound with the concrete beam firmly. The external contour of the girder that is 3,500 mm long is 300x250 mm.

Down pressure (the constant vertical load) is brought into the structure using special PRETS179 elements in connection with BEAM44 elements that allow a horizontal slip at the leaning point on the girder and a delivering area of SHELL63 elements. The setting depends on the compressive force and rigidity in the vertical direction. Thus, the down pressure is implemented at four locations at the "L" type walls (Fig. 6). This method of the pressure forces setting did not prove successful with the short wall models. The upper girder tended to tilt during the movement because of the eccentric action of the vertical forces. The models were supplemented with two sliding beams on the main load distribution beam. Thanks to this, the girder guiding at the forced horizontal displacement was ensured. These beams of the length of 1,000 mm, the height and the width of 250 mm are modelled in a simplified manner. The compressive force is applied by the special PRETS179 elements in the connection with the LINK8 elements and again at four points. The modified model reflects the real behaviour of the compressive device in a better way. The real version of the compressive device is in the Fig. 6.

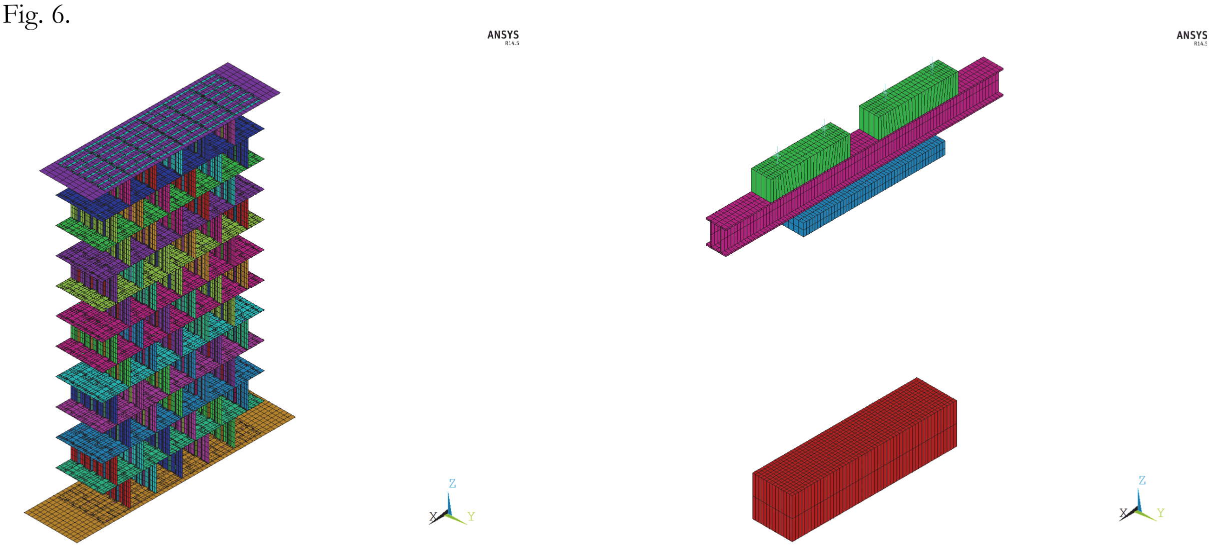


Figure 8: Contact finite elements (on left) and the beams and the concrete blocks (on right) of "S" type model.

Brick body and mortar properties are derived from the measurement [3]. The material model of the steel girders and concrete beams is considered as isotropic and linearly elastic. On the contrary, the material model of the brick body and mortar is considered as nonlinear with different tensile and compression strength. A summary of the properties of the individual parts of the model have been used in calculations as it is mentioned in Tab. 1.

		Brick body	Mortar	Concrete	Steel
Modulus of Elasticity	E [GPa]	14.0	7.9	30	210.0
Lateral Contraction Coefficient	ν [-]	0.1	0.2	0.2	0.3
Specific Weight	ϱ [kg.m^{-3}]	1390	1400	2300	7850
Compression Strength	f_c [MPa]	19.2	17.3	-	-
Tensile Strength	f_t [MPa]	3.7	4.6	-	-

Table 1: Material properties.

The total computational model for alternative solutions with the "L" type wall consists of 113,337 finite elements localized by 134,550 nodes and has 399,477 degrees of freedom.

The total computational model for alternative solutions with the "S" type wall consists of 68,799 finite elements localized by 83,177 nodes and has 246,013 degrees of freedom.

The imposed functions are modified functions taken from response at the experiments. The major adjustment consists of the correction of the excitation point location. The response functions are monitored at the height of 2,824 mm ("L" type) above the wall bed joint, while the excitation point by the forced motion of the girder is at the different place, at higher level from the centre of the bottom of the wall during the experiment. The displacement correction corresponds to approximately 5 to 6 percent. That means that the imposed lateral displacement function used as the excitation were increased by 6 percent.

Calculation

Four calculations were carried out on models L1, L2, S1 and S2. The calculations are nonlinear, time-consuming and required large disc space. The solution is considered as quasi-static due to the slow loading process. The time step is considered as variable with the largest step of 15 s. In each time step an iterative state of equilibrium is searched. In case that the time step cannot be already decreased and the calculation does not converge, the calculation process is terminated.

The displacement, strain and stress fields at the discrete points of the models were obtained by the calculations on the L1, L2, S1 and S2 models. Considering the scope of the data, the results were mainly processed in a form of graphs and figures.

L1 Wall

The cyclic response solution on the L1 model with the preload 807 kN (including the girder and the concrete block) was compared with the values obtained from the test.

Excitation function of time history lateral displacement is shown on the Fig. 9.

The responses of the lateral displacement on the surface in the centre of the concrete beam obtained from the measurement and by the calculation are presented in Fig. 9. The lateral displacement obtained from the measurement is represented by a red dashed line and the lateral displacement of the same variable obtained by the calculation is shown by a blue line. In Fig. 10, there is a representation of the reaction force dependence on the lateral displacement for the both cases of the experiment and the calculation.

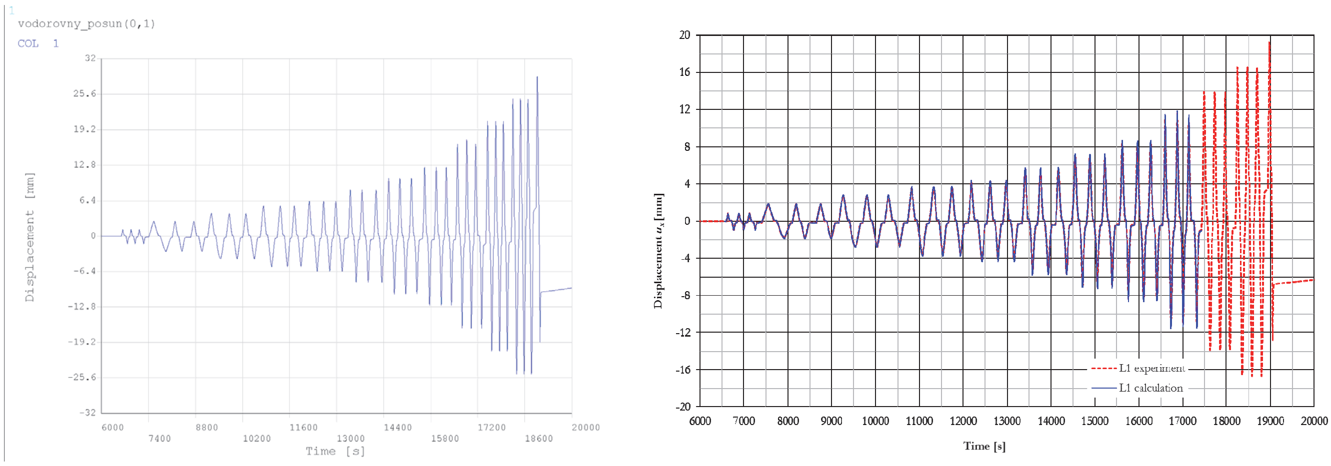


Figure 9: Imposed function – lateral displacement u_x (on left side) and lateral displacement u_x from measurement and calculation at central point of the beam (on right side).

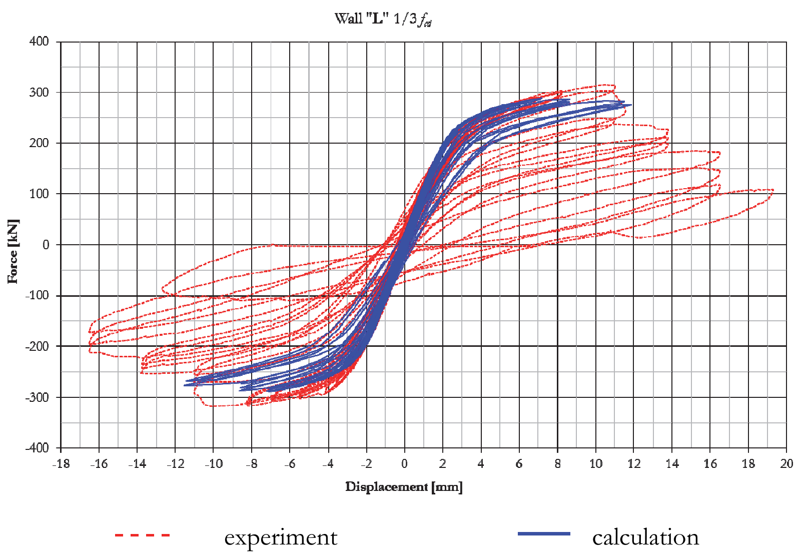


Figure 10: Reaction force dependence on displacement.

L2 Wall

During the solution of the L2 wall the preload was 1,613 kN (including the girder and the concrete block). The results of the comparison are in Figs. 11 and 12.

The mode of "step-by-step" destruction and relevant stages of the walls after testing are shown in Fig. 13.

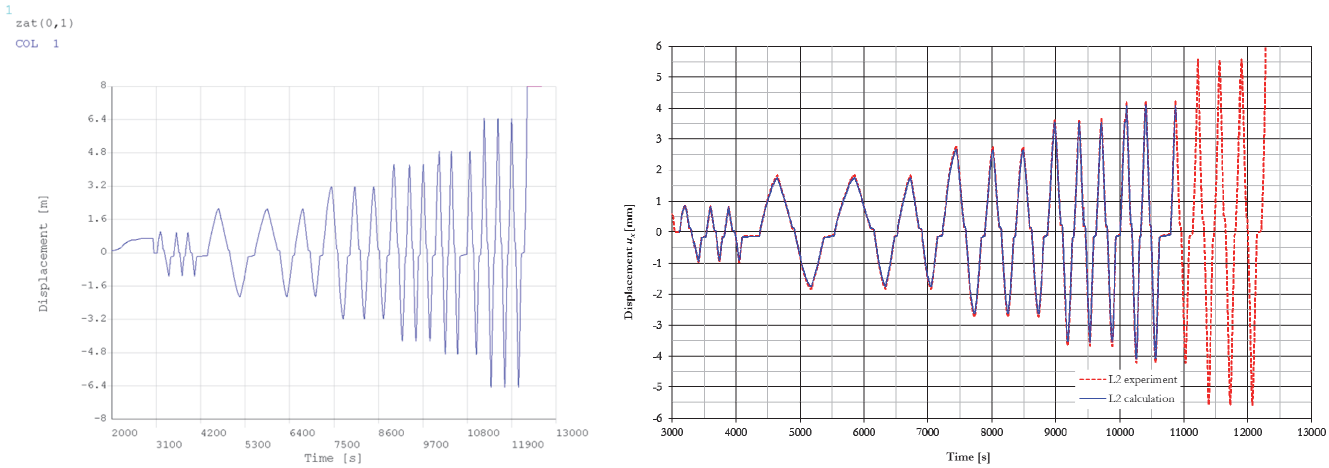


Figure 11: Imposed function – lateral displacement u_x (on left side) and lateral displacement u_x from measurement and calculation at central point of the beam (on right side)

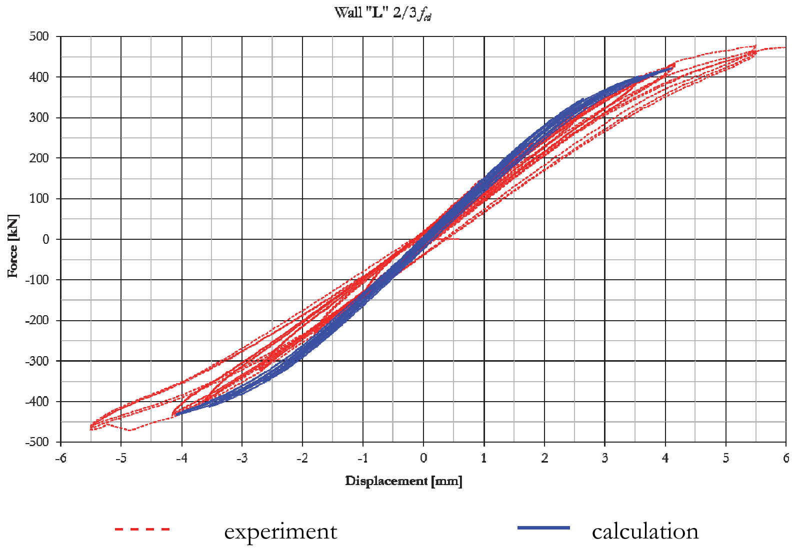


Figure 12: Reaction force dependence on displacement.

Figure 13: Typical view on the walls after testing.

S1 Wall and S2 Wall

The cyclic response solution on the S1 model and S2 model with the preload 484 kN, resp. 968 kN (including the girder and the concrete block) was compared with the values obtained from the test. Excitation function of time history lateral displacement is shown on the Fig. 14, resp. Fig. 16. The results of the comparison are in Figs. from 14 to 17.

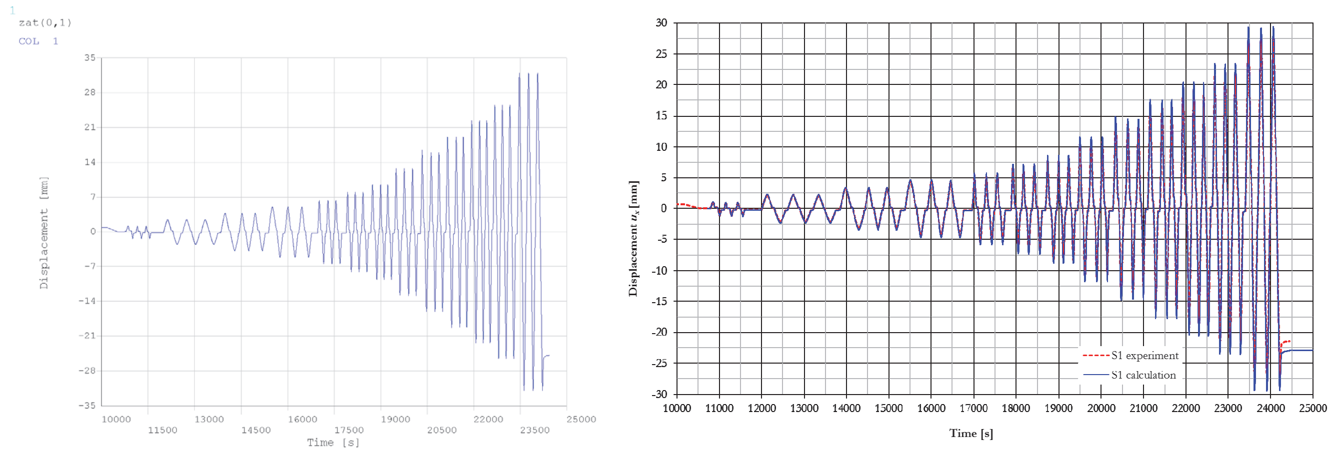


Figure 14: Imposed function – lateral displacement u_x (on left side) and lateral displacement u_x from measurement and calculation at central point of the beam (on right side).

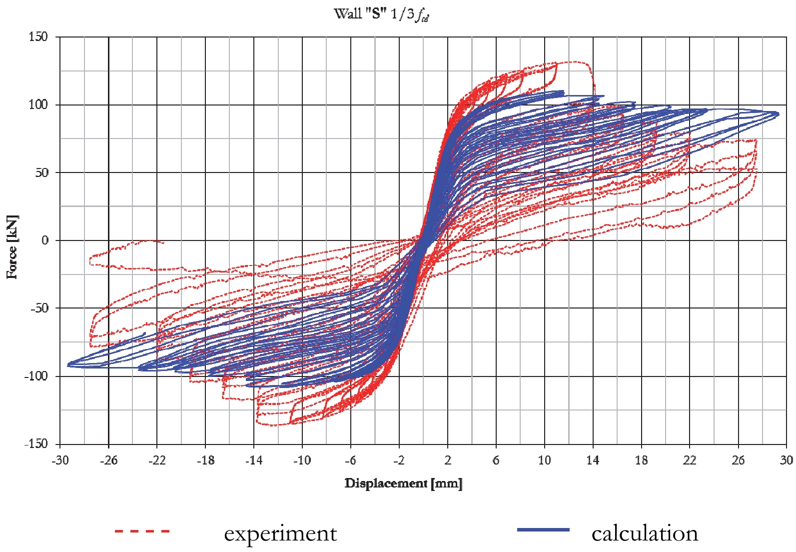


Figure 15: Reaction force dependence on displacement.

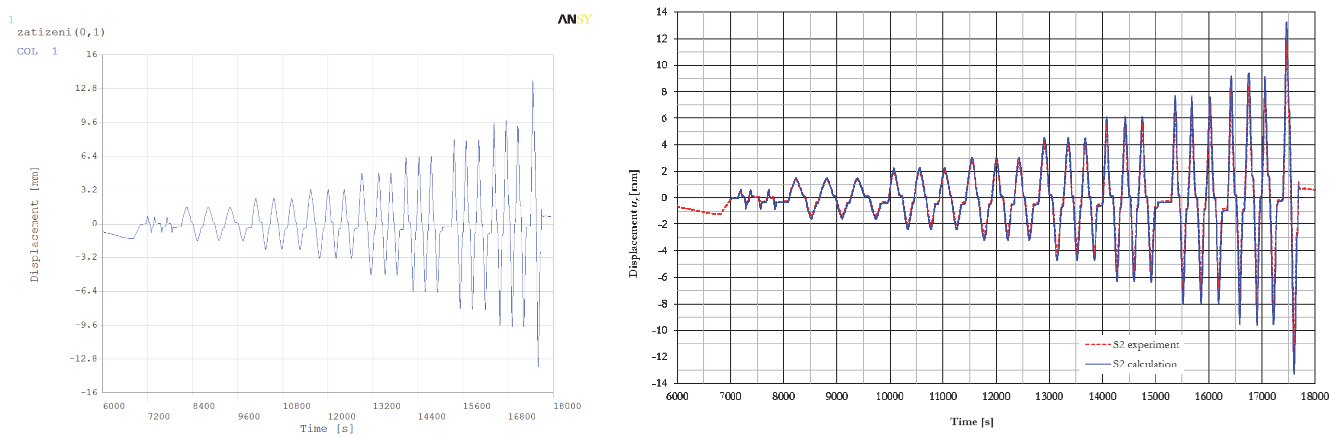


Figure 16: Imposed function – lateral displacement u_x (on left side) and lateral displacement u_x from measurement and calculation at central point of the beam (on right side).

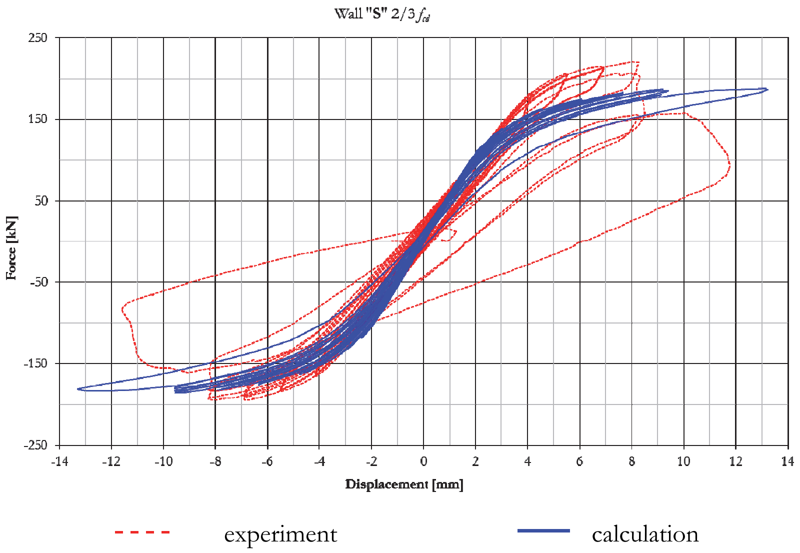


Figure 17: Reaction force dependence on displacement.

The displacement, stress and nonlinear strain fields were monitored at all the walls. Figs. 18-21, on which the displacement, stress and strain fields for the L1 WALL in the time 17.315 s and for the S1 WALL in the time 24.215 s. Case L1 is displayed on left side on figure and case S1 is displayed on right side.

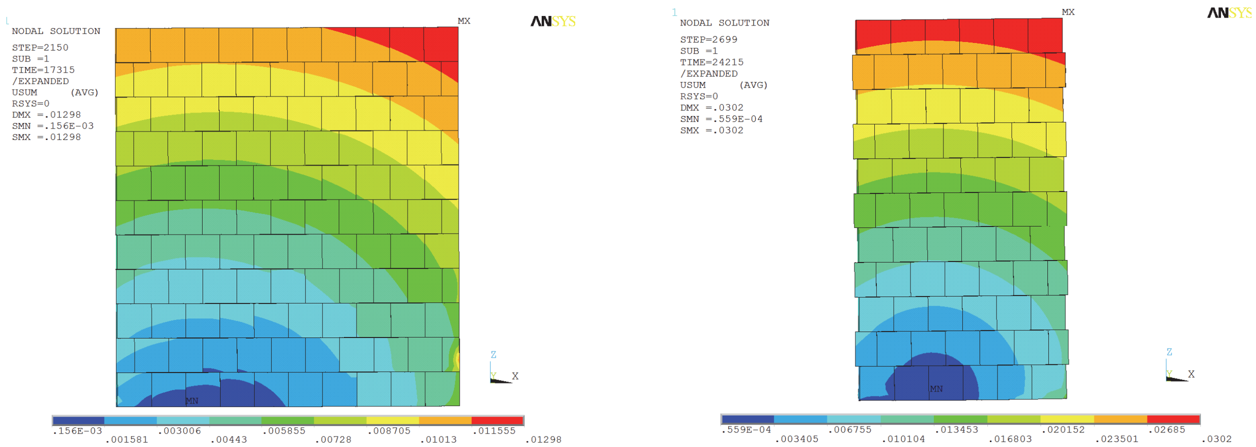


Figure 18: Total displacement u_{sum} field.

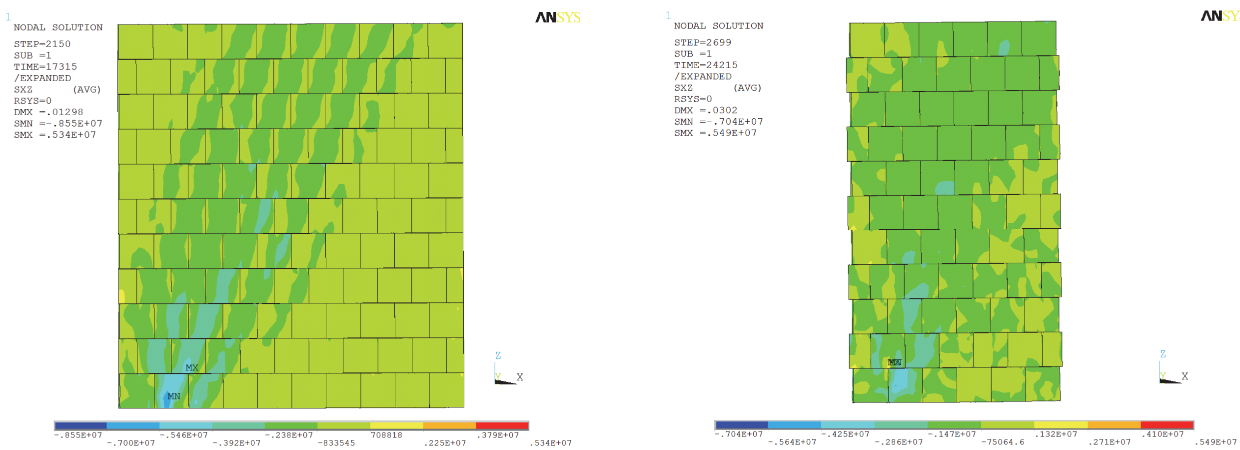


Figure 19: Stress σ_{xz} components field.

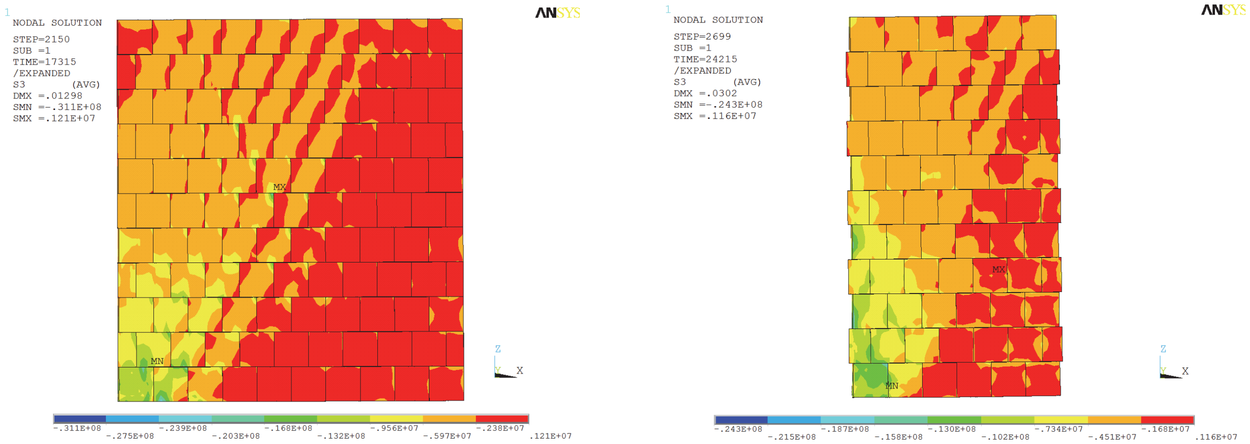


Figure 20: Principal stress σ_3 field.

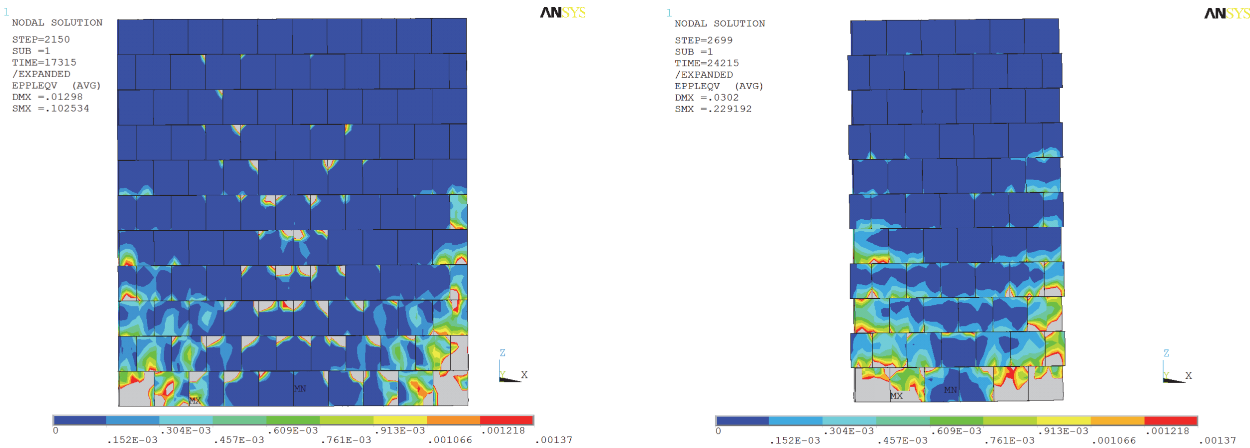


Figure 21: Nonlinear strains ε_{pl} field.

ANALYSIS OF BEHAVIOR OF CYCLIC LOADED CLAY BLOCK WALLS

Two detailed three-dimensional computational models of the structures of the masonry walls from the precise masonry clay blocks POROTHERM 44 T Profi assembled on the thin joint mortar, including the girders, the concrete blocks and auxiliary elements were created using the finite element method in the ANSYS software system. The crucial parts of the model including the clay walls were created from solid elements in the shape of a hexahedron.

Four alternatives depending on the wall lengths and the intensity of the vertical preload were solved. They were the walls 2,750 mm high and 440 mm wide with the different length. The two long walls of the 2,500 mm length are marked “L” and the two short ones of 1,500 mm are marked “S”. The preload including self-weights of the girders and of the concrete block corresponded to the load at the amount of approximately 1/3 f_{cd} and 2/3 f_{cd} of the walls. The calculations were labelled L1, L2, S1 and S2.

The material properties of the clay blocks are nonlinear. A material model corresponding to the model of the “concrete” with the modified Drucker–Prager model was chosen. The model is suitable for a calculation of structures made of concrete, cement, stone and brick.

The calculations are based on the assumption that the walls are loaded by the cyclically forced loading corresponding to the shear tests of the walls of the actual size. Boundary conditions of the conducted tests had to be considered complexly in the calculations. For instance, the method of modelling the compressive device proved to be affecting the calculation stability significantly and thereby the possibility convergence of the solution.

The results of the calculations on the L1, L2, S1 and S2 models include the displacement, strain and stress fields at the discrete points of the models, or reactions. Each calculation was documented with the aid of figures and graphs. The results show that the character and the evaluation of the observed walls behaviour using the finite element method are analogous to the tests. The accuracy of the models is very high. The strain and the stress of the individual blocks, the level of the damage and the state of stress at the selected points during the whole process of the cyclic loading can be determined from the data obtained from the calculations.

The calculations could be made more precise by setting the forced displacement function directly at the level of the girder guiding. Uncertainty also arises at selecting the level of friction in the joints between the blocks, possibly between the mortar and a block.

The results obtained on the computational models describe the behaviour of the test walls under the experimental cyclic loading very well.

ACKNOWLEDGMENTS

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