Stress and Strain Analysis of Prefabricated Unfired Earth Wall Made of Commercial Earth Mixture

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Abstract: The paper is focused of comparison an experiment and numerical model of unfired rammed earth made of prefabricated panels. The numerical model was made in four versions and loaded according to the experiment. The deformations were evaluated and compared. Then the verification of the model to the experiment was made. The position of the load was searched to give the same displacements as the data from the experiment. It was found that a quite big eccentricity in the load is needed to obtain the same deformation. The determination of maximal force and displacement for different thicknesses of walls was made. The determination of maximal force and displacement for walls with thicknesses of 200 mm, 300 mm, 400 mm and 500 mm were searched.

Keywords: rammed earth; prefabricated wall; stress and strain analysis.

1 Introduction

The building with unfired earth is nowadays getting back thanks to its positive environmental properties of natural product. But the mechanical properties and the behaviour of earthen constructions are complicated and not well known, because rammed earth was replaced by fired bricks. Material properties, behaviour of the earthen constructions have to be observed for spreading the building of this material. These data can help engineers and architects to use unfired earth as a material [2–4].

An experiment with load bearing earthen wall was made by J. Ruzicka, F. Havlik (the experiment was a part of Havlik‘s PhD thesis [1]), J. Divis and their team at CTU in Prague in 2013. The wall was made of ten prefabricated rammed earth panels bound with earth mortar. The wall was loaded until it collapsed. The force of the load and deformations were measured and recorded. The aim of the paper is to create a numerical model of the testing wall and

- to made a model of the experiment and made stress and strain analysis to compare the model and the experiment,
- to determine maximal loading forces and deformations for walls of different width.

The first part was divided into several steps

- to define the geometry of model,
- to determine the boundary conditions,
- to set necessary material characteristics that were missing (especially Poisson‘s ratio),
- to set the position of the load.

2 Prefabricated rammed earth wall experiment

The experiment was conducted on the wall of 1.672 m width, 2.944 m height and 0.200 m depth built from ten prefabricated panels. The whole experiment is elaborately described in [1]. Mortar was used both in vertical and horizontal joints, it was from the same material as the panels. The concentric load was made by the load cell with a hydraulic jack. Eight gauges recording local strain on the surface and two recording buckling were installed. Schmidt hammer testing was realized before performing the full scale load test on the finished wall.

The stress-strain curve was recorded. The maximal force was 525 kN and the maximal horizontal displacement was 42.94 mm. Then the wall collapsed. The wall is shown in the Fig. 1.

The problem of the experiment is that it was done just once. So there is a question if it is a representative sample. To prove that the experiment was a representative one - the experiment can be repeated at least twice to get some statistics data or a numerical model can be created. The goal of the paper is to prove if the experiment was a representative one or there was some kind of deviation.

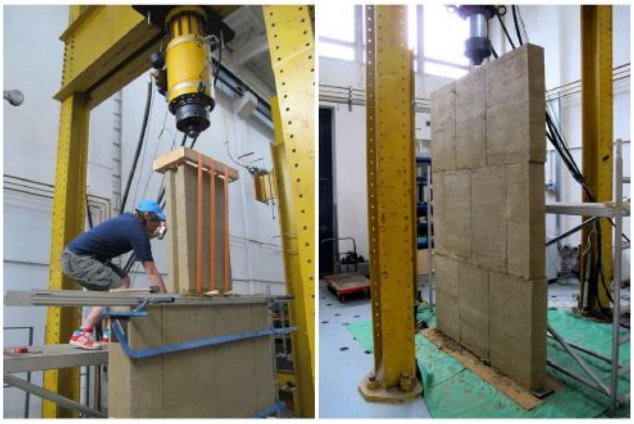

Fig. 1: Precast earth wall [1].

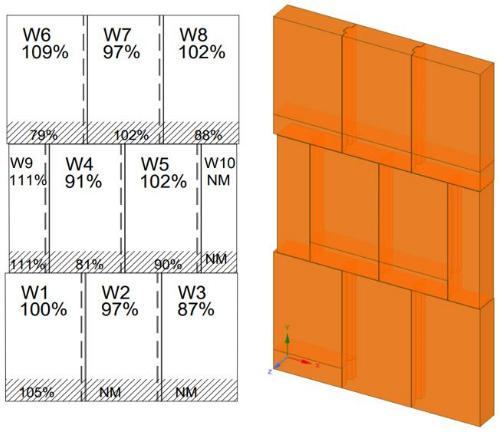

Fig. 2: Schema of the wall and panels.

3 Process of creating the model

The model of the rammed earth was modelled in Ansys 2019 program with a student licence. The model was made in 3D. The issues that need to be solved were the geometry, material characteristics, boundary conditions and position of the load. The results of the model were displacements and values of the loading forces.

3.1 Geometry

The model was made in four versions of geometry. The first one was a simply monolithic wall with no regard to panels and mortar (ver. A). The second one was a wall consisting of panels but without mortar (ver. B). The third one was a wall consisting of panels and mortar (ver. C) and the fourth one was a wall of panels, mortar and different materials in the bottom part of the panel according to the measurement of the Schmidt hammer (ver. D). Non-destructive testing of strength using the Schmidt hammer has shown that the panel bottoms used in this test were weaker than the rest of the panels. The difference is shown in the Fig. 2. The panel W1 was considered as the basic one with the comprehensive strength of value 100 %. Strength measured with the Schmidt hammer on other panels are related to the W1 value.

3.2 Material characteristics

The characteristics needed for the model were volume density, modulus of elasticity, comprehensive strength, tensile strength in bending and Poisson's ratio. Poisson's ratio was the missing value and it was necessary to make new specimens. They were made of the same mixture as the panels. Poisson's ratio was determined from the comprehensive test of three specimens. The value of Poisson's ratio is the negative of the ratio of transverse strain to axial strain. The used material characteristics for panel W1 are described in Tab. 2. Properties of other parts of the wall were modified according to the results of the Schmidt hammer.

3.3 Boundary conditions

The earth wall was built on the ground of the laboratory, it was supported against horizontal displacement in the top and a steel beam was settled on the top of it. The steel beam provided the force distribution to the wall during the test. Schema is shown in the Fig. 4. The simplified 2D model was supported by a clamped

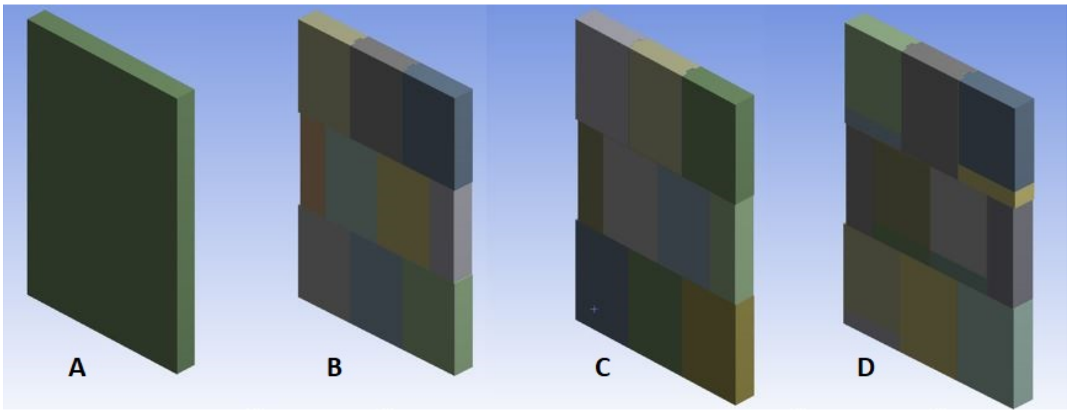

Fig. 3: Four versions of geometry – A) a monolithic wall, B) panels without mortar, C) panels with mortar and D) panels with mortar and different material in the bottom.

Tab. 1: Material characteristics used in the model.

	volume density [kg/m^3]	modulus of elasticity [MPa]	com. strength [Pa]	ten. strength in bending [Pa]	Poisson's ratio [-]
W1	2,079	337	3,350	400	0.2
mortar	1,859	187	3,400	340	0.2

edge at the bottom and by a hinge on top. The wall with these boundary conditions had the maximal horizontal displacement in the top third of the wall. It corresponds with the theoretical deformation. The horizontal deformation for these conditions is the same as was measured during the test. The maximal 40 mm was reached around top third of the wall and 30 mm in the half. These deformations were measured by force 500 kN. The clamped edge in the simplified 2D is caused by the mass of the wall and the relatively big supporting area at the bottom.

The 3D model was supported by setting displacements. The displacements in direction x, y, z (the system is shown in Fig. 5) were settled 0, 0, 0 in the bottom area of the wall and 0, free, 0 in the top area of the wall.

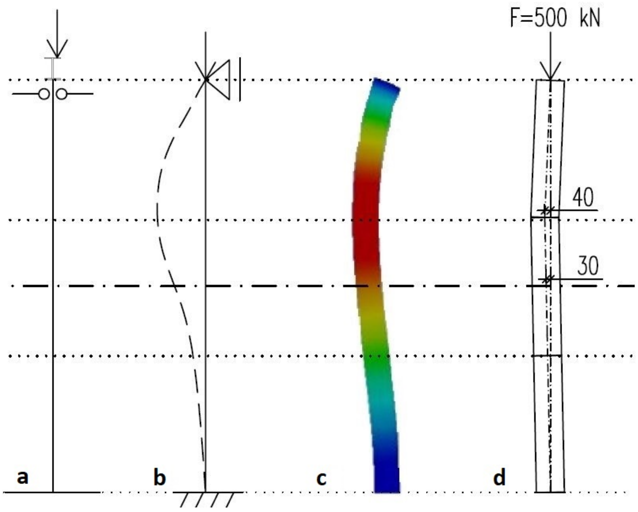

Fig. 4: Boundary conditions – a) the schema of experiment, b)the shape of theoretical deformation, c) the shape of deformation of the model and d) the shape of real deformation of the wall.

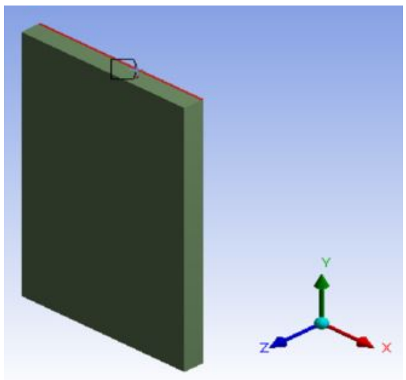

Fig. 5: Coordinate system of the model.

Tab. 2: Deformations from the model and experiment.

model version	deformation (z axis) $e = \frac{1}{6}t$ [mm]	deformation (z axis) (Fig. 5) e according deformation [mm]
A monolithic wall	15.72	39.29
B panels withou mortar	16.23	40.85
C panels with mortar	15.36	38.36
D panels with mortar, weaker bottom	15.74	39.37
experiment	42.94	42.94

3.4 Load

The eccentricity of the load was defined as

$$e = \frac{1}{6}t = \frac{1}{6}200 \sim 35 \text{ mm}. \tag{1}$$

The force was applied as an area load with an eccentric axis 35 mm from the wall axis.

The value of the force was settled according to the experiment. The maximal test force was 519.9 kN. The weight of the steel beam was 475 kg and the maximum test force was 525 kN. The model was also loaded with mass weight caused by earth gravity.

4 Results from the model

The model was made as described above. The wall was loaded with the force of value 525 kN. The results were deformations of the model of the wall that were compared with the deformations of the real wall.

4.1 Eccentricity of load e = 35mm

The deformations of load with eccentricity according to Eq. 1 were observed. The values are shown in Tab. 2. For version A, the deformation is 15.72 mm, version B is 16.32 mm, version C is 15.36 mm, version D is 15.74 mm and the value of the experiment is 42.94 mm.

Fig. 6: 1) The setting of the steel beam and position of the load cell with the hydraulic jack and 2) the gauge for recording local strain [1].

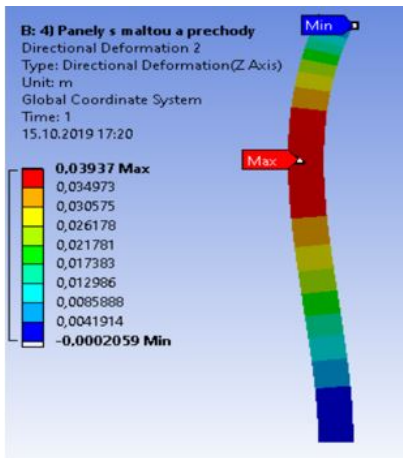

Fig. 7: Deformation of the version D with eccentric load adjusted according to the experiment.

The deformations of all versions are very similar and there is no big difference in it. The differences between versions are very small (Tab. 2) because the comprehensive strength and other material characteristics

Tab. 3: The walls of different thickness and their loading forces and displacements.

thickness of wall [mm]	maximal force [kN]	max. deformation (z axis) (Fig. 5) [mm]
200	525	15.72
300	920	11.51
400	1,300	9.09
500	2,000	9.03

are approximately the same. But the value of the deformation in the real experiment was more 2.6× higher than in the model. Four possible causes of this can be found.

The first one is the imperfection in the transfer of the load through the beam to the wall. A steel beam was placed on the top of the wall, the top of the wall was grinded and leveled with a cement screed and the steel beam was placed on this layer. The position of the beam was probably not exactly in the middle of the wall (the axis of the beam did not lay on the axis of the wall). Because of that, the first inaccuracy was injected in the experiment. The second one is the position of the load cell with the hydraulic jack on the beam (the axis of the jack did not lay on the axis of the beam resp. wall). The stated cube size was 200 mm, it can be seen in the Fig. 6. And the third possibility could be the structural unevenness of the wall. The precision of the vertical plane was controlled with two meter long spirit level lath. Verticality and aligning of panels were adjusted with clips that were left until mortar strengthened and then the next row was built. But the verticality precision was not controlled and measured. There was space for some structural eccentricity. And the last problem could be the process of transferring the load through the beam to the wall. It could have the impact of a solitary force instead of an even pressure on the area.

4.2 Calculated eccentricity of the load

Next, the verification of the model to the experiment was made. The position of the load was searched to give the same displacements as the data from the experiment. For the load strip of width 25 mm from the edge of the wall were found similar deformation as the result of the experiment. In this case, the eccentricity is $e = 87.5$ mm. The calculated eccentricity includes all of the problems described above and simulated them. These displacements are shown in the Tab. 2 in the third column. For version A the deformation is 39.29 mm, version B is 40.85 mm, version C is 38.36 mm, version D is 39.37 mm and the value of the experiment is 42.94 mm. These data showed that there was probably a quite big eccentricity in the load.

5 Walls with different thicknesses

Another target was to determine the maximal force and displacement for different thicknesses of walls. The method was as follows. The value of the normal stress in the place of the maximal deformation was found out. This was done for the wall of 200 mm, loading force of 525 kN and the eccentricity of the loading force was $e = 35$ mm (reference wall). The model of the wall was considered as a monolithic wall. The walls of different thicknesses were made and loaded until the value of the normal stress was at the same value of the reference wall. The displacement in the axis z (Fig. 5) was taken at that moment and considered as the maximal one.

The reference wall of the thickness 200 mm had the loading force of 525 kN and displacement 15.72 mm. The wall of thickness 300 mm had loading force of 920 kN and displacement 11.51 mm, 400 mm wall had the loading force of 1,300 kN and displacement 9.09 mm and 500 mm wall had the loading force of 2,000 kN and displacement 9.03 mm.

The Fig. 8 shows the dependence of the thickness of walls to maximum loading force and shows that the trend of the dependence is linear. The Fig. 9 shows the dependence of the thickness of walls to displacement in z axis. The trend of the dependence seems to be gently exponential.

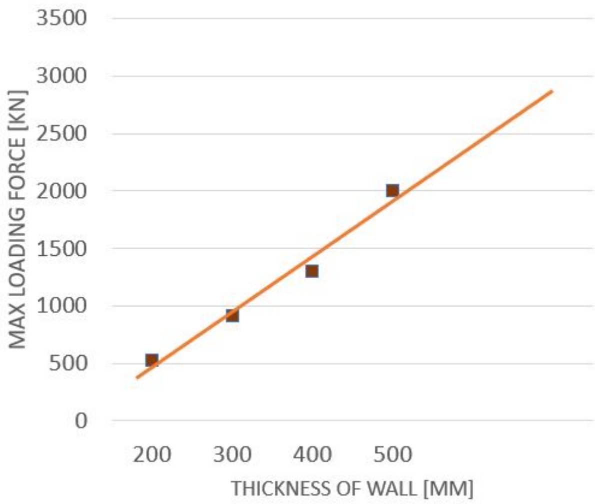

Fig. 8: Dependence of thickness of walls to max loading force.

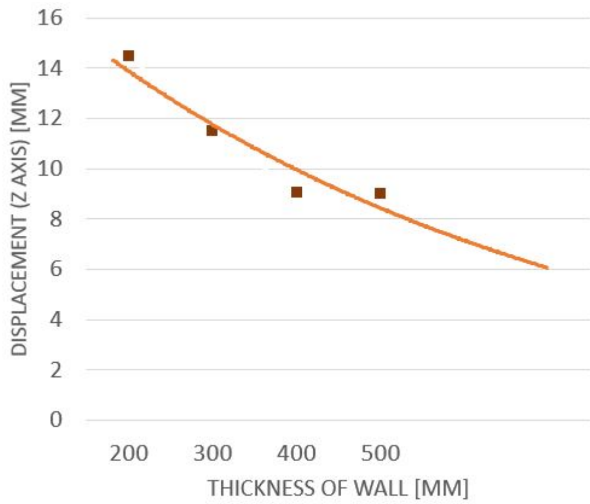

Fig. 9: Dependence of thickness of walls to displacement in z axis.

6 Conclusion

The paper focused on the comparison of experiment and numerical model of unfired rammed earth made of prefabricated panels. The numerical model was made in four versions and loaded according to the experiment, then the deformations were evaluated.

The values of the deformations in the real experiment were more than 2.6× higher than in the model. Four possible causes of this can be found:

- position of the steel beam,
- position of the load cell with hydraulic jack,
- structural eccentricity in vertical precision,
- process of transferring the load through the beam to the wall.

Then the verification of the model to the experiment was made. The position of the load was searched to give the same displacements as the data from the experiment. It was found that a quite big eccentricity in the load is needed to obtain the same deformation.

Finally, the determination of maximal force and displacement for different thicknesses of walls was made. The values were searched for thicknesses of 200 mm, 300 mm, 400 mm and 500 mm.

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