Experimental tests of pre-stressed masonry and numerical modeling of resultant deformations

M. Stara and V. Buchta

***Abstract*—**Due to underground mining and construction of tunnels and collectors in urban areas terrain subsidence occurs with characteristic effects on building structures. In affected areas it is often necessary to detain affected structure with additional pre-stressing of walls and foundations. Pre-stressing masonry is one of the most common and concurrently the most effective method redevelopment. At Faculty of Civil Engineering was constructed laboratory equipment for closer examination of the behavior of tensioned masonry. Specifically for measuring the deformation of brick corner mainly around the anchor plates that used for transmission of tensile forces into masonry. In this masonry corner two pre-stressing bars are placed. These bars are in different height and are anchored to the anchor plates, which transfer pre-stressing forces to the masonry. The masonry was pre-stressed in the both directions. The specimen for laboratory testing is performed in the proportion to the reality of 1:1. Mathematical modeling of the brick corner is based on the finite element method using ANSYS software and then the results are compared with results of the laboratory tests. On the basis of these results it should be possible to improve the models and come closer to achieving an accurate and at the same time, simple procedure for the design of pre-stressed masonry.

***Keywords*—**Pre-stressing, masonry, measurement, laboratory testing, tensile forces, deformation, numerical model, FEM, element.

I. INTRODUCTION

PRE-STRESSING of masonry is one of the most widespread building facility reconstruction methods. In the Czech Republic it is very successful, especially in the Moravian-Silesian Region, which is subject to considerable disturbances of building facilities due to undermining. Pre-stressing in the masonry can be achieved by means of steel wire ropes or rods. These steel elements are inserted into the pre-milled grooves, which may be in the external or internal wall face. Cohesion between the reinforcement and the masonry is secured by means of a special high-strength grout. The ends of the steel elements are clamped into steel angles or special anchors. In these reconstruction methods it is necessary to follow the pre-stressing procedures and technologies. It is important to properly select the pre-stressing and anchoring system, appropriate layout and arrangement of pre-stressing wires, pre-stressing procedure and dimension of pre-stressing forces in the individual wires.

The available literature includes recommended values for the ratio of pre-stressing force and compression strength of the masonry perpendicular and parallel to the bed joint based on the performed experiments.

According to German research [1] it is possible to choose the value of the pre-stressing force ranging from 0.10 to 0.15 of the strength of masonry perpendicular to bed joint. This range is determined using a graph, where the strength of masonry depends on the percentage of filling of vertical joints with mortar. The quality of filling of vertical joints with mortar in masonry decides on the overall strength of the masonry. The less well the joints are filled, the lower is the strength of the masonry. According to [2], [3] the selected pre-stressing strength is about 1/10 of the masonry compression strength perpendicular to bed joints. According to [4], the compressive strength of masonry in parallel to the bed joints can acquire values from 0.1 to 0.85 times the strength perpendicular to the bed joints. According to the results of the work [5], the values range from 0.1 to 0.25 of the strength of masonry perpendicular to bed joints. This range is dependent on sufficient information about masonry and especially its quality filling of vertical joints with mortar. The idea in masonry with well-filled joints is the value of 0.7 to 0.8 providing that this value should not be exceeded. More detailed information to calculate the pre-stressing forces or to analyze stress in the area of anchor plates is not listed in the current technical standards.

Pre-stressing forces in the experimental measurement of deformations described in this article are chosen safely with regard to the quality of filling of joints with mortar as 10, 20, 30, 40 and 50 % of the compressive strength of masonry perpendicular to bed joints. The purpose of this testing is not only the actual deformation measurement, but also the monitoring of the behavior of masonry at the point of local stress induced by gradually increasing pre-stressing. The performed tests simulate the behavior of masonry reinforced by pre-stressing wire ropes at the moment of introduction of pre-stress and these are therefore short-term tests.

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Marie Stara, VSB - Technical University of Ostrava, Faculty of Civil Engineering, 708 33 Ostrava, Czech Republic (corresponding author to provide phone: +420 596 991 375; e-mail: marie.stara@vsb.cz).

Vojtech Buchta, VSB - Technical University of Ostrava, Faculty of Civil Engineering, 708 33 Ostrava, Czech Republic (corresponding author to provide phone: +420 597 321 925; e-mail: vojtech.buchta@vsb.cz).

II. MEASURING PRINCIPLE

A. *Used material*

Laboratory equipment for testing tri-axial stress consists in a steel structure with dimensions of 900 mm x 900 mm x 1550 mm [6, 7, 8]. In the structure there is an in-built brick corner with a height of 870 mm (11 rows of bricks). The wall thickness is 440 mm. The used masonry elements are bricks CP 290 mm x 140 mm x 65 mm, and the jointing material used was lime mortar, mixed with sand in the ratio of 1:4 [9]. The average compressive strength of bricks was determined by a test according to the standard [10] to a value of 12,870,000 Pa. From this value we then derived the standardized mean compressive strength of masonry element f_b = 9,900,000 Pa. The average compressive strength of the mortar was determined by the standard [11] to a value of f_m = 770,000 Pa.

The tested brick corner is considered a part of the existing structure and therefore the procedure in calculation of the characteristic strength of masonry follows the standard [12] - Evaluation of the existing structures, which refers, in determining the strength characteristics, to the previously applicable standards, for the masonry for example to the already invalid pre-standard [13]. The resulting characteristic compressive strength of masonry perpendicular to the bed joints is f_k = 1,663,000 Pa.

Fig. 1 Laboratory equipment

During the brickwork two pre-stressing bars were inserted in the masonry at different heights see Fig. 1. Each pre-stressing bar was marked according to the direction, in which it was placed (direction A and direction B). In the direction A, it was place at the height of 390 mm, in the direction B, it was placed at the height of 530 mm. After the final brick walling of the bricked corner, the upper part of the structure was aligned by a layer of mortar with a steel distribution plate with a thickness of 12 mm with welded steel reinforcements to ensure even load on the masonry. Bars were fitted with steel anchor plates on a layer of mortar for leveling of the surface of the masonry.

B. *Input values for measurements*

Vertical load was introduced by a hydraulic cylinder, which was placed between the distribution plate and the I-profile bolted to the laboratory equipment. The sample was loaded with uniform vertical load of 100,000 Pa.

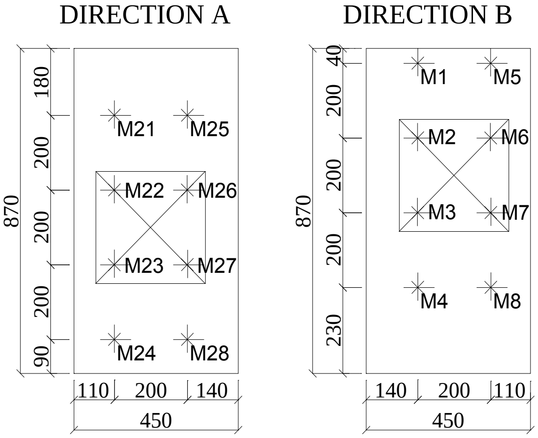

Fig. 2 Layout of measurements sensors in the A and the B direction

Pre-stressing force was introduced in the pre-stressing bars also by hydraulic cylinders through the anchor plates with dimensions of 300 mm x 300 mm and a thickness of 10 mm and 20 mm. The values of pre-stressing forces are shown in Table 1. Measured deformations were recorded using potentiometric sensors attached to laboratory equipment, identified as connected to the measuring station [14, 15]. A total of eight sensors were attached in each direction, sensors labeled M21 to M28 in A direction and sensors labeled M1 to M8 in B direction. The layout of individual sensors in both directions is seen in Fig. 2. The sample was loaded gradually with a pre-stressing force from 10 % to 50 % of the masonry compression strength perpendicular to the bed joints, always at first in the direction B, and then in the direction A.

Table I shows the input load values of the masonry. The area of the anchor plate and also the area of masonry under the anchor plate were considered without weakening by a hole, which was left for the passage of the pre-stressing bar, as the dimensions of the hole is negligible in this case.

Table I. Input values for pre-stressing of masonry

Loading process	Stress [Pa]	Pre-stressing force [N]
10 %	166.3e3	14.97e3
20 %	332.6e3	29.94e3
30 %	498.9e3	44.91e3
40 %	665.2e3	59.88e3
50 %	831.5e3	74.85e3

C. *Results of measurements*

The x-coordinate contains values of deformations with a negative sign induced by the pressure of anchoring plate on masonry.

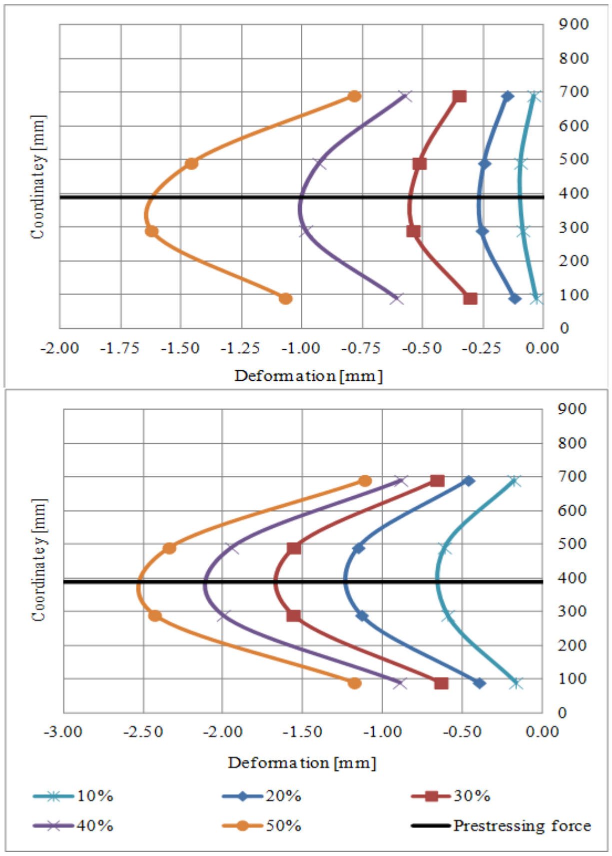

Fig. 3 Progress of masonry deformation in the direction A, anchor plate 300 mm x 300 mm x 10 mm (upper), anchor plate 300 mm x 300 mm x 20 mm (bottom)

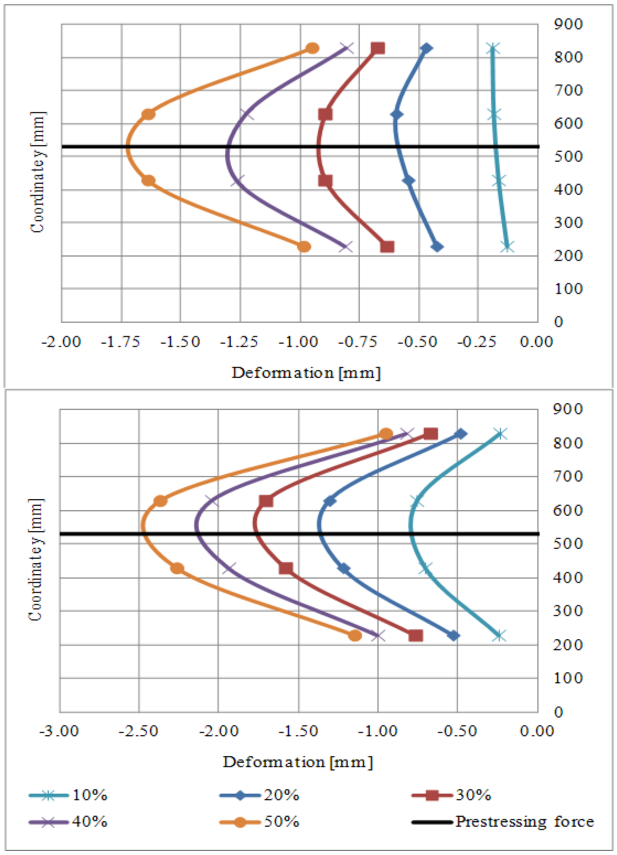

Fig. 4 Progress of masonry deformation in the direction B, anchor plate 300 mm x 300 mm x 10 mm (upper), anchor plate 300 mm x 300 mm x 20 mm (bottom)

Resulting deformations are obtained by averaging of the measurements in vertical sections M21 ~ M24 and M25 ~ M28 in A direction (Fig. 3) and M1 ~ M4 and M5 ~ M8 in B direction (Fig.4).

On the vertical axis there are elevation coordinates of the location of individual sensors according to Fig. 2. All sensors were placed on bricks or on anchoring plates, but not in the mortar joint. Horizontal line in the graph indicates the location of pre-stressing force.

As is evident from all figures, the shape of deformation of masonry in the direction A at the place of pre-stressing bar corresponds to the stress concentration just below the anchoring plate, while above and below the anchoring plate the deformations are smaller. Courses of deformation are approximately at equal distances for each size of pre-stressing force.

Deformation graphs of anchor plates with different stiffness show that in the case of an anchor plates with a thickness of 20 mm there are higher deformation under the anchor plate and around than with using of the anchor plates with a thickness of 10 mm. The reason for this behavior of the anchor plate is higher flexural rigidity of the anchor sheets with a thickness of 20 mm.

The flexural rigidity is dependent on the thickness of plate which enters into a relationship in the third power and the ratio of the rigidity of the two plates is 1:8.

The same of the values of the resulting waveform (for plate thickness 10 mm), in both directions, are achieved at strain corresponding to more than 50 % of the strength of the pressure perpendicular to the bed joints, which operates directly under the anchor plates. While in the case of the anchor plate 300 mm x 300 mm x 20 mm are the same of the values of the resulting waveform, in both directions, at strain corresponding to more than 30 % of the strength of the pressure perpendicular to the bed joints, which operates directly under the anchor plates. We can say that the use of anchor plates with a higher flexural rigidity, the load is from the preload better transferred in both directions than for the plate with a low flexural rigidity. Of course we must not forget the vertical location of the pre-stressing bars, the size of anchor plates and of course modulus of elasticity mortar and bricks, which have an impact on the resulting of deformation.

III. NUMERICAL MODELING OF MASONRY

A. *Input values for masonry modeling*

Modernization of procedures for calculations of masonry structures results in an effort to model the masonry already as more complex 2D and 3D models. These models reflect much better the behavior of masonry structures and the mutual interaction between the individual masonry elements and jointing material, which is usually mortar [16, 17, 18].

Masonry is an inhomogeneous and anisotropic material, consisting of a piece construction material and jointing agent. Both of these masonry components have different physical and material properties. Therefore, the creation of a suitable model that would expresses the actual material and physical properties of masonry is difficult. In masonry structures it is not possible to ensure the same characteristics in all the places, whereby variables enter the modelling process, e.g. different material properties of basic components, geometrical arrangement of brick, interaction between components, quality of manufacturing, environmental influence etc [19, 20].

Modelling of masonry structure is performed in the ANSYS application, based on MKP. Numerical model is created by means of a so-called micromodel, ie. rendering of actual arrangement of masonry elements, which corresponds to the bedding of bricks during bricklaying of the structure, including contact and bed joints of the mortar, where the input values for each material are listed in Table II.

Table II. Input values for numerical modeling of material

Material	Density [kg/m^3]	Modulus of Elasticity [Pa]	Poisson´s ratio
Bricks 290/140/65	1535	4.20e9	0.15
Mortar M5 + sand	1353	7.5e7	0.20
Steel plate, anchor	7850	210e9	0.30
Pre-stressing bar	7850	185e9	0.30

Micromodel is modelled using spatial eight node element SOLID45. The model is further includes pre-stressing using 3D final element LINK8, which was defined by the rod area $A = 0.0005309\ \text{m}^2$ and by initial strain according to Table III. Steel anchoring plates to insert the pre-stressing forces are modelled from the final element SOLID45.

Table III. Values of pre-stressing forces, stress and initial strain

Loading process	Stress of pre-stressing bars [Pa]	Initial strain [-]
10 %	28.19e6	1.52e-4
20 %	56.38e6	3.05e-4
30 %	84.58e6	4.57e-4
40 %	112.77e6	6.10e-4
50 %	140.96e6	7.62e-4

B. *Results of modeling*

Due to the behavior of masonry elements there is a limited field of loading almost linear curves up to the point of damage when can appear brittle fracture. For the mortar that is not true because its behavior is similar to concrete, which exhibits non-linear curves at low values of load in the compression zone. In contrast, in the tension zone development of cracks and thereby a reduction of the material properties occurs.

For modeling was used model with anchor plate about dimensions 300 mm x 300 mm x 10 mm.

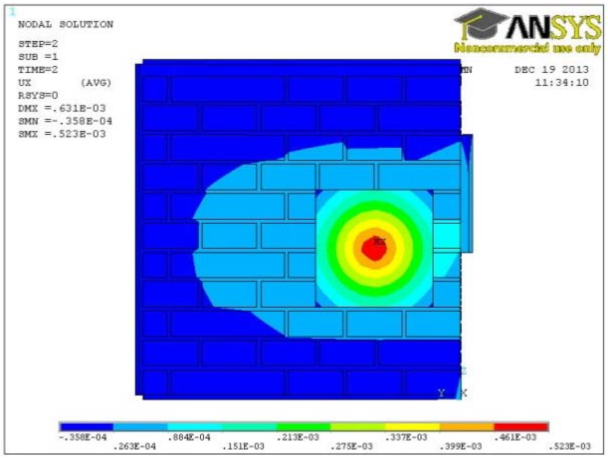

Fig. 5 Numerical model with loading process 40 %, the direction A

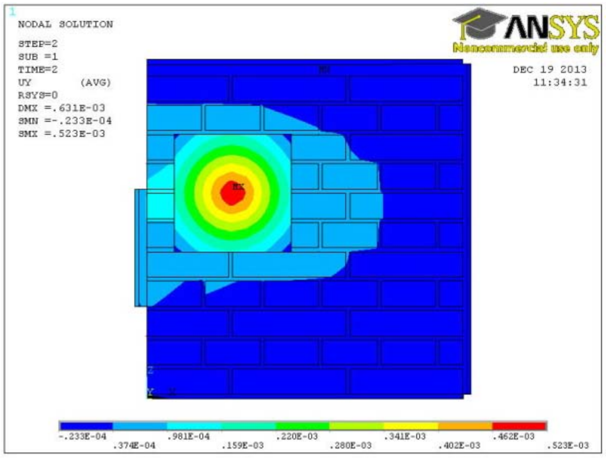

Fig. 6 Numerical model with loading process 40 %, the direction B

For the model was used working diagram of mortar. Mortar was chosen because of the very low strength with low modulus of elasticity, which is signed significantly to the overall deformation of the masonry. Bricks were kept as linearly elastic material because modulus of elasticity of bricks at the stage of pre-stressing changed only minimally, thus the results of numerical modeling has not significantly affected. The elongation of the pre-stressing bars is considered as linear material and its modulus of elasticity is still the same. It was considered also with the effective area of anchor plates in progress of pre-stressing.

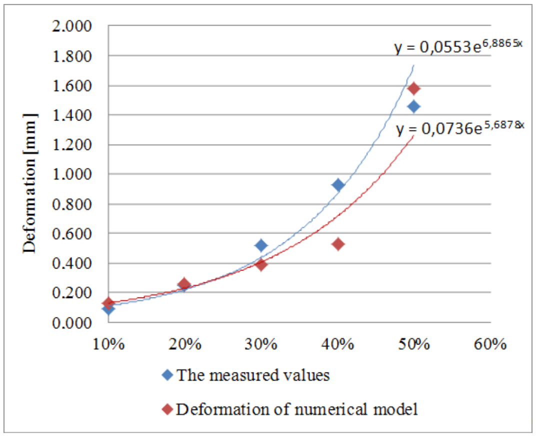

Fig. 7 Comparison of results in the direction A

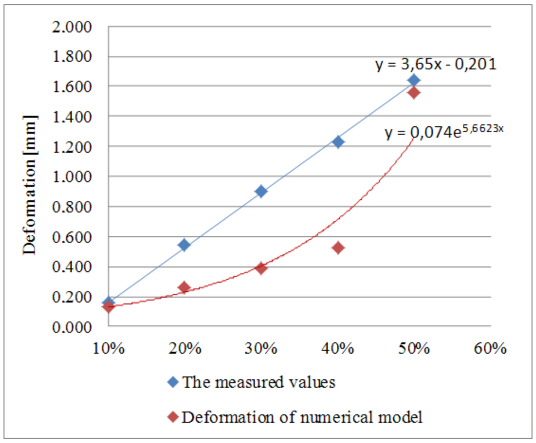

Fig. 8 Comparison of results in the direction B

On the Fig. 7 and Fig. 8 are used maximal values from measurements and numerical model.

The results show that by changing the material properties of mortar are resulting values to the numerical model of masonry significantly closer to the measured values. Considering how much masonry construction, which usually consisting of two elements with very different properties for modeling complex and compliance between simulation and measurement is quite challenging due to the many variables in the calculation, the results can be seen almost excellent.

Of course, we can not assume that this is the final stage of the models. In this way, we can proceed further and change all values until we reach a perfect alignment of boundary conditions including variables in the calculation between numerical models and actually measured values.

It is necessary to remind that the above models are quite idealized, especially the thickness of the mortar joints, brick finish chipping at the insertion point pre-stressing bars and replacing lime mortar (reduced modulus of elasticity in the passage of pre-stressing bars), etc. The final effect of the different deformation in each directions, can also be caused by concentrations of bricks with a low modulus of elasticity in certain places and by failing to ensure the same strength in throughout of the masonry block.

In practice, it is impossible to obtain all the necessary data for modeling. According to the above listed models sufficient obtain only appropriate number of samples and determine the necessary physical and material properties of brick and mortar, which serve as input variables in the calculation. Important values are the strength which is required for introducing the tensile force. Assessment of the effective area of anchor plates, density of materials and modulus of elasticity of both materials.

The ideal situation occurs, if we know the actual process of working diagrams of material used. Then the results of the numerical model come closer to the actual measured values.

Modeling of the test sample with a thickness of 20 mm was not done due to of the interference of the results from the previous pre-stressing.

IV. CONCLUSION

The contribution was dedicated to the experimental measurement of pre-stressing masonry, which was subjected to a tri-axial strain. Using differently sized pre-stressing forces resulted, as expected, in linearly increasing stress and strain (displacement) in the structure. Measurements showed higher local maximum values in the most exposed areas (termination of pre-stressed wire ropes). Generally, the monitored variables are the most acute in the anchor area of pre-stressed wire ropes, where they continuously and evenly disperse further into the structure and their values decrease with the increasing distance from the anchoring plates.

Comparison of finite deformation of anchor plates with different thickness showed different compression masonry around the anchor plates. These differences were caused by the different flexural rigidity plates. When the anchor plate had higher flexural rigidity then deformation of masonry was higher during loading pre-stressing force. To verify the hypothesis will be needed to do measuring of the pre-stressing masonry with using anchor plate with greater flexural rigidity than before. Then comparison will be done with the already obtained values which are in this paper.

Numerical models will be fine-tuned during the experimental testing, so that these models, correspond with their properties, as much as possible to the actual behavior of masonry with regard to the formation of cracks and brittle behavior of bricks. The result should be an easier creation of a model, which could avoid modeling of individual components of the masonry, and would be sufficiently accurate to obtain results without performing time-consuming experiments.

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