The Possibilities of Numerical Modeling of Reinforced Masonry and its Comparison with Real Measurements on a Test Sample of Masonry

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Abstract— The paper deals with various ways of modeling pre-stressed masonry and examination of the influence input data on the modeling results. The process modeling of properties of masonry is carried out for many years. The expression of optimal solution of the modeling is very large and is dealt with in a number of works, therefore should be limited for some procedures. The aim is to create the simplest models with outputs that are most correspond with the actual measurement. The basic model is designed as micro-model. Process of modeling is divided into three phases. In the first stage it is used the material linearity of all input data considering on the initial strain in the pre-loaders element. Subsequently is performed consideration of the effective area in the anchorage zone. In the last phase enters into modeling material nonlinearity of selected materials. All phases are implemented in software ANSYS. At the end all phase are compared. Then the models are compared with real measurements on a test sample of masonry. All input values are obtained from laboratory tests of the experimental measurements including statistical evaluation of the input data. The comparison is serving as verification of the functionality of individual phases of models.

Keywords— Masonry, reinforced, modeling, FEM, pre-stressed structures, deformation of masonry, nonlinearity, experimental measurement.

I. Introduction

With the advent of modern technology is occurring to the development of numerical programs. Part of this development is also an effort to achieve the optimal solution simulating the behavior of masonry elements possibly masonry structures. Generally, for the numerical simulations of masonry are used three basic principles: The detailed micro-model, the simplified micro-model and the macro-model, according to the literature [1], [2], [3] and [4].

Detailed micro-model, hereinafter micromodel is suitable only for small cutout structure in which you can examine in detail the behavior of the individual components of masonry (brick and mortar) which is useful for scientific purposes. For large structure is such a model unrealistic. This is enough difficult for calculation.

Simplified micro-model not considered two different materials as in the case of detailed micro-model. There are used the widespread blocks. There is a need to determine the properties of the interface between those blocks. Interfaces are placed in the mortar joints axes.

The macro-model is suitable for use in practice because there isn´t the interface between masonry elements. Masonry is contemplated herein as a compact orthotropic material with the respective compressive strength, tensile and shear strength. Knowledge and practices of static analysis of structures masonry buildings including an overview of current modeling methods are dealt with in detail [5].

Utilization of material parameters obtained from experiments in accordance with the actual geometry of both materials can be used in numerical models that simulate the behavior of masonry structures [6] and [7]. However, the actual arrangement of bricks and mortar larger part of the building is quite impractical because of the large amount of data entering the calculation.

On the based simplification of the models were focused much research in numerical modeling of masonry on the homogenization process. The problem of solving homogenization was possible approached in two ways. The one from option: gather the experimental dates which were used for analysis. There solutions were limited by the conditions under which the experimental values were obtained. The second from option: create a series of experimental tests with known boundary conditions which were enough expensive.

II. Numerical Simulation of Masonry

The model of masonry structure is modeled according to the parameters of prepared test of masonry. In the first phase were

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carried out numerical models of masonry in order to determine how the structure will behave. Then the prepared test of masonry was tested and was implemented the comparison with already created model - verify the actual behavior of the tests and numerical models. The calculation includes actual measured material properties of masonry obtained from strength tests on the specific samples. The values of modulus of elasticity for masonry units and mortar were also obtained from the tests on the specific samples.

A. Input Values of Used Bricks and Mortar

During the modeling is drawn approximately arrangement of masonry elements which correspond to the imposition of clay bricks in masonry (a thickness of wall is 450 mm) including liaison and bed joints of mortar. The geometry of masonry units and of mortar joints in the numerical models show some deviations by the actual test sample. The geometric deviations are caused due to unrealistic control of the precise location of all components in the test sample. The dimensions of the bricks are 290 x 140 x 65 mm and the thickness of the lime mortar 10 mm. The test sample and the numerical model weren't plastered. Into the model is inserted pre-stressing rod which is anchored into the anchor plate. The anchor plate has the dimension of 300 x 300 x 10 mm. The dimensional parameters of anchor plate and the location of the pre-stressing rod correspond to the parameters of the test specimen according to Chapter 3.

Table 1: Input values for pre-stressing of masonry, anchor plate area A = 0.09 m2

Name	Unit	Material	
		Brick	Mortar
Density	kg/m^3	1500	1400
Compressive strength	MPa	9.90	0.80
Modulus of elasticity	MPa	4.20	0.08
Poisson´s ratio	-	0.15	0.20

The model is created from spatial finite element SOLID45 expressing individual material of bricks and of mortar joints. The steel anchor plate is modeled as the element SOLID45. The modulus of elasticity of steel anchor plate is 210 GPa. The input material parameters bricks and mortar are density, compressive strength, modulus of elasticity, Poisson's ratio, (in the Table 1). The Poisson's ratio of steel units is 0.3.

B. Creation of the Individual Models

The calculations of the numerical models are designed in three main parts which are identified as Model 1, according to the paper [8], [9], Model 2 and Model 3. Models are created in program ANSYS as a three-dimensional models and are modeled as micro-model (detailed rendering of the individual bricks and mortar layers).

The loads of numerical models are divided into two load case. In the first load case is self-weight. In the second load case is vertical load [10], [11].

Model 1

In this model is contemplated insertion of the pre-stressing rod as uniaxial 3D element LINK8 including sectional area.

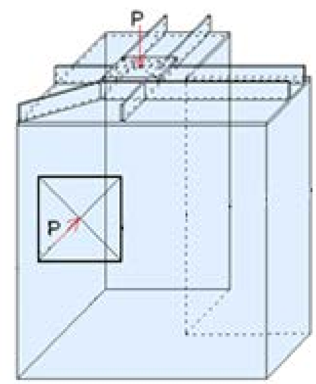

Fig. 1 The 3D schema of numerical model

The pre-stressing force was installed using the initial strain (into the element LINK8).

Table 2: Input values for Model 1

Loading process	Stress [MPa]	Initial strain [-]
10 %	28	1.5e-4
20 %	56	3.0e-4
30 %	85	4.5e-4

The initial strain is expressed by the ratio between the tension in the pre-stressing rod and modulus of elasticity of pre-stressing rod. Both of these values are shown in the Table. 2.

The modulus of elasticity of pre-stressing rod is 185 GPa, rod diameter is 26 mm and area of the rod is A = 5.309.10-4 m2.

The deformations of the Model 1 are shown in Fig. 2 and the resulting values from the numerical model are shown in Table 5.

Model 2

The following model takes into account the effective area during of loading the structure. It is assumed that the pre-stressing force which is transmitted into the walls is divided equally on the effective area.

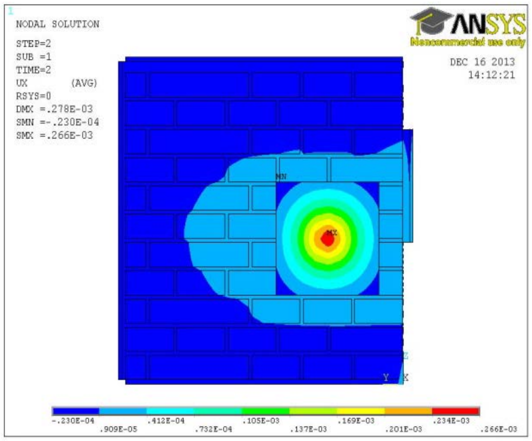

Fig. 2 The resulting deformation of Model 1, for the pre-stressing force 45 kN

If will used as input values for the material strength under the anchor plate the strength of mortar then the effective area of the anchor plate will be Aeff = 0.08 m2. This value was used to calculate the deformation of the brickwork on the numerical model. The original element LINK8 (by the Model 1) for expressing pre-stressing rod with the initial strain was replaced by the stress which acting on the effective area of the anchor plate.

In the Table 3 shows the values of stress under the anchor plate on the effective area about the value 0.08 m2 and the size of the pre-stressing force which was installed into the masonry. The deformations of Model 2 are shown in Fig. 4 and the resulting values from the numerical model are shown in Table 5.

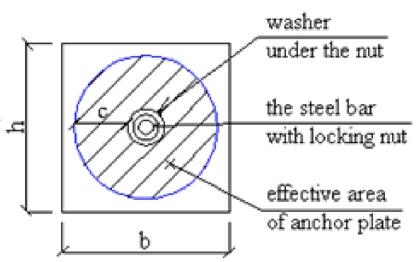

Fig. 3 Scheme of the effective area of the anchor plate about dimensions b, h

Table 3: Input values for Model 2

Loading process	Pre-stressing force [kN]	Stress [MPa]
10 %	15	0.187
20 %	30	0.374
30 %	45	0.561

Model 3

The last model is created on the based the same input data as the Model 2. There was retained effective area of the anchor plates. Additionally there was considered with the material nonlinearity.

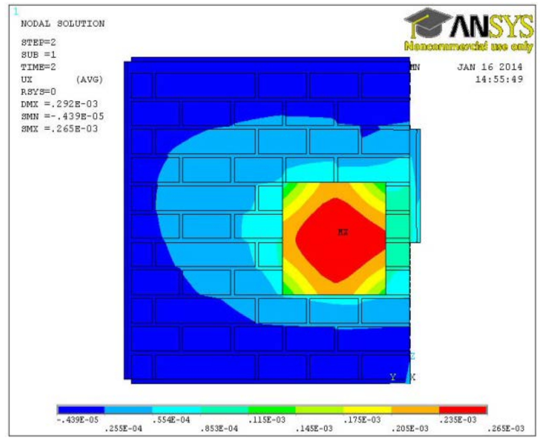

Fig. 4 The resulting deformation of Model 2, for the pre-stressing force 45 kN

The behavior of masonry elements have in the limited area of loading almost linear progression. The behavior of the mortar is similar as the behavior of concrete. The mortar in the compression exhibits nonlinear behavior at low values of loading. It can lead to development of cracks and thereby reduce of the material properties.

The input values of the pre-stressing forces and modulus of elasticity of the Model 3 are shown in the Table 4.

The bricks were left as a linearly elastic material because the modulus of elasticity of bricks at the stage of pre-stressing changed only minimally.

The deformations of Model 3 are shown in Fig. 5 and the resulting values from the numerical model are shown in Table 5.

Table 4: Input values for Model 3

Loading process	Pre-stressing force [kN]]	Modulus of elasticity of mortar [GPa]
10 %	15	5.8e-2

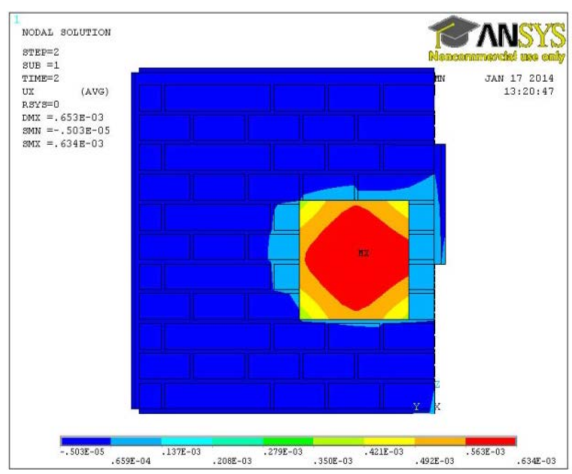

Fig. 5 The resulting deformation of Model 3, for the pre-stressing force 45 kN

20 %	30	4.0e-2
30 %	45	2.1e-2

III. The Actual Behavior of the Structure during the Measurement

Laboratory equipment for testing of tri-axial stress consists of a steel structure with dimensions of 900 x 900 x 1550 mm. In the structure there is an in-built brick corner with a height of 870 mm. The wall thickness is 440 mm. The used masonry elements are CP 290 x 140 x 65 mm and used jointing material was lime mortar, mixed with sand in the ratio of 1:4. During the brickwork pre-stressing rod was inserted in the masonry (see Fig. 6). The pre-stressing rod was placed at the height of 390 mm. After the final brick walling of the bricked corner, the upper part of the structure was aligned by a layer of mortar and was put a steel plate with a thickness of 12 mm and with welded steel reinforcements to ensure even load on the masonry. The steel anchor plates were put on a layer of mortar for leveling of the surface of the masonry [12], [13] and [14].

Pre-stressing force was installed in the pre-stressing rod also by hydraulic cylinders through the anchor plate with dimensions of 300 x 300 mm and a thickness of 10 mm [15], [16]. Area of anchor plate was 0.09 m2. The measured deformations were recorded using potentiometric sensors

Fig. 6 Course of walling

Fig. 7 Course of walling

attached to laboratory equipment, identified as connected to the measuring station. Sensors were attached according to Fig. 7 and Fig. 8.

On the Fig. 9 is graph of resulting deformation. The x-coordinate contains values of deformations with a negative sign induced by the pressure of anchoring plate on masonry. Resulting deformations are obtained by averaging of the measurements in vertical sections M21 ~ M24 (Sec. 1) and M25 ~ M28 (Sec. 2). On the vertical axis there are elevation

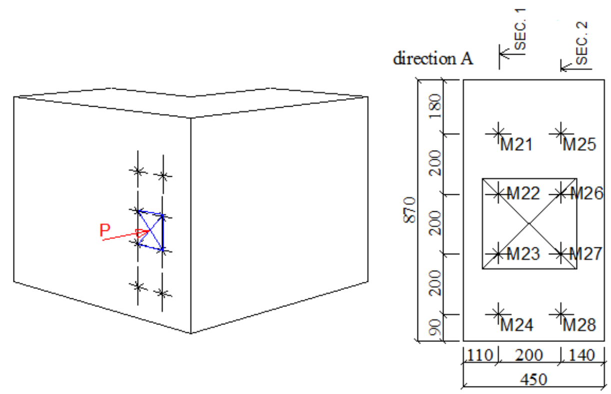

Fig. 8 Layout of measurement sensors, masonry with anchor plate 300 x 300 x 10 mm

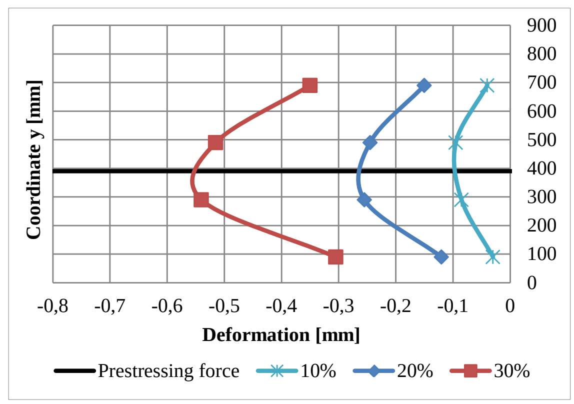

Fig. 9 Progress of masonry deformation, anchor plate 300 x 300 x 10 mm

coordinates of the location of individual sensors according to Fig. 8. All sensors were placed on bricks or on anchor plate 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 at the place of pre-stressing rod corresponds to the stress concentration just below the anchor plate while above and below the anchor plate the deformations are smaller. Courses of deformation are approximately at equal distances for each size of pre-stressing force.

IV. Comparison of Results of the Models and Measured Values

The Table 5 shows the maximum values of deformation obtained from measurements and numerical modeling by the Model 1, the Model 2 and the Model 3.

Table 5: Maximal deformation of masonry from

measurement and numerical model, anchor plate 300 x 300 x 10 mm

Loading process	Measurement deformation	Deformation of the numerical model		
		Model 1	Model 2	Model 3
10 %	0.100	0.020	0.069	0.087
20 %	0.280	0.048	0.145	0.245
30 %	0.580	0.073	0.230	0.528

The above-mentioned results of the comparison of laboratory measurements and numerical models are set to the maximum measured value at the edge of the anchor plate.

To illustrate the differences between the models are shown outputs from software ANSYS on the Fig. 2, 4 and 5. The Models are burdened pre-stressing force of 30% of the strength of masonry in a direction perpendicular to the bed joint which is achieved under the anchor plate.

A prerequisite of the behavior of the compression area was that area will have a circular shape, while according to the model 2 and 3 is this area irregularly shaped. The difference may be caused by insufficient fineness network of anchor plate. Comparison of Model 1 and Model 3: Model 3 is much easier because there isn´t need to model the pre-stressing rod. Nevertheless, in the Model 3 is needed always ensure change of the second load case (the change of the value of stress on the anchor plate with a constant contact area).

From a comparison of the values of the Model 1 and measured values can be stated that they are totally different. In the event that the actual the modulus of elasticity of pre-stressing rod will be lower about 10 GPa (max. deviation given by the manufacturer) then all resulting deformation values increase by only 0.001 to 0.003 mm. In comparison with the values of the measurement this increase hasn´t effect on the

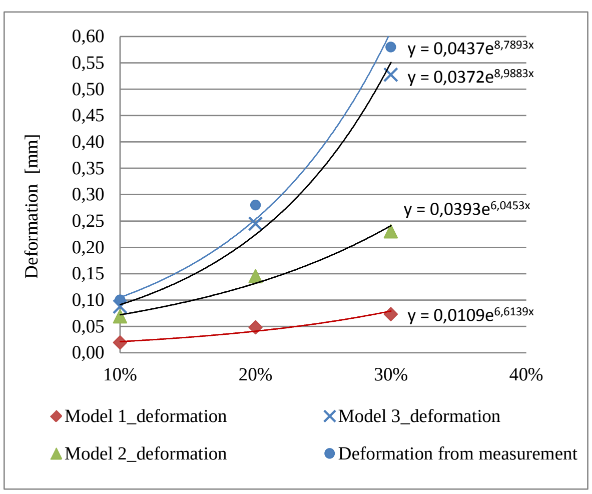

Fig. 10 Comparison of results of the measurement deformation and deformation of the numerical models, anchor plate 300 x 300 x 10 mm

final deformation. The Model 1 is completely inappropriate for any numerical simulation of pre-stressed masonry structures.

Using the effective area of the anchor plate (the Model 2) the maximum deformation of numerical model significantly increased. Although this model is not entirely suitable for the numerical simulation of pre-stressed masonry is visible that the results are better than the Model 1. An appropriate solution would be the introduction of material nonlinearity into the numerical model [16], [17].

The results from Model 3 show that the final values of the deformation of the numerical model are almost identical with measured values. The final results substantially more correspond to the measured values when we changed the material characteristics of mortar in the numerical model.

Finding agreement between simulation and measurement is quite challenging due to the many variables in the calculation. Considering how much is a masonry structure which consisting usually of two elements with quite different properties for the modeling difficult then those results can be considered almost excellent [18], [19].

It must be noted that the above models are fairly idealized. This idealized state has influence on the final deformation. Especially in places where are the bricks or mortar with a smaller modulus of elasticity than is expected (the inhomogeneous structure) [20], [21].

V. The Behavior of the Numerical model and the Measurement of Masonry with Smaller Anchor Plate

A. Used Material and Input Values for Modeling

Input values for laboratory equipment was the same according to the chapter 3. During the brickwork pre-stressing rod was inserted in the masonry (see Fig. 11). The pre-stressing rod was placed at the height of 355 mm [22] and [23].

Pre-stressing force was installed in the pre-stressing rod also by hydraulic cylinders through the anchor plate with dimensions of 150 x 150 mm and a thickness of 10 mm. Area of anchor plate was 0.0225 m2. The measured deformations were recorded using potentiometric sensors attached to laboratory equipment, identified as connected to the measuring station. Sensors were attached according to Fig. 11. The model is created from spatial finite element SOLID45 expressing individual material of bricks and of mortar joints. The steel anchor plate is modeled as the element SOLID45. The modulus of elasticity of steel anchor plate is 210 GPa. The input material parameters bricks and mortar are density, compressive strength, modulus of elasticity, Poisson's ratio, (in the Table 6). The Poisson's ratio of steel units is 0.3.

Table 6: Input values for pre-stressing of masonry, anchor plate area A = 0.0225 m2

Name	Unit	Material	
		Brick	Mortar
Density	kg/m^3	1535	1740
Compressive strength	MPa	9.90	0.429
Modulus of elasticity	MPa	4.20	0.03
Poisson´s ratio	-	0.15	0.20

Table 7: Input values for Model 3, anchor plate 150 x 150 x 10 mm

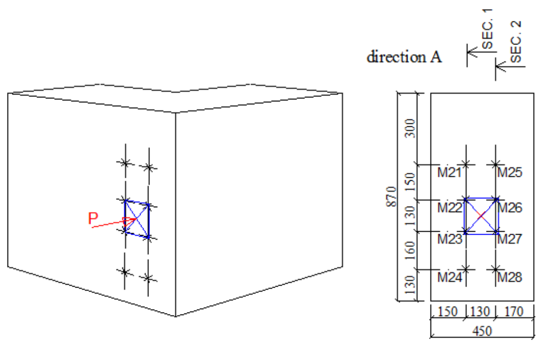

Fig. 11 Layout of measurement sensors, masonry with anchor plate 150 x 150 x 10 mm

Loading process	Pre-stressing force [kN]]	Modulus of elasticity of mortar [GPa]
10 %	3	3.0e-2
20 %	6.5	1.5e-2
30 %	10	1.3e-2

B. Results of Measurement and Numerical Modeling

Table 8: The values of maximal deformation of masonry from measurement and numerical model, anchor plate 150 x 150 x 10 mm

Loading process	Measurement deformation	Deformation of the numerical model		
		Model 1	Model 2	Model 3
10 %	0.140	0.055	0.115	0.135
20 %	0.890	0.080	0.255	0.445
30 %	1.080	0.105	0.390	0.761

In the Table 8 are the maximal values of deformation which were obtained from measurements and maximal deformation from numerical models. Model 1 - linear model according to the Chapter 2.2.1, Model 2 with the effective area of anchor plate according to the Chapter 2.2.2 and Model 3 with effective area of anchor plate and nonlinearity of mortar according to the Chapter 2.2.3. Effective area of the models is the same as the area of anchor plate, Aeff = 0.0225m2.

The resulting values from numerical models are less than the values from measurements. On the Fig. 12 the results (measurements with anchor plate 150 x 150 x 10 mm) are less

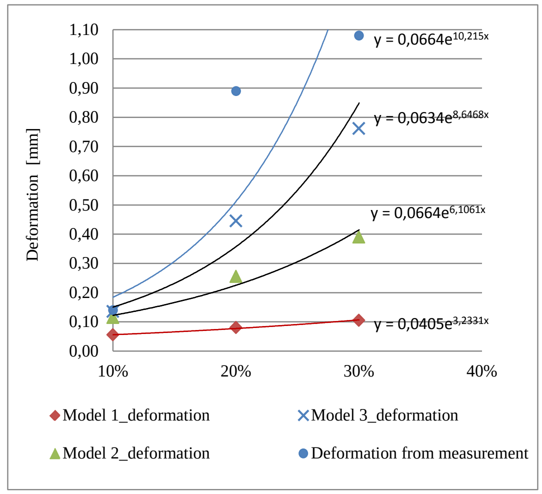

Fig. 12 Comparison of results of the measurement deformation and deformation of the numerical models, anchor plate 150 x 150 x 10 mm

accurate than the results from measurements with anchor plate 300 x 300 x 10 mm. It is perhaps caused higher value of modulus of elasticity. The differences may be caused by unevenness of the substrate. According to ČSN EN 1015-11 [24] is prescribed compaction of mortar in two layers. Each layer has to be compacted with 25 blows but this conditions can´t ensure on the experiment. Hereby occur different diagram of the sample taken of mortar and working diagram of mortar of real experiment.

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. 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. In practice, it is almost 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. The most important values are the strength of materials which are required for introducing the tensile force.

VI. Conclusion

The article deals with the creation of simple numerical models of masonry structures which were then compared with measured data according to laboratory tests.

Using differently sized pre-stressing forces resulted, as expected, in linearly increasing stress and strain (displacement) in the structure. The model created from individual bricks and mortar showed higher local maximum values in the most exposed areas (termination of pre-stressed wire ropes). Stress and strain in these critical areas greatly affected mainly the nearest bricks and mortar, the other elements, however, are influenced only insignificantly.

From the comparison was evident the influence of input values in the numerical models on the resulting behavior of pre-stressed masonry. The adjustment of the effective area had a positive influence on the compressed area and also on the final value of the deformation of the masonry. The material nonlinearity of mortar showed a smaller compressed area than the previous two models but the change caused accordance between the numerical model and actual measurement.

Of course can´t assume that this is the final stage of models. In this way it would be possible to proceed further and change all values up would be achieved perfect accordance of boundary conditions including variables in the calculation between numerical models and actual measurements.

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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