
Radim ČAJKA¹, Lucie MYNARZOVÁ²**NUMERICAL MODELLING IN ANALYSIS OF MASONRY STRUCTURE
ON UNDERMINED AREAS****VYUŽITÍ NUMERICKÉHO MODELOVÁNÍ PŘI ANALÝZE ZDĚNÉ KONSTRUKCE
NA PODDOLOVANÉM ÚZEMÍ****Abstract**

Prestressing of damaged masonry structures is among the most effective ways of reconstruction of buildings on undermined areas. Numerical modelling could be used with advantage for design of prestressing tendons as it is shown in this paper. Considering heterogeneity and orthotropy of masonry, its modelling is not defined sufficiently. After all, some methods for homogenized properties of masonry could be already applied.

Keywords

Masonry structures, pres-stressed masonry, undermined area, reconstruction, FEM

Abstrakt

Předpínání poškozených zděných konstrukcí patří k nejúčinnějším metodám sanace objektů na poddolovaném území. Při návrhu předpínacích lan lze s výhodou využít numerických modelů, jak je ukázáno v tomto příspěvku. Modelování zdiva není zatím s ohledem na jeho heterogenitu a ortotropii dostatečně přesně popsáno a definováno, přesto již lze aplikovat některé postupy pro tvorbu homogenizovaných vlastností.

Klíčová slova

Zděné konstrukce, předpjaté zdivo, poddolované území, rekonstrukce, MKP

1 INTRODUCTION

Masonry structures are among favourite constructions in this territory. There were built throughout ages and still have their place in spite of steel and concrete being preferred materials now. Though the masonry is a well-proven building material with good strength and durability, failures have been appearing in masonry structures. Reasons might include insufficient or unsuitable maintenance of a building, new use of the structure, or changes in functions or purpose of the building which could increase the load. Or neighbouring environment may negatively affect the structure by dust, noise level or near-by transport.

In the north of Moravia, specific failures are due to industrial and mining activities. Though the mines have been shut down in many locations, undermining effects are still appearing even

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several years after such shutdown. The undermining results, among others, in uneven settlement of foundation soil which affects all building structures. In towns, an analogy might be construction of underground combined utilities which may result in similar failures as the mining effects. Masonry structures are very sensitive to the undermining effects – supports are going down or dislocated horizontally, cracks are appearing, walls are collapsing or falling down, and corners or wall crossings become damaged.

2 REDEVELOPMENT OF MASONRY CONSTRUCTIONS IN UNDERMINED AREAS

The masonry constructions affected by the undermining (for instance, by horizontal strain or curvature of the landscape) are typically remediated by introducing an additional horizontal or space reinforcement into the building (Bradáč, 1999). The horizontal reinforcement can be performed by several ways, for instance by reinforced concrete frames, steel towbars or prestressing cables. The reinforcement is done typically in several height levels – at the foundation structure (Fig. 1) and at least in the top floor. Typically, the reinforcement is introduced in all floors in the levels of ceiling structures.

The steel drawbars and prestressing cables are more efficient. They can be used also as a temporary solution for the time when the mining effects exist or to underpin temporarily the building during building adaptations near the building structure. This solution helps to reinforce generally the structure in the space. The prestressing cables, after having been prestressed, create, together with the structure, a sufficient pressure reserve and maintain their efficiency throughout service life of the building.



Fig. 1: Additional prestressing of the foundations

After the prestressing cables clamp in the building structure, not only the necessary prestressing is introduced, but the strength of the structure improves considerably without having to increase the mass (the quantity) of the material. The prestress also prevents tensile cracks from being created or existing cracks may lock in. The introduced prestressing can also balance the external load (wind, earth compression or earthquake) which could result in bended walls or tensile cracks, if the wall were not reinforced.

Using the prestressed steel cables for clamping the damaged building (Fig. 2) is a very efficient and fast solution. It provides a good combination of a reasonable price and considerable effect on statics of the building. This solution can relatively easily save even such buildings which are heavily damaged.



Fig. 2: Clamping the building on the undermined territory using the prestressed cables

The correctly designed system of the prestressing cables is, however, the very end of a rather complex process where some key questions should be answered: what are properties of the masonry, what is the proposed total prestress according to standards in force, what is a numerical model of the masonry, or what is the ultimate carrying capacity and usability in the course of time.

All those four questions should be addressed within a comprehensive solution developed by a designer. Each masonry building is different (the used material and strength, type of failure, wear during the service life, historic or social importance are different). Therefore, the best solution for the designer is to combine several methods: normative procedures, information provided by prestress material manufacturers, masonry sample tests, experiments with several masonry structures and, last but not least, the numerical modelling which is considerably cheaper and simpler, if compared with the experiments. This paper describes creation of a numerical model of the masonry and subsequent use of the model for assessment of various alternatives for locations of the prestressing cables in the wall which has been damaged by subsidence of the supports.

3 NUMERICAL MODELLING OF THE MASONRY

The numerical modelling is a very efficient tool in scholar and design works. FEM software has been used for years in analyses of steel and concrete structures but the masonry is still a specific material with features which cannot be described precisely and reliably or be used as a basis for software intended for experts.

The masonry is anisotropic and heterogeneous material, the basic components of which – the bricks, masonry elements and mortar – have different compositions and behave differently. The masonry elements are typically very fragile, though featuring a relatively high compressive strength. In a certain load range, the behaviour of bricks is almost linear. The linear behaviour ceases upon a failure when a brittle failure may appear. On the other hand, the mortar behaves similarly as concrete – this means, during the modelling procedures available for analyses of concrete structures can be applied. In the compressive domain, the mortar behaves in a non-linear way beginning with very low values and its ductibility is relatively high. If subject to tension, the mortar behaves almost linearly but cracks start appearing quickly, reducing properties of the material. It is also necessary to keep in mind the properties of specific materials because it is also essential to formulate their mutual relations in contact surfaces (the friction parameters) and to determine the behaviour of such elements after they fail.

3.1 Micromodel

In general, there are two basic principles used in the modelling of masonry. They can be referred to as micromodelling and macromodelling (Lourenco, 1996). The micromodel depicts separately individual bricks. It is, however, problematic to solve contact surfaces representing the mortar between the bricks. If a **detailed micromodel** is used (Fig. 3a), the mortar and brick are modelled as two different materials with real dimensions and layout in the construction. A **simplified micromodel** (Fig. 3b) uses „extended“ units (blocks) which comprise the mortar and a part of the surrounding mortar joint. The simplified micromodel is similar, to a certain extent, to the detailed

micromodel. It is not, however, so accurate because it does not take into account two different materials. The contact surfaces – the interface—are located in axes of the mortar joints and the properties of the both materials are included into a characteristic of a kind of homogeneous blocks. The geometry, however, does not correspond to real layout of the bricks. The biggest challenge is to determine properties of the interface.

The micromodel may represent in detail real components of the masonry. Typically, a small cross-section of the masonry is being dealt with and the behaviour of the bricks and mortar are investigated in detail. This model is suitable more for scholar purposes. In case of rather big structures it is not possible to create such a detailed model and the calculation would be too demanding there. The micromodel can be also used as a basis and a starting point for determination of properties of the macromodel.

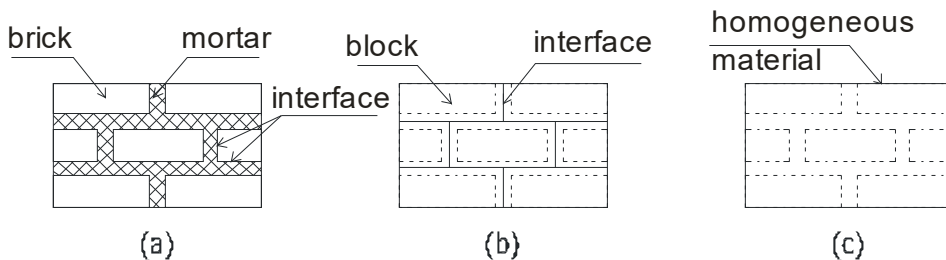


Fig. 3: Basic strategy for modelling of the masonry structures: (a) detailed micromodel; (b) simplified micromodel; (c) homogeneous macromodel.

3.2 Macromodel

The masonry can be regarded as a material with the heterogeneous, though regular structure where individual bricks of the same size repeat in a regular pattern. Then, the masonry modelling can be modified. When using the simplified modelling of the heterogeneous masonry, it is necessary to find a suitable model (the macromodel) with homogeneous characteristics which could be used for the modelling of the whole of the structure.

The macromodel (Fig. 3c) is more useful in practice and designing work. The approach is different from the detailed micromodel. It is not important anymore to describe precisely the interface between the bricks because the masonry is depicted as a compact orthotropic whole, though being a homogeneous material with the respective tensile strength, compressive strength and shear strength. Attention is paid to the resulting behaviour of a rather big section of the masonry which is often loaded in its non-elastic domain. The macromodelling should describe in detail behaviour of the real masonry structure but the tools used in the modelling should also streamline creation of the model and should require reasonable performance of operation memories of standard computers.

The question is, however, how the homogeneous properties of the materials could be determined or identified at best so that could correspond to behaviour of the real masonry. There are several methods or procedures which can be used in determination of the homogeneous properties. Each method has got, however, its pros and cons. In general, two basic approaches can be used in creation of the homogeneous material:

- **the constitutive relations** can be used to describe behaviour of the masonry (the masonry model is modified by adaptation of the models for concrete, the assumption being that the mortar behaves similarly as concrete);
- **the homogenising process** is based on properties of the individual elements (the bricks and mortar) – either calculations or experimental measurements or a micromodel are used as the starting point for definition of the homogeneous orthotropic properties of the micromodel.

3.3 Example – determining the homogeneous properties of the macromodel

The following chapter describes an analysis of a masonry wall damaged by vertical subsidence of supports because of undermining effects. The basis for the analysis is the macromodel. The properties result from the homogeneous process (Brožovský et al., 2007), the first step being creation of a detailed micromodel of the wall with the dimensions of 2.09 x 2.015 x 0.44 m. Using the micromodel, it is possible to plot precisely the individual bricks and mortar joints. In the wall model, stretchers and headers take turns in a regular bond pattern. Along the wall height, the bond alternates in two layers – this means the open joints do not overlap (Fig. 4 right).

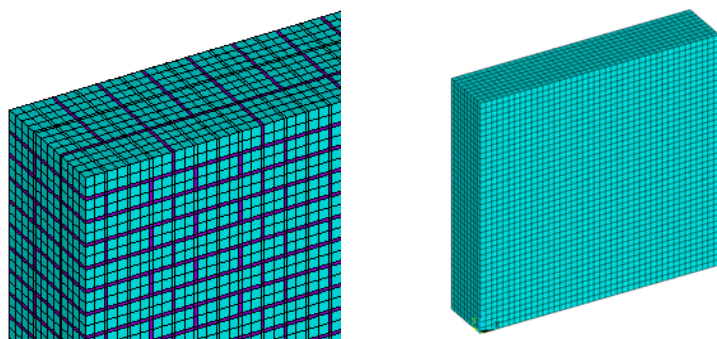


Fig. 4: Detailed micromodel – a part (left); homogeneous macromodel (right)

The masonry in the micromodel consists of two different, though homogeneous materials. The brick and mortar have got each their own parameters - the modulus of elasticity E , Poisson's ratio ν and specific gravity ρ . If only one side of the wall of the micromodel is loaded with constant deformation and the other side is supported, we can obtain, using the resulting reaction/force, the surface and magnitude of the deformation, Young's modulus of elasticity in compression and tension E for that direction. If the sides are loaded by analogy in two other directions, we obtain two other moduli of elasticity.

The modulus of elasticity in shear G is obtained similarly as the moduli of elasticity in compression and tension. The wall was loaded then with gradually increasing deformations so that it became bevelled. Using the resulting response, surface and angle, we obtained the moduli G for all three directions. Poisson's ratio can be regarded as equal to 0.2 or they can be calculated using the ratios between the coefficients and moduli of elasticity for certain directions (see Brožovský et al., 2007).

This is a brief description of one of methods which can be used for determination of nine material constants which are needed for the equations that describe the orthotropic material: 3 Young's moduli of elasticity in tension and compression (E_x , E_y , E_z), 3 Poisson's ratios (ν_{xy} , ν_{yz} , ν_{zx}) and 3 moduli of elasticity in shear (G_{xy} , G_{yz} , G_{zx}).

In the next step, the macromodel was created (Fig. 4 right) – it was simply modelled as a homogeneous block with necessary dimensions and defined orthotropic properties. If compared with the micromodel, the creation of the macromodel is rather easy and not so high performance of PC's operation memory is required.

4 VERTICAL SUBSIDENCE OF SUPPORTS

The case below describes a brick wall loaded with forced strain because of landscape curving. The undermining resulted in vertical subsidence of supports. Using of prestressing tension cables would be, in this case, a good solution to redevelopment of the building. The designer can use a well-proven macromodel and verify several locations for and numbers of the prestressing cables,

magnitude of the prestressing forces and similar parameters. This chapter describes influence of the prestressing cables on stress in the construction.

A 2D model of the brick wall with orthotropic properties was created. The dimensions are 10 x 2.5 m (Fig. 5). The homogeneous orthotropic properties were determined by analogy pursuant to chapter 3.3. The wall is supported along the lower edge in such a way that the load applied from above results in vertical subsidence of the supports. In the central part of the wall, the subsidence is zero and increases symmetrically towards the both edges of the wall, reaching finally 42 mm. The subsidence caused undesirable tensile stress to be created in the wall without reinforcement. If prestressing cables clamp in the construction, the tensile stress decreases or even ceases to exist. Efficiency of the prestressing depends, however, on suitable location of the cable and magnitude of the prestressing force.

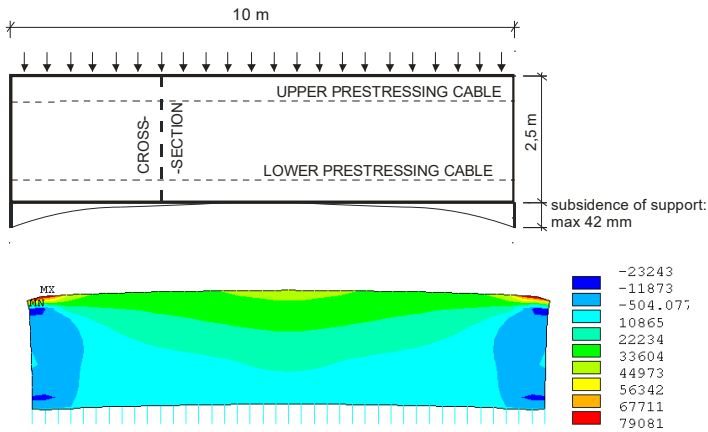


Fig. 5: Wall with vertical subsidence of support - geometry and development of vertical stress

Fig. 6 shows development of the stress along the wall height in a cross-section made approximately in one third of the wall length about 3 meters from the left edge of the wall. Several alternatives of prestressing cable's effects were investigated into. The leftmost curve ("without the cables") shows the development of the stress along the wall which is not reinforced at all. It is clear that the masonry is fully subject to tension along the cross-section.

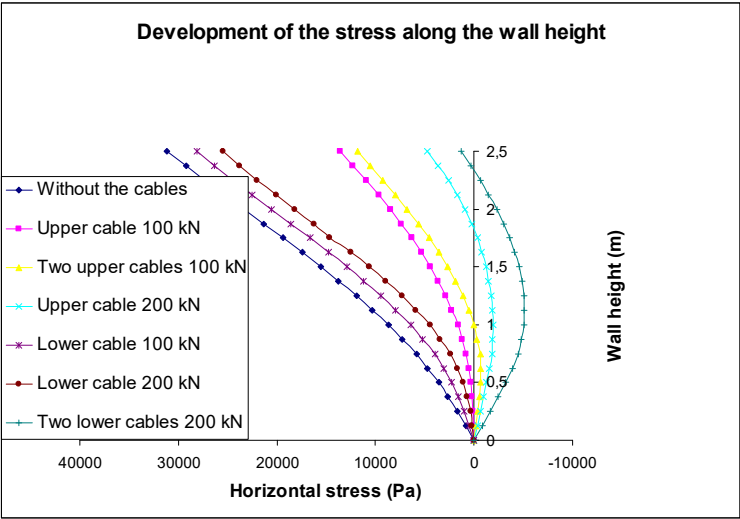


Fig. 6: Development of the stress along the wall height

If outer parts of the wall have gone down and the cables are installed close to the lower edge only, the prestressing almost does not play any role (see the curves “Lower cable 100 kN” and “Lower cable 200kN”) even if the prestressing force is increased from 100 kN up to 200 kN. Only after the prestressing cables are installed onto the upper surface of the wall or, simultaneously, onto the lower and upper parts, there is a considerable dislocation of values towards the compressive load which is transferred well by the masonry. The upper cable with the prestressing force of 200 kN eliminates considerably tensile stress, the most of the cross-section being compressed. If the same prestressed cable is added to the lower part of the wall, the tensile stress developed there is negligible only.

5 CONCLUSION

Using the software in designing or assessment of redevelopment measures for damaged masonry structures can be a very useful tool for all designers. Through the modelling of the wall is a very specific domain and a simple and clear solution does not always exist, so far, there is still a chance of using some methods for definition of homogeneous orthotropic properties of the masonry. The correctly designed system of prestressing cables can prolong service life of the structure by many years.

ACKNOWLEDGEMENT

This project has been carried out thanks to the financial contribution of the Czech Republic Ministry of Education, Youth, and Sport, project 1M0579 within activities of CIDEAS Research Centre.

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