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Numerical Modelling of Connections Between Stones in Foundations of Historical Buildings

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Abstract. The aim of this paper is to analyse the behaviour of old building foundations composed of stones (the main load-bearing elements) and mortar, based on numerical analysis. Some basic aspects of historical foundations are briefly discussed, with an emphasis on their development, techniques, and material. The behaviour of a foundation subjected to the loads transmitted from the upper parts of the structure is described using the finite element method (FEM). The main problems in analysing the foundations of historical buildings are determining the characteristics of the materials and the degree of degradation of the mortar, which is the weakest part of the foundation. Mortar is graded using the damaged-plastic model. In this model, exceeding the bearing capacity occurs due to the degradation of materials. The damaged-plastic model is the most accurate model describing the work and properties of mortar because it shows exactly what happens with this material throughout its total load history. For a uniformly loaded fragment of the foundation, both stresses and strains were analysed. The results of the analysis presented in this paper contribute to further research in the field of understanding both behaviour and modelling in historical buildings' foundations.

1. Introduction

Historical buildings are an important part of cultural heritage. The amount of historical objects and places constantly increases. Registers and records expand, the public interest grows, and everything old is fashionable. More and more often the theme of objects of historical value is discussed in the international arena. Relics of the past give us an information about the development of civil engineering, building materials, architecture and other branches of life.

One of the most important elements of historical buildings are their foundations. The analysis of their behaviour is an extremely complex issue. Lack of documentation, the variety of materials used over the centuries, and damages results in the stability assessment of the structure being problematic. In the literature, there is much research associated with the structural behaviour of today's foundation, which are made using modern technology. However, many historical structures are supported by foundations made in times when mechanical properties were much worse than the materials currently known. Such foundations are an assemblage of stones or bricks placed upon one on another to form a stable structure in a heritage construction. Mortar may be used to fill interstices, but it cannot be assumed to add strength to the assembly. The stability of the whole masonry structure is ensured by the compaction under gravity of the various elements. Only a few studies are devoted to foundations of historical buildings [1, 2, 3, 4] or the mortar of historical masonry walls [5, 6]. Regarding the numerical approaches, distinct element formulations have been applied to the study of foundations by

Giordano et al. [7] or Lourenco et al. [8]. Most of the papers concern the diagnostics and maintenance of specific buildings, and only a few analyse the mechanical behaviour of old foundations. Among the latter, numerical analyses (FEM - finite element method) of a settlement-induced damage to masonry have been presented by Prabhu et al. [9], by Acito and Milani [10] and by Milani [11], and some empirical equations for predicting the bearing capacity of brick masonry walls have been proposed by Sandoval and Roca [12]. The need to analyse the foundations of historical buildings and some solutions have been discussed by Kerisel [13], Dardzińska [4] as well as Przewłócki and Zielińska [14].

2. Characteristics of foundations of historical buildings

Since the beginning in the history of construction, the most popular building materials have been brick, stone, and lumber. Brick foundations in ancient times were made initially with sun-dried mud bricks, and later with fired bricks. Starting from the middle of the 3rd millennium BC, the size of bricks was standardized. Unfortunately, the literature provides scarce information on the physical and mechanical characteristics of dried clay bricks. It is known, however, that they are extremely sensitive to changes in moisture. Dried bricks obviously cannot be used to construct foundations. Their use in ancient times was due to the lack of better options, and it significantly reduced the durability of structures of that era in which they were employed.

There are notable differences in the basic physical and mechanical characteristics between fired brick of the past epochs and those produced today. They arise from a different course of forming bricks and a different firing process. Fundamental changes in brick manufacturing methods occurred eventually by the mid-19th century among others, as a result of the invention of the bend press, which produced bricks by the pulling method; the use of a vertebral furnace; and the improvement of the drying system.

Stone foundations were used mostly for sacred buildings and public utility structures. Various types of stone were used, depending on the function of specific elements of the building, the available equipment and workmanship, and the geographical location. They were often granite, limestone, sandstone, sandstone volcanic tuff, or even marble. The majority of stone foundations of historical buildings did not have offsets at all or they did not extend to the bottom. In addition, it would have been difficult in the past to find a mortar satisfying the current mortar strength requirements (excluding pozzolan). The fact that such foundations still effectively support many historical buildings should therefore be explained by their oversized dimensions.

A major breakthrough in construction occurred in the 3rd century BCwith the discovery and use of volcanic ash (puteolanum clay), later known as pozzolan. It was a variety of clay with excellent binding properties, originating from one of the cities on the Gulf of Naples. It became the raw material for the production of hydraulic lime. Its mixture with lime and water constituted a binder called Roman cement. Combining it with sand and small stones produced a material with properties similar to those of concrete used today. With time it came to be used on a large scale, first for making foundations, and then for other structural building elements – even for watertight platforms.

Among mortars in general, a binder used the longest and most widely was burnt lime. This material has been used continuously since the times of ancient Greece to the present day. In time, it was fired more precisely, mixed with sand (without admixtures of clay and contamination), often with charcoal or ceramic ballast. Sometimes, crushed limestone or gypsum was also added. In the Middle Ages, a special mortar was also produced with admixtures of organic substances, such as sugar solutions, beer, honey, milk, or chicken eggs, to accelerate the bonding process. Sometimes a decoction of fir cones was added, which, due to its content of resins, would additionally seal the wall, while at the same time protecting it from cracking in the cold. It should be emphasized that only few historical mortars could fulfil the current minimum requirements for such materials. In general, it seems reasonable to say that almost throughout history mortar was the weakest part of the foundation.

Over many centuries, wood was used to construct the underground elements of buildings, such as primers, piles, and rafts. In antiquity, to make piles, Vitruvius recommended the use of alder, olive, and oak wood. In the Middle Ages, piles were mostly made of oak, pine, or larch, and in modern times just oak or pine. As a rule, during the medieval period, piles with a length of 1–2.5 m and a diameter of 0.1–0.3 m were used in order to increase the compaction of the substrate.

Figure 1 presents selected old foundations dating from the sixteenth century in two Polish cities.

a) b)

c) d)

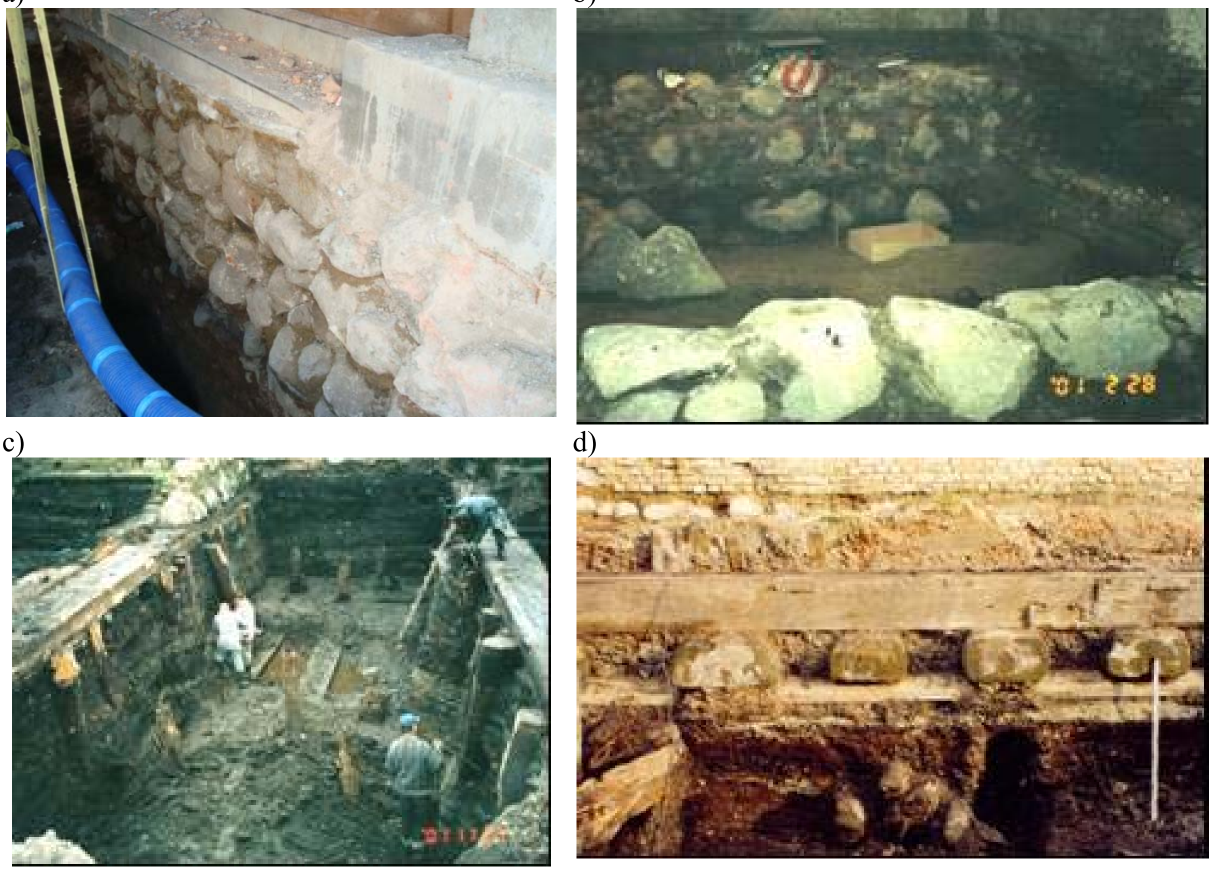


Figure 1. Foundations: a) a historical building in Olsztyn in Staromiejska Street, b) a Romanesque church in the Market Hall in Gdańsk, c) old granaries in Basztowa Street in Gdańsk, d) old granaries in Chmielna Street in Gdańsk

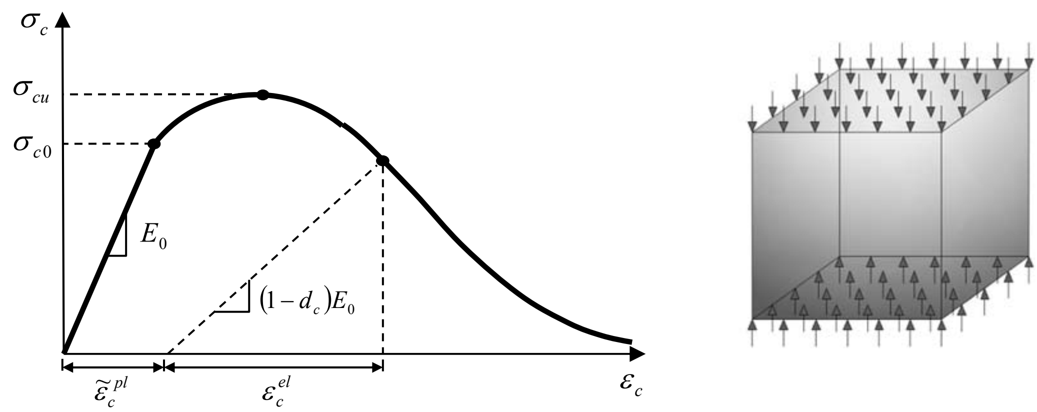
3. Damaged-plastic model

The damage-plastic degradation model of a material concerns the degradation of stiffness. The main essence of the model is to define the mechanism of destruction in the state of uni-axial and then improve the transformation of this mechanism for states more complex, multi-axis. The damaged-plastic model was investigated and developed by Lubliner in 1986 [15] under the name "Barcelona model". Lubliner proved that in the process of applying a load on concrete, the exhaustion of load-bearing capacity occurs due to the material's degradation from the increase of the external load. Hence, the loss of load bearing capacity takes place as a result of the increase of plastic deformations. The constitutive behaviour of material is defined by introducing a scalar variable d which quantifies the influence of microcracking. The change of the modulus of elasticity E due to variable d is given by the following formula:

$$E = (1-d)\cdot E_0 \tag{1}$$

, where E_0 denotes the initial modulus of elasticity and $(1-d)$ denotes the ratio of effective surface area carrying the load (total area less damaged surface) to the total cross-sectional area.

a)



b)

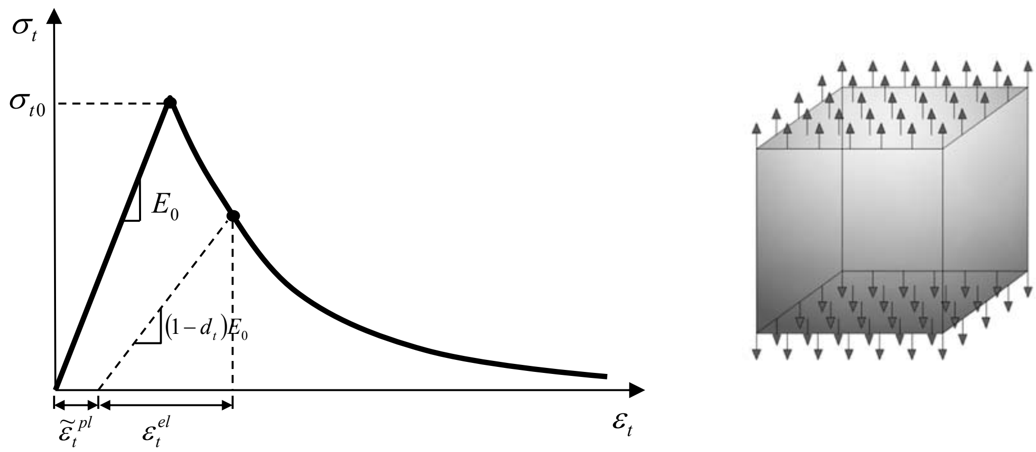


Figure 2. Concrete damaged-plastic model: a) compression, b) tension

The parameter d is a scalar variable describing stiffness degradation, which takes a value from 0 (undamaged material) to 1 (material completely destroyed). This parameter allows the tie mechanism of destruction in the form of cracking and crushing with a reduction in the stiffness of the material, but it is different in compression (figure 2a) and tension (figure 2b). The only similarity is the result of degradation which increases with the plastic deformation. In order to investigate the response of the material, two independent variables describing the material subjected to degradation, were introduced. Both of the function of plastic strain, temperature and additional variables.

4. Example of damaged-plastic model for modelling mortars

Numerical analysis was carried out only for the part of the stone foundation, due to the continuity of this element (figure 3). The considerations on the strengthening foundations were focused on a mortar, as it is often the weakest point of the historical building foundations. Behaviour of subsoil was not taken into account in this analysis. The analysed foundation has dimensions of 60×100×200, which are respectively width, height and length. Numerical analysis has been carried out by the finite element method. The stone foundation model was divided using solid elements. The number of the foundation elements generated by the FEM equals 2362 whereas the number of nodes equalled 4568.

The chosen part of the foundation is uniformly loaded on the top surface by load, which simulates higher parts of the building. The foundation element is secured at the base against vertical and horizontal displacements. The numerical analysis ensures compatibility solutions by applying the appropriate boundary conditions on the respective plane of symmetry. The components of the displacement of nodes lying on each plane of symmetry were blocked, so movement in the direction of the *y*-axis (figure 3) was impossible. For side foundation walls no restriction along *x*-direction are applied.

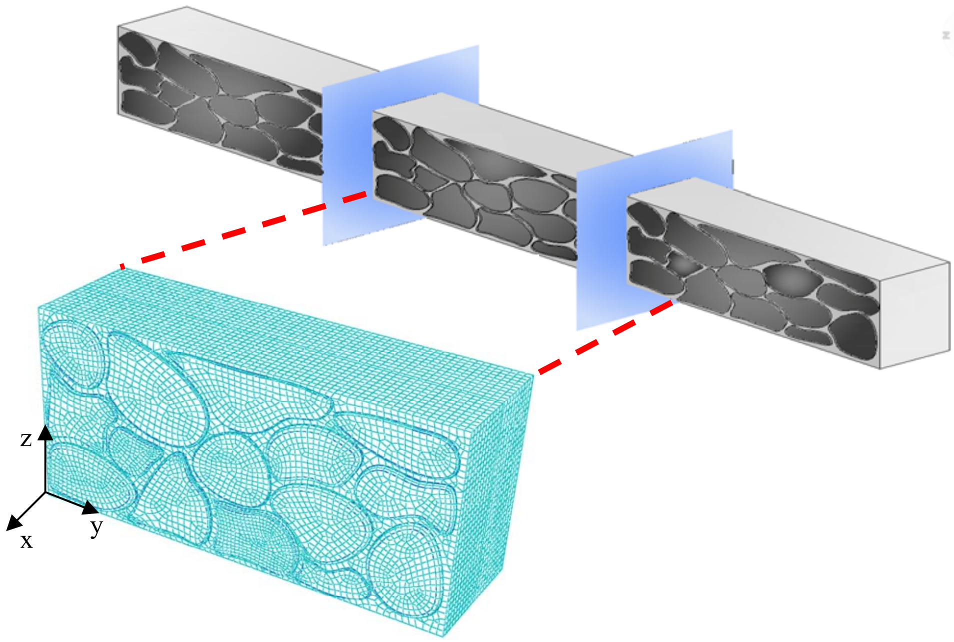


Figure 3. Part of the stone foundation taken to analysis with FE model

Four types of mortar were analysed: cement mortar, cement-lime mortar, lime mortar and gypsum mortar. Characteristic parameters for each of them are summarized in table 1. For historical building foundations the most accurate are gypsum and lime mortar. The other two were taken into account in the analysis for comparative purposes.

Table 1. Parameters of four types of mortar

Type of mortar	cement mortar	cement-lime mortar	lime mortar	gypsum mortar
Modulus of elasticity E [GPa]	20	12	7	4
Bulk density ρ [kg/m^3]	2000	1800	1500	1500

The results of the numerical analysis of the stone foundation, according to the damaged-plastic mortar model, are presented in figures 4 and 5. Maps of stresses for the four types of mortars are given in figure 4, while in figure 5 graph of stresses vs. strains for the measurement point marked on the maps is shown. Based on these results, it was found that the cement mortar, which is used today, is even 3 times stronger than the mortar used in historic buildings. For cement-lime, lime and gypsum strength is from 2.5 to 4 MPa, while for cement mortar strength reaches a value of 7 MPa.

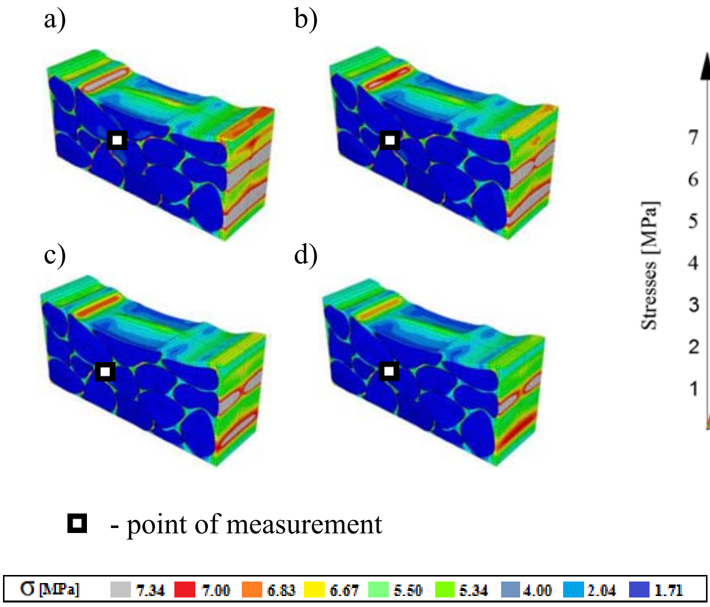


Figure 4. Damaged-plastic model: a) cement mortar, b) cement-lime mortar, c) lime mortar, d) gypsum mortar

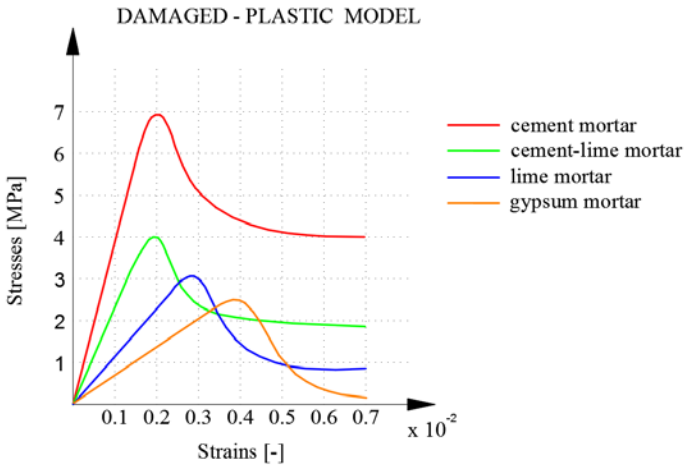


Figure 5. Stresses vs. strains for the damaged-plastic model

The maximum values of displacements and stresses for damaged-plastic model in relation with the modulus of elasticity are presented respectively in figures 6a and 6b. The largest displacements - 6.2 mm, were obtained for the mortar with the lowest modulus of elasticity (gypsum mortar - 4 GPa). The highest strength - 6.6 MPa were achieved by mortar with the highest modulus of elasticity (cement mortar - 20 GPa). For each type of mortar, which are expressed by Young's modulus, values of displacement and stresses can be estimated.

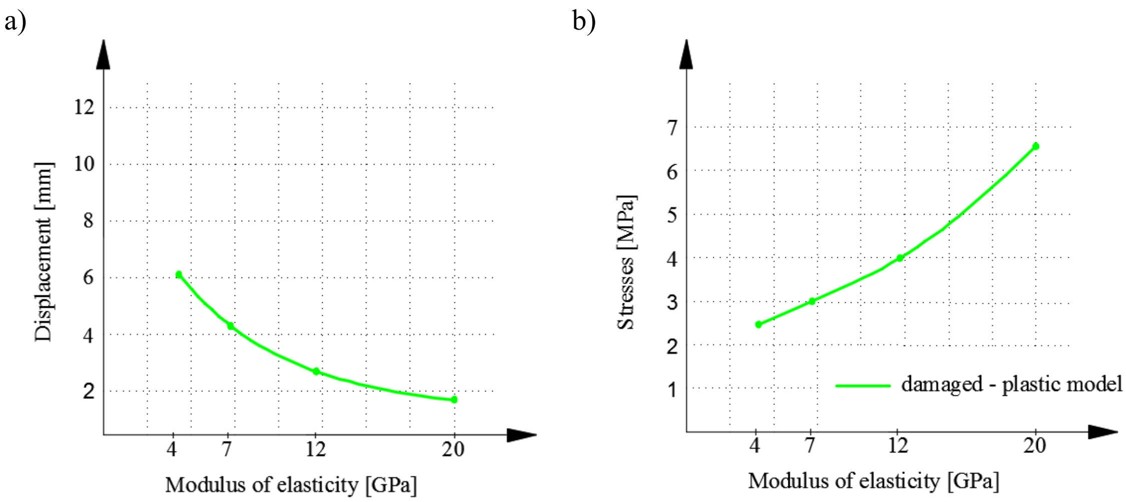


Figure 6. a) Maximum values of displacements and b) stresses for damaged-plastic model vs. modulus of elasticity

5. Conclusions

The assessment of behaviour of historical building foundations is a very complicated task. Correctly applied computer methods, based on the finite element methods, greatly simplify this process. They allow to estimate the strength of foundations and help to choose the methods of strengthening and improvement the condition of these building elements.

The numerical analysis of historical building foundations, shows that parameters of mortar have a significant impact on the results. Mostly, lime and gypsum mortar were usually used in Middle Ages in the past. Both of them have low bearing capacity relative to the cement mortar. The results show what the relationship between different types of mortars is. In the past, mortars were made of materials with weaker parameters. Currently, many historical buildings need to strengthen their foundations. The proposed method of modelling mortar (damaged-plastic model) in historical buildings shows, that values of displacements and stresses depend on the type of applied mortar. Results are the most preferred for cement mortar, because it achieves a strength of 7 MPa and a displacement of 1.8 mm. This is very important for strengthening foundations. Therefore, defects in the historical foundations, in order to strengthen them, are supplemented with cement mortar. The results of the analysis presented in this paper give a contribution to the further research in the field of understanding a behaviour and modelling of historical building foundations.

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