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Case Study of Masonry Pillars Reinforcement in a Medieval Church

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ABSTRACT: In medieval buildings there are several important carrying elements, in which there are substantial strains. One of these elements are masonry pillars. They transfer the majority of forces between the construction (e.g. arches, vaults) and the ground. In historic structures the basic problems are: the construction age, the mortar joints and damage to hand-made bricks. There exist many methods of preserving the masonry pillars. The main objective of this paper is to examine one of them using 15th century Church of the Most Virgin Mary in Summo in Poznań as an example. Besides pillars also the inner columns and vaults were considerable deflected. Finite element modeling was employed to determinate the best window pillars reinforcement method. The analysis of the model was carried out with environment ABAQUS, with finite element modeling strategy, based on the concepts of homogenized material. The results of the analysis show the possibilities of using the numerical techniques and enable the reliable assessment of preservation work, as for as the masonry carrying elements are concerned.

1 INTRODUCTION

The history of the site where Church of the Most Virgin Mary stands is very interesting. Under the ground there are foundations of a much older building. The archeological investigations prove that these remains date back to the 10th century and are the foundations of the mansion belonging to the Prince of Poland – Mieszko the First. At present a neogothic church from 15th century stands there. The first records of the church date back to the year 1247 AD. The building was built in a gothic style; it is believed to have been erected in several phases, between years 1431 and 1448. The building has three aisles with the altar in the centre orientation and five sided ambits. Above the floor there is the sidereal vault, beneath 10th century foundation structure of mansion Mieszko the First. The vault is supported by the six internal columns, circuit walls and ten window pillars. There is speculation regarding the existence of the 10th village on this site. The configuration below, follow Fig. 2 shows the church as it presumably was one thousand years ago.

The following paper presents part of all preservation work undertaken in the church. The rapid deterioration of the church necessitated the beginning of the preservation process. Apart from the aforementioned preservation of the pillars, an attempt has been made to assess the state of the vault's structure. The location of the church in the centre of the town, the proximity of the cathedral as well as its interesting history prompted the preservation work. At present the church is closed to the public. In the near future the archeological investigation is going to be undertaken inside the church.

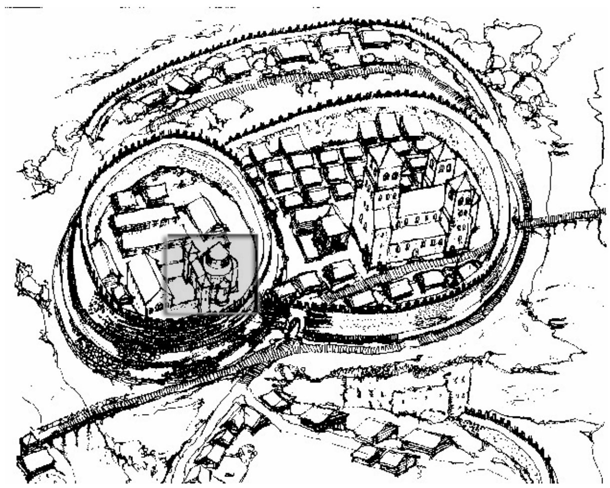

Figure 1 : Possible view of Mieszko the First mansion in X century

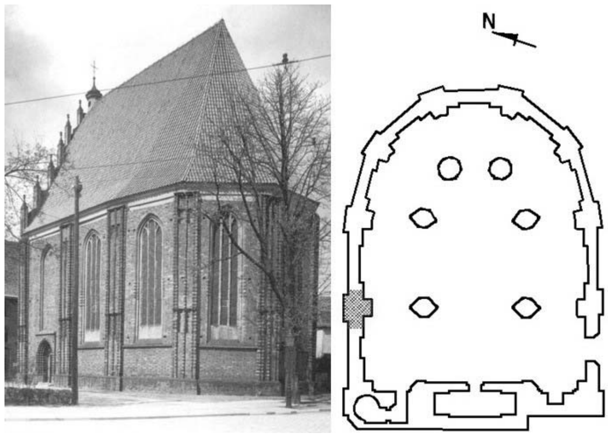

Figure 2 : Present configuration view Church of the Most Virgin Mary

Last century the construction deteriorated rapidly and twisted, as a result of the ground sedimentation. Consequently, some preservation work was undertaken, including the reinforcement of the pillars. In this paper we are going to concentrate on the most deflected pillar.
The experiment reveals the effective reinforcement method of the pillar. This project was based on M.Sc thesis. There are ten window pillars situated in around the building, as shown in Fig 2. The numerical analysis was carried out for the most damaged pillar, three alternative designs were examined. The first model of the pillar was ideal perfect, loaded with the boundary displacement and dead weight. The second one, was the pillar having the real geometry, with the same case of loading. The third variant, resembled the previous one, however the pillar was reinforced by the steel sections. In each experiment the job was formulated by moving the top boundary, in vertical compressive direction. In all these cases the history of internal and boundary forces, cracks propagation and weak points of element were analyzed. Finite element method with program – ABAQUS v.6.5.4. were used for the analysis. All exercises were made using Explicit module.

2 GEOMETRY AND REINFORCEMENT

Type the the real geometry model is extremely important, as even small changes can alter significantly the load distribution in the analyzed structure. The most deformed pillar was chosen. For its shape, and intersection follow Fig. 3. The pillar structure is 650 cm high, with the area ca 4 m^2 and 90 mm perpendicular, outside direction deformation. The solid element was created from 84 real points (12 measured points on 7 levels). The geometry model was divided into three stages and three separate jobs were carried out: ideal perfect non-deformed solid, real geometry follow 84 measured points, and the third one real solid with steel reinforcement. All geometry was made using the ABAQUS CAE module, with the help of AutoCad.

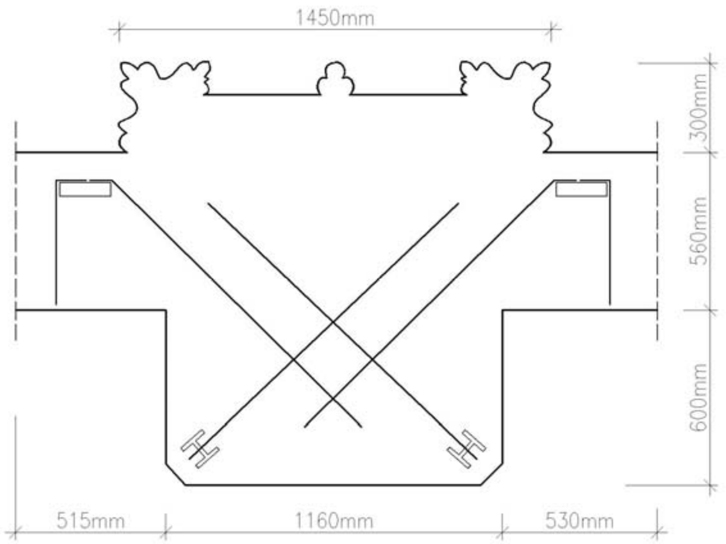

Figure 3 : Cross section of the pillar with reinforcement

Every pillar was reinforced with four steel profiles, inserted between units and mortar. Every bricks in each of pillars was marked. The next phase involved at taking out bricks with regard to the pillars load carrying capability and with the aim of putting reinforcement section. Finally, the marked bricks were inserted in their original places. The reinforcement was made with using two HEB-100 sections and two steel flat-sheet 140x50 mm^2 in each of the pillars, see Fig. 3. Steel elements were connected with the masonry by means of rib anchors and glue. The anchors were placed in previously drilled holes and special mortar was injected under pressure. Computational model was created with regular shape, see Fig. 4.

Figure 4 : Cross section of the pillar model with reinforcement

Additionally, the secondary calculations made during the reinforcement process of each of the pillars, showed that the further boundaries were useless. The work on the site was completed quickly, but accurately.

3 JOB SETUP

In each of the three pillar variants the exercise aimed at assessing the ultimate load carrying ability, and the reinforcement effect. The pillar was formed as a three dimensional bracket, loaded with dead weight and vertical compression force. The job was formulated as kinematic forced. The upper boundary causes the compression force in the pillar structure. The compression force depends on the displacement of the articulated joint upper boundary. The load i.e. dead weight and variable boundary displacement increased over the course of time. The job lasted 2 second. Within the first second gravity force grew and stabilized, within the second one the 20 mm (70 mm in the third variant) vertical boundary displacement was forced.

The usage of accruing compression force produced the critical stress, consequently cracks. The original deformation of the real geometry contributed to creating the formulation the tension zone in the element. This experiment enabled us to see damaged points in the pillar. One of the main objectives was to find out how much force reserve the pillar had, when the steel sections were inserted and to asses the reinforcement effect.

4 MATERIAL PROPERTIES

Masonry buildings are made of units connected in two directions by mortar joints. The properties of the materials in medieval structures are influenced by a large number of factors, such as mortar and bricks properties i.e. bed, head and cross joints arrangements, anisotropy of units or dimensions of joints, etc. Homogeneous material data used in the three-dimensional pillar model was first verified in the two-dimensional wall micromodel. The individual properties of a brick and mortar were distinguished and on the basis of that all required parameters of homogeneous composite were derived, on support (Lopez et al. 1999). One of the material models applied in ABAQUS – Concrete Damaged Plasticity (CDP) was used. Following the help of program manual, the CDP material model used concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior. The CDP model considered two failure mechanisms, there were tensile cracking and compressive crushing. Material provided general capability for modeling quasi-brittle materials. The authors are aware that only true laboratory test of the real masonry should give right result of material properties.

4.1 Parameters calibration

Two kinds of different material parameters for bricks and mortar were defined in the introductory job. The representative cell (974x879 mm^2, with real shape 45 bricks) of masonry wall was analyzed, follow Fig. 5.

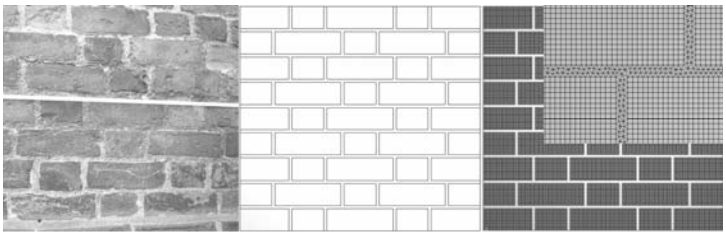

Figure 5 : Representative masonry cell

Accurate modeling of masonry structures required a reliable experimental description of the material. The presence of vertical and horizontal mortar joints causes anisotropy. Two-material approach was used in the micromodel i.e. separate bricks follow dimension 259/125x87 mm^2 and 12 mm mortar thickness. The average dimension of units and mortar was calculated on the basic of the tens of random specimen of units, occuring in all pillars. Different constitutive models were adopted. The Table 1 below shows the individual properties of the two components.

Table 1 : Material properties

Phase	Material	Density [kg/m^3]	Young's module [MPa]	Poisson's ratio [-]	Compression strength [MPa]	Tensile strength [MPa]
1	Brick	2200	6000	0.15	20.00	2.00
2	Mortar	1200	1400	0.20	2.50	0.20

Tests were carried out according the typical failure patterns follow Fig.6. The run of analysis were based on the other papers (Lourenço 1996, Lopez et al. 1999). The task enabled to mark the failure points in the principal stress space. The conclusions were used in the main pillar analysis.

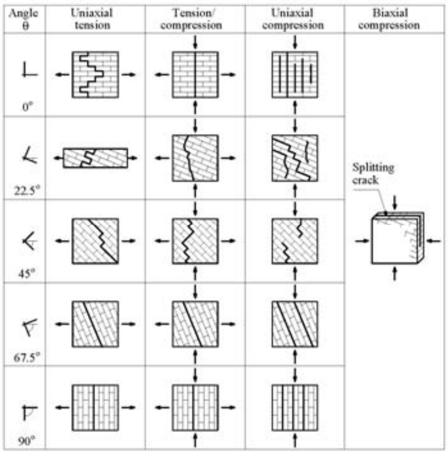

Figure 6 : Typical failure models in terms of principal stresses (Lourenço 1996)

Assigning correctly the material properties and the direction of the cracks propagation requires the usage of a great number of finite mesh element. The masonry 2D-panels were modeled using the CPS4R elements for brick and CPS3 for mortar, with three elements at the mortar thickness. The first are 4-node bilinear plane stress, quadrilateral elements with reduced integration and hourglass control, second 3-node linear plane stress triangle. The total mesh of the cell, has been generated by ca. 40k finite elements with three elements at mortar thickness. The boundary conditions are generated as the articulated joints at each edge of the wall specimen.

4.2 Accepted material model

The macromodel assumes that the masonry element is homogeneous continuum and to be discretized with finite elements mesh which does not allow for the pillar topology. Parameters of homogeneous material derived from the previous exercise were used in the main pillar analysis. Fig. 7 shows constitutive properties.

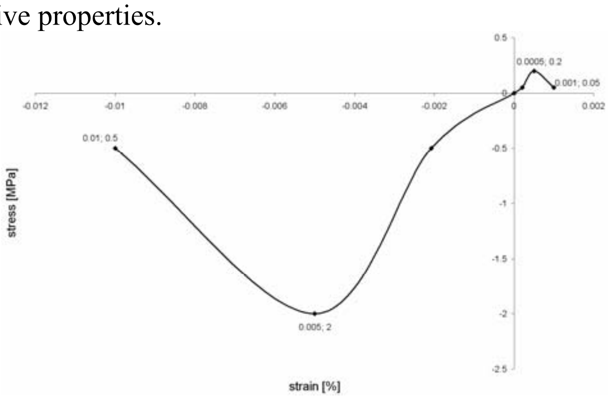

Figure 7 : Constitutive properties of homogeneous material

Table 2: Homogeneous material properties

Phase	Material	Density [kg/m^3]	Young's module [MPa]	Poisson's ratio [-]	Compressive behavior			Tensile behavior		
						Yield Stress [MPa]	Inelastic Strain		Yield Stress [MPa]	Inelastic Strain
1	Homogeneous Masonry Pillar	2200	2400	0.16	1	20	0	1	0.2	0
					2	5	0.008	2	0.05	0.0008

5 ANALYSIS

In finite element analysis moving boundary caused the compression and tension stresses. The history of the boundary reaction and strain energy show the limits of the ultimate load carrying capability. On the basis of the damage scalar parameter *d* in tension or compression, propagation of cracks was observed. At any increment during the analysis, new value of each of the damage variables was obtained as the maximum between the value at the end of the previous increment and the value corresponding to the current state, based on the tabular data introduced by the user. The damaged variables can take values from zero, representing the undamaged material, to one, which represents total loose of strength, unique full crack propagation. In the example damage variable equal 0.9 corresponds to a 90% reduction of the stiffness. In finite element analysis and engineering analytical approach, used in the engineering reinforcement project (follow polish standards), there were used absolutely equal properties of the components.

5.1 Ideal perfect and real geometry pillar

In this job the loading capability of the ideal perfect and real geometry pillars was compared. Under the influence of moving boundary compression forces were realized. The duration of this experiment shows, that the vertical deformation ca. 0.1% causes the loss of stability in two non-reinforcement pillar variants. Exemplary cracks expansion and failure scheme are shown below. Pillar failure scheme for two first of variants were presented at Fig. 8.

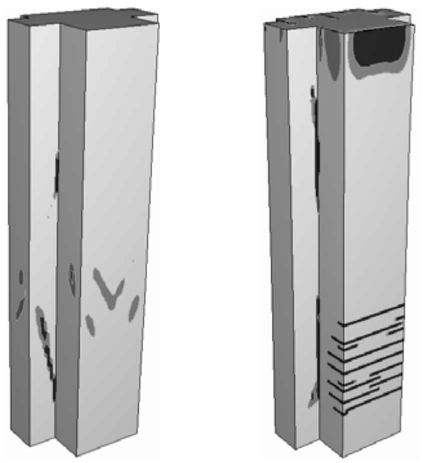

Figure 8 : Pillar failure scheme: (a) perfect geometry, (b) real deformated structure

The analysis of stress components and variation of load history, confirm the initially deformation had a significant impact on the propagation damage zone in the pillar. Cracks, conditioned by geometry, located at the bottom part and inside concave-corner of the pillar. Conclusions concerning vertical cracks were of great importance as for as work on the site was concerned. The steel sections were inserted slowly, taking into consideration their connection with internal bricks.

5.2 *Real structure with reinforcement*

Steel core inside the pillar was joined to the upper boundary by means of a flat bar on the circuit. It allowed the spatial work of the pillar skeleton structure. Undertaking preservation work aimed at improving the capacity of pillars by minimum +20%. In fact, the limit of ultimate force increased ca. +80%. Such conclusions enable us to undertake further conservation work in the near future. The results of ultimate pillar capacity, in all variant have been compared below, Fig. 9 and statement see Table3.

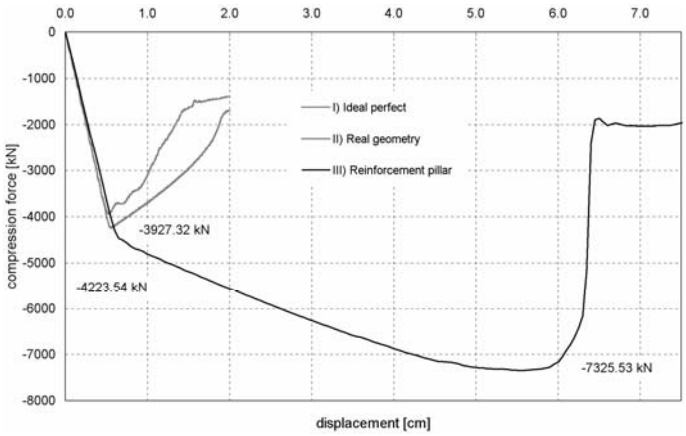

Figure 9 : Ultimate compression force

Table 3 : Statement of pillar capability

Job	Name	Ultimate Force [kN]	Displacement [mm]	Performance [%]
1	Ideal Perfect	4226	6	100
2	Real Geom.	3927	5	93
3	Real Geom. with Reinforcement	7325	55	173

The study of the model has been carried out by comparing the numerical analysis and polish standards calculations. The results are coincident. Conclusions confirm that ultimate capability corresponds with the sudden decrease of strain energy. The third variant show, that the improvement of ultimate force increase ca. 1.8 time. Crack propagation in the third variant is presented below at Fig. 10.

Figure 10: Crack pattern in of reinforced model

6 CONCLUSIONS

Advanced technical planning as well as modern methods of repair are of great significance as far as the conservation of medieval masonry structures is concerned. However, failure criteria of brittle materials e.g. masonry are still difficult to define. The poor technical condition of the pillar necessitated repairs and was a need to assess the load capacity in the course of weakening the section. The present knowledge and advanced structural engineering allowed us to assess one of the main carrying elements in the church as well as to predict and prevent the cracks. The finite elements method is still one of the most exact and the least destructive methods of assessing the state of stress and strain in the existent construction. Securing the structure of the building lets us look into the future and plan further conservation works. In next stage of analysis will be making shape optimization of reinforcement section. There are planning studies of sensitivity of units-mortar arrangement. Authors are aware, that only labolatory tests of material lead to reliable properties of masonry data. The work is prevent of following structure deformation. The possibility of cracks expansion on vault is hold back. This analysis of this medieval structure will be continue successive on example other primary elements, which in historical building occurred. Its following stage is going to be the analysis of the vault using Church of the Most Virgin Mary in Summo in Poznań as an example to.

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