The Basic Tasks in Evaluation of Ancient Structures Sustainability and in Estimation of Enclosure Walls Bearing Capacity

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***Abstract*—The paper deals with the nonlinear computational modeling of the baroque enclosure masonry walls. The main tasks are input parameters for efficient advanced numerical tools and techniques, which are based on nonlinear and quasi brittle constitutive FEM modelling. For the work was used the knowledge and results from the Broumov Group Churches survey acquired in the frame of international SAHC university cooperation. There are presented nondestructive tests, comparing with laboratory ones. The goal of the contribution are real bearing capacity parameters of the composite enclosure walls, which leads from standard homogenization techniques.**

***Index Terms*—FEM, transversal tension, nonlinear behavior, fracture mechanics, nondestructive testing, laboratory testing**

I. Introduction

The Czech Republic is blessed with the rich history of events and because of these events, many architectural heritages came into existent and became a symbol of the rich history. Within this wide variety of monuments, baroque architecture can be considered as a heart of this region's legacy. One such case is the case of Broumov Group of Churches [1], which is very significant not only for its unique Baroque architecture but also for the short duration of construction and relation between the single client and a single family of architects. The nonlinear computational modeling of the structure was carried out to validate their bearing capacity and the sustainability. Material parameters were estimate using preliminary investigation, geotechnical background studies and some laboratory testing. The set of models aims to assess the bearing capacity of the enclosure wall, which is the main structural element in the church [2,3,4]. We present the results from the two sides, mainly from Vižňov, more details in [5] and partially from Ruprechtice, all details in [6].

II. Investigation in Site

We have chance to observe the bricklayer assembling in longitudinal direction due to delamination of render. The surface hardness and superficial strength of the stones can be tested using a non-destructive test performed by the Schmidt hammer. This test can yield the useful value of
the superficial strength of the stones through the available transformation criteria provided by the hammer manufacturer [7]. To best describe the strength of the different stones, present in the outer layer of the masonry wall, it was necessary to describe the strength of these different stone units. The wall samples which were chosen are of size 1 meter by 1 meter at two different locations in the church and these two locations of the sample represent the different combinations of the stones to build the masonry as shown in Figure 1. On each stone sample the rebound hammer was performed for 10 times and then the average value of the rebound number was chosen, this average number of rebound numbers was transformed into the equivalent strength values from the formula provided by the manufacturer of the equipment [7]. Following is the TABLE I. showing the estimation

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of the strength of the sample stones from Wall 1 using Silver Schmidt type L hammer. The measured values are presented for rough orientation as the stone are natural and not man-made materials and in general different stone has different genesis. Concerning the future nondestructive analysis would be necessary to develop for different stones different hammers and different analysis.

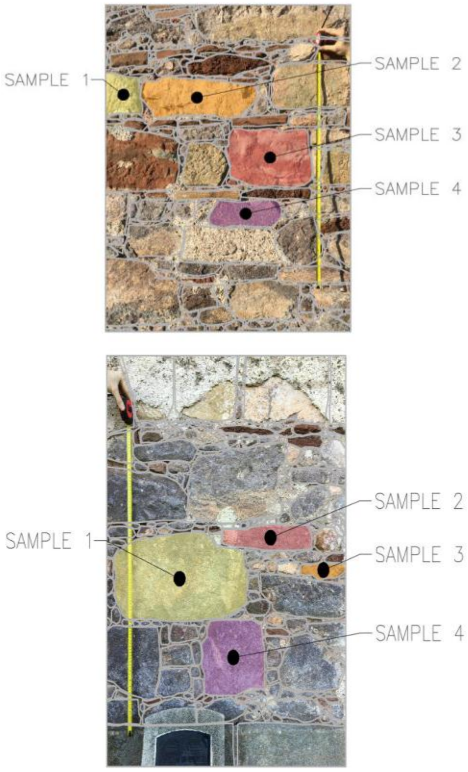

Figure 1. Wall samples considered in the analysis. Wall sample 1 (Up) wall sample 2 (Down)

TABLE I. TABLE SHOWING THE SUPERFICIAL STRENGTH OF THE STONE SAMPLES IN WALL 1

Stone Sample	Average Rebound Hammer Value	C.O.V. [%]	Equivalent Strength [MPa]
Sample 1	52.48	9.45	41.48
Sample 2	52.83	8.80	41.96
Sample 3	43.20	10.14	29.81
Sample 4	49.45	12.00	37.47

III. LABORATORY TESTING

Several laboratory tests were carried out to validate and calibrate nondestructive Schmidt hammer investigation. The samples were extracted from boreholes, each had approximately 5 cm in diameter. The core of borehole was cat on sur/plus 5 cm high cylinders. The situation on site and the sand stone (borehole 4) specimen is introduced in Fig. 2. The tests were arranged according to the Czech Standard respecting the required speed of load. Mixture of stones were use in bricklayer assembling within the baroque epoch. From the Broumov site we can list the results of tests for sandstone, limestone and ignimbrite. The compression strengths of ignimbrite reach the level 90 (MPa) in average and limestone maximum even surprises by 130 (MPa). The selected stress strain diagram is plotted in the following Fig. 3.

Figure 2. Floor plan, location of borehole in site and details from borehole core simple compression testing

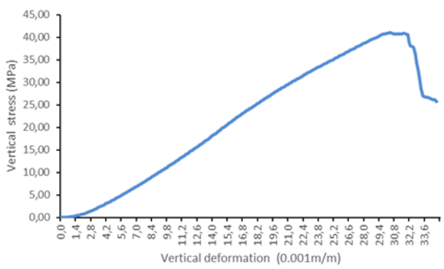

Figure 3. Stress vs Strain plot for borehole core number 4

Resulting compressive strengths of eight borehole cores are listed in Table II.

TABLE II. COMPRESSIVE STRENGTH OF GIVEN STONE

Borehole number	Kind of stone	Schmidt Hammer (MPa)	Laboratory tested (MPa)	Difference in %
1	Sandstone brown	39,10	47,37	17,46
2	Ignimbrite	34,99	60,76	42,41
3	Ignimbrite	47,83	88,57	46,00
4	Sandstone brick red	38,18	41,00	6,88
5	Sandstone red	47,83	51,10	6,40
6	Sandstone brown	43,57	42,51	2,49
7	Limestone	44,97	104,64	57,02
8	Sandstone red	38,83	49,10	20,92

IV. FEM STRATEGIES AND CALCULATION RESULTS

Simple compression test carried out in numerical way. The walls are modeled as the combination of various stone units, lime mortar, and rubble masonry infill. From the different available stone units, mainly three different types of stones were observed to be present in the walls outer leaf, namely red sandstone, grey limestone, and ignimbrite. These stones are bonded together with the lime mortar [8, 9]. While for the internal leaf, rubble masonry was considered [10]. Here the values of the mechanical parameters used are derived from both the typical values of such stones and the values obtained by the Schmidt hammer test. Observing the degraded state of the outer leaf [11, 12, 13], it was considered to use the lower bound value as a general for these types stones present in the wall, which will be a conservative approach and will result in the lower bearing capacity of the wall. Furthermore, for modeling of the longitudinal wall section, since only a single layer of masonry can be modeled in this 2D model [14, 15, 16], to account for the effect of the multi-leaves wall, reduced parameters are applied on the outer wall masonry blocks that are modeled. The reduction factor is obtained by modeling

TABLE III. MATERIAL PARAMETERS USED IN THE ANALYSIS

Material Type	Young's Modulus [GPa]	Poisson's ratio ν	Tensile Strength [MPa]	Unit Weight [kN/m^3]
Lime Mortar	0.126	0.17	0.1	20
Red Sandstone	20	0.2	1.5	21
Grey Sandstone	13	0.2	2	21
Green Sandstone	8	0.2	1.2	21
Rubble Masonry	0.7	0.2	0.1	20

Material Type	Compression Strength [MPa]	Fracture Energy [N/m]	Peak Compressive Strain
Lime Mortar	1.5	10	0.0119
Red Sandstone	30	43.5	0.0015
Grey Sandstone	20	58	0.00154
Green Sandstone	12	34.8	0.0015
Rubble Masonry	2	10	0.00286

only the outer leaf in the sectional wall. subjecting this wall to the same uniform loading, a load-displacement curve is obtained. The ultimate reduction factor used is a factor of 0.33 for Young's modulus and 0.8 for the yield strength and the shear strength [8, 17]. The material parameters considered in the analysis are listed in the Table III.

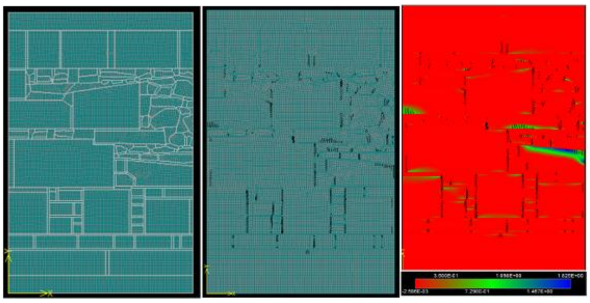

Figure 4. Longitudinal wall 1 configuration; crack patterns; maximum principal stress

From this analysis, results can be plotted in the table as shown in Table IV, where the tensile strength of the wall as a homogeneous material is considered as 1/10th of the peak compressive strength.

TABLE IV. THE COMPRESSIVE STRENGTH AND CORRESPONDING OTHER PARAMETERS FOR LONGITUDINAL WALL CONFIGURATIONS

Wall Configuration	Compressive Strength [MPa]	Tensile Strength [MPa]	Global Vertical Strain	Young's Modulus [GPa]
1	1.81	0.18	$4.43\ 10^{-3}$	0.94
2	2.11	0.21	$3.70\ 10^{-3}$	1.01

Transversal wall configuration. As mentioned, two different configurations of the walls with the different build up were used and performed in the analysis, as different configurations of the walls with the different build up were used and performed in the analysis, as shown in Figure 5. After performing the analysis, to observe the damage and performance of the wall under the compressive stress applied as the deformation, cracks and the maximum principal stress was observed on the section as shown in Figure 6. The analysis leads information including the bearing capacity and many others, which are listed in Table VI.

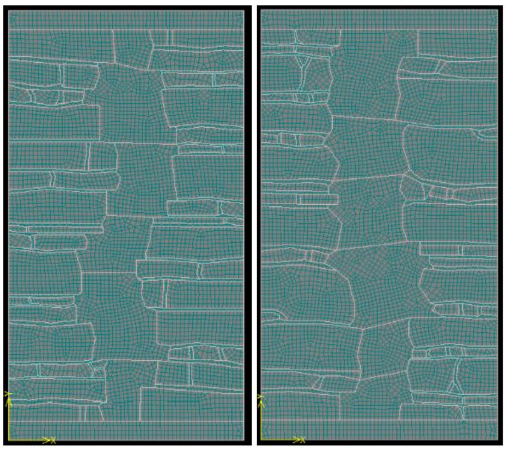

Figure 5. Transversal wall configuration 1 (Left) configuration 2 (Right)

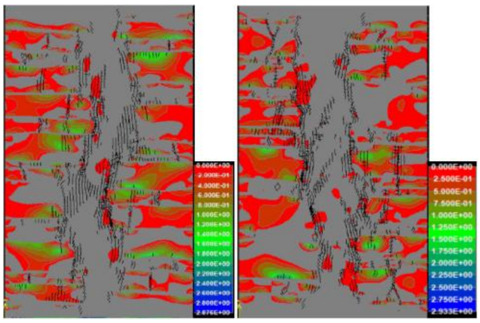

Figure 6. Horizontal tensile stress in transversal wall configuration 1 (Left) configuration 2 (Right)

TABLE V. THE COMPRESSIVE STRENGTH AND CORRESPONDING OTHER PARAMETERS FOR WALL CONFIGURATIONS

Wall Configuration	Compressive Strength [MPa]	Tensile Strength [MPa]	Global Vertical Strain	Young's Modulus [GPa]
1	1.90	0.19	2.90 10^{-3}	1.08
2	2.08	0.20	3.30 10^{-3}	1.03

V. CONCLUSION

There is evident necessity of Engineer Geologist assistance during survey of the ancient structures. We need information not only about subsoil, but about the stones from close locality as well, as they were used in structures. Concerning nondestructive testing we could recommend the Schmidt hammer idea, but it necessary to use special type of it for special type of stone. In our case we reached very good accuracy between Schmidt hammer Proceq type L and laboratory tests for sandstones. In general, the nondestructive Schmidt hammer investigation underestimate the real compressive strengths. Now a day there is a lot of highly sophisticated computers tools for multilevel modelling of structures. We obtained very good results in numerical modeling using the ATHENA code, Cervenka consulting Ltd. and the ADINA code, ADINA R&D Inc USA, respectively. Concerning the Broumov Group of Churches, the compressive strengths of the enclosure walls reached from 1.5 (MPa), All Saints Church in Hermankovice, to 3 (MPa), St. Jacob Church in Ruprechtice. Here mostly presented values, for St. Anne Church in Viznov, were in the middle. But anyway, the main task is still to use carefully proper tests for description of all material parameters. It is the main task to be focused on in the future vicinity.

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REFERENCES

[1] B. Prokop, J. T. Kotalik, and P. Suva, *Broumov Group of Churches–Guide to Czech Baroque in the Landscape of Sandstone Rocks*, Vernerovice: Modry Andel, 2007.

[2] M. Angelillo, P. B. Lourenço, G. Milani, (2014) Masonry behavior and modelling. In: Angelillo M. (eds) Mechanics of Masonry Structures. CISM International Centre for Mechanical Sciences, vol 551. Springer, Vienna, pp. 1-26.

[3] *EN 1990: Eurocode - Basis of structural design.*

[4] *Eurocode 6: Design of masonry structures*.

[5] P. Gajjar, "Nonlinear numerical evaluation of the wall bearing capacity and the structure stability of the St. Ann Church from the Broumov group of churches," Master Thesis, CR, Prague: Czech Technical University in Prague, 2018.

[6] J. Scacco, "Nonlinear numerical evaluation of the wall bearing capacity and the structure stability of the St. Jacob Church from the Broumov Group of Churches," Master Thesis, CR, Prague: Czech Technical University in Prague, 2018.

[7] Proceq, *Operating Instructions SilverSchmidt & Hammerlink*. Proceq SA: Schwerzenbach, 2012.

[8] M. Drdacky, et al., "Compression tests on non-standard historic mortar specimens," HMC08 Historical Mortars Conference, Characterization, Diagnosis, Conservation, Repair and Compatibility, 2008.

[9] P. B. Lourenco, "Structural masonry analysis: Recent developments and prospects," in *Proc. 14th International Brick and Block Masonry Conference (14IBMAC)*, pp. 17- 20, 2008.

[10] N. Tarque, A. Benedetti, G. Camata, and E. Spacone, "Numerical modelling of the In-PLane behaviour of rubble stone masonry," in *Proc. SAHC2014_9th International Conference on Structural Anlysis of Historical Constructions.* Mexico City, 2014.

[11] ICOMOS-ISCS. (2008). *Illustrated glossary on stone deterioration patterns.* ICOMOS.

[12] M. Labus and J. Bochen, "Sandstone degradation: an experimental study of accelerated weathering," *Environ Earth Sci*, vol. 67, no. 7, p. 2027, 2012.

[13] P. Reiterman, O. Holcapek, "Deterioration of different sandstones due to freeze-thaw cycling," in *Proc. 53rd Conference on Experimental Stress Analysis 2015-06-01 Český Krumlov*. Praha: Czech Technical University in Prague, s. 332-435, 2015.

[14] V. Cervenka, L. Jendele, and J. Cervenka, *ATENA Program Documentation Part 1: Theory*, Prague: Cervenka Consulting, 2016.

[15] C. G. Sluzba, "Geologicka mapa," [Online]. Available: http://mapy.geology.cz/geocr_50/. [Accessed June 2018].

[16] E. Susanti, "Numerical evaluation of the bearing capacity of the all saints church walls in Broumov," Master Thesis, CR, Prague: Czech Technical University in Prague, 2017.

[17] J. Valek, M. Veiga, and M. Rosário, "Characterisation of mechanical properties of historic mortars testing of irregular samples," in *Proc. STREMAH 2005 9th International Conference on Structural Studies, Repairs and Maintenance of Heritage Architecture*, Msida, Malta, 2005.

[18] Circolare 2 febbraio 2009, n. 617 Istruzioni per l'applicazione delle «Nuove norme tecniche per le costruzioni» di cui al decreto ministeriale 14 gennaio 2008.

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