Minor Destructive Testing of XVIII century brick wall using Compact Diagnostic Test CoDiT

Marek SKŁODOWSKI

Institute of Fundamental Technological Research, Polish Academy of Sciences,
ul. Pawińskiego 5 B, 02-106 Warszawa, Poland

msklod@ippt.gov.pl

Abstract Compact Diagnostic Test (CoDiT) procedure allows one to test mechanical properties of historic materials in a minor destructive way using micro-cores drilled out of a masonry wall. CoDiT procedure applied to brick masonry gives insight into the non-homogeneity of material properties both at a brick and a wall scale level. The test site was the orthodox monastery in Supraśl, north-east of Poland. Micro-cores of 6 mm in diameter were drilled out using diamond core drill bits. The micro-core samples were used to prepare specimens for optical, mechanical and ultrasonic testing of brick properties. Material parameters were measured, including tensile, bending and compressive strengths and longitudinal wave velocity together with optical analysis of sample inhomogeneities. It is shown that all these measurements can be done using specimens made of a single micro-core. The correlation between various measured parameters and applicability of CoDiT to measurement of old brick strength are also discussed.

Keywords: micro-cores, Compact Diagnostic Test, CoDiT, minor destructive testing, architectural heritage, brick strength,

Presentation of the monument and of the research method

Research place Supraśl is a small town situated in the North-East part of Poland close to the Belorussian border. Monastery of the Annunciation in Supraśl also known as the Supraśl Lavra was erected in 16^{th} century and its current architectural complex consists of Monastery buildings built in the 17th and 18th centuries, the Archimandrites' Palace built in 1635-1655, the Church of St. John the Theologian built in 1888 and the Gate-Belltower built in 1752. The *Supraśl Codex* elaborated here was included in the UNESCO's Memory of the World list in 2007 (UNESCO 2007). South façade of the monastery presented in Fig. 1 was chosen as the location suitable for sampling the brick material for its mechanical properties testing.

Figure 1: Orthodox church(left) and South façade of Monastery buildings(right) in Supraśl Lavra (Poland)

Outline of the experimental method In order to preserve the heritage structure and constituent material to the greatest possible extend one decided to use the minor destructive testing method of Compact Diagnostic Test (CoDiT) (Skłodowski 2006a) for measuring mechanical parameters of old bricks. The CoDiT method is an experimental procedure based on a sequence of experimental steps (Skłodowski 2006a, Skłodowski 2006b) the aim of which is to gain a maximum knowledge from the experiments on micro-cores of diameter of several millimeters. The cores are preferably drilled out of masonry during restoration or installation works when various components of equipment are attached to the walls. The holes used for fastening the equipment (sensors, electrical cables, scaffolding, anti-burglar systems etc.) are drilled using core drill bits leaving a small cylinder of a heritage material for testing purposes. In this way one saves the valuable material instead of pulverizing it during the ordinary drilling.

Consecutive steps of the CoDiT are:

Step 1. Draw a line to permanently mark the reference coordinates of the material within the structure e.g. mark the vertical plane crossing a hole to be drilled.

Step 2. Measure the velocity of propagation of the Rayleigh surface wave along the marked line and in the perpendicular direction.

Step 3. Drill a hole with a core drill bit, preferably during installation works and take out a micro-core.

Step 4. Flatten the core's base which resulted from breaking off the core and copy the line mark from Step 1 on it and on the cylindrical side surface of the core.

Step 5. Measure the core dimensions and weigh the core.

Step 6 . Record an image of the side wall of the core and analyse micro-cracks, pores and material inhomogeneities.

Step 7. Perform three-point bending test of the core in the plane marked. Two "half-cores" will come into being.

Step 8. Cut the half-cores to the desired length and then measure the velocity of propagation of the longitudinal wave along the cores.

Step 9. Perform uniaxial compression test using one half-core (see Step 7).

Step 10. Perform diametral compression test of the other half-core along the originally vertical plane (comp. Step 1 and Step 7).

Applicability of the CoDiT to testing heritage stones of Portland Whitbed and Sander Schilfsandstone was confirmed by comparison of the CoDiT results with standard tests and was reported in (Skłodowski 2006b, Skłodowski, Snethlage & Kocher 2008). In the next Sections the results of testing brick micro-cores from the Supraśl Monastery are presented.

On-site works

Restoration works performed in the Supraśl Monastery gave us a possibility of accessing the brickwork after plaster removal. The brickwork was accessible in the eastern part of the South wing of the monastery. Visual inspection of the bricks revealed deterioration in the lowest brick layers which is the usual case due to an increased dampness close to the ground level. Various colors of bricks in the wall showed that they were made of various primary material. For this reason sampling strategy allowing to get specimens from several bricks on various levels above the ground was chosen. The bricks were sampled at the levels of 25, 41, 52, 70, 96 and 114 cm, that is from the 3rd, 5th, 6th, 8th, 11th and 14th brick layers. Sampling positions on the wall are shown in Fig. 2.

Micro-cores were drilled with thin wall 8 mm diameter core drill leaving 6.4 mm cylindrical sample of the brick. Several drilling attempts were unsuccessful due to numerous internal cracks and voids in the brick material. Some cores were broken into 2, 3 or more pieces during drilling, some others broke along their weak planes during specimens preparation. This was the reason of small number of bending tests because only four micro-cores had the length and homogeneity suitable for three point bending strength measurement. The most disadvantageous case was with specimens from the brick from the 11th layer for which no test could be performed. The only brick without internal cracks was that at level 114 cm (Fig. 3, specimen 61). Its material differed completely from the rest of bricks. Its colour was light yellow instead of red and surface texture was similar to a very fine sandstone. Therefore it was also chosen to get wider insight into the wall material properties.

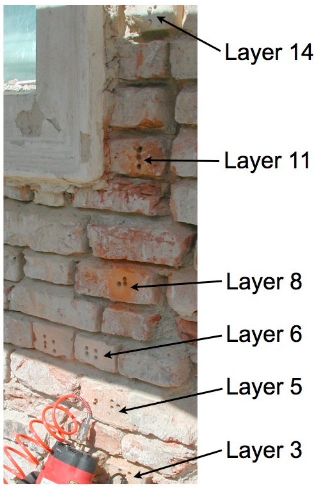

Figure 2: Position of micro-cores samples in the brick wall of the monastery

Experimental results

A set of 32 specimens prepared from micro-cores after bending tests is shown in Fig. 3. The shorter cores were used for ultrasonic tests and indirect tensile strength measurements (Steps 8 and 10 of CoDiT), and longer specimens were used for ultrasonic tests and uniaxial compressive strength measurements (Steps 8 and 9 of CoDiT).

Figure 3: Set of micro-core specimens and unwrapped surfaces of micro-cores No 22, 37, 61 from layers 5, 6 and 14 respectively

Images of micro-cores surfaces are presented in Fig. 3 to demonstrate two things. The first aim is to show the power of the optical analysis used in CoDiT method where resolution of 20 μm per pixel is easily achieved, which is better than the resolution obtained by borescopic analysis (resolution presented here is much lower for practical reasons). The second aim is to show the great inhomogeneity observed both in a single brick element and in the wall as a whole. All micro-core images were taken under the same lighting conditions and colour differences are attributed to the material composition (clay mixture) and burning procedure. Hard inclusions accompanied by cracks are visible in micro-cores Nos 22 and 37. The inhomogeneity of micro-core No 22 was the reason of the breaking of the sample before the specimen was drilled to its full length and for the purpose of presented optical analysis the pieces had to be glued to form the one cylinder. The observed material inhomogeneity is responsible for large scattering of the local strength properties of the bricks which is demonstrated in Fig. 5 and Tab. 2.

One example of the uniaxial compressive test performed on micro-cores is presented in Fig. 4. This is the specimen from the third layer of the bricks for which the lowest compressive strength $f_c = 3.7$ [MPa] was registered, while the mean value of the measured compressive strength of the bricks was $f_c = 14.9$ [MPa]. The result is attributed to stress concentration at tips of a visible quasi-vertical crack at which initiation of the crack propagation was observed.

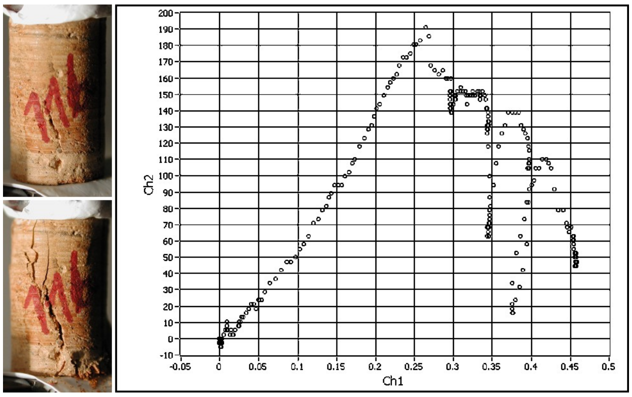

Figure 4: Micro-core specimen from the lowest level of tested bricks before and after the uniaxial compression test and its load-displacement curve

Mean values of measured strength parameters cannot be compared with results for large specimens due to lack of other laboratory measurements because no brick was allowed to be removed from the structure. Instead, a useful source of comparative studies was found in (Domasłowski 2004) where compressive and bending strengths of old bricks from another part of Poland from gothic and XIX century monuments are reported.

Table 1: Comparison of flexural (f_b) and compressive (f_c) strengths reported in (Domasłowski 2004) and measured on micro-core specimens from Supraśl Monastery

Source	f_b [MPa] Min	f_b [MPa] Max	f_c [MPa] Min	f_c [MPa] Max
(Domasłowski 2004), gothic	2.6	3.2	6	9
(Domasłowski 2004), XIX century	--	--	5	11
CoDiT, from Supraśl Monastery.	1.2	4.8	3.7	25.7

Taking into account that old bricks were hand made and always manufactured locally, close to the monument place, it can be argued that the strength comparison presented in Tab. 1 is mostly of an illustrative value. Despite this drawback the comparison presented in Tab. 1 gives an insight into applicability of CoDiT measurements to monumental bricks testing.

Analysis

Interesting observation can be made based on Fig. 5. The left graph suggests quite random compressive strength distribution measured for the bricks. This is confirmed by statistical analysis presented in Tab. 2 showing the high probability that the results come from the population which has a normal distribution of strength. However the center graph, based on the sample location in the wall, confirms expected large scattering of the local properties at various levels and suggests that brick at the lowest level is much weaker than the rest of the bricks. Here the optical analysis included in CoDiT procedure comes to our aid. Images in Fig. 4 explain the reason for the low measured strength of specimen No 11 at the lowest level. Hence one may conclude that there is no meaningful difference between the uniaxial compressive strength of bricks from various locations above the ground level.

The right graph clearly shows that velocity of ultrasonic P-wave is not correlated with uniaxial compressive strength for bricks with many cracks, voids and inclusions. In such a material mechanical wave travels along the real path which is very complicated and much different from the nominal path which is equal to the length of the specimen.

The figure shows that the evaluation of the compressive strength based on NDT ultrasonic tests can be doubtful for historical bricks.

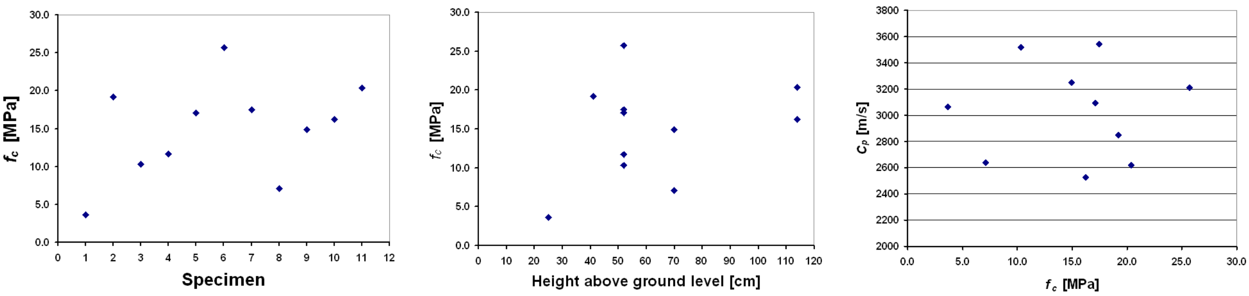

Figure 5: Compressive strength f_c of brick micro-cores from the Monastery in Supraśl: left – sequence of measured values; center – depending on the height position in the wall; right – compared with velocity of ultrasonic pressure wave C_p

To analyse whether measured results come from populations having normal distribution Shapiro-Wilk normality test (*W statistics*) was used (Shapiro and Wilk 1965). The choice of this test is justified by a small number of samples (below 30) in each result group.

Table 2: Statistical analysis of measured flexural (f_b), compressive (f_c) and tensile (f_t) strengths and longitudinal wave velocity (C_p) for brick specimens

Measurand	*Max*	*Min*	*Median*	*Mean*	*Std. dev.*	*No of spec.*	*W stat.*	*p(normality)*
f_b *[MPa]*	4.8	1.2	2.5	2.6	0.8	4	0.9343	0.620
f_c *[MPa]*	25.7	3.7	16.2	14.9	6.3	11	0.9811	0.972
f_t *[MPa]*	4.0	2.9	3.7	3.6	0.5	15	0.8951	0.080
C_p *[m/s]*	3860	1880	3095	3060	515	19	0.9615	0.602

W statistics given in Tab. 2 is accompanied by *p(normality)* value, calculated for the Shapiro-Wilk test by PAST software (Hammer, Harper & Ryan 2001), that the measurand comes from the normally distributed population. The compressive strength f_c is very likely normally distributed, despite the standard deviation as large as 42% of the mean value. In contrast the tensile strength f_t measurement almost certainly deviates from the normality with *p(normality)* of 0.08. The two other material parameters, the flexural strength f_b and longitudinal wave velocity C_p, are probably normally distributed but with low probability of around 0.6 only. Thus only in the case of measured compressive strength f_c the standard deviation is of meaningful value. These results indicate that the minimum, maximum and median values of the measured parameters might be more informative for practical purposes than the mean value and standard deviation.

Conclusions

The presented micro-cores testing based on the CoDiT procedure allowed us to measure in a minor destructive way the strength parameters of bricks coming from a historical structure. Strength measurements are better justified if they are accompanied by optical analysis of material composition and inhomogeneities, which are helpful in explaining unexpected measured values.

The CoDiT method is at the moment the only one which successfully combines all those tests into a practical experimental procedure of almost no intervention to the structure.

Measurements revealed a great variation of material parameters both at the brick and wall level. Particularly noteworthy is the lack of correlation between the measured ultrasonic longitudinal wave velocity and the compressive strength of the specimens. This shows that for heterogeneous materials like bricks with multiple internal cracks and inclusions the nondestructive ultrasonic evaluation of the elastic properties can be doubtful.

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References

[1] UNESCO Memory of the World Programme web site (2007). "Codex Suprasliensis – Mineia četia, Mart (The Supraśl Codex – Menology, March)". [Online]. Available: http://portal.unesco.org/ci/en/ev.php-URL_ID=22473&URL_DO=DO_TOPIC&URL_SECTION=201.html.

[2] Skłodowski, M, (2006a). “Compact diagnostic test: outline of historical monuments testing procedure,” Prace IPPT, 3/2006, Institute of Fundamental Technological Research Polish Academy of Sciences, Warszawa. [also Online]. Available: http://prace.ippt.gov.pl/IFTR_Reports_3_2006.pdf

[3] Skłodowski M. (2006b). “Quasi-non-destructive testing of historical structural materials using micro-cores", in *Proc. Structural Analysis of Historical Constructions, New Delhi 2006. P.B Lourenço, P. Roca, C. Modena, S. Agraval (Eds)*. p. 859-865, Delhi, MacMillan, ISBN: 978-1403-93156-6.

[4] Skłodowski M., Snethlage R., Kocher M., (2008). “Micro Drill Cores - A New Tool For Testing Stones For Conservation Purposes”, in *Proc.11th Int. CONGRESS on Deterioration and Conservation of Stones, 15-20 Sept. 2008, Toruń, POLAND, Vol. 1, J.W. Łukaszewicz & P. Niemcewicz (Eds.), 513-520,* Nicolaus Copernicus University Press, Toruń, , ISBN 978-83-231-2236-4

[5] Domasłowski W., Kęsy-Lewandowska M., Łukaszewicz J.W., (2004). “Badania nad konserwacją murów ceglanych” (Research on Brick Walls Conservation), Nicolaus Copernicus University, Toruń, 78 & 105. ISBN: 83-231-1718-7 (in Polish).

[6] Shapiro S. S., Wilk M. B., (1965). “An Analysis of Variance Test for Normality (Complete Samples)”. Biometrika, Vol. 52, No. 3/4. 591-611.

[7] Hammer 0., Harper D.A.T., Ryan P.D. (2001). *PAST: Paleontological Statistics software package for education and data analysis.* Paleontologia Electronica, 4(1): 9pp. [Online] Available: http://palaeo-electronica.org/2001_1/past/issue1_01.htm