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P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Quasi-Non-Destructive Testing of Historical Structural Materials using Micro-Cores

Marek Skłodowski
Institute of Fundamental Technological Research, Polish Academy of Sciences, Warszawa, Poland

ABSTRACT: Report presents a new method of testing of mechanical properties of structural heritage materials. Suggested QNDT (quasi non-destructive) method is an adaptation of the methods known in rock mechanics and mechanics of concrete and is used f here or testing of micro-cores of 6 mm in diameter. Discussion shows that together with flexural, tensile and compressive strength measurements it is also possible to use the same micro-core for the measurement of ultrasonic wave velocity and for material microstructure analysis. No additional destruction to the object of cultural heritage is introduced if micro-cores come from the holes drilled in heritage structures in their everyday maintenance. The results of measurements performed on micro-cores are compared with data presented in the relevant literature showing very good agreement in some tests and poor agreement in others.

1 INTRODUCTION

Assessment of structural health of historical monuments is based on experimental and numerical modelling of their behaviour and on laboratory and in-situ measurements of material properties and structural response to the static and dynamic loadings. Assessment and diagnosis always includes an experimental evaluation of mechanical properties of a structural material. Mechanical parameters like modulus of elasticity, uniaxial compressive strength and Poisson's number are evaluated through direct and indirect tests (Macchi 1995). The most reliable results are given by direct destructive tests that are performed in a very little number, in the form of testing of the core specimens in laboratories and testing the compressive strength in-situ, using double flat jack test.

The use of cores in material testing is known for decades if not for a century. Cores are the most widely used in rock and mining engineering and in geotechnical and civil engineering. They are used to get samples of material from soil and ice, concrete and stones and also from heritage constructions. The idea is always the same – to sample a material on-site and get specimens for mechanical, physical, chemical and optical testing. The cores drilled out of the material have diameter of tens up to hundreds of millimetres as they must form the representative volume element of the material. However overcoring of samples of materials from heritage constructions is done very rarely and only in the case when sampling is really necessary to interpret the results of non-destructive ultrasonic, thermovision and radar tests. This is dictated by the great value of monuments where any destruction to the originals structure is regarded as the last instance action.

In spite of what has been said above, hundreds of small holes are drilled every year in monumental structures and the small destruction accompanying the drilling is regarded as being meaningless to the heritage value. These are the holes necessary for mounting installations and fixing sensors. In every cathedral hundreds of holes have been made within last decades to place fire-fighting systems, loudspeakers, heating and lighting installations, mounting the safeguarding and alarm systems of various kinds and finally holes have been made by scientists for fixing the displacement sensors, inclinometers and telecoordinometers for deformation monitoring purposes and structural health assessment. Many holes are usually drilled in a single session of flat-jack measurement including a row cut made in a wall for flat-jack insertion (Nappi 1998, Rossi and Rossi 1998)

These all holes and cuts are, up till now, useless from the point of view of material property testing. Valuable historical material is pulverized during cutting and drilling instead of being used as a source of additional knowledge about a monument. Observation of this fact has led to a preliminary study of feasibility of using micro-cores drilled out from small holes made in everyday maintenance of cultural heritage monuments. Result of such a study and a method called Compact Diagnostic Test (CoDiT) (Skłodowki 2006) is presented in next sections.

It should be pointed out that the suggested measurements are based on already mentioned widely used large core testing, with three main differences:

- the micro-core usually can not be regarded as a representative volume element in the sense of standards existing for testing of stones, bricks and concretes;
- micro-cores do not introduce destruction to cultural heritage due to that the material used in Compact Diagnostic Test would be otherwise pulverized and lost forever, so the CoDiT is a quasi-non-destructive (QNDT) or sometimes even NDT method of testing;
- the CoDiT method is a sequence of testing procedures giving more information about mechanical properties of the material than any single standard in civil engineering but it is not a standard.

An idea of using small cores in material testing has been published in (Kasal 2003) where special core drills were used to get 5 mm diameter cores of wood for further laboratory testing. Main part of the research presented in the present work is based on testing of Portland Whitbed limestone – the material used in many London heritage buildings including St. Paul's Cathedral, but for obvious reasons such preliminary tests are done on a fresh-from-quarry limestone sample and they are compared with the results of standard tests reported elsewhere by other laboratories to validate the experiments and discuss the results measured on micro-core specimens.

2 TESTING METHOD: THE COMPACT DIAGNOSTIC TEST

Holes in historical monuments are drilled really frequently. Therefore, changing a method of everyday drilling into micro-core drilling enables intentional collecting and storing of samples as a part of conservator's documentation of a monument. The micro-cores might be used for research at any time when such a need arises. Thus, despite of the fact that drilling is a destructive operation itself, adopting the hollow drilling of micro-cores as a general rule results in literally no additional damages to the structure and might be regarded as non-destructive in most practical situations.

Having in mind this advantage, a sequence of research steps was developed which serves a purpose of gaining the maximum of knowledge based on micro-core investigations. Such a sequence of measurements, non-destructive from the monuments' perspective, constitutes a very promising research practice. Consecutive ten steps of this general method named Compact Diagnostic Test (CoDiT) are (Skłodowski 2006):

Step 1. Draw a line to permanently mark the vertical plane of a hole to be drilled.

Step 2. Measure the velocity of propagation of surface wave (Rayleigh wave) along the marked vertical line and perpendicularly to it (Skłodowski 2005).

Step 3. Drill a hole with a core drill bit, preferably during installation works, with possible simultaneous measurement of drilling resistance (DRMS) (Tiano et al. 2000) and take out a micro-core.

Step 4. Flatten the core base which has resulted after its breaking off and copy the vertical line marking (from Step 1) on it.

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

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

Step 7. Measure the velocity of propagation of the longitudinal wave along the core.

Step 8. Perform the bending test of the core in plane marked as vertical. Two half-cores will arise.

Step 9. Perform the uniaxial compression test using one half-core (see Step 8).

Step 10. Perform the diametral compression test of the other half-core along the originally vertical plane (comp. Step 1 and Step 8).

Destructive tests of Steps 9 and 10 can be modified as necessary. This is especially recommended when the number of micro-cores available for testing is greater than the number required for basic measurements. In such a case

- an uniaxial cyclic compression of the one half-core, and
- a creep test of the other half-core

might be of special interest.

In next sections most of the steps of the CoDiT method are practically verified on Portland limestone, an important structural material used in London in its historical monuments.

3 SPECIMENS AND EXPERIMENTS

Specimens used in the following study are small cylinders of nominal diameter of 6 mm. They are called micro-cores by analogy to much larger cores widely used in civil and mining engineering. They have been drilled out by overcoring using 8 mm core drill with diamond drill bit shown in Fig. 1. Micro-cores of other diameters were also drilled with core drills of 7 mm and 10 mm to test the universality of the approach as the key idea is to use cores from holes drilled in historical structures for mounting sensors and installations.

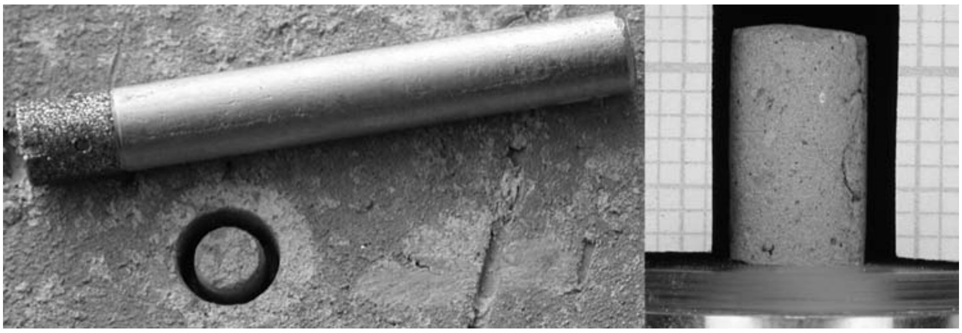

Figure 1 : Micro-core of 6 mm diameter in old brick and on a rotary table ready for image recording.

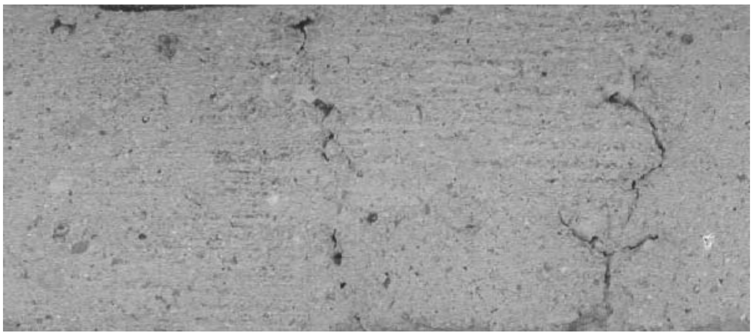

Figure 2 : Unwrapped surface of 6 mm brick micro-core with visible micro cracks and inclusions. Original image resolution 1 pixel = 20 micrometers.

Short micro-cores of slenderness 1:1 can usually be produced in a single drilling step. They can be used in every step of the CoDiT except for the flexural strength measurement – Step 8. As an interesting example of optical experiments, a medieval brick micro-core with microcracks and inclusions is shown in Figs. 1, 2. The unwrapped cylindrical surface of the core from Fig. 2, is analogous to images resulting from boroscope testing but here it is obtained at almost no cost and with great image resolution of 20 μm/pixel.

Long micro-cores need to be drilled in many steps due to material heating and problems with chips removal. To illustrate the potential of the CoDiT method long specimens of slenderness greater than 3:1 were overcored in several materials including bricks, sandstones and marbles. Here, a set of micro-cores of the length of nearly 30 mm was used to test mechanical properties of Portland Whitbed limestone. Specimens were tested in three point bending, then cut into cylinders of slenderness 1:1 and 2:1 which were used in ultrasonic tests and further in uniaxial compression and diametral compression tests. These four experiments are illustrated below.

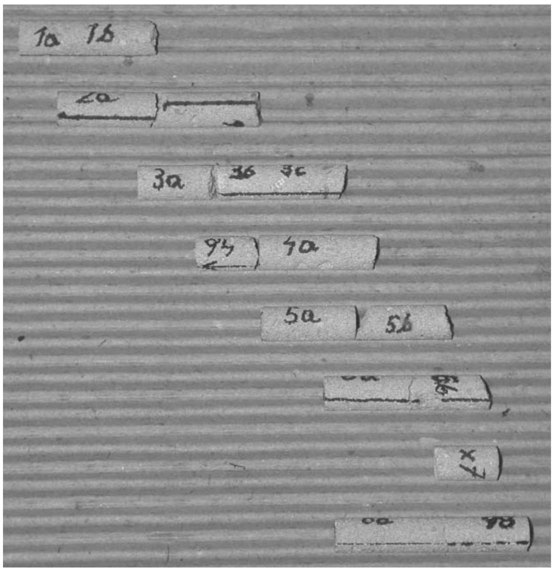

Figure 3 : Set of micro-cores of Portland Whitbed limestone after three point bending tests.

Portland micro-cores after three point bending are shown in Fig. 3. Visible lack of symmetry in fractured specimens is intentional. Long cores were placed in a testing stand non-symmetrically with one end hanging over the support. This allowed to get sub-cores of various length to make it possible to cut short and long specimens (of slenderness 1:1 and 2:1) for the next tests.

In three point bending, the cracks originated from open pores on a surface subjected to tension. Specimens broke slightly off the loading cross-section in four cases and far from this cross-section (more than a half of specimens diameter) in two other cases. These two tests were discarded and the measured flexural strength was FS = 8.9 ± 2.1 N/mm^2.

Ultrasonic measurement of longitudinal 1 MHz wave velocity is exemplified in Fig. 4.

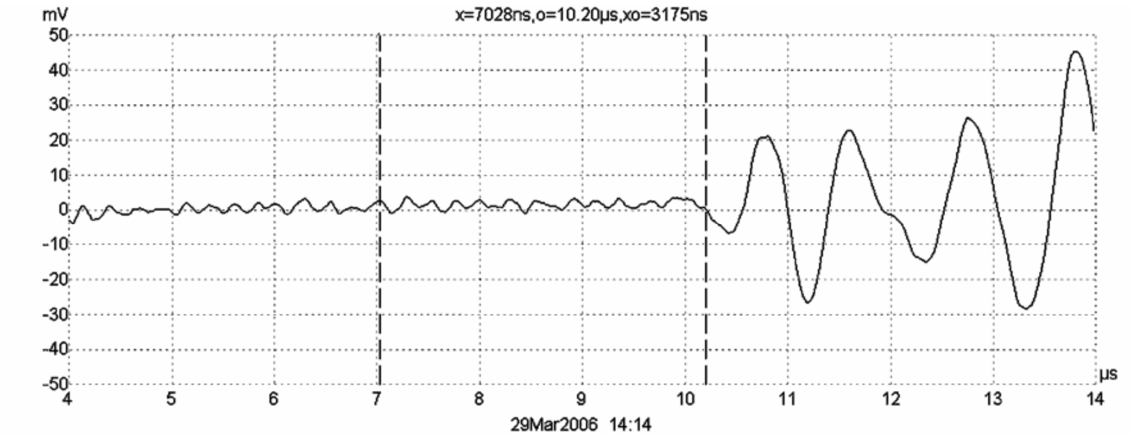

Figure 4 : Recorded longitudinal ultrasonic wave of 1 MHz in PW5b micro-core of length 6.04 mm.

Altogether 22 specimens of various lengths were tested and the average measured velocity was $C_L = 3790 \pm 140$ m/s.

The same specimens were used in strength tests following the ultrasonic tests. Short specimens (6 x 6 mm) were tested in diametral compression to measure indirect tensile strength (ITS) and long specimens (6 x 12 mm) were used to measure uniaxial compressive strength (UCS).

Both tests were performed on Tinius Olsen one-column press type H5K-S with loading capacity of 5 kN. Very thin Teflon sheets were inserted between the platens and specimens to minimize frictional forces and increase load uniformity over specimens' surfaces. This is shown in Figs. 5, 6, where specimens after the experiments are also shown to demonstrate observed damage modes. Measured average strength values were ITS = 5 ± 1.3 N/mm^2 and UCS = 26.5 ± 3.9 N/mm^2.

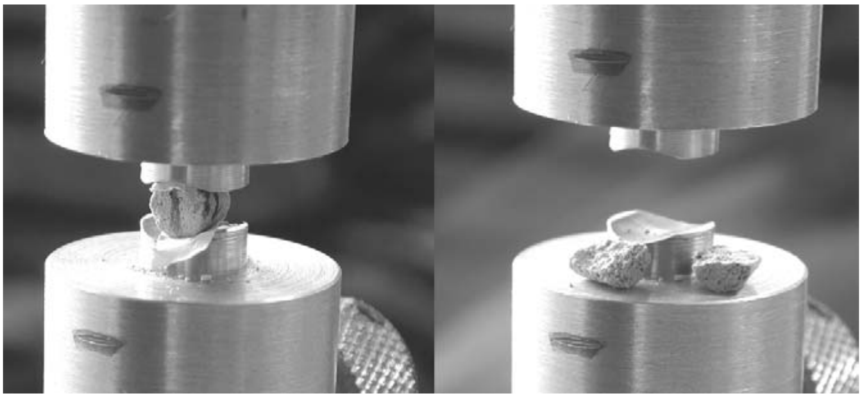

Figure 5 : Diametral compression of a micro-core and broken parts of the specimen.

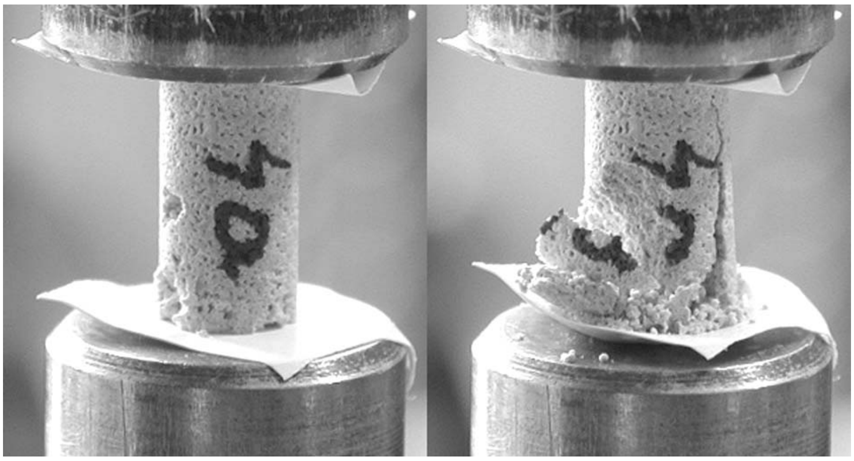

Figure 6 : Uniaxial compression of a slender cylinder. Specimen's dimensions are: d = 6.03 mm, h = 12.08 mm.

4 RESULTS AND DISCUSSION

Results of tests performed on micro-cores according to the steps of the CoDiT measurement sequence were compared to the results obtained by other laboratories in tests on large samples of Portland Whitbed. These are mainly the results from EC 5th Framework Project MCDUR (Contract No G6RD-CT2000-00266) where measurements of C_L velocity, UCS and ITS were performed. Flexural strength results were compared to those published by Building Research Establishment (BRE) available in the BRE web page.

Table 1 includes a comparison of ultrasonic wave velocities. In this test perfect a agreement of the average value was observed. Lower standard deviation for micro-core measurements was probably achieved due to using a single measurement equipment whereas MCDUR results are from four different laboratories.

Table 1 : Comparison of velocities of longitudinal wave measured in Portland Limestone in Y direction.

Specimen set	Velocity m/s	Standard deviation
Prismatic specimens 10 cm x 5 cm x 5 cm *	3780	234
Micro-cores **	3790	140

* Average from measurements made by Bavarian State Department of Historical Monuments, Building Research Establishment, Laboratorio Nacional de Engenharia Civil and Politechnico di Torino in (Delgado Rodrigues, unpubl.).

** Average for 22 micro-cores drilled out of a single prismatic sample.

Comparison of strength measurements presented in Table 2 shows reasonable agreement between tensile and flexural strength data reported by other research laboratories and the ITS and FS data measured on micro-cores. Compressive strength is however much lower in the case of micro-core measurements. The results reported by Technical University of Chania and E.R.I.C.A. differ much from that reported by BRE and in the present work. This is due to different direction of the applied compressive load in both groups of results. Results from BRE and micro-cores are in better agreement as specimens were compressed in the same direction, that is,. perpendicular to bedding. Nevertheless, the results obtained from micro-core testing are still much lower than those from BRE research. One of the possible reasons might be the different value of lateral frictional forces in the tests. In the case of micro-cores, Fig. 6, it is justified that Teflon sheets greatly reduced the friction between machine stamps and the specimen as the dominating damage mode is vertical splitting.

Table 2 : Mechanical properties of Portland Whidbed as measured by various research centres.

Laboratory	Tensile Strength N/mm^2	Compressive Strength N/mm^2	Flexural Strength N/mm^2
Building Research Establishment (England) in (BRE 1996)	-	39.0***	7.6***
E.R.I.C.A. (Italy) (Exadaktylos, unpubl.)	-	53.2*	-
Technical University of Chania (Greece, Crete) (Exadaktylos, unpubl.)	4.7	51.2**	-
Present research using micro-cores	5.0	26.5***	8.9***

* Cubical specimens 70 x 70 x 70 mm (1:1).

** Cylindrical specimens 100 x 50 mm (2:1).

*** Perpendicular to bedding.

5 CONCLUSIONS

The research confirmed that the Compact Diagnostic Test (CoDiT) is a prospective method of studying historical materials from architectural heritage. The method is QNDT and makes it possible to evaluate many important mechanical parameters at low cost and with practically no destruction of monuments. However it should be remembered that CoDiT does not give masonry parameters as a whole but its components only.

Testing of mortar joints has not yet been done as fixing of sensors, monitoring and alarm networks etc. is done in brick and stone elements so micro-cores of these materials can be more widely used without additional local destruction of a historical structure.

It should be also pointed out that compressive strength can only be measured in the direction of overcoring i.e. horizontal one, which is not so important as being perpendicular to the structural dead load. On the other hand flexural strength and indirect tensile strength can be measured in any direction perpendicular to the core axis thus yielding the partial information about material anisotropy and including the most important horizontal tensile and flexural strength parameters.

Preliminary study presented in this work leads to the following conclusions:

- Images of unwrapped surface of a side wall of a micro-core can easily be recorded with a great resolution for further analysis of pores, inclusions and micro-cracks existing within the material.

- Many technical problems are yet to be solved for successful overcoring of micro-cores of diameter of 6-10 mm and slenderness greater than 3:1. However such micro-cores are to be preferred in experimental analysis of properties of historical construction materials as they can be used for bending tests and yield information about material flexural strength, which is a non-measurable parameter by other QNDT methods up till now. The results from the three point bending test are in general agreement with that reported for standard size specimens. However the crack plane has developed usually slightly off the loading cross-section of the specimens, which suggests that four point bending tests might be more appropriate in future.
- It is possible to measure longitudinal wave velocity in micro-core of the length of few millimetres, that is the length comparable to the ultrasonic wavelength used in testing. Mean value and standard deviation are in perfect agreement with that for large size specimens.
- Damage modes of micro-cores in uniaxial compression and diametral compression were the same as known from standard tests.
- Indirect tensile strength measured in diametral compression on short cylinders (6 x 6 mm) was slightly greater than that reported in the literature for large specimens.
- Uniaxial compressive strength measured on cylindrical specimens of slenderness 2:1 (6 x 12 mm) was about 40% lower than that known from other tests. This problem deserves special attention in further research.

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