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Deformations and volume changes due to moisture variations in heritage buildings - Use of NDT techniques

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Abstract

Elements of building envelope, during service life, are subjected to deformations and volume changes due to moisture variations, which can cause anomalies in the building, such as the cracking of facade walls and consequent rain penetration, with increase of their moisture content. In case of heritage buildings with structural concrete elements and infill masonry walls, when, besides moisture variations, other different causes can be hypothetically possible, it can be justifiable to investigate more profoundly the anomalies with the available NDT techniques. This study is related to the application of non-destructive testing (NDT) techniques, with a view to the evaluation of anomalies related to the presence and flow of moisture in masonry walls, notably through Ultrasound, Infrared Thermography (IRT) and Photogrammetry. These NDT techniques are used in the evaluation of masonry specimen with variable moisture content, subjected to compression test, before and after been tested, when cracking will be present.
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1. Introduction

Elements of building envelope, during service life, are subjected to deformations and volume changes due to moisture variations, which can cause anomalies in the building, such as the cracking of facade walls and consequent rain penetration, with increase of their moisture content. In case of heritage buildings with structural concrete elements and infill masonry walls, when, besides moisture variations, other different causes can be hypothetically possible, it can be justifiable to investigate more profoundly the anomalies with the available NDT techniques. This study is related to the application of non-destructive testing (NDT) techniques, with a view to the evaluation of anomalies related to the presence and flow of moisture in masonry walls, notably through Ultrasound (US), Infrared Thermography (IRT) and Photogrammetry. These NDT techniques are used in the evaluation of masonry specimen with variable moisture content, subjected to compression test, before and after been tested, when cracking will be present. Here, the aim is to use NDT techniques to analyze the anomalies that can be attributed predominantly to deformations due to moisture variations in masonry walls and structural elements; it refers to the buildings with reinforced concrete integral structure or with mixed structure of reinforced concrete and masonry.

2. Potential use of NDT to access movements in buildings masonry walls and concrete elements due to moisture variation and their consequent degradation

Many buildings suffer, during their use, from cracking of finishes, spalling of surfaces, which can affect, sometimes, in case of exterior finishes, their weathering characteristics, and permit substantial wetting or rain penetration, that, consequently, may lead to severe weakening of the structural building elements as deterioration progress. Often, the mechanisms responsible for such anomalies are usually associated with deformations in materials due to moisture content. As many common building materials have a porous structure and can absorb water more or less readily, the nature and magnitude of moisture deformations assume considerable importance [2] and is important to access, namely through NDT techniques. Moisture deformation is generally reversible, except in materials such as concrete, mortars and plasters. To access the type of movements that is present in masonry, the use of NDT techniques can be explored, taking in due account the type of constituent material of the masonry and their possible variation in moisture content and in volume. IRT allows to relate observed situations of thermal inhomogeneity with an internal “picture” and state of the element, such as the characteristics of the materials as well as the occurrence in the wall renders of detachment, surface discontinuities and internal cracks and, particularly interesting for present analysis, the distribution of moisture on the masonry wall [5]. That distribution possibly can reveal zones with different moisture expansion rate.

In respect to the use of NDT in detection of moisture presence and its evolution, it should be noted that several factors might, however, restrict the use of thermography. The method of detection depends on the wall surface temperature changes due to water evaporation rate or to the change of thermal characteristics of the constituent materials [5].The causes of deformations of building materials, elements and concrete structures may be due, to moisture content changes resulting in swelling or shrinkage, but also can be combined with other causes. In particular, can be combined to the following causes [2]: temperature changes resulting in expansions or contractions; chemical action in the presence of moist, air or water resulting in volume change, usually expansion; applied loads resulting in elastic and inelastic deformations.

When subjected to long-term loading, many building materials suffer supplementary deformation, which does not fully vanish when the loading is removed (deformation associated to creep, which is in relation to structural deflections for the particular case of concrete elements). Photogrammetry can possibly give the first information about this case, when this creep deflection, mainly occurring in beams or pavements, is visibly considered anomalous and, clearly, these deformations can be, mainly, attributed to creep and, with less importance, to the moisture deformations. Although it may not be possible, generally, to determine precisely the deformations or stresses due to moisture content changes, it is possible to access them approximately, in case this effect of creep can be neglected.

Cracking can, for example, occur when stresses are induced in materials by restraint to deformation imposed. When the linkage to other building materials, in order to form a building element, restrains the materials, deformations from changes of moisture content may be restricted. Stresses may be induced, which, in certain cases, maintain the deformation controlled; but, in other cases, these stresses exceed the strength of the material, and the material can crack. Photogrammetry can explore in detail the apparent state of the surface of the building element, namely superficial defects associated to cracks [5].

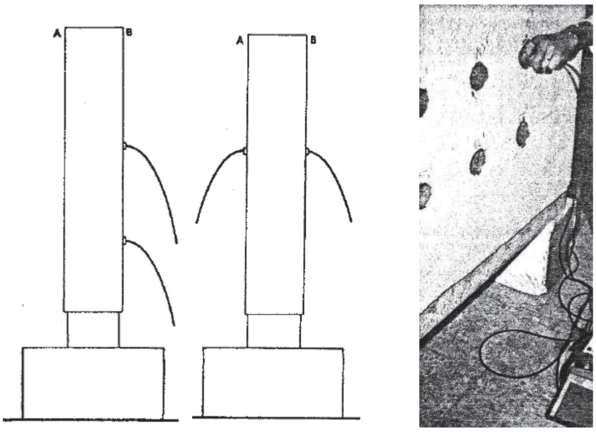
For example, in the analysis of cracks in facades, both metric and interpretive photogrammetry should be used: the first because it enables measurements from photogrammetric products (measuring the length and aperture of a crack is an example); the second because it allows, using image processing techniques, the recognition and identification of relevant features on the surfaces [5]. Through the enhancement of some features one can extract information such as the type of anomalies related, in particular, to presence of moisture changes in concrete elements that accelerates their carbonation (cracking and delamination of concrete, and reinforcement corrosion) or in masonry walls (cracking, detachment of renders, degradation of the paintings, and presence of mould in the external surface of the facade).

2. Previous experimental tests for the evaluation of the variation of moisture in masonry wall specimen through ultrasound method

Ultrasound tests have been used as a non-destructive inspection technique of not homogeneous materials, such as the masonry walls. The advantages of their use are the easy data acquisition and speed of operation. These tests can be used in detection of cracks or other discontinuities, as well as in the detection of significant variations in moisture content of masonry wall constituents and their rendering. Previously, ultrasound tests were performed to access their potential use for detection of significant variations in moisture content on a masonry wall specimen, which was primarily subjected to a test for the determination of the rainwater permeability [1].

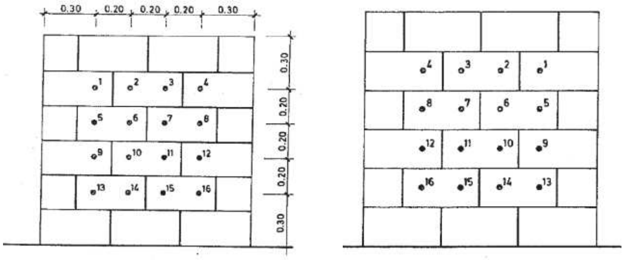
Intended to record the evolution of ultrasonic velocity during the hardening of the rendering and to detect possible changes of that velocity after wetting one face of the wall, during the test, on different dates, measurements of ultrasound velocity were carried out. A first measurement was made a week after the construction of this wall specimen; 2nd measurement was made before the test of rainwater permeability of that masonry wall. That test started about 1 month after the construction of the wall, and lasted for 48 hours; and a 3rd measurement was made few hours after the end of the of rainwater permeability test, during which the specimen was moistened. Direct and indirect measurements were made in a frame of points (see Figure 1) deployed on each face of specimen, as shown in Figure 2.

A global analysis of these results revealed that it was possible to register some dominant trends in the evolution of ultrasonic velocity values. It was noted that, in general, since the 1st week after the construction of the wall, the direct measurements values decreased, until they reach a minimum before the test. After being moistened during the rainwater permeability test, ultrasound measurements taken in the specimen afterwards the end of that test, a generalized rise of direct measurements values was registered. This allows launching the hypothesis that the ultrasound velocity in direct measurements of that type of specimen was sensitive to changes of moisture content of masonry renderings. As regards indirect measurements, although it was registered, generally, a decrease of the values from the 1st week until the date that the test was performed, however, no dominant trend was detected in the evolution of the values, after the humidification of the face (B) subject during the test.



a) Indirect measurements on the face B of the specimen
b) Direct measurements on the face A/ face B of the specimen
c) Phase of ultrasound direct measurements

Figure 1: Indirect and direct measurements of ultrasound velocity on the face A and face B of the specimen, which was subjected to humidification during the rainwater permeability test



a) measurements on the face A of the specimen
b) Measurements on the face B of the specimen

Figure 2: Schematic representation of the frame points for ultrasound measurements in the face A and Face B of the wall specimen.

	Direct measurements				Indirect measurements		
Point	Ultrasound velocity (km/s)			Point	Ultrasound velocity (km/s)		
	7nd Day	29nd Day	After Test		7nd Day	29nd Day	After Test
1 - 2	2.00	1.94	1.95	1 - 2	2.30	2.22	2.17
2 - 2	2.66	2.23	2.25	1 - 3	2.55	2.50	2.35
3 - 3	2.02	1.97	2.08	1 - 5	2.22	2.11	2.22
4 - 4	2.72	2.21	2.60	1 - 9	2.34	2.13	2.22
5 - 5	2.03	2.16	2.21	2 - 3	2.44	2.20	2.22
6 - 6	1.97	1.88	1.92	2 - 4	2.52	2.41	2.20
7 - 7	2.60	2.07	2.08	2 - 10	2.45	1.62	1.75
8 - 8	1.91	1.85	1.89	3 - 4	2.27	2.20	2.20
9 - 9	2.55	2.03	2.02	3 - 11	1.86	2.44	2.02
10 - 10	2.19	2.14	2.21	4 -12	2.56	2.23	1.83
11- 11	2.05	2.03	2.03	5 - 7	2.48	2.37	2.50
12 - 12	2.08	2.12	2.50	5 - 9	2.25	2.13	1.82
13 - 13	2.72	2.27	2.21	5 - 13	2.22	1.79	1.82
14 - 14	1.87	1.89	1.92	6 - 8	2.37	2.25	2.30
15 - 15	2.78	2.16	2.25	6 - 14	2.55	1.75	1.72
16 - 16	1.89	1.89	1.89	7 - 15	1.75	1.77	1.79
-	-	-	-	8 - 16	1.72	1.71	1.75
-	-	-	-	9 - 11	2.56	2.37	2.25
-	-	-	-	9 - 13	2.30	2.20	2.27
-	-	-	-	10 - 12	2.48	2.47	2.50
-	-	-	-	13 - 15	2.29	2.23	2.26
-	-	-	-	14 - 16	2.22	2.11	2.19

Table 1: Results of indirect and direct measurements of ultrasound velocity on the face A and face B of the wall specimen, one week after construction; 29 days after construction; and after the rainwater permeability test

3. Laboratory test

3.1 General

To access the potential use of NDT techniques (US, IRT and Photogrammetry) in the detection and evaluation of the progression of cracking in masonry walls with variable moisture content, a compression test was made in a masonry specimen with variable moisture content.

Masonry specimen M1 was subjected to three loading phases of axial compression until it reached, in the third loading phase, a state of significant cracking, without reaching a global collapse. During the three loading phases, a combined use of NDT was used to assess the presence of cracking and of variable moisture content.

Specimen test M1 (Fig. 3) was built with massive ceramic blocks, which have average dimensions of approximately 213 mm (length) x 108 mm (thickness) x 60 mm (height), and cement mortar joints (cement sand ratio - 1: 4 / volumetric ratio).

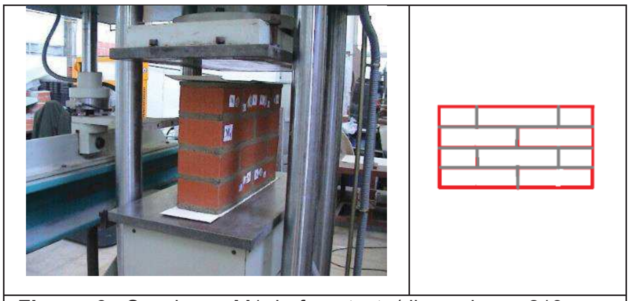


Figure 3: Specimen M1 before test (dimensions: 213 mm (length) x 108 mm (thickness) x 60 mm (height)

Initially, the specimen, in dry condition, was sightly loaded (pre-loaded correspondent to 10 kN of axial compression load), and then was discharged. Subsequently, the specimen was weighted (28830 g of weight), before going to a phase of complete immersion in water, during approximately 12 hours. After retiring from immersion, a thermographic analysis was made. And, the wet specimen was again weighted (30856 g of weight – increase of moisture content of 7.1% relatively to the previous weighting of the dry specimen), before subjected to a second loading phase, where a gradual axial compression load was applied, with loading steps of 10 kN (0.21 MPa), 20 kN (0.42 MPa), 40 kN (0.85 MPa), 60 kN (1.27 MPa), 80 kN (1.70 MPa), 100 kN (2.12 MPa), 120 kN (2.54 MPa), 140 kN (2.97 MPa),180 kN (3.81 MPa), and 300 kN (6.36 MPa); then the loading phase was halted. The third loading phase was initiated 6 days after the previous loading phase, and, before the application of load, the specimen was again weighted (29457 g of weight – increase of moisture content of 2.1% relatively to the dry specimen, and decrease of 4.5% relatively to the previous weighting, after immersion)

In the third loading phase, a gradual axial compression load was applied, with loading steps of 10 kN (0.21MPa), 120 kN (2.54 MPa), 180 kN (3.81 MPa), 300 kN (6.36 MPa), 420 kN (8.90 MPa), 540 kN (11.44 MPa) and final load of 660 kN (13.98 MPa); then ended this loading phase. During the three loading phase, for each loading step, after reaching the corresponded load, the specimen was discharged, and immediately after that discharge, the horizontal and vertical residual deformations were measured with alongameter (registering the residual deformations after load), Also, the ultrasound velocity measurements (direct and indirect measurements), and the acquisition of images of IRT and the photos were made during these tests breaks.

Then, after all NDT measurements were made, a new phase load was initiated. It was tried to find out, during the process of applying increasing axial load, the degree of sensitivity of each of these techniques in the detection and evaluation of the progression of cracking in masonry with variable moisture content.

3.2 Main results

The results of the measurement of deformations with alongameter in specimens show that the variation of horizontal (A1-A3; A2-A4: see reading points in Figure 10) and vertical (A2-A5; A3-A6: see reading points in Figure 10) residual deformations, measured after discharge of the specimen, in end of each load step, were generally correspondent to a gradual expansion of the specimen (Figures 4 to 5); and can detect, with the increase of load, the gradual progression of cracking (see signs of cracking in Figures 9 and 10, which could affect, especially, measurement dv1/A2-A6 and dh1/A1-A3), that occurred in final part (after the 420 kN (8.90 MPa) of load) of the 3rd loading phase.

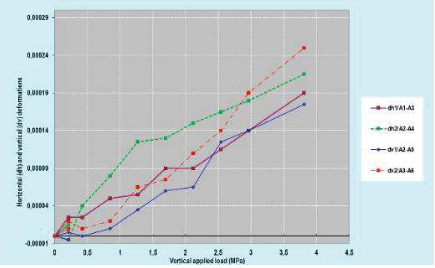


Figure 4: Deformations of the specimen M1 during 2nd loading phase for the vertical applied load

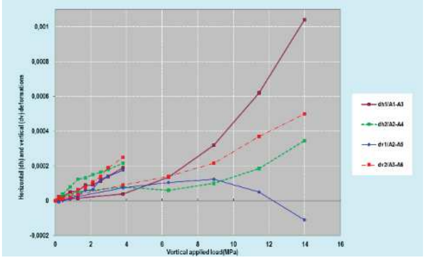


Figure 5: Deformations of the specimen M1 during the three loading phases for the applied load

Concerning the results of the application of ultrasound method in the specimen, the indirect measurements show that, in the dry specimen, with the application of the first load step of 10 kN (1st loading phase), there was an increase of the ultrasound velocity measured after discharge of that load, relatively to the correspondent value for 0 kN, for all the measurements, namely horizontal (U1/U2 (path with no mortar joints); U3-U4 (path with one mortar joint) - see reading points in Figure 10) and vertical (U1/U3 and U2-U4 (path with three mortar joints) - see reading points in Figure 10) measurements. After the end of immersion of the specimen, the ultrasound velocity measured (indirect), for 0 kN, was significantly lesser than the correspondent value (for 0 kN) in the dry specimen - which indicates that the ultrasound velocity is sensible to the increase of moisture content (7.1% as was previously referred in 3.1). Subsequently, with the application of the first load step of 10 kN, in the 2nd loading phase, there was an increase of the ultrasound velocity measured after discharge of that load, for all the measurements, namely horizontal measurements (see Figure 6); in the direct measurements, similarly, a reduction of velocity value was observed, although only in U1/U1´ and U4/U4´, and it was less expressive than in indirect measurements (see Figure 7).

Furthermore, these results reveal an almost constant decrease of the values of the ultrasound velocity (indirect measurements) in the 2nd and 3rd loading phases (see Figures 6 to 9), more in the vertical than in horizontal measurements, due presumably to the number of joints covered by vertical measurement (three mortar joints), that are higher than in horizontal measurement (one mortar joint or no mortar joints). Moreover, due, likewise, to the same effect, horizontal measurements generally are higher than vertical; and, in horizontal measurements, the U1/U2 velocity values (path with no mortar joints) are higher than U3-U4 values (path with one mortar joint).
The results reveal a decrease of the values of direct measurements of the ultrasound velocity, for higher loads, in the 3rd loading phase, probably due to the correspondent increase of micro-cracks inside the ceramic blocks.

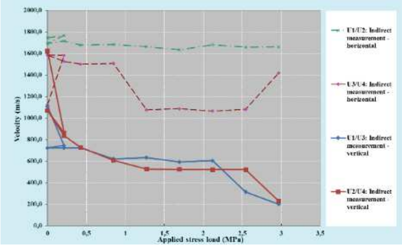


Figure 6: Ultrasound velocity (indirect measurements) of the specimen M1 during 1st loading and 2nd loading phase for the vertical applied load

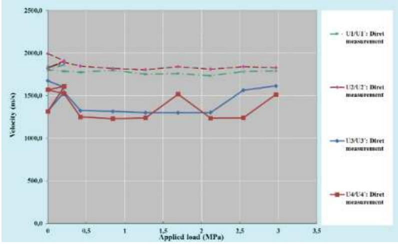


Figure 7: Ultrasound velocity (direct measurements) of the specimen M1 during 1st loading and 2nd loading phase for the vertical applied load

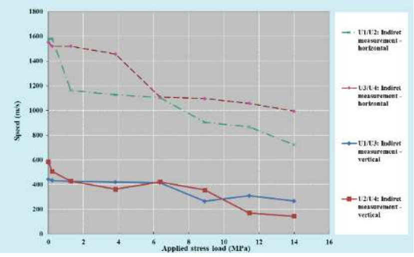


Figure 8: Ultrasounds indirect measurements of the specimen M1 during 3rd loading phase

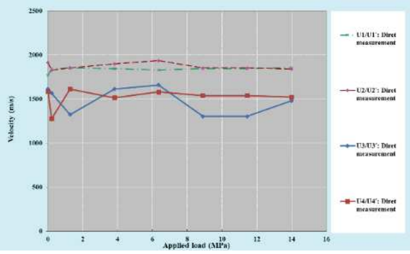
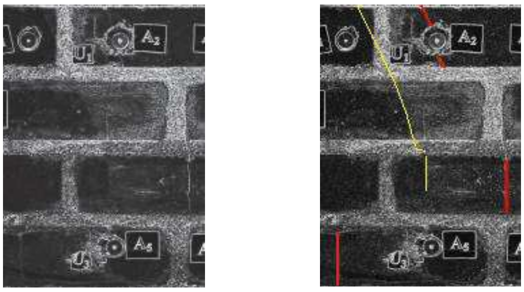


Figure 9: Ultrasound velocity (direct measurements) of the specimen M1 during 3rd loading phase

In addition, for the same level of loads, some of the ultrasound velocity values (indirect) measured, in the 3rd loading phase, are higher (horizontal: U1/U2 and U3-U4 values) others are lesser, than the correspondent values of 2nd loading phase, due presumably to the significative decrease of moisture content (4.5% as was previously referred in 3.1), 6 days after the end of the immersion of the specimen. In the 3rd loading phase, an expressive reduction of velocity values was observed, particularly, with the gradual progression of cracking (cracking that affect, especially, U1/U2 velocity values (indirect) and U1/U1´ (direct)) that occurred in final part (after the 420 kN (8.90 MPa) of load) of that loading phase.

Concerning the use in this test of photogrammetry, to generate an orthomosaic (image that is the result of stitching several orthorectified images) with a pixel of 0.12 mm it was necessary to make the photo survey with a high quality digital camera. Several photos were taken from different locations in front of the surface, but all at the same distance (70 cm). Digital image processing was applied to enhance the cracks. On Figure 11-A is presented the result of the enhancement applied to the gray-scale version of the image. Two types of edges can be detected. These were manually coloured in Figure 11-B. In red the cracks, only perceivable in the bricks since the mortar presents great variability in intensity (is a heterogenous area, mixing pixel whites, blacks and grays). In yellow, the borders between two different images used to create the orthomosaic. These borders, barely perceived in the original orthomosaic, were enhanced also.

Figure 10: Orthomosaic of the surface. Pixel size 0.12 mm



A B

Figure 11: Detail of an image created by applying digital image processing tools to the orthomosaic (A). Edges coloured (B)

Concerning IRT analysis, Figure 11 shows a thermogram obtained some days after the last loading phase. The humidity content (2.1%) is still visible with IRT (cold central zone) but no cracks were detected.

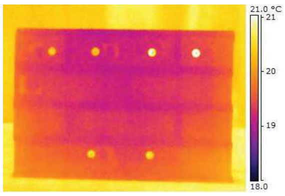


Figure 11: Test specimen thermogram after last loading phase

Figure 12 shows thermogram and photo of dry test specimen after a quick heating period (2 minutes). The heating of surface specimen allows, more clearly, to "see" the different materials of the specimen (Figures 11 and 12), but cannot detect obtained cracks. Increasing the heating period (30 minutes), IRT results indicate the same facts. However, it should be noted that visible cracks are very small.

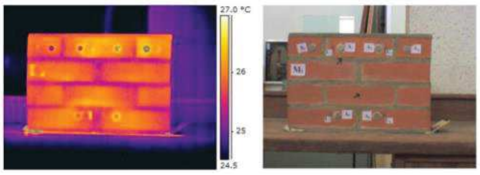


Figure 12: Test specimen thermogram and photo after heating (2 min)

4. Conclusion

In this paper, a study was made related to the application of non-destructive testing (NDT) techniques, with a view to the evaluation of anomalies related to the presence and flow of moisture in masonry walls, notably through Ultrasound (US), Infrared Thermography (IRT) and Photogrammetry. These NDT techniques were used in the evaluation of masonry specimens with variable moisture content, subjected to compression tests. The results of test of the specimen M1 reveals that the ultrasound velocity is sensible to the increase of moisture content, and show a decrease of the values of the ultrasound velocity (indirect measurements), after wetting the specimen, and application of load in the 2nd and 3rd loading phases; also, reveals a reduction of the velocity values particularly, with the gradual progression of cracking. Concerning the use in this test of photogrammetry, digital image processing was applied to enhance the cracks, and two types of edges can be detected. IRT analysis allows the evaluation humidity state of test specimen and the identification of its constituent's materials. No cracks were detected with this NDT technique. However, it should be noted that visible cracks are very small.

Acknolegdments

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