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DEFORMATIONS AND VOLUME CHANGES DUE TO MOISTURE VARIATIONS IN HERITAGE BUILDINGS - USE OF NDT TECHNIQUES

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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:

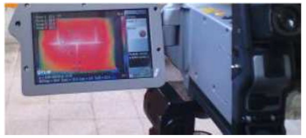
- Investigate more profoundly the anomalies;
- And using the available non-destructive testing (NDT) techniques.

Introduction

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);

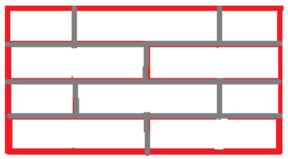


- Photogrammetry.

Introduction

These Non-Destructive techniques (NDT) are used in the evaluation of a masonry specimen with variable moisture content, subjected to compression test, before and after been tested, when cracking will be present.

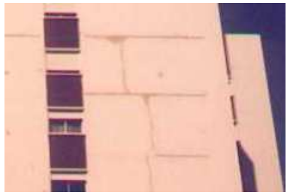
- Here, the aim is to use NDT techniques to analyze the anomalies that can be attributed predominantly to deformations due to moisture variations in masonry walls and structural elements;



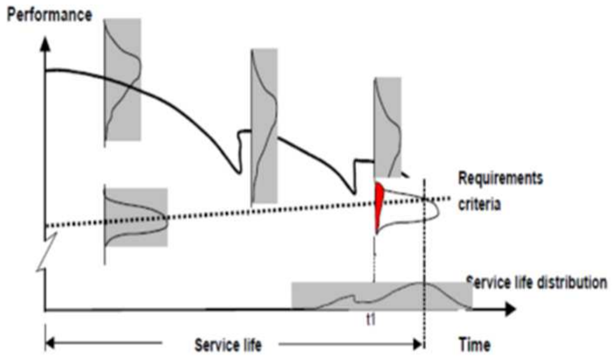
- It refers to the heritage buildings with reinforced concrete integral structure or with mixed structure of reinforced concrete and masonry.

Potential use of NDT to access movements in buildings masonry walls and concrete elements due to moisture variation

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;
- And 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, and the nature and magnitude of moisture deformations is important to access, namely through:

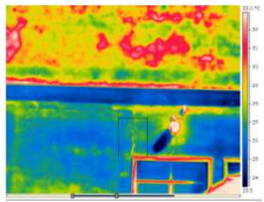
- NDT techniques.

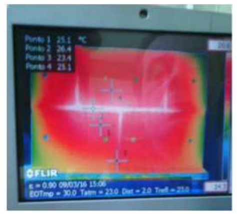
Potential use of NDT to access movements in buildings masonry walls and concrete elements due to moisture variation

To access the type of movements (reversible or irreversible moisture deformation) **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 (Infrared Thermography) **allows to relate observed situations of thermal inhomogeneity with an internal “picture” and state of the element, such as:**



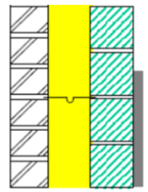


- **the characteristics of the materials;**
- **the occurrence in the wall renders of detachment;**
- **surface discontinuities and internal cracks;**
- **and, particularly interesting for present analysis, the distribution of moisture on the masonry wall.**
  - **That distribution possibly can reveal zones with different moisture expansion rate.**

Potential use of NDT to access movements in buildings masonry walls and concrete elements due to moisture variation

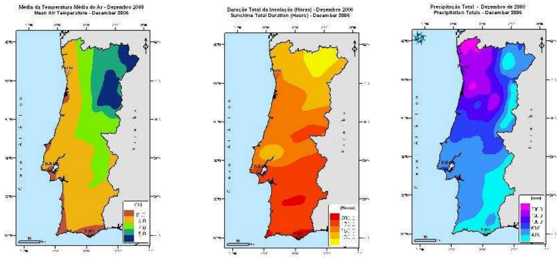
The causes of deformations of building materials, elements and concrete structures may be due:

- **to moisture content changes that result in swelling or shrinkage:**

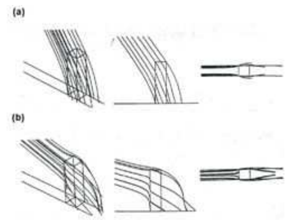


But can, also, be combined with other causes; in particular, can be combined to the following causes:

- **temperature changes resulting in expansions or contractions;**



- **chemical action in the presence of moist, air or water resulting in volume change, usually expansion;**

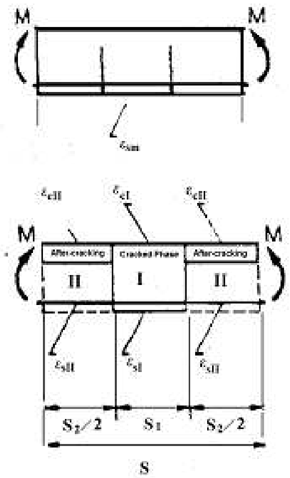


- **applied loads resulting in elastic and inelastic deformations.**

Potential use of NDT to access movements in buildings masonry walls and concrete elements due to moisture variation

When subjected to long-term loading, many building materials suffer supplementary deformation, which does not fully vanish when the loading is removed, such as:

- Deformation associated to creep, which is in relation to structural deflections for the particular case of concrete elements.



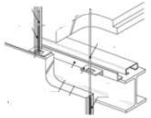
Photogrammetry can possibly give the first information about this case, when this creep deflection, mainly occurring in beams or pavements, is visibly considered anomalous and, clearly, these deformations can be, mainly, attributed to:

- Creep;
- And, with less importance, to the moisture deformations.

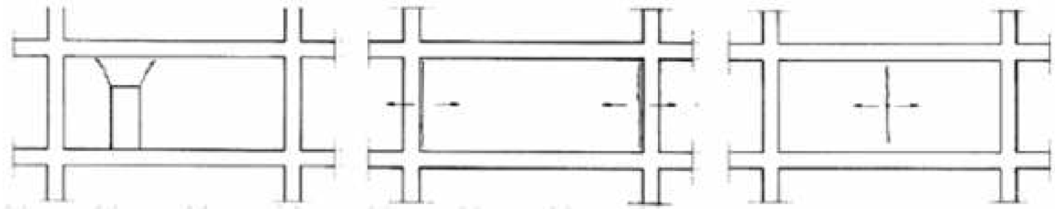
Potential use of NDT to access movements in buildings masonry walls and concrete elements due to moisture variation

Cracking can 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;**

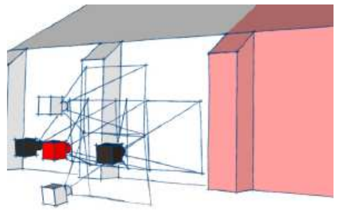


- **Stresses may be induced, which, in certain cases, maintain the deformation controlled;**
- **But, in other cases, these stresses exceed the strength of the material, and the material can crack.**



Photogrammetry can explore in detail the apparent state of the surface of the building element, namely:

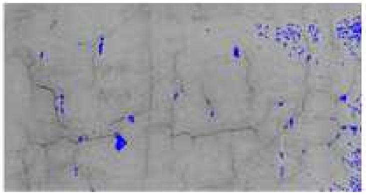
- **superficial defects associated to cracks.**

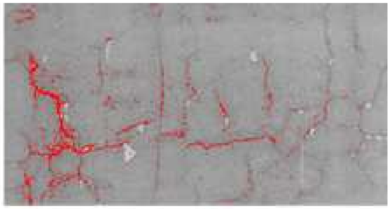


Potential use of NDT to access movements in buildings masonry walls and concrete elements due to moisture variation

For example, in the analysis of cracks in facades, photogrammetry should be used:

- **it enables measurements from photogrammetric products** (measuring the length and aperture of a crack is an example)**;**
- **it allows, using image processing techniques, the recognition and identification of relevant features on the surfaces.**





Through the enhancement of some features one can extract information, such as the type of anomalies related, in particular, to the:

- **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 mold in the external surface of the facade)**.**

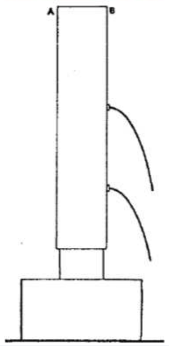
Previous experimental tests for the evaluation of the variation of moisture in masonry wall specimen through ultrasound method

Ultrasound tests have been used as a non-destructive inspection technique of non-homogeneous materials, such as the masonry walls. The advantages of their use are the easy data acquisition and speed of operation.

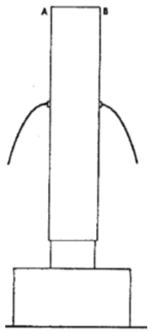
- **These tests can be used in detection of cracks or other discontinuities, as well as in the detection of significant variations in moisture content of masonry wall constituents and their rendering.**

Previously, ultrasound tests were performed to access their potential use for detection of significant variations in moisture content on a masonry wall specimen.

- **The masonry wall specimen was primarily subjected to a test for the determination of the rainwater permeability.**



Indirect measurements on the face B of the specimen



Direct measurements on the face A/ face B of the specimen

Phase of ultrasound direct measurements

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

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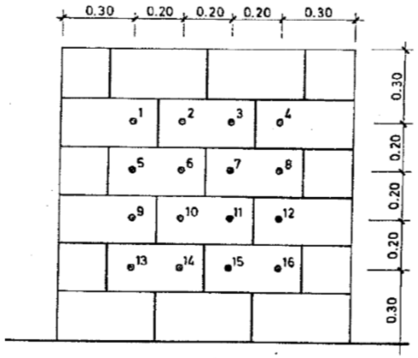
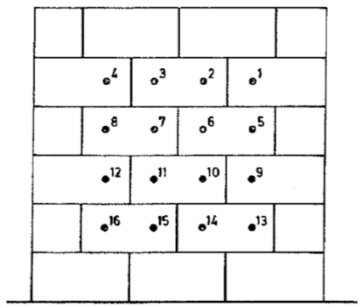
Previous experimental tests for the evaluation of the variation of moisture in masonry wall specimen through ultrasound method

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.

- That test started about 1 month after the construction of the wall, and lasted for 48 hours.

Direct and indirect measurements were made in a frame of points deployed on each face of specimen.





- 1st 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;
- 3rd measurement was made few hours after the end of the of rainwater permeability test, during which the specimen was moistened.

Laboratory test

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 M1 with variable moisture content.

- Specimen test M1 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).

Masonry specimen M1 was subjected to three loading phases of axial compression.

- In the third and last loading phase, it reached a state of significant cracking, without occurring 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.

1st loading phase → 2nd loading phase → 3rd loading phase

Laboratory test

General

In the 1st loading phase, the specimen, in dry condition, was slightly loaded (pre-loaded correspondent to 10 kN of axial compression load)**, and then was discharged.**

1st loading phase → Immersion in water (12 h) → 2nd loading phase → 3rd loading phase

1st loading phase

The specimen, in dry condition, was slightly 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.

Laboratory test

General

The wet specimen was again weighted and subjected to a second loading phase.

1st loading phase → Immersion in water (12 h) → 2nd loading phase → 3rd loading phase

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),

2nd loading phase

Subsequently, 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);

And, then the loading phase was halted

Laboratory test

General

The third loading phase was initiated 6 days after the previous loading phase, and, before the application of load, the specimen was again weighted.

1st loading phase → Immersion in water (24 horas) → 2nd loading phase → 6 days → 3rd loading phase

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)

3rd loading phase

Subsequently, 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.

And, 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),

During the three loading phases, for each load 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);
- The ultrasound velocity measurements (direct and indirect measurements), and the acquisition of photos (photogrammetry) were made during these tests breaks.
- Then, after all NDT measurements were made, a new load step was initiated.

It was tried to find out, during the process of applying increasing axial load, the degree of sensitivity of each of these NDT techniques, namely:

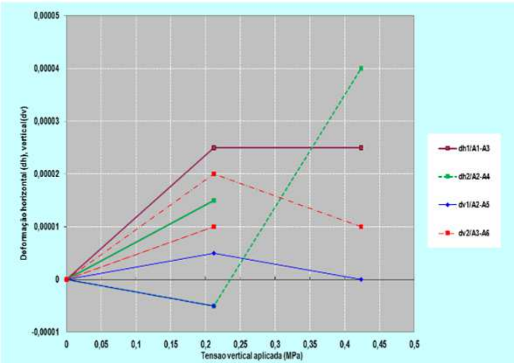
- In the detection and evaluation of the progression of cracking in masonry with variable moisture content.

Laboratory test

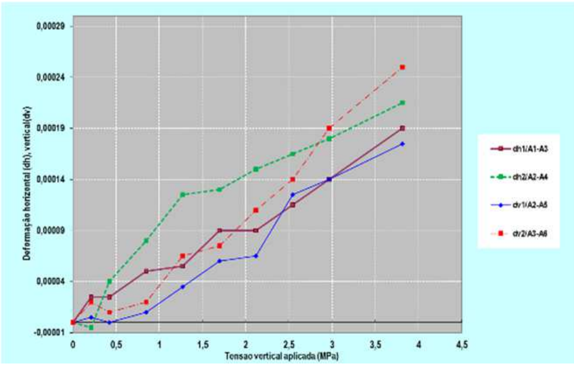
Main results

The results of the measurement of deformations with alongameter in the specimen show that the variation of horizontal (A1-A3; A2-A4: see reading points) and vertical (A2-A5; A3-A6: see reading points) residual deformations, measured after discharge of the specimen, in end of each load step, were generally correspondent to a:

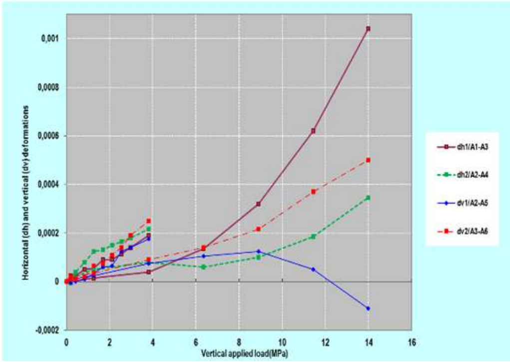
- gradual expansion of the specimen;
- and can detect, with the increase of load, the gradual progression of cracking (cracking which could affect, especially, measurement dv1/A2-A6 and dh1/A1-A3), that occurred in final part (after the 420 kN (8.90 MPa) of load) of the 3rd loading phase.



Deformations of the specimen M1 during 1st loading and initial part of 2nd loading phase (see comparison of results for load between 0 and 0.2 MPa)



Deformations of the specimen M1 during 2nd loading phase



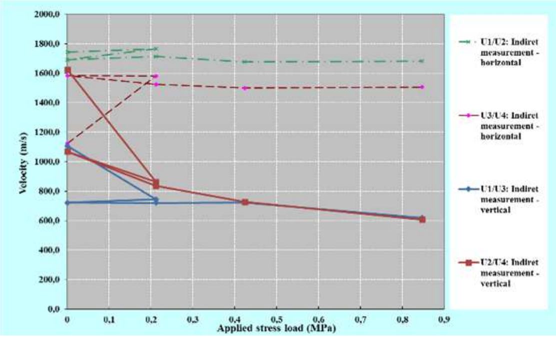
Deformations of the specimen M1 during the three loading phases for the applied load

Laboratory test

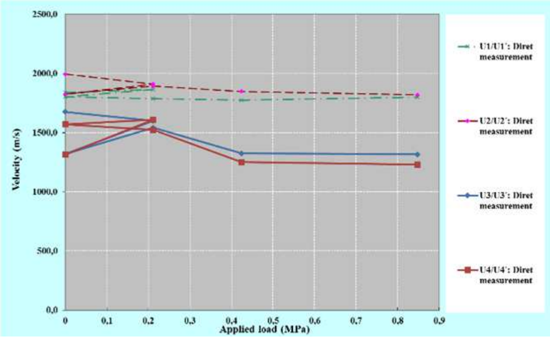
Main results

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 some of the measurements, namely:

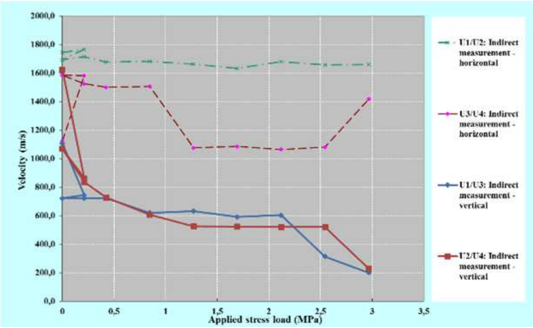
- **horizontal** (U1/U2 (path with no mortar joints) and U3-U4 (path with one mortar joint));



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



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



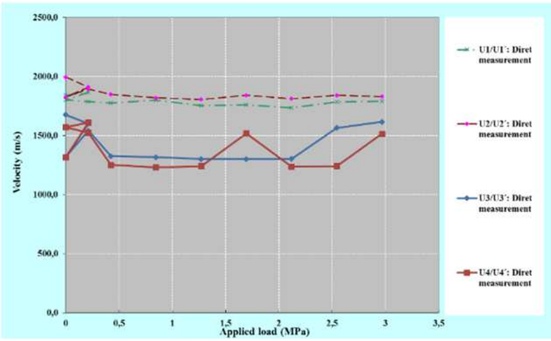
Ultrasound velocity (indirect measurements) of the specimen M1 during 1st loading and 2nd loading phase for the vertical applied load

Laboratory test

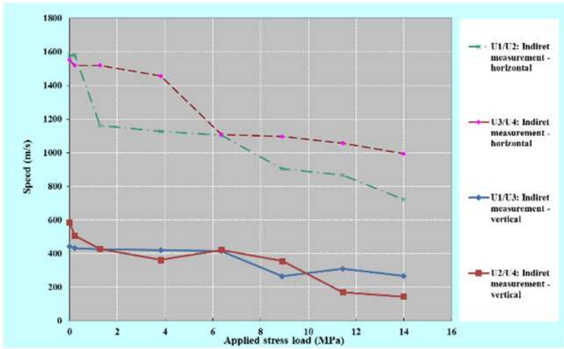
Main results

After the end of immersion of the specimen, the ultrasound velocity measured (indirect measurement)**, for 0 kN, was significantly lesser than the correspondent value in the dry specimen** (for 0 kN) **- which indicates that the ultrasound velocity is sensible to the increase of moisture content** (7.1%)**. Subsequently, with the application of the first load step of 10 kN, in the 2nd loading phase, there was:**

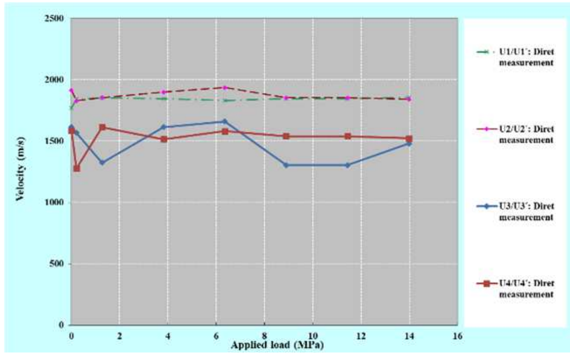
- **a decrease of the ultrasound velocity** (indirect measurement) **measured after discharge of that load, namely for vertical measurements;**
- **in the direct measurements, similarly, a reduction of velocity value was observed, although only in U1/U1´ and U4/U4 measurements; that reduction was also observed in the end of 3rd loading phase.**



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



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



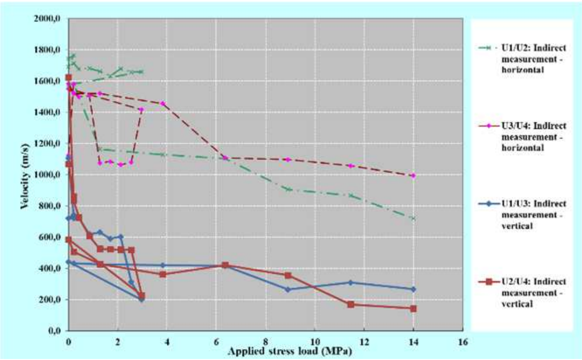
Ultrasound velocity (direct measurements) of the specimen M1 during 3rd loading phase

Laboratory test

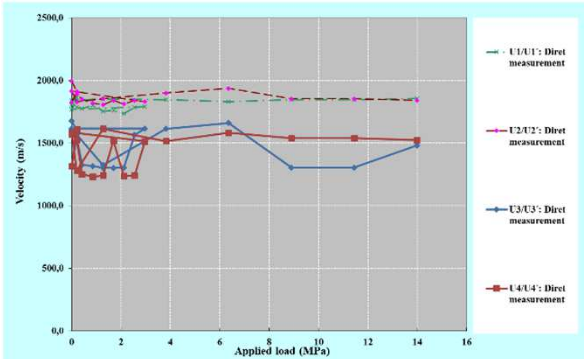
Main results

These results reveal an almost constant decrease of the values of the ultrasound velocity (indirect measurements) **in the 2nd and 3rd loading phases, 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)**.**

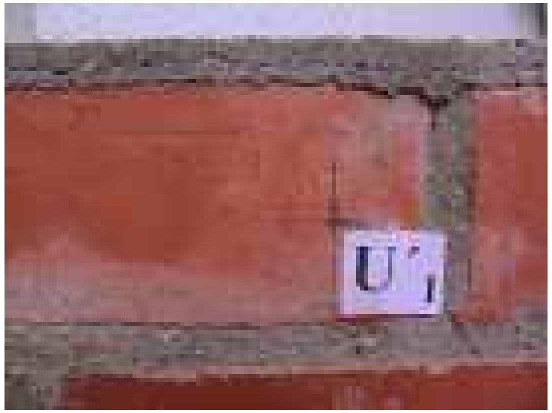
- **Moreover, due, likewise, to the same effect, horizontal measurements generally are higher than vertical** (in indirect measurements)**; and, in horizontal measurements, the U1/U2 velocity values** (path with no mortar joints) **are higher than U3/U4 values** (path with one mortar joint).
- **The 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.**



Ultrasound velocity (indirect measurements) of the specimen M1 during the three loading phases



Ultrasound velocity (direct measurements) of the specimen M1 during the three loading phases



Laboratory test

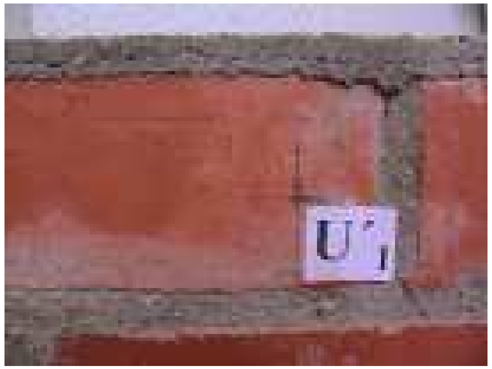
Main results

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, which can be presumably related to:

- the significant decrease of moisture content (4.5%), 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 on that loading phase (cracking that affect, especially, U1/U2 velocity values (indirect) and U1/U1´ (direct), that occurred in final part of the load (after the 420 kN (8.90 MPa))



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.**

Orthomosaic of the surface. Pixel size 0.12 mm

Several photos were taken from different locations in front of the surface, but all at the same distance (70 cm).

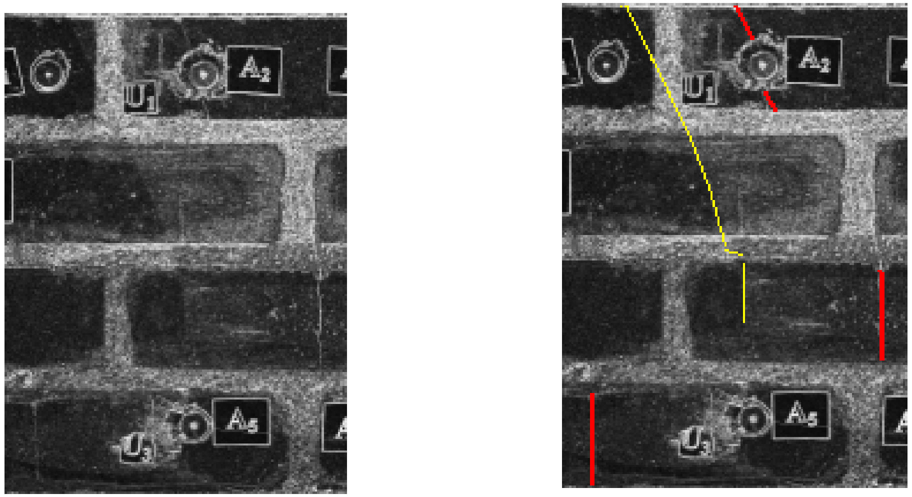
- **Digital image processing was applied to enhance the cracks.**

Laboratory test

Main results

On Figure bellow (A and B) 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 colored in Figure B.
- In red the cracks, only perceivable in the bricks since the mortar presents great variability in intensity (is a heterogeneous area, mixing pixel whites, blacks and grays).
- In yellow, the borders between two different images used to create the orthomosaic.



A B

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

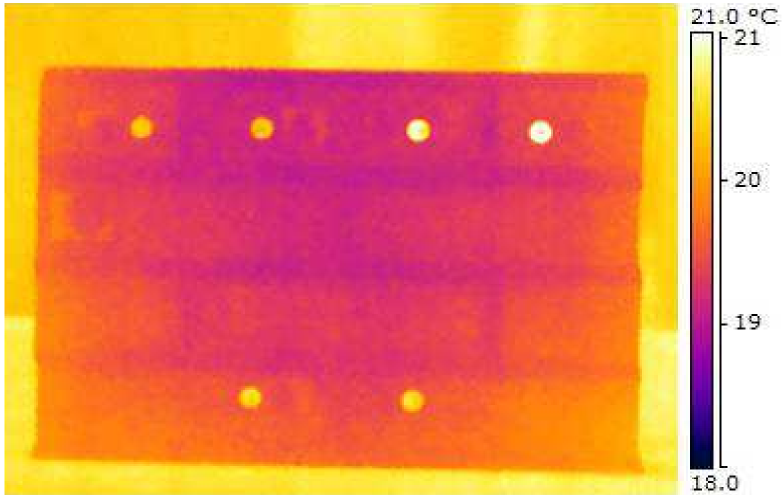
These borders, barely perceived in the original orthomosaic, were enhanced also.

Laboratory test

Main results

Concerning IRT analysis (Infrared Thermography), the figure bellow 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.



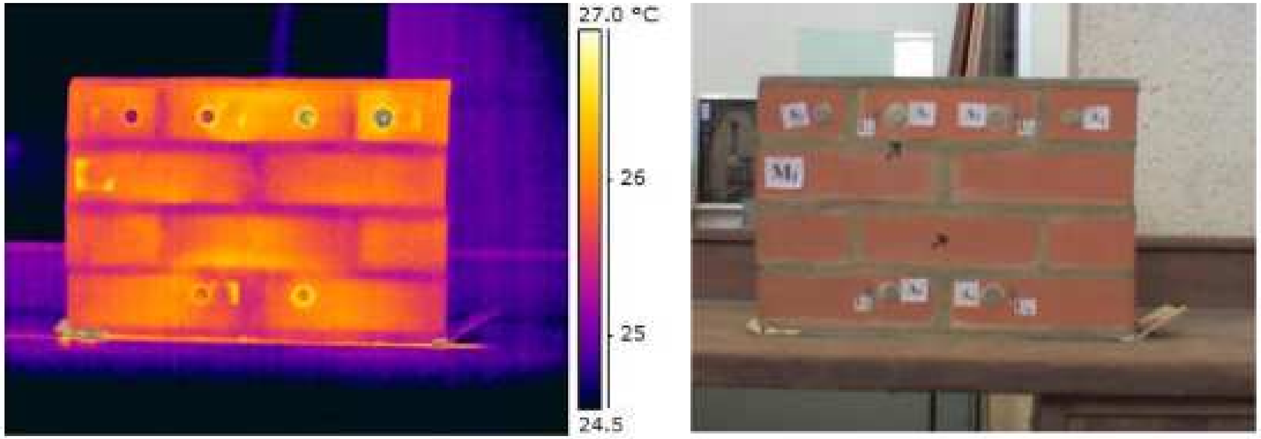
Test specimen thermogram after last loading phase

Laboratory test

Main results

Figure bellow shows a thermogram and a 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, but cannot detect obtained cracks.



Test specimen thermogram and photo after heating (2 min)

Increasing the heating period (30 minutes), IRT results indicate the same facts.

- However, it should be noted that visible cracks are very small.

CONCLUSIONS

- 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

CONCLUSIONS

- The test 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.

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