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Masonry walls of buildings with reinforced concrete structure - Detection of cracking due to the effect of temperature variations through NDT techniques

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Abstract

In buildings with reinforced concrete structure, it is observed that, in many cases, the cracking in facade masonry walls and internal walls is essentially related to deformations due to temperature variations (thermal deformations). In fact, thermal deformations can induce significant stresses in these building elements and cause appreciable cracking, the repair of which may incur high costs. Where the effect of temperature variations is presumed to be predominant, the detection of the respective cracking situations shall involve the identification, with high reliability, of the characteristic signs that clearly can be associated to the typical pattern of cracking due to thermal deformations. The purpose of this paper is to analyse, in heritage buildings, thermal deformations in masonry walls and their confining reinforce concrete elements. It also addresses the process of identification of this kind of cracking associated with the effect of temperature variations. In particular, the potential for using NDT techniques, namely ultrasound testing, infrared thermography and photogrammetry, in this process of identification, is here evaluated.

Key-words: Masonry walls; Concrete structure; Non-destructive techniques; Thermal deformations; Heritage buildings

1 INTRODUCTION

In buildings with reinforced concrete structure, it is observed that, in many cases, the cracking in facade masonry and internal walls is essentially related to deformations due to temperature variations (thermal deformations). In fact, thermal deformations can induce significant stresses in these building elements and cause appreciable cracking, the repair of which may incur high costs. Where the effect of temperature variations is presumed to be predominant, the detection of the respective cracking situations shall involve the identification, with high reliability, of the characteristic signs that clearly can be associated to the typical pattern of cracking due to thermal deformations.

With this objective, it is important to distinguish this cracking from another type of cracking attributable to other possible causes, such as foundations settlements, excessive vertical loads or moisture variations. In cases of heritage buildings with reinforced concrete structure, considering their relevant cultural/historical value or public utility and the consequent need of assuring the functionality, aesthetics and the safety of the referred heritage buildings, this objective may justify a detailed survey of such anomalies carried out using in-situ inspection techniques, preferably the non-destructive techniques (NDT. The purpose of this paper is to analyse, in heritage buildings mentioned above, effects of thermal deformations in masonry walls and their confining reinforced concrete elements. It also addresses the process of identification of this kind of cracking. In particular, the potential for using NDT techniques, namely ultrasound testing, infrared thermography and photogrammetry, in this process of identification, is here evaluated.

2 SPECIFIC CHARACTERISTICS OF CRACKING DUE TO THERMAL DEFORMATIONS

2.1 Characterization

Temperature variations in masonry walls and in the confining elements, such as reinforced concrete beams, slabs and roofs, are often related to significant stresses induced in these elements, which may lead to considerable cracking. These phenomena, besides the increased risk of rainwater infiltration, can affect relevant building functional performance and durability of the building.

According to temperature variations, the construction elements expand or contract, and because these elements are partially (or wholly) restrained, stresses are consequently induced and can be considerable, even more than those resultant from external loading. Thermal expansion or contraction is here considered as the tendency of the constituent material of masonry and reinforced concrete elements to change its shape, area, and volume in response to a change in temperature. These changes of temperature may act uniformly on these elements, but under normal climatic conditions, the temperature gradient set up is usually non-linear and the induced internal stresses can be significant, and cracking in these elements is likely to occur.

2.2 Identification of the cracking situations

Heritage buildings are subjected, along the service life, to changes in environment and in loading, which can result in constructional anomalies such as the cracking of masonry walls. Cracking is a frequent type of pathology in the external envelope and in internal partitions of buildings. The characterization of that cracking can be made through the assessment of their main features, particularly: location, extension and depth of the cracks and orientation. Different causes can be attributed to masonry cracking, but the following causes are the most common and relevant [1] to [5], [8]: deformations of masonry walls and structural elements due to temperature and moisture variations; deformation due to vertical loads of the structural elements that support the walls; and settlements of buildings.

Here, it is intended to analyse the anomalies related to cracking that can be attributed predominantly to deformations due to temperature variations in masonry walls and structural confining elements of reinforced concrete. The temperature variations effects are usually associated to: the variation of external temperature; solar radiation incidence, difference of external and internal temperature in the building; and temperature variation inside the construction element. This type of anomalies can affect the functionality and aesthetics, and, in some situations, the safety of heritage buildings. In buildings with reinforced concrete integral structure or with mixed structure of reinforced concrete and masonry, cracking associated with the effects of temperature variations, usually, is noticeable through specific features, related, predominantly, to shear effects (Figure 1).

Figure 1. Example of cracking situations associated with the effects of temperature variations

Thermal deformations (expansion and contraction) in construction elements can have different expressions [1], in terms of the construction elements affected. In fact, movements in the masonry walls can lead, in certain cases, to vertical cracking. Moreover, movements in framed reinforced concrete structures can lead to the cracking in the interface between masonry wall and reinforced concrete structure; to vertical cracking in masonry walls; to oblique cracking in the extreme building central masonry panels; and to vertical cracking in the central masonry panels of the building. Lastly, movements in the roof concrete slabs can lead to cracking in the masonry wall near their connection zone to that slabs.

Generally, infill walls have no significant resistant function in the building, but due, particularly to thermal effects, some transference of loading can occur due to their interaction with the reinforced concrete structure, and this interaction can lead to cracking. This type of cracking associated to that interaction can, particularly, manifest in terms of horizontal cracks at slab level, affecting the rendering of the masonry wall or both the masonry wall and their rendering; and of shear cracking at the transition zones of support conditions of wall facade.

3 IN-SITU NON-DESTRUCTIVE INSPECTION TECHNIQUES

3.1 General

In a routine inspection, visual observations of anomalies depend on the knowledge and experience of the observer. Automatic image-based anomaly detection can be a complementary tool to visual inspection and the respective analysis can be based on the image processing techniques, eventually more objective and with more accuracy. The automated anomalies detection, based on image processing techniques, can be done using the non-destructive testing (NDT) techniques available [6] to [8]: ultrasound testing (US), infrared thermography (IRT) and photogrammetry (terrestrial/aerial survey using an unmanned aerial vehicle - UAV). So, the potential use NDT techniques in the survey of temperature cracks in masonry walls or in their structural confining elements are here evaluated.

US, IRT and photogrammetry are most valuable in inspection of heritage buildings; and IRT and photogrammetry can be, especially, useful when a simple visual observation is not possible: areas too far away from the observer (example: the higher floors of the building); or areas of limited accessibility.

The recognition of the most relevant patterns of these anomalies of cracking related to thermal deformations could be explored, in particular through image processing and features extraction of anomaly patterns in facade walls and on confinement elements of reinforced concrete.

3.2 Ultrasound testing (US)

US aims the evaluation of the state of conservation of the construction elements based on estimation of mechanical resistance and deformability of constituent material and it allows the evaluation of the compactness and stiffness by determining the rate of spread of ultrasonic waves through the material.

Previous study [6], where US was used in the analysis of anomalies of the facade of a heritage building showed that, with the indirect measurement, it was possible the detection of cracking and local detachment of the facade renders (Figure 2).

Figure 2 - Use of ultrasound testing (indirect measurements) for the detection and evaluation of anomalies occurring in a building façade [6]

3.3 Infrared thermography

IRT (active and passive methods) can, possibly be used to the search cracks due to thermal effects, because they probably can introduce a change of thermal properties that alters heat transfer. For instance, a different temperature pattern might appear or not at the surface depending on the thermal properties of the materials or air presence; this feature could be, particularly, interesting to analyse masonry mortar joints, with possible cracking (Figure 3c), but also the current zone of rendering.

IRT was used, in a previous study [6], for detection of cracking and local detachment in the wall renders and in concrete elements, and detection of transition zone between concrete elements and masonry walls. Using solar radiation for imposing a heat flux (passive method), IRT detected cracks in facade (Figure 3a), difficult to spot when seen at ground level. In other facade, the structural concrete elements could be visible with IRT, and the zone of interaction of the vertical concrete element and the masonry wall (Figure 3b). The area under the window on the left side is more noticeable (warmer) probably due to the presence of a heater inside the room (Figure 3b). The white area between the windows identifies detachments of coatings.

a) Facade showing rendering crack that can probably be associated, in part, to temperature variations

b) Facade showing structural concrete elements (in particular the column of East corner zone of the façade - in the photo at right), and also signs of cracking that can be attributable, in part, to the effect of temperature variations

c) Example of use of IRT to highlight the presence mortar joints in a masonry specimen

Figure 3 - Use of infrared thermography for the detection and evaluation of anomalies related to cracking [6]

3.4 Photogrammetry

Photogrammetry can be used in the survey of this type of cracking; through the enhancement of some features it is possible to extract information such as the type of anomalies in concrete elements (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).

Photogrammetry was used to get orthomosaics of facade of a building and a point cloud of the set [6]. There were made a terrestrial survey in the facades of a building and an independent aerial survey, with a drone DJI Inspire 1V2 (Figure 4). It was applied image processing techniques in the analysis of anomalies, for detection of the cracking and detachment in the wall renders, and the cracks and repair zones in concrete elements.

Figure 4 - Photos taken by the drone of building facades with signs of cracking that can probably associated, in part, to temperature variations [6]

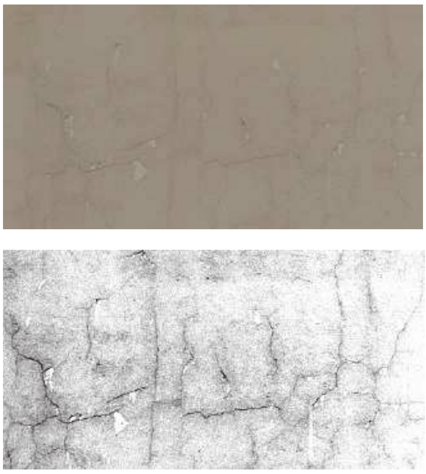


Figure 5 - Detail of an orthomosaics of a facade (top) and the enhancement, by image processing techniques, of the cracks on the surface (bottom)

3.5 Combination of ultrasound testing, infrared thermography and photogrammetry

3.5.1 General

In real situations, sometimes one of the causes of cracking in heritage buildings is presumed to be the principal responsible cause of an anomaly, and it is necessary to investigate more profoundly, and with the available NDT techniques, to confirm that assertion. In other cases, when more than one of these causes act in combined way to generate the anomaly, survey results must be carefully accessed to estimate the relative importance of each of these causes.

The combined use of different NDT techniques can eventually permit to obtain information enabling the identification of patterns of anomalies related to thermal effects and already sufficiently known by the existing experience, and guiding the phase of detailed characterization of anomalies, including using *in situ* tests, laboratory tests or analytical studies.

NDT could be useful in determining the most probable cause of the anomalies, in the identification of the type of construction elements, as well as the specific nature of the anomalies [7]. For example, combining ultrasounds, IRT and photogrammetry (terrestrial or aerial/drones) could lead to identify the transition zone between structural concrete elements and confining masonry walls and the type of cracking that occur in that interface (shear or tension cracks, crushing, etc.). It can be evaluated, also, the use of NDT to capture signs of movements due to temperature variations, occurred along the years, in buildings with limited expansion joints, where their reinforced concrete structure and masonry walls can present opposite movements that possibly lead to cracking in different areas of masonry; NDT can, likewise, be used in cases where temperature variations causes high deformations in reinforced concrete slab roofs (especially for cases of insufficient thermal insulation or other protective solutions of these slabs), which induce significant shear stresses at the top of the confining masonry walls, that can result in their cracking.

To explore the adequate methodology for the use of NDT techniques to provide relevant information about cracking of construction elements, some significant types of anomalies are presented bellow with the aim of showing the potential use of NDT techniques (US, IRT and photogrammetry) in the identification of these anomalies, taking into account the relationship to their presumed causes associated to temperature variations [4], [5].

3.5.2 Oblique cracking in masonry walls

Photogrammetry combined with IRT can be useful for assessing oblique cracking due to temperature variations (expansion) in the top part of the building facade (zone of upper floors before the roof), far from visual observation, where NDT techniques can be useful to search their presumable relation to thermal deformations occurring in the direction of the facade wall plane. This type of oblique crack has typically a downward tracing movement in the direction of expansion movement (Figure 6a), and are usually related to significant shear effects, which can possibly be examined in detail through photogrammetry. In case of facade masonry zone, near the roof slab, the NDT techniques could try to confirm that the referred oblique cracking is worse in the upper floors (with cracking beginning closer to the slab and revealing, in that zone, a greater crack width, a typical of this type of anomaly).

Similarly, oblique cracking on the facade wall, in the last floor (Figure 6b), near the roof zone (cracking occurring, sometimes, in both facades of a building corner), can possibly be detected throughout the use of NDT techniques, which could also try to search for likely associated horizontal shear cracking along the interface between the wall and the roof slab (see more detailed description of this type of horizontal cracking in 3.5.3). Sometimes, symmetrical oblique cracking, resulting from contraction movement, can be also associated to the former oblique cracking (expansion movement).

3.5.3 Horizontal shear crack along the interface between the facade wall and the roof slab

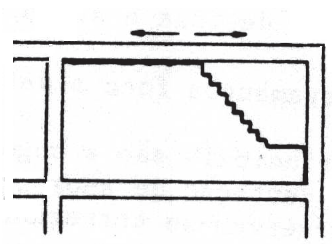
IRT together with photogrammetry can be used to identify the transition zone between concrete roof slab and confining masonry walls, and search a possible horizontal shear cracking along the interface between them (Figure 6a), which can occur, due to the thermal movement of the concrete roof slab in the direction of the wall plane, particularly when the vertical load transmitted from the roof slab to the facade wall is low and the mechanical resistance of the connection between the two elements is weak.

Regarding that connection between masonry elements and reinforced concrete elements, particularly in roof level, it is sometimes difficult to estimate, in a real situation, with adequate precision, their behaviour characteristics; but, for that estimation, a possible variation between two extreme types of connections can be admitted: one which the connection is considered a perfect rigid link between the two materials (masonry and concrete); and the other which assumes the possibility of sliding between the two surfaces of materials in that interface. Therefore, pictures captured by IRT, complemented with photogrammetry, could possibly try to evaluate, qualitatively, if the connection can be assumed near one extreme or near the other, or if it can be presumed in a near middle term situation, mainly through a careful analysis, by IRT, of the degree of “intensity” the hotter zones, in this interface zone.

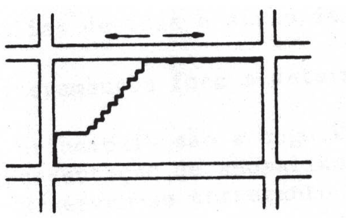
Horizontal cracking at the top of the facade walls of last floor, that can sometimes occur, with significant expression in terms of crack width, during certain short periods of the year that correspond to greater insolation days (and with variable width of that cracking along the period of building use) can, possibly, be detected by NDT techniques; that cracking could, mainly, result from the differential heating between the outer and inner face of the slab, that can cause the arching of the slab (downward concavity).

3.5.4 Horizontal crack along the upper horizontal mortar joint close to the roof slab

If there is a presumption of thermal movement of the roof slab, in a direction perpendicular to the facade masonry wall, the photogrammetry and IRT can explore, carefully, if a horizontal crack along the upper horizontal mortar joint (Figure 7), close to the roof slab can be detected. Another clue, linked to this movement, to search with these NDT techniques, is the misalignment of the two edges of the cracking in that mortar joint, as a result of masonry wall bending (Figure 7); in some extreme cases of high horizontal deformation of the roof slab, the part of wall above that horizontal mortar joint can be dragged with the roof slab (Figure 7). However, in the case of slight movements of the roof slab, perpendicular to the facade wall, NDT techniques should also be aware, for detection of slight shear cracking in the interface of the slab/masonry panel, that may occur, or of a horizontal cracking on the tensioned face of the wall, when it is subjected to bending.

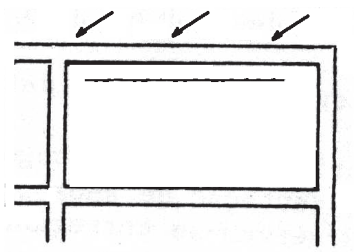


b) Last floor near the roof



a) Upper floors near the roof

Figure 6. Example of oblique cracking/horizontal shear craking in top of the building, due to the effect of temperature variations (movement in the plane of the facade wall)



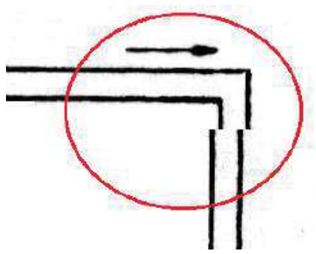


Figure 7. Example of horizontal shear cracking/oblique cracking in top of the building (roof level), due to the effect of temperature variations (movement perpendicular to the plane of the facade wall)

Figure 8. Cracking in window corners, in last floor, due to effect of temperature variations

3.5.5 Cracking in connection zones of facade masonry walls with other building elements or in weak zones

Due to the possible ability of NDT to identify zones of transition of construction elements, and heterogeneity of material, there is a potential interest for the use of NDT to detect cracking in the most weak areas of the walls or other construction elements, and in zones where there is a concentration of stresses, particularly in the connection with other elements (columns, beams, slabs, doors and windows, etc.; example of doors and window corners - Figure 8); cracking in the connections of masonry facade walls with internal partition masonry walls (cracking, possibly, inside the elements and non-visible).

3.5.6 Vertical and horizontal cracking in masonry walls

Combined use of US, IRT and photogrammetry could be explored to examine probable relationship of near vertical and horizontal cracking occurring in masonry walls, in all the extension of building (and not, only, in the top part of the building as analysed previously in 3.5.2 to 3.5.4), to the different possible types of thermal movements: movements in the masonry walls; movements in framed reinforced concrete structures; and movements in the roof concrete slabs.

For example, these NDT can be applied in the cases of onset of cracking in areas of the masonry walls where the temperature transition occurs at weak points (example of thickness reductions); in this type of situation, the cracking in the horizontal masonry joints, arching and loss of wall stability (especially in the deficient connection of the masonry elements to the reinforced concrete elements) can be, possibly, a result of differential heating of the masonry wall due, mainly, to: the presence of zones with different thermal resistance; the presence of localized indoor heat sources; the specific conditions of insolation of the wall facade.

4 CONCLUSIONS

In this paper, thermal deformations theme in masonry walls and their confining reinforced concrete elements of heritage buildings was analysed. It also addressed the process of identification of this type of cracking associated with the effect of temperature variations. In particular, the potential for using NDT techniques, namely ultrasound testing, infrared thermography and photogrammetry, in this process of identification, was evaluated. Some significant types of anomalies were presented, in the perspective of the potential use of NDT techniques (US, IRT and photogrammetry) for their identification, taking into account the relationship to their presumed causes associated to temperature variations.

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