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Original article

Validation of non-destructive characterization of the structure and seismic damage propagation of plaster and texture in multi-leaf stone masonry walls of cultural-artistic value

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ABSTRACT

Assessment of multi-leaf stone masonry in earthquake-prone areas is mostly related to the evaluation of its texture, morphology, leaf detachment and structural cracking due to previous seismic activity, as well as disintegration due to material deterioration. For the plastered masonry with heritage or artistic value (paintings, frescoes etc.), both the type of structure and the extent of damage should be characterized with minimal interference to the structure, which could be overcome solely by non-destructive testing (NDT). However, due to the complexity of plastered multi-leaf masonry structure, the performance of well-known NDT methods could be significantly worsened. Therefore, as a prerequisite for applying NDT on multi-leaf stone masonry in practice, a validation process should be carried out. In this study, complementary ground penetrating radar (GPR) and infrared (IR) thermography measurements on plastered laboratory three-leaf stone masonry walls were performed. Apart from assessing the wall texture and morphology with the type of connection between the leaves, detection of gradual plaster delamination and crack propagation while subjecting the walls to an in-plane cyclic shear test was taken into account. The results showed that GPR could successfully visualize header stones passing through the whole depth of the specimen. The masonry texture behind the plaster could be well resolved by both methods, although GPR near-field effects worsened its localisation. For the detection of plaster delamination, IR thermography outperformed GPR by detecting delamination as small as 2 mm as well as structural crack patterns, whereas GPR only detected delamination larger than 8 mm. It was shown that the performance of both methods for defect detection could be further improved by image fusion based on unsupervised clustering methods.

1. Research aims

The aim of this study was to evaluate the complementary performance of ground penetrating radar and infrared thermography in non-destructively assessing the type of structure (texture and morphology with type of connection) and seismic related damage (plaster detachment and crack propagation) of plastered multi-leaf stone masonry. The application of NDT methods to such masonry with artistic or cultural-heritage value is of particular importance in evaluating the structural condition with minimal interference.

2. Introduction

A large proportion of existing stone masonry buildings in European Mediterranean countries, as well as elsewhere, represent cultural heritage assets. Very often, the stone masonry consists of several leaves, of which three-leaf masonry is one of the most characteristics [1]. Here, the outer leaves consist of stones arranged in various masonry bonds (hereinafter referred to as texture), whereas the inner core is a mixture of stone rubble and loose adhesive material. The leaves may be connected with so-called header stones, i.e. connecting stones passing through the whole depth of the specimen [2].

In most cases, this type of building is vulnerable to material deterioration and seismic action, resulting in leaf detachment and cracks which can be further emphasized due to the presence of internal voids. For effective repair of the masonry, an accurate diagnosis of the defects present and visualization of the structural model defining the behaviour of the structure should be carried

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out. For that, the structure's geometry, texture and morphology (the multi-leaf structure and connections between the leaves), as well as the material properties of the masonry and its constituents (stones/bricks and mortar) need to be determined [3].

Taking into account that for cultural heritage buildings with artistic value the structural condition should be assessed with the minimal possible intervention, the application of non-destructive testing (NDT) methods for both structural visualization and defect detection play an essential role. Several NDT methods have been proposed for structural investigation of building elements [4]. Contact methods, such as ground penetrating radar (GPR), ultrasonic, sonic and impact echo are especially promising in imaging the inner structure of buildings at depths of more than 5 to 10 cm, depending on the specific method [5]. On masonry, such methods have been applied for detection of the morphology, localization of voids and metal inclusions, determination of the moisture distribution, detection of severe delamination, as well as to control the effectiveness of repair by injection techniques [6–10]. On the other hand, non-contact active infrared (IR) thermography (hereinafter we omit "active") has been shown to be a powerful technique for imaging the structure very close to the surface, such as for visualization of the masonry texture, surface cracks, moisture distribution and plaster delamination [1,11–13], as well as for the investigation of mosaics [14,15].

All the above methods are characterized by a certain optimal depth resolution (i.e. the ability to detect defects at a certain depth with high probability), penetration capability, as well as sensitivity to the different physical properties of the masonry [16–18]. Moreover, due to the inhomogeneity of the masonry material, several methods have been used complementarily to fully characterize the structure [1,3,19]. Taking into account that the inhomogeneity of a complex structure of multi-leaf stone masonry could further worsen the performance of well-known NDT methods, the methods should be validated as a precondition for their practical application on-site.

Within the framework of the EU research project PERPETUATE (www.perpetuate.eu), the complementary use of GPR and IR thermography was studied for the structural assessment of plastered laboratory three-leaf stone masonry walls. Additionally, the performance of both methods was evaluated for defect detection such as gradual plaster delamination and crack propagation while subjecting the walls to an in-plane cyclic shear test monitored by a three dimensional (3D) digital image correlation (DIC) technique. The well-defined conditions enabled performance of a complete validation process of the efficiency of the methods applied for the detection of seismic related damage, this being of the utmost importance for bringing NDT into practice for on-site investigations.

3. Experimental

3.1. Specimen description

The performance of NDT methods was studied on four plastered laboratory three-leaf masonry walls measuring $100 \times 150 \times 40\,cm^3$. For the two layers of plaster (both coarse and fine), traditional recipes based on lime mortar were used. The external leaves of the masonry were constructed from regular coursed squared ashlar rough tooled limestone, while the internal core was filled with stone rubble and lime mortar. Two of the specimens had header stones in every second row passing through the whole depth of the specimens (Fig. 1a), whereas the other two had no connecting stones (Fig. 1b).

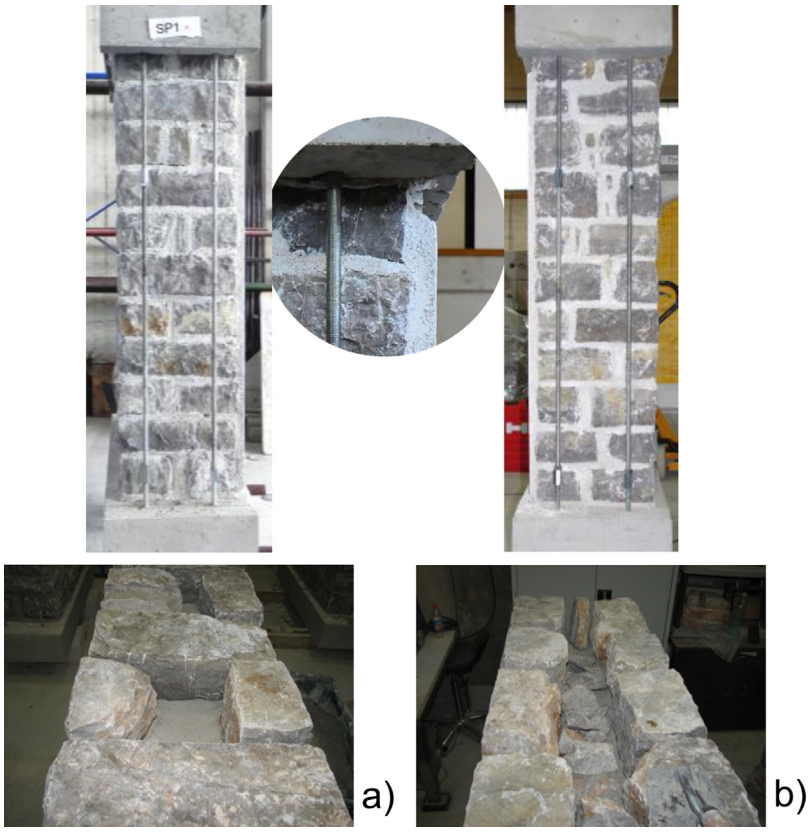

Fig. 1. The morphology of the connected (a) and unconnected (b) walls with two layers of plaster applied.