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Crack monitoring in historical masonry with distributed strain and acoustic emission sensing techniques

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HIGHLIGHTS

- Qualitative and quantitative comparison of novel techniques for crack monitoring in historical masonry.
- Crack monitoring in masonry with integrated optical fibres with distributed fibre Bragg grating sensors.
- Use of masonry surface layout for digital image correlation without speckle pattern.
- Observation of Felicity effects during AE monitoring on a full-scale masonry wall.
- Analysis of the effects of temperature fluctuations on monitoring data from a cracked masonry sample.

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ABSTRACT

The analysis of crack patterns and crack growth is one of the most important steps in the assessment of structural damage in historical masonry. In a search for integrated and accurate monitoring techniques for crack measurements in masonry, several novel techniques based on distributed strain monitoring and acoustic emission (AE) sensing have been investigated in an experimental test campaign. Aim of the test program was to develop integration procedures for the strain and AE sensors, analyse their use for crack monitoring specifically in historical masonry and assess their robustness and efficiency with respect to the experimentally observed crack pattern. The applied techniques were integrated optical fibres with distributed fibre Bragg grating sensors (FBGs), stereo-vision digital image correlation (DIC) without the use of a speckle pattern, optical fibre sensors for acoustic emission sensing (AE-FOS), piezo-electric transducers for acoustic emission sensing (AE-PZT) and LVDTs. While the latter two were applied as reference techniques, the former three were under investigation as novel application. This paper discusses the efficiency of the monitoring techniques with respect to their use in masonry, explains the developed integration procedures, and relates the obtained data sets with the deformations and crack pattern obtained in a full-scale masonry wall test. Additionally, the effects of temperature fluctuations are investigated. The configurations that were developed proved effective for crack monitoring in historical masonry. The highest sensitivity and robustness was observed for the integrated optical fibres with FBGs.

1. Introduction

Structural cracking in unreinforced, historical masonry can be caused by differential settlements, creep and fatigue, vibrations and earthquakes, impact, temperature- and load-induced stresses. Depending on the cause and severity of the damage, cracking in masonry might lead to loss of cohesion in load-bearing walls, reduction of structural capacity and even collapse in case of unstable crack growth [1], loss of static equilibrium or additional earthquake loading. As the crack patterns provide vital information on the cause and severity of the damage, mapping and monitoring of the structural cracks is one of the most important steps in the assessment of damage [2]. In severe cases, crack widths are to be monitored to assess the damage progress and ascertain the structural integrity of the monument.

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Monitoring techniques for detection of structural damage in existing structures can be divided in local and global techniques. At the scale of materials and structural components, local monitoring methods, such as crack measurements, mostly focus on individual cracks and displacements, and might therefore not provide enough information to address the overall structural integrity. At the structural scale, a well-known global method is the vibration-based method, in which changes in modal characteristics are monitored to detect the initiation or increase of damage [3,4]. For historical masonry structures, the type of information to be gathered and the data processing to be done in order to optimise vibration-based damage analysis is not always straightforward. The efficient application of such global methods for detection, localization and quantification of "local" damage in existing structures remains a major challenge for the research community, especially under ambient vibrations and for heritage structures. Distributed sensor networks are applied for upscaling local and global methods. At the scale of a building, local strain sensors and accelerometers can be combined in a system with other devices, such as temperature and humidity sensors, to enable linking of the output data. As such, a multi-scale sensor network allows a more comprehensive understanding of the structural behaviour and damage progress, and results can be used for calibration or evaluation of numerical models [5,6].

At regional scale, global monitoring techniques can be coupled in a network to allow monitoring of several structures at once and relate their behaviour and observed damage with detected ground motions, such as earthquakes or differential settlements. For monitoring of differential settlements, remote sensing techniques such as terrestrial laser scanning at the scale of building blocks, aerial laser scanning at city scale or Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) at regional scale can be applied [7–9].

This paper focusses on the monitoring of settlement-induced cracking at the scale of historical masonry walls, to obtain reliable monitoring data at the scale of a structural component that can be coupled to (settlement) data obtained at the scale of building blocks. Traditional crack monitoring devices, such as tell tales, crack width meters, LVDTs and DEMEC measurements have certain drawbacks with respect to upscaling; They can only locally detect 1D displacements, they often need to be reachable for read-outs, it is laborious to integrate them in a distributed sensor network and they cannot be integrated within the structure, thus remain visible. However, these techniques also have the advantage of long-term reliability and limited data drift.

In this work, distributed strain and acoustic wave sensing are investigated for crack monitoring in masonry. Optical fibre sensor systems are applied, which can combine the accuracy of local sensors with the advantages of distributed sensor networks. In total, five different techniques have been applied on a full-scale masonry wall during an experimental three-point-bending test. In addition, temperature data and load-displacement data were also recorded.

The applied techniques are:

- Optical fibres with distributed Fibre Bragg Grating sensors (FBG) [10];
- Digital Image Correlation (DIC), without the use of a speckle pattern;
- Optical Fibre Sensors for Acoustic Emission sensing (AE-FOS) [11];
- Piezo-electric transducers for Acoustic Emission sensing (AE-PZT) [12];
- Linear Variable Differential Transducers for displacement measurements (LVDTs).

While the latter two were applied as reference techniques, the former three were under investigation as novel applications. A prerequisite for the selection of the applied techniques was their ability to be integrated within the masonry or to be applied as a non-contact technique. The optical fibre sensors were integrated within the masonry's bed joint and digital image correlation was applied without the use of a speckle pattern. As cracks were expected in the mortar joints, strain-based techniques needed to include or bridge these weak areas in the structure. In comparing the results of the different monitoring techniques, specific attention was focused on accuracy, temperature influences and possibilities for on-site application. The investigated systems can be seen as distributed sensor networks of local sensors.

Firstly, the novel crack monitoring techniques and developed installation procedures are discussed. Secondly, the experimental test setup and loading scheme are briefly introduced. Hereafter, the results of the FBG, DIC and AE measurements are presented and compared with the results of the reference techniques. A discussion on the robustness, accuracy and temperature influences concludes this paper.

2. Monitoring techniques and installation procedures

2.1. Optical fibre with distributed FBGs

Strain monitoring with optical fibres engraved with Bragg gratings relies on the analysis of the wavelength spectrum that is reflected by the Bragg gratings. If a change in length of the optical fibre occurs, a shift in the reflected wavelength is induced, where a positive shift in wavelength is related to elongation of the fibre [10,13]. The length change may be caused by a mechanical strain or by thermal expansion.

In the reported lab experiment, an optical fibre type SMW-01 based on Draw Tower Gratings technology has been applied. The optical fibre with a primary ORMOCER coating is extra protected by a glass fibre reinforced polymer (GFRP) jacket, with a total diameter of 1 mm to allow embedment of the sensor in harsh environments. A high-resolution FBG interrogator was applied for read-outs of wavelengths around 1500 nm.

The optical fibre was equipped with five FBG sensors, which were installed with a base length of 0.8 m or 0.55 m for strain monitoring. At one end of the wall, the optical fibre was bent to enable coverage of two horizontal joints with just one fibre and to

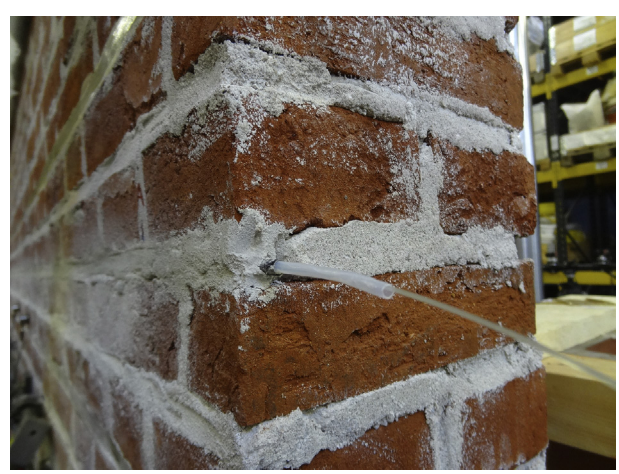

Fig. 1. Ends of the optical fibre (pig tails) at the entrance point in the mortar joint.

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