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Method based on digital image correlation for damage assessment in masonry structures

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ABSTRACT

This paper presents a new approach based on the digital image correlation (DIC) technique for evaluating damage in masonry structures on the basis of the opening of joints. An application is proposed on experiments that are performed using a large-scale physical model reproducing both the soil-structure interaction and the masonry structure. Displacement fields of blocks obtained by DIC analysis are described in a new Discrete Element System (DES) where cracks appear near joints with openings between blocks. A damage indicator associated with the total length of cracks is proposed for a complete damage evaluation. Monte Carlo simulations are used for estimating the confidence interval of this indicator. Recommendations are suggested for the assessment of damage in masonry structures due to underground excavations or soil subsidence.

1. Introduction

The monitoring of crack propagation in physical modelling by conventional means (such as a crackmeter) suffers in situations with complex cracks. This can be overcome by using the digital image correlation (DIC) method, which provides full-field displacement measurements. In particular, for brittle materials, many algorithms proposed in the literature are inspired by the eXtended Finite Element Method (X-FEM) [1]. We can cite eXtended Digital Image Correlation (X-DIC) based on a finite element decomposition of displacement fields [2–4]. Another approach uses Integrated Digital Image Correlation (I-DIC), which consists in the use of the full description of displacement fields such as Williams' series and integrates Stress Intensity Factors (SIF) in a crack propagation law [5]. These two approaches are useful for the investigation of the development of arbitrary cracks. The main disadvantage of these approaches, however, is the necessity of direct modifications in the correlation algorithm. Consequently, this is not easy for the users of commercial DIC software, who are becoming more and more numerous. Actually, a few applications have been developed that are based on DIC output in order to study crack propagation. We can cite the DIC-F model [6], which was developed for the fracture investigation of soft rock.

Masonry is considered as a brittle structure, and crack propagation can be therefore predicted using the approaches mentioned above, but this can be simplified by considering that the cracks only appear near joints. In fact, the failure mode could be of the I type (failure by traction) or II type (failure by shear), and the failure mode in compression rarely appears in reality [7]. Using the DIC technique, the difference between Mode I and Mode II can be provided with respect to Von Mises strain and their high values can indicate the location of cracks [8,9]. Nevertheless, crack identification is insufficient for a full damage assessment, which must take four important properties into account: crack location, length, width and orientation. To begin with, the approaches mentioned above need to be improved in order to take crack width into account.

In this paper, we develop a new eXtended Digital Image Correlation method dedicated to the physical modelling of masonry structure in order to assess damage. This research attempts to tackle crack identification by integrating the specific aspect of crack width. The new point of view here for crack propagation is the use of physical modelling combined with an experimental damage criterion based on DIC technique. The novel key is the decomposition of displacement fields in DIC into rotation and translation components for each block. Consequently, the blocks move independently as discrete elements, so cracks appear at their interfaces. In particular, this investigation provides a specific

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indicator referring to the total length of cracks with the purpose of damage assessment. The uncertainty/accuracy of this indicator is also analyzed using Monte Carlo simulation.

Our work also extends to applications for damage assessment of masonry structure due to soil settlement and ground subsidence using the physical model developed (Fig. 1). In Fig. 1a, D is the depth of the void (cavity), O is the layer opening, and Wc is the width of the cavity. The structural model presented in Fig. 1b associates a masonry structure made of block in contact with a raft foundation made of silicon (interface Γ_1) resting on an analogue soil made of sand (interface Γ_2). The first interface Γ_1 is a perfect collage for an easier setup of the model structure on the soil surface. In contrast, the second interface Γ_2 is a simple frictional contact between the silicon foundation and the sand.

Conventional methods for damage assessment refer to different criteria, such as tensile limit strain [10], limit slope (see [11]), and crack width [12]. In most cases, the building is considered as an elastic continuous beam with the same dimensions. The damage indicators based on these criteria can refer to the angular distortion [10] or the deflexion ratio [12], with the soil-structure interaction being represented by the relative stiffness [13,14] or the final structural form [15]. Such indicators allow damage to be quantified but are insufficient for determining the location of the damage on the structure. As a consequence, they often over- or under-estimate the true potential for structural damage. Recent physical models have been developed in order to observe crack propagation [16,17]. However, investigations are limited to the analysis of crack location and do not provide for a quantification of damage. Here, the proposed method can overcome this drawback, enabling both crack identification and quantification.

This paper is organized into three main sections. In Section 2, we first propose a way to quantify DIC measurement errors for further consideration in the evaluation of the different strategies for damage assessment. The reconstruction of the blocks, discussed in Section 3, is concerned with the reconstruction of motion based on DIC outputs. Here, we consider the blocks to be rigid bodies and the centers of rotation to be their centers of gravity. The last hypothesis is applicable when the difference between calculated and experimental displacement is less than 5%. Thus, a cost function is introduced to ensure the accuracy of the model reconstruction. In this section, we also introduce a damage indicator, which is useful for assessing damage in masonry structures. The effects of measurement errors are determined using the Monte Carlo method, which is a powerful tool for the simulation of uncertainty in complex systems [18]. Section 4 contains two illustrations of the applications of the proposed method for damage assessment of masonry structures in the particular case of ground movements induced by underground excavations. A comparison with conventional indicators is also included.

2. DIC measurement errors

DIC is a non-contacting method for measuring displacement using video cameras to record images of the surface of objects. This technique was used as early as 1975 [19] and has increasingly gained consideration since the 1980s [20]. Nowadays, this technique is used in a wide range of disciplines, especially in mechanical tests [21]. The basic idea of the method is the matching of one point on the reference image with a corresponding point of the deformed image. Depending on the number of cameras, different strategies can be employed: (i) 2D version with only one camera and the motion of specimen must be in plane, and (ii) 3D version using two cameras, which allows for the measurement of three-dimensional displacements [22,23].

Although DIC is a powerful technique for mechanical tests on materials and structures, the measurement errors are not discussed sufficiently and difficult to improve in practice. The sources of errors are numerous and can be divided into two main categories: quality of the measurement devices and working environment, and correlation algorithm [24]. The first category is associated with the materiel (e.g., mire, optical lens), and the working environment such as epipolar constraint, process of calibration, lighting, image contrast and the presence of out-of-plane displacements. The second category concerns aspects of the correlation algorithm, such as subset size, speckle pattern and correlation algorithms.

Many studies focus only on optimizing algorithms and neglect the other source errors. Practically speaking, improving the optimization algorithm is not possible for scientists or engineers using commercial software. Few studies show how to integrate DIC measurement errors into the experimental results. One way is through the use of rigid body motions [24], but this is not applicable to brittle materials because of the associated failure phenomena. Another approach is to analyse two images of a specimen in consecutive instants t and $t + 1$ while the specimen is loaded. Considering slow variations in load, DIC results can be considered as measurement errors. However, this approach is difficult to employ in the case of rapid loading or a highly stiff specimen.

For brittle materials such as concrete and masonry, it is possible to take the measurement errors into account using the DIC technique. Here, we adopt a static approach, i.e., analysing images in static state [25]. In the initial state of the specimen, there are theoretically no displacements but residual values exist after DIC analysis because of working environment and optimization processes in algorithms. Therefore, these values can be considered as systematic measurement errors. Briefly, once the test set-up is realized and before the beginning of the test, static images (5–10 images) are recorded. These images (except the reference image) are duplicated and renamed. The copy-rename process is repeated until the desired number of images. The number of static images should be equal to the number of real images in the test, as is discussed in the following paragraphs. The last step is to analyze all these images with the DIC software: since there is no real movement between the images, the obtained displacements are the measurement errors. Another way to obtain the desired number of static images consists in recording images continuously until the desired number. These two solutions give the same results. The static approach has numerous advantages: (i) This is easy in practice and can be applicable for all material. (ii) We can multiple images as we wish in order to investigate the performance of algorithms. In particular, depending on the algorithm, the displacement errors can increase with the number of images, and a loss of correlation can occur with a sufficient large number of images, as is discussed in the following paragraphs.

The performance of the static approach is illustrated through an example with the DIC commercial software VIC-3D [26]. Here, we analyse 1000 static images of a small-scale model of the masonry structure described in Section 4. Each static image has more than 3×10^4 points, and the DIC analysis provides the coordinates, displacements, strains, etc. Here, we focus on the horizontal and vertical displacements, because the conclusions will be used directly for the error analysis in the crack width development in the next sections. Other information can be determined by the same process.

Taking the measurement errors into account actually corresponds to a determination of a probability distribution which matches well with the DIC outputs. Distribution functions can vary depending on the choice of the strategy for the DIC analysis, such as itineration procedure or optimization options [27]. In particular, the itineration procedure of images is the most important. For VIC-3D, the itineration choice can be: (i) the default option in which each image is compared to the reference image, or (ii) the