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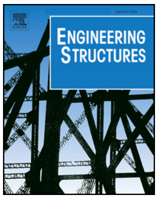

Mapping deformations and inferring movements of masonry arch bridges using point cloud data

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ABSTRACT

Many historic masonry arch bridges experience damage due to support movements during their lifetime. This damage may influence the performance of the bridge and reduce its load carrying capacity. This paper proposes a new method to quantify past support movements by investigating distortions in bridge geometry. In this method, the bridge geometry is recorded in point cloud format and segmented into different structural components (e.g. 3D piers and barrels or 2D pier and barrel cross-sections). The geometry of each component is investigated further by fitting primitive shapes (e.g. 3D planes and cylinders or 2D lines and arcs) which represent the design intent. The discrepancy between these fitted shapes and the point clouds reveals a characteristic distortion signature. This signature is compared with theoretical distortion traces, which are obtained from kinematical analyses of the arch subjected to a range of support movements. The most likely support movement scenarios identified from these comparisons are then validated with visual indications of damage, such as crack location and size, and other geometric quantities, such as the change of the bedding joint elevations along the bridge. The proposed technique is applied to two masonry rail viaducts in the UK, which demonstrate different evidence of damage. Using the proposed method, past support movements of both bridges, which led to the observed damage, are inferred.

1. Introduction

Masonry arch bridges are an integral part of Europe's rail, road and waterway infrastructure. According to a recent study, 60% of the European rail bridge stock is constructed of masonry. In the UK, the rail network includes approximately 18,000 masonry bridges [1]. These structures have endured increasing load demands throughout the 20th century. While this loading may not exceed the ultimate capacity, most masonry bridges experience damage or deterioration for service loading well below their predicted ultimate capacity. Service level damage may be initiated by, or exacerbated by, deformations caused by support movements or material degradation caused by environmental loading. Thus, the combination of increased loading, support movements, and material degradation can cause increased deterioration rates. This eventually causes their safety to be questioned as further damage continues to decrease their ultimate load carrying capacity. This is clearly demonstrated in a survey performed by Zoltan [1], where representatives of several European railways report the frequent occurrence of relative movement of structural components (e.g. spandrel walls and foundations) while damage due to overloading is rarely observed.

Assessment of the load carrying capacity of damaged masonry bridges is a challenging task [2]. Before carrying out an assessment of the capacity of a bridge, it is necessary to identify its loading history and model the existing damage [3]. Due to the large uncertainties involved in modelling the formation of damage, conservative methods have been developed to account for commonly observed damage types in structural assessments. For instance, the influence of spandrel walls on the load carrying capacity of masonry arches are typically neglected, since spandrel wall detachment is commonly observed [3]. In a similar way, longitudinal cracks in masonry arches are assumed to limit the effective bridge width [4].

However, many other types of damage in masonry bridges cannot be accounted for using simple assumptions. In particular, many historic masonry arch bridges experience damage due to support movements during their lifetime [3,5]. Support movements involving relative horizontal and vertical displacements or rotations of bridge piers may occur during construction, notably during the removal of bridge centring [5,6]. Similarly, progressive support movements may occur during the service life of the bridge, for example due to soil consolidation,

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environmental effects and cyclic loading of foundations. These movements may not be visible to the naked eye, and may have different influences on the response mechanisms of the bridge [7], and the resulting observable damage. Therefore, quantifying support movements is a necessary step for improving the capacity assessment of damaged masonry bridges.

This paper proposes a new assessment method to map 3D deformations and identify the historic support movements of a bridge by evaluating existing bridge distortions. In this method, the distorted bridge geometry is quantified using laser scanning technology and point cloud processing. The method involves processing of the point cloud by: (i) segmenting it into bridge components, (ii) fitting suitable primitives to each component, and (iii) describing the discrepancy of the actual and fitted geometries with 2D and 3D error maps. In order to determine historic support movements using the error maps, a theoretical arch mechanism database is created. This database quantifies distortions of kinematic arch models using a wide range of support movements. It is proposed that comparisons between the error maps, theoretical mechanisms and visual signs of damage may help identify the most likely support movements experienced by the bridge. Finally, the proposed technique is applied to two damaged masonry rail viaducts in the UK: Marsh Lane Viaduct in Leeds and Stapleton Road Viaduct in Bristol.

2. Applications of laser scanning for structural assessments

Laser scanning describes a method of non-contact sampling of the shape and appearance of an object using laser technology. Lasers are ideally suited for this purpose, since they do not require ambient lighting or surface features for sampling. A number of different scanning techniques can be used to scan real-world objects [8]. Modern scanners have acquisition times of hundreds of thousands of points per second and this allows capturing a 3D environment with a dense point cloud in a matter of minutes, although post-scanning registration can require significant post-processing times.

In the last two decades, laser scanning has found widespread application in the documentation of heritage masonry structures (e.g. [9]). Since detailed construction drawings are rarely available for masonry arch bridges, laser scanning has been widely used to quantify the external geometry of the structure. Achieving this requires denoising the data and identifying different bridge components (e.g. arch barrel) using manual and automated processing techniques [10]. Key geometry components such as span and rise are then determined from distance measurements on relevant parts of the clouds (e.g. [11,12]). While manual measurements can be used to retrieve distance measurements between identified objects on a point cloud, automated algorithms which measure closest [13] or normal [14] distance between sets of points, meshes and analytical surfaces can also be utilised. This critical geometry information can later be used in the quantitative assessment of the bridge [12].

Another relevant application of laser scanning for masonry arch bridge assessment concerns direct assessment of geometry data for structural purposes. Previous studies in this area can be divided into two broad categories. First category involves detailed analysis of the distorted structural geometry from a point cloud via primitive shape fitting. The characteristics of the fitted shape, and its comparison to the actual point cloud, can be useful to infer important phenomena concerning structural behaviour of the asset. The studies in the second category focus on calculating precise displacements by comparing point clouds [14,15]. This approach is especially useful to monitor structural response of masonry bridges during nearby construction works by comparing point clouds before and after construction [7,16]. Since this paper is concerned with determining historic settlements, where limited data concerning the original design of the bridge is available, the following literature review focuses on the first category.

When boundary conditions of the structure and loading types are known, theoretical analyses of simple structures (e.g. beams, portal frames) can provide a generic description of deflected shapes that the structure may be expected to experience. These generic shapes (e.g. polynomials) can then be fitted to the point cloud data to identify the deformation experienced and to infer the loading [17,18]. However, it is difficult to ascertain boundary conditions for masonry arch bridges, and reliably relate their internal deflections to given support movements. In such cases, a fitted geometry can be evaluated to highlight 'anomalies' in the observed point clouds. In three recent works [19–21], tower facades and cross-sections were characterised with planar and circular shapes, in order highlight change of cross-section properties along height as well as the leaning angle of the tower. Comparisons between fitted geometry and the actual point cloud complemented this information by highlighting local anomalies in the cloud, such as bulging, brick displacement or material loss. Shape-fitting was also used to evaluate distortions of historic masonry structures, including domes and vaults [22].

Due to the lack of construction drawings, it is more challenging to identify anomalies observed in point clouds of masonry arch bridges. For instance, it is well-known that asymmetric bridges with different springing heights were commonly constructed to deal with uneven terrain conditions. In their study, Armesto et al. [23] have proposed an algorithm for the non-parametric estimation of arch shape and determined significant asymmetry in the bridge. However, it is not certain if this asymmetry relates to a structural phenomenon or the original design of the bridge. More recently, Conde et al. [24] have solved this issue by determining the original shape of the masonry arch and the unknown settlements by an optimisation process aimed to capture the deflected shape of the structure obtained from the laser scan. Despite these recent advances, there still remains a need for simple cloud processing methods which can identify distortions and relate them to support movements of the structure. A method to achieve this objective is proposed in the next section.

3. A new assessment method to estimate historic support movements of masonry arch bridge

In this section, a new method is proposed to estimate historic support movements of masonry arch bridges. The workflow associated with this new method is schematically described in Fig. 1 and discussed systematically in the following sections. Capturing the bridge geometry with a laser scan requires an initial understanding of the bridge characteristics. Therefore, the first step of this method involves collecting preliminary information on the bridge.

3.1. Preliminary bridge information – Step 1

Preliminary bridge information may be retrieved from construction drawings, inspection reports and field measurements. This includes the form of the bridge (e.g. square or skew), the basic arch shape (e.g. segmental or elliptical), fundamental arch and pier geometry (e.g. span, rise and springing height). Field work can complement this information by highlighting the bridge defects such as cracks and the remedial works such as repointing.

3.2. Laser scanning data acquisition and point cloud processing – Step 2

Preliminary bridge information provided in Step 1 can be used to plan the laser scanning data acquisition. Once the laser scan data has been gathered, the raw point cloud data needs to be processed for primitive shape fitting (Step 3). The processing consists of five stages: registration, cleaning, sampling, segmentation and alignment. During the registration step, multiple laser scans are combined together to obtain one single point cloud which contains the entire bridge. This was achieved using FARO SCENE for this study (Version 6.0, Lake Mary, FL, USA). In Fig. 2a, an example point cloud of a masonry railway viaduct is shown.