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Dynamic response of a damaged masonry rail viaduct: Measurement and interpretation

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A B S T R A C T

Despite recent advances in modelling and testing techniques, assessing the serviceability of ageing masonry rail bridges remains a significant challenge. Most assessment methods are based on ultimate strength, while reliable measurement-based assessment criteria are lacking. This paper aims to improve the understanding of serviceability behaviour through detailed dynamic monitoring of the bridge locally (e.g. in locations of damage) and globally (e.g. interaction of different components). Quasi distributed sensing techniques (Fibre Bragg Grating cables and Digital Image Correlation) were used to quantify the bridge dynamic response through extensive measurement of strains and displacements. Specifically, these techniques were applied to two damaged spans of the Marsh Lane viaduct in Leeds, UK. A detailed investigation of the dynamic pier and arch barrel movements reveal how the response mechanisms relate to, and likely propagate, the existing damage. For instance, rotation of piers in the bridge longitudinal plane causes significant span opening and closing, which in turn causes the skewbacks and backing to rock on the piers. This is accompanied by flexural deformation of the arch, which forces the existing transverse cracks to experience high compressive strains. Similarly, the transverse rotation of piers due to the presence of the relieving arches causes spreading of the relieving arches and opening of the longitudinal crack above. These observations provide new insight into behaviour and lead to suggestions for improving assessment techniques for masonry viaducts.

1. Introduction

In the last decades, passenger and freight numbers have been rapidly increasing on the European rail network [1]. In the UK, this has been accompanied by a 20% increase in the axle weight of modern vehicles and an increase in maximum line speeds on some railway routes [2]. Increased loading demands requires re-assessment, which can be a complicated task for ageing rail infrastructure. For instance, masonry arch bridges constitute 60% of the European bridge stock [3]. Most masonry bridges were constructed before the 20th century, and were not designed to sustain the increased loading that has occurred. Therefore, the engineering community have focused on developing reliable methods to determine the ultimate load carrying capacity of masonry arch bridges. These studies provide valuable understanding of the complex mechanical behaviour of masonry bridges (see [4] and the references therein). Importantly, they distinguish between the behaviour of single span arch bridges and arched viaducts with multiple spans [5]. They also establish that the limiting failure mechanism under static loading, and hence the capacity of a masonry viaduct, involves the interaction of two or more spans [6]. Other research has demonstrated the significant influence of arch backing [7], ring separation [8] and the presence of spandrel walls [9] on load carrying capacity.

However, most masonry bridges experience progressive damage for service loading well below their predicted ultimate capacity [10]. This causes their safety to be questioned as further damage and material degradation, which can occur due to cyclic environmental or dynamic loading, can decrease the load resistance. Accurately predicting the progressive damage for masonry bridges would require replicating the effects of the loading history, modelling the existing damage and simulating the dynamic response of the damaged structure to further cyclic loads with appropriate degradation models. However, significant uncertainties exist in identifying typical sources and propagation of damage observed in masonry arch rail bridges. These uncertainties limit the ability of uncalibrated computational models to capture critical progressive damage mechanisms.

To advance the current understanding of the serviceability response

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of masonry bridges, field measurements to quantify the current damage state of the structure are essential. In recent years, useful non-contact methods have been developed to achieve this [11–15]. These include (a) ultrasound testing to determine the surface material characteristics, (b) ground penetrating radar surveys to determine the interior structure and (c) laser scan surveys to determine the current distorted geometry of the structure. These techniques, alongside traditional measurements such as crack measurement and hammer tapping, provide important information regarding the damage state of the existing asset.

For assessments, it is equally important to capture the dynamic response of the structure to cyclic loads and document its degradation process. Traditional monitoring tools, such as displacement gauges, tiltmetres, strain gauges and accelerometers, are typically used for this purpose [16–20]. However, these techniques capture the local behaviour of the material and are difficult to interpret without multiple measurements at different locations [21]. In contrast, quasi-distributed monitoring techniques, such as sensing with Fibre Bragg Gratings (FBGs) and digital image correlation (DIC), make it feasible to obtain strain and displacement measurements across wide areas of the structure. Direct strain and displacement measurement is useful because visible damage in a masonry arch may not always quantify the active degradation processes. Further, distributed techniques enable local measurements around locations of damage (e.g. cracks), as well as global displacement measurements (e.g. span opening and closing) simultaneously. Useful quantities, such as rotation and crack opening, can be determined by post-processing, in order to identify the governing response mechanisms.

This paper describes a novel application of the aforementioned quasi-distributed techniques for monitoring a masonry viaduct and demonstrates the understanding of structural response that can be obtained from a comprehensive monitoring programme. To do this, two spans of the Marsh Lane Viaduct in Leeds, UK, are investigated. The structure, the observed damage, the monitoring installation, and the data processing are first discussed, followed by the interpretation of measurements to understand the complex three-dimensional dynamic behaviour. The response to a typical passenger train is examined in detail, followed by the investigation of the bridge response to different vehicles and evaluation of degradation over a six month monitoring interval.

2. The investigated structure

Marsh Lane viaduct is a masonry viaduct on the Leeds-Selby route (see Fig. 1a). The investigated section, which comprises of Arches 37 and 38, was constructed during the North Eastern Railway Leeds Extension between 1865 and 1869 [22]. The bridge carries two electrified tracks, and has a speed limit of 35 mph.

The plan view of the viaduct in Fig. 1a shows that the investigated arches are on a gently curving section of the railway. At the location of arches 37 and 38, the curvature is primarily achieved by varying the pier thicknesses by approximately 0.25 m across the bridge width. The average pier thickness is approximately 0.85 m. It is noteworthy that the piers are not completely solid. Relieving arches consisting of 3 rings and spanning 2.5 m lies in the middle of the piers. This relieving arch is visible in the photo in Fig. 1b, which was taken in July 2015. Fig. 2, a photo taken shortly after the remedial works in September 2015, shows the same arch filled with concrete.

Table 1 lists the key dimensions of Arches 37 and 38. The height of the brick piers from the ground level is measured as 2.7 m, although the foundations of the bridge run deeper. During the remedial works, it was observed that the relieving arch has a mirror image invert beneath the current ground level and a corbelled foundation underneath. Assuming that the invert lies just under the ground level with a 0.5 m foundation underneath, suggests that the total pier height from the bottom of the foundation is approximately 5.2 m. The construction of the arch above its pier is shown on the right side of Table 1. Both investigated arches have an approximate span of 7.7 m and a width of 8 m. According to this schematic, a series of large skewback stones, approximately 0.6 m high, were placed above the pier, along the width of the bridge. The primary arch barrels have 4 rings with a total thickness of ~0.5 m and a rise of 1.8 m. Just above the skewback, there is evidence of a 1.15 m layer of backing, including the coinciding presence of drainage holes and horizontal cracking on the spandrel wall. Above the backing, a layer of compacted earth fill supports the ballasted tracks, and is contained from both sides by 0.5 m thick spandrel walls. Further information was not available on the properties of materials used in the construction of the bridge.

The side photo of the bridge in Fig. 2 highlights visible structural damage as well as the related structural interventions. The photo shows the north-facing spandrel wall of Arch 38, where significant damage has concentrated. The damage includes horizontal cracks on the spandrel wall, which appear due to higher flexural stiffness of the spandrel wall in comparison to the arch barrel [7]. There is also evidence of partial separation between the spandrel wall and the extrados of the arch (Fig. 2). These damages have led to repointing on the western side of the 38N spandrel wall. Signs of damage and interventions can also be observed on the piers. In particular, water drainage issues have affected the western pier of Arch 38, which has been repointed. In addition, the significant use of steel ties can be observed. In the 1990s, ties were installed through the arch barrel to limit further opening of longitudinal barrel cracks. In September 2015, several other ties were installed; ties on the piers were located close to the ground level, to arrest transverse movements of the piers, whereas the ties on the spandrel walls aimed to prevent bulging.

Damage visible from the underside of Arch 38 is discussed with annotated photos in Fig. 3. In particular, the significant movements and

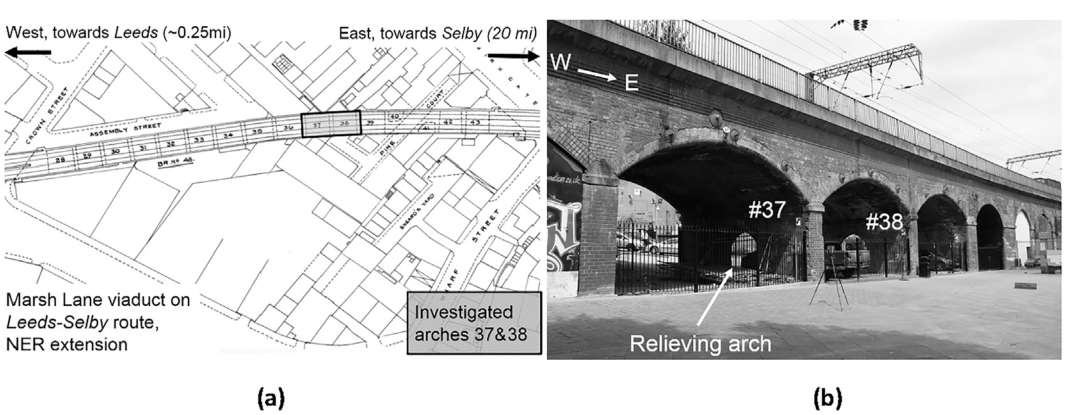

Fig. 1. (Left) Plan view drawing of a section of the Marsh Lane viaduct (British Railways drawing 73-YWR-513) and (Right) a photo showing the southern side view of the investigated arches 37 and 38.