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Application of Digital Image Correlation to Field Monitoring of Masonry Arch Bridges

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Abstract

Many masonry bridges constructed in Europe during the Industrial Revolution are still in service. For over a century, continuous operation and weathering effects have contributed to material degradation in the main bridge components. To ensure that old masonry bridges remain safe even under increasing traffic loading, it is crucial to identify potential deterioration in bridge performance before the onset of critical irreversible damage. This task can be accomplished via periodic monitoring of the bridge response under traffic loading. Digital Image Correlation (DIC) is an effective non-contact method to measure displacements and strains. Most DIC applications have been in laboratory settings, and DIC techniques have yet to be extensively applied in the field. This paper showcases the potential of DIC monitoring for serviceability assessment of masonry bridges. Some results of an extensive monitoring program on railway viaducts in the UK are presented. Structures with different geometrical characteristics, including pier heights, span lengths, and span-to-rise ratios, have been investigated. The results obtained using specific targets attached to the monitored structures or using the actual masonry texture as natural targets have been compared; consideration is also given to the influence of camera characteristics and settings. A significant impact of the camera depth of field has been established, especially when measuring deflections at different locations on the intrados of the arch barrel.

Keywords: Masonry Bridges; Non-contact Monitoring; Digital Image Correlation

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1. Introduction

Many masonry bridges constructed in Europe during the Industrial Revolution are still in service. However, the extended service period, cyclic dynamic loading and natural weathering have inevitably led to material degradation within these historic structures. To ensure that these ageing bridges can carry ever-increasing traffic, it is necessary to identify a practical approach to monitor changes in the safety margins and structural integrity of these structures. Traditional methods of assessing the condition of masonry bridges rely primarily on periodic visual inspections. While valuable, these inspections may not always detect signs of internal deterioration that could lead to critical damage. Moreover, the focus on visible cracks developed over time may not provide timely insights into the actual structural health of these bridges. Lastly, masonry bridges are usually assessed based on ultimate strength using simplistic numerical models, while developing a reliable measurement-based method for the serviceability assessment of the masonry bridge remains a challenge (Dhanasekar et al., 2019).

To address this challenge, there is growing interest in utilising advanced monitoring techniques to track displacements and crack growth under traffic loading. Real-time performance obtained under the passage of trains may serve a dual purpose. Firstly, it can be adopted as an initial assessment criterion to provide insights into ongoing structural degradation and facilitate proactive decision-making for damaged bridges. Secondly, it can aid in calibrating high-fidelity numerical models, essential for studying structural behaviour and collapse mechanisms of masonry bridges under both serviceability and ultimate conditions. This information can be used with detailed numerical models to reduce the uncertainty associated with material properties and internal bridge makeup by calibrating numerical responses against collected measurements under known loading conditions.

In current engineering practice, monitoring techniques often rely on sensors that require direct contact with the structure, such as mechanical extensometers, electromechanical transducers, and deflection poles. Mechanical extensometers and electromechanical transducers are commonly used for medium to long-term measurements of relative displacements, focusing on phenomena such as crack growth and sliding. By contrast, deflection poles typically monitor vertical displacements induced by traffic loading. However, these standard monitoring methods have limitations. They generally necessitate complete contact with the monitored parts, leading to a time-consuming installation of the monitoring devices. Deflection poles are limited to monitoring short pier viaducts and require full occupation of the monitored span.

Furthermore, these methods only provide information at localised, pre-determined locations and fail to facilitate full-field studies of large surface areas of the structure. These deficiencies give an impetus to explore using non-invasive, non-contact techniques for collecting data on bridge deformations. Digital Image Correlation (DIC) is a technique capable of real-time displacement and strain acquisition (Sutton et al., 2009). DIC systems use digital cameras to capture a series of high-resolution images and analyse them to measure the relative displacement of objects in the image. This is achieved by finding the relative movement of image features between consecutive frames. Artificial patterning can be applied to monitored surfaces to recognise image features. Alternatively, optical targets can also be used. It is worth noting that reliance on targets prevents the DIC from calculating strain fields of the monitored structure. Unlike the traditional method, DIC eliminates the need for physical interaction with the monitored structure. Application of DIC for monitoring of masonry structures holds another benefit as the natural patterning exhibited by a combination of masonry units and mortar joints can be exploited, removing the need for any additional patterning work or installation of optical targets while preserving capabilities to calculate strains of the monitored structure.

Notwithstanding the benefits of DIC monitoring, its application in the field of masonry structures has been chiefly confined to laboratories, with only limited applications in the field (Koltsida et al., 2013; Acikgoz et al., 2018a; Dhanasekar et al., 2019). This paper explores the viability of the DIC technique in different field conditions. Results from an extensive monitoring program conducted on various viaducts and bridges, each characterised by distinct geometrical internal and external features, are presented hereafter. A key focus of this study is the optimisation of DIC monitoring protocols to mitigate environmental noise and ensure reliable data acquisition.

2. Comparing 2D and 3D DIC techniques for monitoring masonry bridges

Most conventional application of DIC involves positioning a camera for monitoring normally to the plane of the monitored surface, focusing only on capturing the in-plane displacements; this monitoring technique is called 2D DIC. It has primarily been utilised in laboratory settings to study full-field displacement and strains of masonry specimens. Transferring this technique from laboratory conditions to field environments poses specific challenges (Jones et al., 2018). Firstly, ensuring the normality of the camera optical axis to the monitored object plane is not always possible, especially when monitoring larger structures (e.g. bridges with tall piers) or due to the setup restrictions (being limited to the extreme proximity of a bridge due to the surrounding buildings). Secondly, masonry arch bridges exhibit 3D movements, particularly in structures with tall piers. These two deficiencies can mutually exacerbate difficulties in getting good measurements, as large out-of-plane deflections when overlayed with non-normal camera angles, result in readings that are difficult to interpret correctly. Acikgoz et al. (2018b) proposed a method to correct in-plane movement using known parameters, including the angle between the optical axis of the lens and the monitoring plane, intrinsic camera and lens parameters, pixel position of the point of interest, and evaluated out-of-plane movement. However, in this method, the out-of-plane movement must be measured with some other technique to disentangle the displacement components accurately. To address some of these issues, more robust DIC techniques with a stereoscopic camera setup can be employed; these approaches are referred to as 3D DIC.

3D DIC is commonly recommended for monitoring non-planar surfaces or surfaces with substantial out-of-plane movement in laboratory settings. Utilising stereo-correlation (finding identical features in two images of the same object taken from different angles) and stereo-triangulation (determination of camera 3D position based on the projection of the same point on two individual camera images), along with temporal tracking by image correlation, 3D DIC can recover both the 3D surface and the 3D movement of the specimen. This capability makes 3D DIC particularly advantageous for monitoring masonry structures in the field, especially on non-planar surfaces such as arch soffits. However, the primary challenge in applying 3D DIC lies in its setup requirements. Firstly, to achieve stereo vision, 3D DIC necessitates using at least two cameras positioned in a way that captures the same region of interest from multiple angles. Incorrect camera positioning may result in the loss of displacement information or difficulties in stereo-correlation. Secondly, unlike the calibration process for 2D DIC in the field, which can be achieved by scaling real-life dimensions with pixels in images, 3D DIC requires a more rigorous calibration process. This usually entails capturing images of a calibration plate simultaneously with two cameras and then performing geometric transformations to determine 3D transformation for the camera set-up. To ensure the high quality of such transformation, the calibration plate must adequately cover the field of view and be positioned within the depth of field. This process is complicated when monitoring masonry structures with tall piers. The objective of calibration is to determine two sets of parameters: the intrinsic parameters (including image scale, focal length, image centre, and lens distortions) and extrinsic parameters (such as stereo-angle and distance between cameras) for both cameras. Once calibration is completed, all parameters, including camera focus and relative positions, must remain unchanged. Hence, it is also essential to prevent relative camera movement after calibration. In laboratory settings, relative movement between cameras is typically avoided by securely mounting the cameras to a rigid bar. However, this approach is not practical for monitoring real-scale structures, as cameras are usually positioned at a substantial distance from each other.

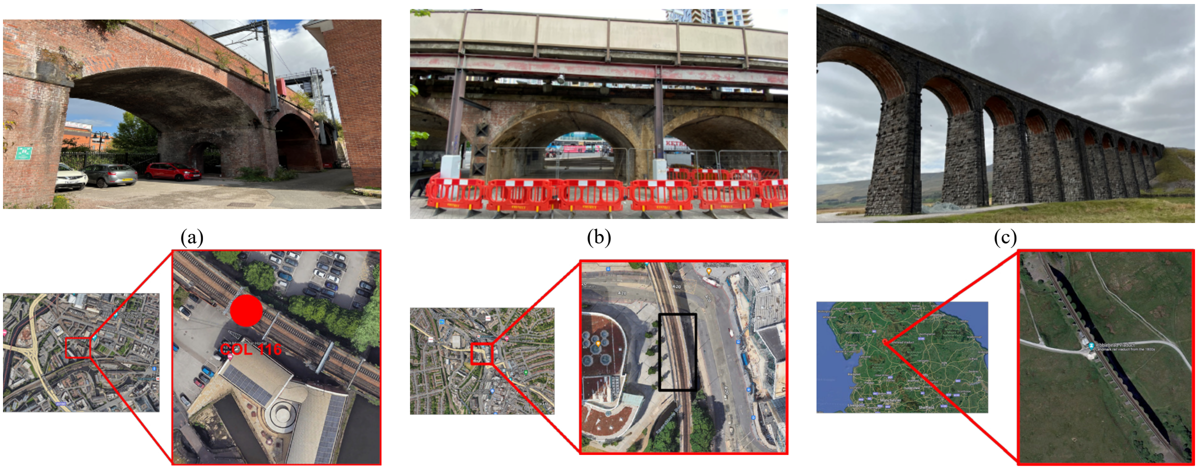
3. Resolution and sources of errors for monitoring masonry bridges

When assessing the DIC monitoring results, there are two key factors: resolution and error. The minimum detectable displacement of the DIC system defines resolution in this context. Commercial software typically quantifies this as the 1/100 subpixel resolution. For instance, given a typical field-of-view with a 5 m width and a camera resolution of 2000 pixels, a 1/100 subpixel resolution equals 0.025 mm. This level of resolution proves adequate for capturing vertical displacement at masonry arch bridge soffits under passing trains, with observed maximum displacements ranging from 0.5 mm to 4 mm, depending on the bridge type and condition and axle loading of the trains. In practical operations, the accuracy is influenced by various factors, introducing different types of errors. These errors can be broadly categorised into two types: noise and bias errors. Noise refers to random fluctuations around the actual value and may arise from environmental factors affecting the camera, such as wind, heat waves, rain, and ground vibrations. Also, noise may result from the image-correlation process, which is attributed to suboptimal DIC setup, including low-resolution cameras, poorly defined targets, out-of-focus targets, inadequate subset size, and under/overexposure. Filtering techniques can mitigate noise to some extent.

In contrast, bias error denotes the offset from the true value and cannot be easily corrected through filtering. Sources of bias error include out-of-plane movements in 2D DIC, uncorrected lens distortions, improper camera calibration, camera movement or rotation post-calibration, camera heating during extended usage, and excessive data smoothing. It is important to note that the sources above are typical examples encountered by the authors in practical applications, but they do not cover all possible sources of error.

4. Monitoring three viaducts in the UK

The current study presents a DIC investigation conducted on three viaducts in the UK: COL viaduct (Figs 1a,e), Mill Road viaduct (Figs 1b,f) and Ribblehead viaduct (Figs 1c,g). The combination of these structures provides a good sample set of representative old masonry bridges and viaducts that are still in operation. They include viaducts with various pier heights, span lengths, span-to-rise ratios, and construction materials; these details are summarised in Table 1.



(a) (b) (c)

(e) (f) (g)

Fig. 1. Monitored viaducts and their locations:
(a, e) COL viaduct; (b, f) Mill Road viaduct; (c, g) Ribblehead viaduct

Table 1. Characteristics of the monitored bridges.

Bridge name	Total number of spans	Monitoring span label	Arch width (m)	Arch span (m)	Arch rise (m)	Pier height (m)	Construction material
COL viaduct	-	116	8.58	12.19	2.72	4.37	brick masonry
Mill Road viaduct	6	3	8.54	7.33	2.01	2.03	brick masonry
Ribblehead viaduct	24	8	8.96	13.66	5.49	17.95	bricks and stone masonry

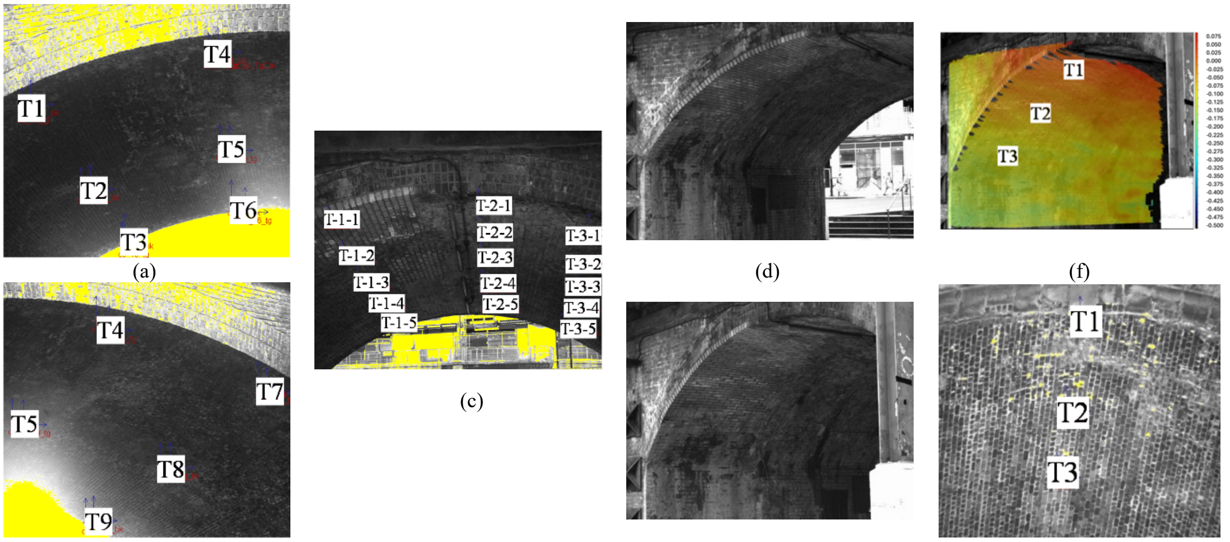
The results for the COL viaduct compare displacements obtained from tracking pre-installed optical targets and those obtained from tracking natural patterns of the masonry surface. Good agreement was observed between these two scenarios. Subsequent monitoring was conducted using natural patterns only. Further investigation on the Mill Road viaduct site highlighted the significant influence of camera depth of field, which is undeniable when measuring deflections across the width of the arch barrel.

In this study, 2D DIC was utilised as a primary tool for monitoring all four structures, as it allows for a more straightforward camera setup that monitoring engineers could quickly adopt. Meanwhile, the 3D DIC technique was also investigated in the case of the Mill Road viaduct, where no disruption to regular bridge operation was required to conduct the necessary calibration.

4.1. Monitoring COL Viaduct

COL viaduct, designated by the Engineers Line Reference COL, runs across central Manchester, UK, with a monitored span in the vicinity of the Potato Wharf (Fig. 1e). Before the monitoring activity, nine customised optical targets were affixed to the specific monitoring positions on the monitored arch soffit. These monitoring positions formed a three-by-three grid with positions in the longitudinal direction corresponding to the arch quarter-span, mid-span, and three-quarter span, and for the transverse direction corresponding to both edges and mid-section (Figs 2a,b). 2D DIC was used to capture the vertical displacement of these nine positions. To ensure sufficient resolution for each target, two cameras were positioned on the south side of the bridge (Fig. 1a) to capture the nine monitoring points. The chosen position results in targets T4 and T5 overlapping; this positioning was selected to perform cross-validation of the results obtained for each camera, where excellent agreement was found. Figs 2a and b show the field of view captured by the two cameras and depict the target positions monitored in this investigation.

Results presented hereafter pertain to the passage of a Class 150 passenger train travelling on the southern track of the bridge (observed side of the bridge). The vertical displacement of the nine positions obtained from tracking pre-installed optical targets is compared with those obtained from tracking adjacent natural patterns of the masonry surface, as shown in Fig. 3a. Excellent agreement was found between both tracking options. This result demonstrates that the natural patterning of the bridge can be sufficient for obtaining reliable tracking of the structure displacements. These results also highlight the effectiveness of DIC as an investigating technique. It allows for zero contact monitoring of masonry structures, precluding any need to install specific optical targets, which can be of particular benefit when dealing with listed or protected structures.



(a) (b) (c) (d) (e) (f) (g)

Fig. 2. Field of view and monitored locations observed during monitoring:
(a) COL viaduct - Camera 1; (b) COL viaduct - Camera 2; (c) Mill Road viaduct (2D DIC); (d) Mill Road viaduct - Camera 1 (3D DIC); (e) Mill Road viaduct - Camera 2 (3D DIC);(f) Mill Road viaduct – visualisation of vertical displacement field (mm) by 3D DIC;
(g) Ribblehead viaduct;

4.2. Monitoring Mill Road viaduct

Mill Road viaduct (Fig. 1b) is a multi-span masonry arch bridge in Lewisham, South London (Fig. 1f). This junction experiences a high volume of relatively slow-moving traffic on both sides of the bridge, as the viaduct serves as a platform for the Lewisham train station. The viaduct consists of four straight masonry arches and two skew masonry arches, with the last crossing the Ravensbourne River. Details about bridge dimensions can be found in Table 1.

In conjunction with regular monitoring, an investigation was conducted to determine the influence of different camera settings on the obtained response. To this end, two identical cameras were used, one designated as a "reference" and another with settings that varied between tests. Attention was given to the following options: the influence of camera aperture, the effect of various depths of field, and the angle between the camera and the monitored surface. Overall, it was possible to obtain results in all considered cases, although the quality of obtained results varied. It was found that underexposed images yield better results compared to overexposed ones.

On the other hand, the influence of angle was not particularly distinct; it is worth noting, though, that this lack of influence was observed only on this viaduct, characterised by very short piers, and subsequent monitoring found that high angle does adversely affect the quality of results, as it makes the overall setup far less robust to external influences when compared to cases where the camera is near normal to the monitored surface. By far, the most significant contributor to the quality of observed results was the effect of depth of field, where even a tiny reduction in the depth of field can yield erroneous results. Fig. 3b illustrates this effect, where the blue curve indicates results obtained with the reference camera, and the red curve is associated with a camera where the focus was intentionally suboptimal. It is worth noting that even the reference result suffers from insufficient depth of field, as the reported curve is associated with a train travelling above target T-2-4 (Fig. 2c), while the camera was focused on the bridge segment associated with target T-2-2. This effect becomes even more severe for the "poor focus" camera, where the response is polluted by noise and indicates the difference in the overall magnitude of deformations.

Alongside the investigation using 2D DIC, the 3D DIC technique was also used to monitor the same span of the Mill Road viaduct. Two cameras with a 27-degree stereo angle were placed to capture part of the arch, spandrel wall, and the pier, with the field of view from both cameras shown in Figs 2d,e. In contrast to the 2D DIC setup, where each camera is independent, an additional cable is required to synchronise the shutters of both cameras. This process "slaves" one camera shutter to another, ensuring synchronisation of captured images. During post-processing, images are further synchronised using timestamps to guarantee alignment up to the millisecond level.

Camera calibration was conducted with a dedicated 1 m^2 calibration plate that covers a substantial portion of the 4 × 6 m^2 field of view. As both intrinsic and extrinsic calibration is performed for 3D DIC monitoring, no separate displacement results scaling is necessary, contrary to the case of 2D DIC applications.

This streamlined calibration process offers two significant advantages over its 2D DIC counterpart. Firstly, it does not require specific pixel scaling, facilitating monitoring structures where local measurements are impossible. This is particularly advantageous for structures with irregular configurations, such as the arch barrels of skew-bridges. Secondly, the 3D DIC system allows for the direct generation of full-field displacement and strain maps for non-planar surfaces, which could serve as a meaningful information source for assessing viaducts, providing capabilities to visually identify areas with significant deformations that require further investigation or strengthening.

In contrast, 2D DIC, when applied to non-planar surfaces, relies on piecewise approximation of the complex surface with individual planar ones. Each sub-surface requires independent calibration and scaling based on the features local to the calibrated surface. This fact makes generating continuous displacement and strain maps for non-planar surfaces like the arch barrel challenging when monitored using 2D DIC algorithms.

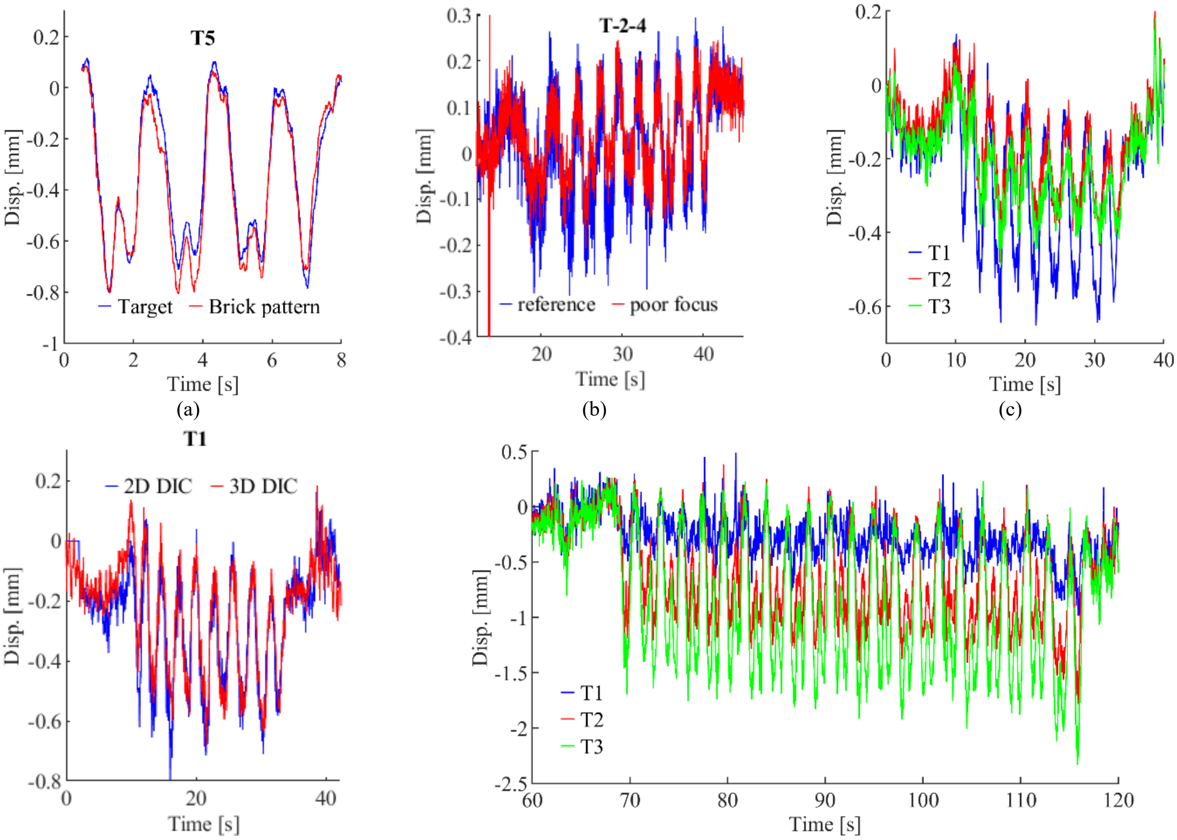
The results presented hereafter pertain to the Class 465 passenger train passing on the track facing the cameras. Fig. 2f presents a snapshot of the contours of vertical displacement taken at the 15th second of the recording. Fig. 3c provides displacement histories for the given targets. A comparison of results obtained for target T1 from 2D and 3D DIC is provided in Fig. 3d. A good agreement is observed for this case, with only minor discrepancies for some of the peak values. This difference seems only to be observed for the first two peaks and can be partially attributed to slightly different "zero" obtained in 2D and 3D cases. Obtained results from the Mill Road viaduct underline the applicability of DIC monitoring strategies for small viaducts and bridges, while results obtained on the COL viaduct extend this conclusion to mid-size structures. As such, the following section will provide some insights into monitoring large viaducts.

4.3. Monitoring Ribblehead viaduct

Ribblehead viaduct (Fig. 1c) is located in the Ribble Valley in North Yorkshire (Fig. 1g). The viaduct comprises 24 spans and is more than 400 m long. It was constructed between 1870 and 1874. Its piers and spandrel walls were made of bonded stone blocks, while the arch barrel was made of blue and red bricks.

Tall piers characterise the Ribblehead viaduct; when monitoring such a structure, a balance must be found between the optimal optical angle, stand-off distance from the structure, and the desired field of view for the camera. For the results presented hereafter, the camera angle of elevation towards the arch barrel was set to 45 degrees; this angle was chosen as an optimal compromise for the factors above. The resulting field of view captured by the camera is depicted in Fig. 2g.

Only a single rail track located at the mid-width of the viaduct is present on the monitored structure. Fig. 3e presents vertical deflections of the bridge under a freight train consisting of the class 66 locomotive and 21 HTA wagons carrying aggregate. The presented graph accurately captures the passage of every axel over the monitored point. The results also highlight the apparent differences between the displacements observed for the three targets across the arch crown. These differences are associated with the overall 3D response of the monitored structure. In particular, the results for T1 are indicative of stiffening provided by the spandrel wall. On the other hand, T3, positioned beneath the rail track, exhibits the most significant level of displacement.



(a) (b) (c) (d) (e)

Fig. 3. Results obtained in the course of monitoring (a) COL viaduct; (b) Mill Road viaduct 2D DIC; (c) Mill Road viaduct 3D DIC; (c) Mill Road viaduct 2D vs 3D DIC comparison; (e) Ribblehaed viaduct

5. Summary

The paper found that DIC is a promising non-invasive solution for monitoring masonry bridges. DIC monitoring offers full-field displacement and strain measurement without direct contact with the structure. This study compared the effectiveness of 2D and 3D DIC techniques for monitoring masonry bridges, where it was found that 2D DIC can be successfully applied for field monitoring. However, it requires the collection of data from non-planar surfaces and can suffer from the presence of substantial out-of-plane movement. In contrast, 3D DIC, although substantially more complex to set up, offers advantages for monitoring non-planar surfaces and out-of-plane movement in the field.

DIC monitoring was conducted for three distinct viaducts in England, and good-quality monitoring data was obtained in all cases. An investigation of the COL viaduct confirmed that natural masonry patterns can be used to obtain accurate displacement results. This fact expands the applicability of the DIC technique to a broader range of structures, as it removes the need for optical target installation. The DIC monitoring of Mill Road viaduct showcased both 2D and 3D DIC applications for comprehensive displacement monitoring.

Overall, the study highlights the potential of DIC as a reliable and effective tool for monitoring the structural health of masonry bridges and provides insights into optimising DIC monitoring protocols for field applications, improving accuracy, and mitigating environmental noise.

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