Masonry Bridge Inspection Using Point Cloud Data and 360-Degree Images: A Case Study on Railway Bridges.

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Abstract

In the context of the UK's aging infrastructure and reliance on railway masonry bridges, this study addresses the vital challenge of enhancing bridge longevity and safety through effective and accurate inspection methods. Traditional inspection techniques, while established, often disrupt service, pose safety risks, and incur high costs. In contrast, digital inspection techniques, such as 360-degree imagery and point cloud data, offer increased efficiency and minimal disruption. However, these methods have not been extensively tested in real-world settings beyond the experimental conditions. Addressing this gap, our research aims to evaluate the effectiveness of these digital techniques against conventional inspections across four masonry bridges. By replicating existing examination results with digital datasets, this study explores the potential of the integration of a digital examination approach into the UK railway bridge inspection protocols, engaging industry experts to assess the applicability of broader adoption. Employing an exploratory case study methodology, the research collected and analysed data to ascertain digital detection rates for various structural defects. Findings indicate a 46% detection rate using digital methods, with joint defects and spalling achieving over 85% success when excluding repaired and tactile-related defects. However, challenges in detecting cracks, fractures, and bulging were evident, primarily due to image quality issues and physical obstructions. Proposed corrective strategies, such as improved data capture techniques and more precise specifications, suggest potential advancements in detection rates. Nevertheless, the absence of a correlation between defect severity and detection rates underscores the limitations of digital methods, particularly for defects requiring tactile examination. Despite these challenges, discussions with industry experts supported the operational viability of digital examination methods, highlighting anticipated benefits in safety, efficiency, and decision-making, thus suggesting their suitability for widespread application. This study not only advocates for the integration of digital inspection techniques into existing protocols but also underscores the necessity for further research to refine these methods for practical use.

Keywords: Bridge inspection, Point cloud data, 360-degree image, Railway bridge

1. Introduction

The United Kingdom's transportation infrastructure heavily relies on masonry bridges, known for their durability and low maintenance needs, particularly due to their arch-centric designs (Wiggins 2018). These bridges, crucial to the UK's transport system, include a significant portion that has been in service for over a century (Augusthus-Nelson and Swift 2020). With roughly 47% of the UK's railway bridges (Orbán 2004) and 60% of European railway bridges being masonry (Jing, Sheil and Acikgoz 2022), regular inspections are imperative to ensure their prolonged operability. Traditional inspection methods, involving onsite visits and manual assessments by engineers, not only disrupt traffic and pose safety risks but also incur significant time and financial costs (Talebi et al. 2022). The traditional method of examination involves identifying surface defects through visual inspection, discovering subsurface defects by tactile approach (e.g. hammer tapping), and taking measurements using rulers, crack gauges, plumb points, and inclinometers (Turksezer et al. 2021; Parry 2004).

Digital examination techniques offer a more efficient and economical alternative to traditional bridge inspection methods, especially for large structures. For instance, Omer et al. (2021) demonstrated that digital inspections of bridges using Terrestrial Laser Scanning (TLS) data not only outperform conventional techniques in accuracy but are also more cost-effective and time-efficient. This method has become a key tool in detecting and measuring defects in masonry bridges (Ye et al. 2018). It enables a nuanced analysis of structural behaviours by examining distorted geometries and fitting primitive shapes, highlighting innovative approaches for defect assessment in masonry bridges (Kim et al. 2021). Moreover, the use of 360-degree images and the virtual environments crafted from them have proven to be beneficial tools in the realm of structural defect detection (Masciotta et al. 2023). These images, either used alone or in combination with point cloud data analysis, enable a thorough identification and examination of defects. Use of 360-degree imaging offers a non-invasive and effective approach for defect detection in masonry structures, suitable for periodic monitoring and inspections (Chaiyasarn et al. 2023). When combined, this approach provides a comprehensive view, offering both an expansive overview and a detailed analysis of structural defects (Zhang et al. 2022). Such techniques have been found to be a low-cost and low-risk way of supporting conventional bridge inspection by providing rigorous and accurate data towards data-driven and optimal decision-making for asset management (Wells and Lovelace 2021).

The application of 360-degree imaging in infrastructure analysis marks a significant shift towards more efficient inspection methodologies. Rau et al. (2017) demonstrated the efficacy of high-resolution 360-degree images in identifying structural damage such as cracks and spalling. Further studies by Karim, Dagli and Qin (2020) and Jeong, Seo and Wacker (2020) underscore the technology's potential, evidencing reductions in inspection times by 60% to 80% and accuracy rates of measuring a critical spalling exceeding 97%, respectively. Moreover, the growing reliance on point cloud data for defect detection represents a notable advancement in structural engineering practices. This method, as demonstrated by several researchers (Rashidi et al. 2020; Kim et al. 2021; Saleem et al. 2021 and Yan et al. 2021) offers a detailed three-dimensional view of structures, facilitating the detection and quantification of a wide range of defects from cracks to efflorescence. The development of frameworks for automated detection of surface damage, such as those proposed by Kim et al. (2021), highlights the method's potential to streamline inspection processes and enhance accuracy. In short, these developments mark a critical shift towards more accurate and non-invasive inspection and maintenance techniques for masonry bridges. Such technologies promise not only to enhance the precision and reliability of bridge examinations but also to offer fresh perspectives on the structural and historical analysis of masonry bridges, thereby facilitating improved strategies for their preservation and rehabilitation (Cucuzza et al. 2024).

Despite these advancements, the deployment of digital inspection techniques frequently remains limited to experimental settings or utilises methods not wholly compatible with real-world industry practices and standards. Moreover, there is a notable absence of direct comparisons between the outcomes of digital and traditional inspections, which poses a practical challenge for asset owners considering a switch to digital bridge inspection using point cloud data and 360-degree imaging. Our study addresses this shortfall through a detailed case study of four masonry bridges, aiming to reproduce the existing examination results using 360-degree imaging and point cloud datasets, thereby providing a solution for asset owners. This research does not just compare digital techniques with traditional manual inspections but also evaluates their potential integration into the examination protocols of the UK railway system with industry experts, suggesting possible wider adoption by organisations managing transportation infrastructure. By initially utilising 360-degree imaging to locate defects, followed by an in-depth analysis using point cloud data for the necessary measurements, this study aims to deliver crucial insights into the practical and efficient application of digital approaches in real-world settings in order to enhance current inspection methodologies.

2. Research Method

This study employs an exploratory case study approach. As delineated by Yin (2018), this methodology is particularly apt for investigations aimed at describing, elucidating, and delving into contemporary phenomena within their natural settings, primarily addressing 'how' questions. Such an exploratory case study approach is selected for its ability to facilitate a detailed examination and uncover insights into the digital inspection of masonry bridges, highlighting its practices, challenges, and potential enhancements within the context of real-world application. The exploratory nature of this case study is ideal for this research as it aims to explore the effectiveness, accuracy, and practical implications of utilizing digital inspection methods for identifying defects in masonry bridges. and answer the following 'how' questions:

- How do digital inspection methods, more specifically point cloud data and 360-degree imagery, compare to traditional inspection techniques in identifying and assessing defects in masonry bridges?
- How can the challenges encountered in the digital inspection process be addressed to improve defect detection rates and measurement accuracy?
- How do experts in the field perceive the integration of digital inspection methods into current bridge inspection practices?

2.1 Rationale for Case Selection

Given the lack of a universally accepted strategy for case selection, this study followed Brinkmann's, (2013) guideline to choose cases most likely to illuminate the research aim. Purposive sampling was thus employed, a method underscored by Saunders, Lewis and Thornhill (2023) for its emphasis on deliberate, informed selection in scenarios where detailed insights from a small sample are desired. The criteria for case selection were defined to ensure comprehensive coverage of the study's objectives: (1) a diverse range of defects as identified in physical inspection reports, (2) accessible bridges for the acquisition of point cloud data and 360-degree imagery, and (3) minimal obstructions from vegetation or ongoing repairs that could impede data capture. The selected bridges, detailed in Table 1, were carefully chosen to ensure they collectively cover the wide range of conditions and scenarios relevant to our research objectives. This strategic selection allows for a comprehensive analysis across a diverse set of conditions, with point cloud data and 360-degree images of these bridges captured in November 2019.

2.2 Equipment and Data Capture Process of the Selected Bridges

The 360-degree images and point cloud data were captured using the FARO Focus 3D X330 TLS scanner. The technical specifications include a point distance of 6.136 mm/10m, a resolution of 10240 × 4267, and an approximate scan duration of 6 minutes per scan. The data was processed using FARO Scene 7.1.1.81 software. The scanner was mounted on a tripod and calibrated according to the manufacturer's guidelines to ensure accurate data collection. Target-based registration was used, with at least six sphere targets placed in a zig-zag pattern across the inspection area. The distance between scan positions was carefully selected within 2-3 meters to ensure comprehensive coverage and accurate data alignment. The point cloud and 360-degree images were captured onsite, with multiple scans taken from different angles to ensure comprehensive coverage of the bridge structure.

2.3 Data Collection

The data collection in this research involves four steps, as shown in Figure 1. In the first step, detailed reports from the most recent physical examinations of selected bridges are studied and analysed to systematically organise and document the defects' category, location of the defect, description of the defect, and quantification information related to the severity of the defect. If any image showing the defects is available from the examination report, it will be added with the documentation. The masonry defects are categorised as bulging, crack/fracture, spalling, joints defect and loss of section according to a reference document related to the UKs Railway structure examination. For the determination of overall bridge condition, the same document suggests the procedure to determine the severity and extent of defects in a bridge element based on some measurements. The severity value is defined on a scale of zero to ten, with zero being no defect and ten being the most severe defect. The defect description and measurement requirements are presented in Table 2.

The second step involves a visual inspection of 360-degree images to identify the defects according to the information obtained from the previous step. The third step involves conducting point cloud data analysis for each of the defects for further identification and quantification. Point cloud analysis involves segmenting the area containing the defect along with adjacent intact structure to define the target surface for investigation. This segmentation narrows the focus of the analysis to the defect, improving analysis efficiency (Mirzazade et al 2021; Riveiro, DeJong and Conde 2016). A reference surface is established from multiple points on the intact area, representing the baseline, defect-free state. The accuracy of the reference surface increases with the number of points collected. Subsequent analysis measures deviations between this reference surface and the target area to identify and assess the severity of defects. Following the establishment of a reference surface, deviation analysis between the target and reference surfaces employs the cloud-to-mesh (C2M) method due to its efficient balance of accuracy and reduced computational demands compared to the more resource-intensive multiscale model cloud comparison (M3C2) (Zhao, Seo and Chen 2022). This computation facilitates the identification of defects, with positive deviations often indicating bulging and negative deviations normally suggesting issues such as spalling or cracks. Measurements for defect dimensions are then derived to quantify the identified issues.

The evaluation of the digital inspection approach, utilizing point cloud analysis and 360-degree imagery, was facilitated through a focus group in the fourth step. Focus groups are recognized as a potent qualitative tool for eliciting feedback on the practicality and perceived value of innovative methodologies (Breen 2006). In this case study, a single focus group session was held, incorporating both exploratory and confirmatory elements to ensure a thorough exploration of insights (Tremblay, Hevner and Berndt 2010). The participant details for the focus group are documented in Table 3. The participants of the focus group are from the major infrastructure owner in the UK, with each participant having over 10 years of experience in masonry bridge examinations and being proponents of transitioning to digital inspection methods. This purposive sampling strategy was crucial to ensure that the focus group comprised individuals who could offer substantial, expert insights into digital examination practices, as emphasized by Brinkmann (2013), prioritizing the quality and relevance of participant contributions over sheer numbers.

Participants engaged in discussions around the functionality of the digital approach, assessing its relevance and effectiveness for bridge inspection challenges. The evaluation framework, detailed in Table 4, categorizes the assessment into two primary dimensions: 'Usefulness' and 'Effectiveness,' each further broken down into specific attributes. These attributes are defined and accompanied by targeted questions that guided the focus group dialogue. Feedback from this session was crucial in corroborating the digital inspection approach's applicability in real-world settings.

2.4 Data Analysis

The examination reports for all four bridges underwent a thorough review, with key data on defect types, locations, measurement specifics, and associated photographs extracted. This data was organised into tables for each structural element of the bridges, such as barrel arches, abutments, and wingwalls, to facilitate a detailed analysis. Subsequently, defects were marked on 360-degree images that offered the clearest view of each identified issue. To enhance the visual inspection process, a bespoke integrated platform named 'Asset Visualizer' was developed specifically for this research.

The Asset Visualizer enables an in-depth examination of the 360-degree images, allowing researchers to identify and record various masonry defects on the bridge surfaces. Defects are marked by drawing a rectangular box around them directly on the images, a method chosen for its ability to clearly delineate and catalogue the defects for further analysis.

Figure 2 illustrates the process of marking a defect on a 360-degree image using the Asset Visualizer platform, which demonstrates the platform's utility in bridging the gap between traditional examination methods and digital visualization techniques.

After identifying a defect using the Asset Visualizer, the defect was marked, and a corresponding screenshot was captured for documentation. This screenshot, along with the defect’s description, location, and type, was recorded in a comprehensive table, as exemplified in Figure 3(a). The fifth column of this table showcases the screenshot from the Asset Visualizer, providing a visual reference for each recorded defect.

Subsequent to this initial documentation, point cloud data analysis was conducted for each defect using CloudCompare (Daniel, no date), an open-source software selected for its robust analysis capabilities suitable for this study’s requirements. The findings from this analysis were meticulously recorded in detailed tables for each bridge element, with an illustrative example presented in Figure 3(b). These tables extend the initial documentation by including the results of the point cloud data analysis in a new sixth column, thereby facilitating a direct comparison with the detailed examination reports.

For defects that were not detected by either 360-degree image inspection or point cloud analysis, reasons for their omission were carefully documented. This documentation process ensures a thorough understanding of each method's limitations. Conversely, for detected defects, necessary measurements were conducted and recorded. Any instances where measurements could not be performed were also noted, with explanations provided to understand the challenges encountered.

Through this structured approach, the study leverages both visual and quantitative data to offer a comprehensive assessment of masonry bridge defects, aligning closely with the detailed examination reports for further analysis. Moreover, content analysis was conducted on the focus group transcripts to distil key themes and insights, guided by the methodology outlined by (Fellows and Liu 2021). This involved a careful examination of the dialogue to identify prevalent opinions and observations on the digital examination approach.

3. Results

A total of 262 defects consisting of five types are found from the analysis of four examination reports, which are listed in Table 5. Of these, 118 (46%) defects are detected from digital datasets, and rest of the defects (144) are neither detected from 360-degree image analysis nor from point cloud analysis.

Figure 4 presents a combined chart showing the frequency and raw detection rate of each defect type using the proposed digital examination method. The chart reveals that joints defect is the most efficiently detected defect type, while crack/fracture defects are the least efficiently detected. It should be noted that the occurrence of bulging and loss of section defects is very low, and therefore the detection efficiency for these defect types is not statistically significant.

The heatmap in Figure 5 categorically presents the causes for non-detection of different types of defects and their statistics. It is found that 65 defects require tactile examination including 54 spalling and 11 loss of sections. These are spalling with hollow and drummy to hammer, and loss of section with loose bricks to hammer. The next most significant number of undetected defects is 33 which are due to not being visible on 360-degree images. Of those, there are 13 defects that are not visible due to image quality issues, 13 has other reasons (e.g. bulging and displacement not visible in 2D image) and 7 are not visible because the defects are not covered within the image frame, such as at the rear face of the parapet and the track sides of the bridge. Furthermore, 18 defects are not visible because they are obstructed by vegetation, fencing, railings, and signboards on the surface. Finally, 25 defects were found to be repaired, all of which also belong to Bridge B and Bridge C, which were digitally captured 6 months and 39 months after the physical inspection. In addition, 3 defects cannot be located on the digital datasets because the location of these defects are not detailed in the examination report.

4. Discussion

The results section of this study indicates that a significant number of defects are not detected using the digital examination approach. However, there are various reasons why they may remain undetected. In the ensuing discussion, we explore some of the primary factors that contribute to the non-detection of these defects. Additionally, potential strategies for addressing these issues and improving the detection rate are discussed.

4.1 Detection of Crack / Fracture

The reasons for non- detection of cracks are mainly image quality issues, although some of them are attributed to data void and obscured image due to presence of vegetation or fencing. Analysis of the 360-degree images identified potential causes for the image quality issues which include:

a) *Viewing angle of the camera*: The camera's viewing angle has a significant influence on the visibility of a crack. For example, the cracks found in Figure 6 are both a maximum of 2mm wide and run from the spandrel wall to the top of the parapet, according to the examination report. However, when looking at the spandrel wall on the 360-degree image in Figure 6, the crack 'A' on the left is clearly visible, while the crack 'B' on the right side of the image is not very clear. The cracks become invisible on the parapet area 'C'. Additionally, the visibility of cracks is more prominent near the face ring than towards the parapet at the top. In 5 cases the cracks are not visible in the 360-degree image due to this reason. Taking additional images from near the bridge at perpendicular angles to the surface and capturing higher resolution images could solve this problem, especially for known cracks from previous examinations.

b) *Inadequate light level*: The light level and contrast of light at different parts of the image influence the visibility of defects, mainly cracks. Such a situation is shown in Figure 7 where the approximate location of the crack found from the examination report is marked in red. The area under the arch is very dark, and the illumination from the sky near the arch portion creates high contrast that makes it impossible to see the crack. There are 3 instances found where the cracks are not visible in the 360-degree images due to inadequate light levels. Ensuring adequate light levels during data capture and taking additional images focusing on the dark area only would solve this problem.

c) *Image resolution*: The resolution of 360-degree images is a key reason for the non-visibility of defects. The image presented in Figure 8 has a series of horizontal bed joint fractures throughout the parapet, which are open to a maximum of 3mm. However, with a 100% zoom level, the cracks are not visible. In 3 cases, the crack was not visible due to this reason. Taking higher resolution images during data capture would solve this problem.

d) *Surface texture*: Surface texture is also responsible for the non-visibility of cracks, as shown in Figure 9. If the surface becomes dark or reflective due to water percolation, then it is difficult to see the crack. In 2 cases, the non-visible cracks were in such areas. The presence of graffiti, especially if it is drawn after a crack has developed, could create a similar problem regarding the visibility of cracks.

This situation is also very challenging during physical examination, as cracks may not be visible to the examiner in the first instance unless it is a known defect from previous examination. For a known defect, taking additional images from different angles would maximize the probability of the crack being visible in one of the images. There is a possibility that a crack may have developed after the point cloud data was captured. One such case exists in Bridge D, where the physical examination was conducted six months after the point cloud data was captured. When viewed at the approximate location in 360-degree image no crack was found.

The cracks that are visible in the 360-degree images but cannot be detected through point cloud data analysis are related to the density of the point cloud data. The aperture of these cracks ranges from less than 1mm to a maximum of 3mm, which is smaller than the density of the point cloud data. In the core areas of the bridge, the distance between any two points in the point cloud dataset ranges between 2-3mm, making it challenging, if not impossible, to detect these cracks through point cloud data analysis. Figure 10 shows the only crack that was detected using point cloud data analysis. However, according to the examination report, the width of the crack opening is only 2mm. Upon examination of the 360-degree image in Figure 10(a), it is evident that the maximum crack width is more than 2mm. The crack belongs to Bridge B, which was examined approximately six months before the point cloud data capture, and from the 360-degree image, it appears that the defect has deteriorated since then. The measurement made on the point cloud reveals the crack width as 33mm. The accuracy of this measurement depends on the selection of points on both edges of the crack opening. However, it is clear from the image and point cloud measurement that the crack opening had significantly increased, which would enable it to be detected through point cloud analysis.

4.2 Detection of Joints Defect

The primary reason for non-detection of joints defect is obstruction due to vegetation and fencing, as well as data void. Additionally, some of the joint defects are found to be repaired in the 360-degree image. All of the visible joint defects in the 360-degree image have been detected using point cloud data analysis except for one. The joint defect that could not be detected using point cloud data analysis falls on the junction between the wingwall and abutment. It is highlighted using blue rectangles in Figure 11, where Figure 11(a) shows the defect on the 360-degree image, and Figure 11(b) shows the corresponding result of point cloud analysis. As the defect is located precisely at the junction of two elements, it is challenging to construct a highly accurate reference plane. Hence, the point cloud analysis failed to pick up the defect.

4.3 Detection of Spalling

The non-detection of spalling is primarily attributed to the requirement of tactile examinations for detecting defects. Additionally, there are 2 cases of data voids and 3 cases of repaired defects, respectively. In 4 other cases, the non-detection of spalling could not be attributed to any specific reason, three of which are due to the unclear location of the defects. The location of these spalling occurrences was not specified but referred to as generalized spalling. The other case, which belongs to Bridge D, is described as damage resulting from a vehicle strike at the arch face, and it is probable that the vehicle strike occurred after the point cloud data was captured. All of the detected spalling from 360-degree image analysis are also detected using point cloud data analysis except for one. Figure 11 shows that particular spalling defect occurred at the junction between the wingwall and abutment, which is highlighted in yellow rectangles. As the defect is located precisely at the junction of two elements, it is challenging to construct an accurate reference plane to conduct the point cloud analysis, similar to the case of joint defect explained earlier.

4.4 Detection of Bulging

The examination report identified 13 bulges, but only 2 were visible in both the 360-degree images and point cloud data. One was an arch flattening (as shown in Figure 12), and the other was brickwork pushing out, both visible in existing 360-degree images. However, detecting bulges in a 360-degree image is challenging when the viewing angle is perpendicular to the surface with the defect. This is because the image lacks depth and may appear as a flat surface. The bulge is more visible when viewed parallel to the surface. Fortunately, the arch flattening was easily detected in an image captured from the opposite end of the arch, allowing for a clear view of the bulge almost parallel to the arch. Similarly, brickwork pushing out was detected in an image captured by directing the camera's viewing angle towards the parapet from the ground. Out of the 13 bulges, point cloud analysis could not be conducted in 2 cases due to vegetation and fencing. In the remaining 9 cases, the analysis was conducted on the bulging location specified in the examination report, and two bulges were detected through point cloud data analysis. The analysis could not detect 7 bulges, out of which 3 belonged to Bridge D where the point cloud data was captured about six months before the examination. This suggests that bulges might have developed after the point cloud data capture. It is also possible that the point cloud analysis was not conducted precisely on the actual defect location as it wasn't visible in the image, which could be the reason for non-detection in 4 other cases.

4.5 Detection of Loss of Section

The majority of the non-detection of loss of section is due to the tactile examination requirement. Additionally, there are three cases caused by data voids, one case of obstruction due to vegetation, and four cases of abutment displacements. The abutment displacements, such as abutment leaning out or leaning back, is not visible from the 360-degree image, and these are detected during the physical examination with the help of a spirit level indicator or using a plumb point. The point cloud data analysis is also unable to detect displacement of the abutment as it is not possible to create a reference plane in such a case. However, the displacement can be detected using point cloud comparison if reference point cloud data is available.

4.6 Detection Rate and Severity

Defects necessitating tactile examination and repaired are not identifiable using 360-degree imaging or point cloud data. Figure 13(a) shows the detection rate in different bridges considering all defects (including tactile examination-required defects along with defects that have been repaired before the digital data capture) while Figure 13(b) presents the detection rates in different bridges excluding defects required tactile examination and repaired defects. Moreover, the image quality issues, except surface texture, can be resolved by taking high resolution image. The data voids can be improved by taking additional images. The vegetation and obstruction can be removed prior to digital data capture to improve the detection. Considering all these corrective actions, the detection rate of different defects is presented in Figure 13(c). It is apparent from Figure 13(a) and (b) that the overall detection rate improves for all defect types except bulging. For spalling and loss of section, the detection rate almost doubles. It is found from Figure 13(c) that the detection rate of cracks improves to over 85%, and the detection rate for spalling and joint defects is 100%. There is no significant improvement in the detection rate of bulging and loss of sections; however, these are very low in number, and the detection rate for these two types of defects does not fully explain the capability of the proposed digital examination method. Figure 14 compares the defect count and detection status at different ranges of severity values (found from examination report), where Figure 14(a) considers all defects, 14(b) excludes repaired and tactile examination-related defects, and Figure 14(c) considers all corrective actions.

From Figure 14(a), it is found that more defects are detected in the severity range of 0-2 than in all other ranges. Excluding repaired and tactile examination related defects, more defects are detected in both the 0-2 and 2-4 severity value ranges than in the rest of the severity ranges as shown in Figure 14(b). When considering the implementation of corrective actions, Figure 14(c) indicates that there are more detections than non-detections in the 0-2, 0-2-4, and 4-6 severity value ranges, respectively. In the 6-8 severity value range, the number of detections and non-detections is equal, and in the 8-10 severity value range, the number of detections is less than the number of non-detections. However, the total number of defects having severity values above 4 in their respective ranges is very low (less than or equal to 10). This does not provide statistical reliability of the detection status for those severity value ranges because one more detection or non-detection could significantly change the scenario/statistics. The analysis provides insight that there is no significant correlation between detection status and severity value. Instead, the proposed digital approach is capable of detecting defects in all severity ranges.

4.7 Performing Measurement:

Upon reviewing the reference document related to the UKs Railway structure examination it was found that the area covered by spalling, joint defects, loss of sections, and bulging are the primary parameters for quantifying the severity of the defect. For cracks, it is the length of the crack. The above-mentioned measurements were performed for all detected defects to evaluate the capability of the proposed approach in relation to performing measurements.

Figure 15 illustrates an example of area measurement, where the measured area on the point cloud data is bounded by a polyline. The presence of joint defects at the edge of the bounded area is indicated by black arrows. Figure 16 presents an example of measuring the length and width of a crack by calculating the distance between two points. The area covered by the defect, the width of joint opening, and the depth of joint defects were successfully measured for all detected cases in joint defects. Similarly, the area covered by the defect and the depth of spalling were measured for spalling. Finally, the area covered by the defect and the distance of brickwork pushing out were measured for bulging and loss of section.

The study concludes that all required measurements related to defect quantification can be successfully performed. Area measurements for any defects are much easier to perform than physical examination.

Depth measurements of spalling and joint defects can also be performed, although their accuracy depends on the selection of data points to construct the reference surface. The length of a visible crack can be measured easily, but the width measurement of cracks is challenging. The width of open joints can also be measured provided accurate points are selected to represent the edge of open joints.

The accuracy of measurements in a point cloud dataset depends on the density of the points, which in this study ranges from 2 to 3 mm. However, a direct comparison between the examination report and digital measurements was not feasible for two primary reasons. Firstly, the examination report does not specify the accuracy of the measurements and often provides approximations without detailing the measurement methodology (e.g., which points were measured). No standardised method is specified in the examination report; instead, the accuracy of the measurements depends on the examiner's judgement. Secondly, due to the time interval between examinations, the measurements may have changed. Furthermore, the measurement process requires a degree of examiner judgement, which applies equally to both physical and digital examination processes.

5. Evaluation of The Digital Examination Approach

The focus group was conducted with three expert engineers and the participants are encouraged to discuss on the questions mentioned in Table 3. The organisation that owns the asset recommends the focus group members and has assured that they are experts and able to represent the views of the industry. They were selected based on the following criteria: (1) all of them had more than 10 years of experience in bridge examination, (2) they were familiar with the study, and (3) they were familiar with the digital solution adopted in the project. These criteria ensured that purposive sampling had been followed carefully and that the right participants had been invited to the focus group, which is more important than the number of participants (Brinkmann 2013).

Prior to the presentation of those questions, the procedure used for defect detection in the case study has been demonstrated using a short video. The response from the participants are discussed below:

5.1 Flexibility

All the participants’ opinion converges towards adapting the proposed approach of digital examination for various types of railway bridges, including concrete, viaduct, and metallic bridges; however, the accuracy and method of collecting point cloud data may differ depending on the type of structure (Expert 1). Concrete structures may be a simpler transition since some of the defects are similar to those in masonry structures (Expert 1), while metallic structures pose more challenges due to hidden areas where the point cloud analysis may not detect certain elements such as the space between the girders (Expert 3). Overall, point cloud analysis in combination with 360-degree imaging remains a valuable tool applicable to various structure types, although a one-size-fits-all approach will not suffice (Experts 2 and 3).

5.2 Practicality

Based on the conversation among the experts, it can be inferred that training is essential for the successful implementation of the digital approach in bridge examinations (Experts 1-3). The specific roles and responsibilities within the process need to be determined, including who will be responsible for data capture, post-processing, and analysis, as well as how to use the tools effectively (Expert 3). The training may vary depending on the chosen individuals for these roles and the desired level of expertise in data collection and analysis (Expert 1). Expert 2 believes that the question of who validates the captured defects and recommendations can be approached in different ways, and a customizable approach can be adopted, where specific roles and their corresponding training requirements are determined based on the region's operational preferences and needs (Expert 1).

5.3 Efficacy

The experts all agree that the digital examination approach has the potential to provide significant benefits in improving the examination of masonry bridges. Expert 1 believe that it can provide a more detailed and objective assessment of structures, as well as detect and measure defects that may go unnoticed by the human eye alone. Experts 2 and 3 emphasise the strength of such approach in relation to preventing information loss in process of translation of examiner’s observation. The experts discuss the potential to perform repetitive defects identification during subsequent exams which would eliminate ambiguity and provide clarity. Moreover, the measurements of area on a curved surface (e.g., barrel arch's surface) would be quicker and easier than the existing procedure of doing this (Experts 1 and 3).

5.4 Efficiency

Using digital technologies for asset examinations can increase safety by reducing the need for examiners to access hazardous areas or work at heights (Expert 3). Expert 1 recognise that digital data can be used for different purposes and it can add a new level of efficiency in asset management in relation to rapid and informed decision making. Expert 2 supports Expert 1 and underline that proposed digital approach provides a comprehensive view of the asset, allowing for a thorough analysis of its structural condition, scenario simulation, and evaluation of different maintenance or optimisation strategies. Additionally, 360-degree imaging and point cloud technology can be utilised for training new examiners and facilitating knowledge transfer (Experts 2 and 3)

5.5 Acceptability and Applicability

All the experts believe that the digital examination approach has the potential to be adopted and embraced by examiners at their organisation. The benefits of point cloud analysis, such as detailed and objective examination comparisons, would provide examiners with better information to make informed decisions (Expert 2). Expert 1 points out that the transition to the digital examination approach may require early adopters and some individuals who require assistance, but once the benefits are apparent, examiners would likely embrace it. Both experts 2 and 3 agree that achieving a higher level of automation is key to facilitate adoption, and a roadmap that outlines the path towards increased automation and verification would greatly support the case for digital examination. Expert 1 confirms that the digital examination approach largely meets the current examination requirements except for the hidden flaws, but if it can reliably and accurately identify defects on assets through automated analysis, it significantly improves decision-making to prevent unacceptable deterioration of an asset. Expert 2 added that the ability to automate and verify the results will boost confidence in the accuracy and reliability of the findings, further strengthening the adoption of digital technologies in the examination process. Expert 3 recognizes that there are several steps involved in implementing this approach, but all the experts agree with others that the digital examination approach has the potential to benefit the entire organisation as a whole.

5.6 Summary and Discussion of Focus Group Findings

The focus group discussions with industry experts concluded with a strong endorsement of the digital examination approach for masonry bridges. They collectively agreed that digital methods could significantly enhance bridge inspections by offering greater standardisation and adaptability across various bridge types. The experts identified the digital approach's strength in its flexibility, allowing for effective application to diverse structural forms, and its potential to streamline current practices. Additionally, they acknowledged the necessity for specialised training and defined operational roles as key factors for successful implementation, indicating a readiness to overcome these challenges for the benefits offered by digital inspection tools.

Moreover, the efficacy of digital examinations in providing detailed and objective assessments was a highlight, with experts noting the added benefits of enhanced safety and time efficiency in inspection processes. This method not only aligns with but also enhances current examination standards by facilitating more precise and quicker evaluations, potentially transforming inspection practices. The applicability and acceptability within organisational frameworks were discussed, highlighting a positive outlook towards integrating digital methods into existing inspection protocols. The focus on developing a roadmap to increase automation and digital adoption underscores the broader industry's readiness to embrace these technological advancements, albeit with considerations for overcoming initial implementation hurdles.

In synthesising these insights with the predefined evaluation criteria, it is evident that the digital examination approach offers a tangible alternative to traditional methods, promising improvements in comprehensive assessments, safety, and operational efficiency. The collective expertise presented during the discussions suggests a fertile ground for the integration of digital techniques in bridge inspections, provided that practical challenges are addressed through systematic training, procedural clarity, and ongoing technological enhancements.

6. Conclusion

This study evaluated the effectiveness of digital examination techniques compared to traditional physical inspections across four bridges. The findings show a 46% detection rate of all defects from digital data, highlighting both the challenges encountered in the field and the potential of digital methods for routine inspections. Joint defects and surface spalling were identified with over 85% success rate when repaired and tactile related defects were excluded, outperforming the detection rates for cracks/fractures, loss of sections, and bulging, which fell below 50%. This discrepancy was largely attributed to factors affecting image quality, such as suboptimal viewing angles, low resolution, reflections, and surface textures. Additionally, obstructions like vegetation and data voids also hindered the detection of certain defects.

Corrective actions, including improved data capture techniques and more precise data specifications, are projected to increase the detection rates for joint defects and spalling to 100%, and to over 85% for cracks/fractures. However, challenges in identifying bulging and specific loss of section cases, such as abutment displacement, showed only slight improvements after adjustments. Due to the infrequency of these defects, the statistical significance of these detection rates remains uncertain.

The research found no direct correlation between the severity of defects and the likelihood of their detection, with failures primarily due to data capture issues or physical barriers. It also confirmed that digital methods can fulfil the measurement requirements necessary for inspecting masonry bridges. Despite its advantages, the digital approach has limitations, especially in detecting defects that typically require tactile feedback. This gap suggests the need for further research into innovative technologies that could enhance defect detection. Certain loss of section scenarios, like abutment and spandrel wall displacements, remained elusive within the study's dataset, pointing to the potential of comparing scans from different inspections as a solution. The digital examination strategy demonstrated its utility in bridge inspection processes, providing accurate and detailed data. Feedback from focus group discussions with industry experts affirmed the strategy's operational viability, highlighting its potential for safer, more efficient, and better-informed bridge maintenance and management. These benefits arise from the capability for remote inspections, streamlined processes, and the sophisticated analysis enabled by point cloud data and 360-degree imaging.

The case study underscores the applicability of incorporating digital inspection techniques into the protocols of a leading UK transportation agency. This initiative, integrating point cloud data and 360-degree imaging with conventional defect identification and quantification practices, marks a significant step towards digital transformation in bridge inspection practices. It also opens the door to the application of cutting-edge technologies like Artificial Intelligence and Digital Twins, fostering a move from manual to digital inspections across the industry. Moreover, the study acknowledges the need for more comprehensive datasets to fully assess the range of defects, urging additional research with broader datasets implemented by experienced inspectors for both approaches (traditional and digital). Such comparative studies will further validate digital examination's effectiveness and guide the refinement of these techniques for real-world applications, ultimately leading to a more precise, efficient, and dependable methodology for masonry bridge inspection and facilitating a shift towards digitised asset management.

Data Availability Statement

Some data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. List of items includes:

a) Spreadsheet of defects' list found from the four bridges.
b) Transcripts of the focus group.

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Reference:

Augusthus-Nelson, L. and Swift, G. (2020) ‘Experimental investigation of the residual behaviour of damaged masonry arch structures’, *Structures*, 27(August), pp. 2500–2512. doi:10.1016/j.istruc.2020.08.008.

Breen, R.L. (2006) ‘A Practical Guide to Focus-Group Research’, *Journal of Geography in Higher Education*, 30(3), pp. 463–475. doi:10.1080/03098260600927575.

Brinkmann, S. (2013) *Qualitative Interviewing (Understanding Qualitative Research)*. 1st edn. New York, USA: Oxford University Press.

Chaiyasarn, K. *et al.* (2023) ‘Defect Change Detection in Masonry Structures Using Image-Based 3D Photogrammetry’, *Journal of Architectural Engineering*, 29(3), pp. 1–10. doi:10.1061/JAEIED.AEENG-1446.

Cucuzza, R. *et al.* (2024) ‘Vulnerability assessment and lifecycle analysis of an existing masonry arch bridge’, *Engineering Structures*, 302(November 2023), p. 117422. doi:10.1016/j.engstruct.2023.117422.

Daniel, G.. (no date) *CloudCompare*. Available at: https://cloudcompare.org/ (Accessed: 26 March 2024).

Fellows, R.F. and Liu, A.M.M. (2021) *Research Methods for Construction*. 5th editio. Chichester, West Sussex, UK: Wiley-Blackwell.

Jeong, E., Seo, J. and Wacker, J. (2020) ‘New Bridge Inspection Approach with Joint UAV and DIC System’, in *Structures Congress 2020*. Reston, VA: American Society of Civil Engineers, pp. 349–359. doi:10.1061/9780784482896.033.

Jing, Y., Sheil, B. and Acikgoz, S. (2022) ‘Segmentation of large-scale masonry arch bridge point clouds with a synthetic simulator and the BridgeNet neural network’, *Automation in Construction*, 142(April), p. 104459. doi:10.1016/j.autcon.2022.104459.

Karim, M.M., Dagli, C.H. and Qin, R. (2020) ‘Modeling and Simulation of a Robotic Bridge Inspection System’, *Procedia Computer Science*, 168(2019), pp. 177–185. doi:10.1016/j.procs.2020.02.276.

Kim, H. *et al.* (2021) ‘Automated Damage Localization and Quantification in Concrete Bridges Using Point Cloud-Based Surface-Fitting Strategy’, *Journal of Computing in Civil Engineering*, 35(6), p. 04021028.

doi:10.1061/(ASCE)CP.1943-5487.0000993.

Masciotta, M.G. *et al.* (2023) ‘Integration of Laser Scanning Technologies and 360° Photography for the Digital Documentation and Management of Cultural Heritage Buildings’, *International Journal of Architectural Heritage*, 17(1), pp. 56–75. doi:10.1080/15583058.2022.2069062.

Mirzazade, A. *et al.* (2021) ‘Workflow for Off-Site Bridge Inspection Using Automatic Damage Detection-Case Study of the Pahtajokk Bridge’, *Remote Sensing*, 13(14), p. 2665. doi:10.3390/rs13142665.

Omer, M. *et al.* (2021) ‘Inspection of Concrete Bridge Structures: Case Study Comparing Conventional Techniques with a Virtual Reality Approach’, *Journal of Bridge Engineering*, 26(10), pp. 1–13. doi:10.1061/(asce)be.1943-5592.0001759.

Orbán, Z. (2004) ‘Assessment, reliability and maintenance of masonry arch railway bridges in Europe’, *Proceedings of 4th International Conference on Arch Bridges, Barcelona*, (152–161), pp. 1–10. Available at: https://caminstech.upc.edu/sites/default/files/Assessment, Reliability and Maintenance of Masonry Arch Railway Bridges in Europe.pdf.

Parry, J.D. (2004) *Overseas Road Note 7, Vol 2 - Bridge Inspector’s Handbook*. 2nd edn. Berkshire: Transport and Road Research Laboratory. Available at: https://trl.co.uk/uploads/trl/documents/ORN7 V2.pdf.

Rashidi, M. *et al.* (2020) ‘A decade of modern bridge monitoring using terrestrial laser scanning: Review and future directions’, *Remote Sensing*, 12(22), pp. 1–34. doi:10.3390/rs12223796.

Rau, J.Y. *et al.* (2017) ‘Bridge crack detection using multi-rotary UAV and object-base image analysis’, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(2W6), pp. 311–318. doi:10.5194/isprs-archives-XLII-2-W6-311-2017.

Riveiro, B., DeJong, M.J. and Conde, B. (2016) ‘Automated processing of large point clouds for structural health monitoring of masonry arch bridges’, *Automation in Construction*, 72, pp. 258–268. doi:10.1016/j.autcon.2016.02.009.

Saleem, M.R. *et al.* (2021) ‘Instant bridge visual inspection using an unmanned aerial vehicle by image capturing and geo-tagging system and deep convolutional neural network', *Structural Health Monitoring*, pp. 1760–1777. doi:10.1177/1475921720932384.

Saunders, M.N.K., Lewis, P. and Thornhill, A. (2023) *Research methods for business students*. 9th edn. Harlow, UK: Pearson Education.

Talebi, S. *et al.* (2022) 'The development of a digitally enhanced visual inspection framework for masonry bridges in the UK', *Construction Innovation*, 22(3), pp. 624–646. doi:10.1108/CI-10-2021-0201.

Tremblay, M.C., Hevner, A.R. and Berndt, D.J. (2010) 'Focus Groups for Artifact Refinement and Evaluation in Design Research', *Communications of the Association for Information Systems*, 26. doi:10.17705/1CAIS.02627.

Turksezer, Z.I. *et al.* (2021) 'Development and Implementation of Indicators to Assess Bridge Inspection Practices', *Journal of Construction Engineering and Management*, 147(12), pp. 1–14. doi:10.1061/(ASCE)CO.1943-7862.0002195.

Wells, J. and Lovelace, B. (2021) *Unmanned Aircraft Systems (UAS) – Metro District Bridge Inspection Implementation*. Minnesota. Dept. of Transportation. Office of Policy Analysis, Research & Innovation.

Wiggins, D. (2018) *Masonry Bridges And the Importance of Lime*, *The Building Conservation Directory*. Available at: https://www.buildingconservation.com/articles/masonry-bridges/masonry-bridges.htm (Accessed: 9 September 2022).

Yan, Y. *et al.* (2021) 'Towards automated detection and quantification of concrete cracks using integrated images and lidar data from unmanned aerial vehicles', *Structural Control and Health Monitoring*. doi:10.1002/stc.2757.

Ye, C. *et al.* (2018) 'Mapping deformations and inferring movements of masonry arch bridges using point cloud data', *Engineering Structures*, 173(April), pp. 530–545. doi:10.1016/j.engstruct.2018.06.094.

Yin, R.K. (2018) *Case Study Research and Applications: Design and Methods*. 6th edn. Thousand Oaks, CA, USA: SAGE Publications, Inc.

Zhang, C. *et al*. (2022) ‘Towards fully automated unmanned aerial vehicle-enabled bridge inspection: Where are we at?’, *Construction and Building Materials*, 347(June), p. 128543. doi:10.1016/j.conbuildmat.2022.128543.

Zhao, Y., Seo, H. and Chen, C. (2022) ‘Displacement analysis of point cloud removed ground collapse effect in SMW by CANUPO machine learning algorithm’, *Journal of Civil Structural Health Monitoring*, 12(2), pp. 447–463. doi:10.1007/s13349-022-00555-7.

Tables:

Table 1: Detailed information about the case study bridges.

Bridge	Material	No. of span	Height (m)	Length (m)	Span (m)	Date of physical detailed examination	Date of digital data capture	Number of scans
A	Brick	1	3.68	8.96	4.36	03/12/2019	21/11/2019	7
B	Brick	1	4.30	9.60	3.80	15/05/2019	22/11/2019	7
C	Brick	1	3.24	5.27	6.12	18/08/2016	21/11/2019	5
D	Brick	1	4.17	9.26	3.83	29/06/2020	22/11/2019	7

Table 2: Classification and measurement criteria for masonry bridge defects as provided by the asset owner.

Defect Type	**Description**	**Measurement Requirements**
Bulging	Bulge from construction and post-construction solid sounding bulge.	Area covered by the defect and amount of distortion.
Crack/Fracture	Horizontal, vertical, diagonal crack, transverse/circumferential crack, island crack, and ring separation.	Length of the crack, width of crack opening, and step of the crack.
Joints Defect	Deterioration of mortar pointing and open joints.	Area covered by the defect, width of opening, and depth of opening.
Spalling	Hollow and drummy to hammer, surface damage, chips, scrapes, and surface spalling.	Area covered by the defect, and depth of spalling.
Loss of Section	Loose or wedged brick/blocks (not to full depth), displaced & tilting bricks/blocks,	Area covered by the defect and amount of displacement.

	missing bricks, stone, blocks (to full depth).	

Table 3: Role and position of participants in the focus group

Participants	Position	Department
Expert 1	Principal Examiner	Buildings and Civils
Expert 2	Senior Asset Examiner	Structure and compliance
Expert 3	Project Manager	Research and Development

Table 4: Evaluation criteria for focus group assessment, including criteria, attributes, and corresponding questions.

Criteria	**Attributes**	**Attribute Definitions**	**Corresponding Questions**
Usefulness	Flexibility	Generalizable to different types and sizes of bridge (e.g., single span, viaduct).	In your opinion, how versatile is the digital examination approach when it comes to adapting to various types of railway bridges, such as concrete, viaduct, or metallic bridges?
	Practicality	Ease of the use and simplicity of implementing the digital examination approach for bridge examination.	In terms of the implementation, what do you think that is required for an examiner to implement the digital examination approach for bridges?

	Applicability	Appropriateness of the digital examination approach for the current practice of examination of bridges.	How well do you think the digital examination approach aligns with your organisation's specifications and requirements for masonry bridge examination?
Effectiveness	Efficacy	Ability of the digital examination approach to achieve the intended output (i.e., detailed examination of masonry bridges).	What are your thoughts on the potential benefits of the digital examination approach for improving the examination of masonry bridges, such as providing a more detailed and objective assessment, as well as detecting and measuring defects?
	Efficiency	Whether reasonable resources (i.e., time, cost) are used to achieve the intended output	What do you think are the potential benefits of the digital examination approach with regards to factors like health and safety and the amount of time required to be on-site, among other considerations?
	Acceptability	Ability of the proposed digital examination approach to make users believe in its value to practice.	To what extent do you believe the digital examination approach might be adopted and embraced by engineers at your organisation?

Table 5: Defect count and detection of bridge defects.

Defect type	No of defect recorded in the	No. of defects detected using	No. of defects detected using	No. of defects detected using	No. of defect not detected

	examination report	360-degree image analysis only.	point cloud data analysis only	both 360-degree image and point cloud data analysis	from the digital datasets
Crack/ fracture	56	11	0	1	44
Joints defect	60	1	0	48	11
Spalling	110	1	0	47	62
Bulging	13	0	2	2	9
Loss of Section	23	0	1	4	18
Total	262	13	3	102	144

Figure Caption:

Fig. 1: Overview of the four-step data collection process.

Fig. 2: A screenshot from Asset Visualizer tool with the arrow showing how a defect is marked.

Fig. 3: (a) An example of organising defect information and replication of these in the Asset Visualizer, (b) an example of comparing the outcome of point cloud analysis.

Fig. 4: Defect count in different bridges and detection rate by different defect type.

Fig. 5: Reasons of non-detection for different defect types.

Fig. 6: visible and invisible cracks on 360-degree image

Fig. 7: Visibility of cracks on 360-degree image influenced by light level and contrast of light.

Fig. 8: Visibility of cracks on 360-degree image influenced by image resolution.

Fig. 9: Visibility of cracks on 360-degree image influenced by surface texture.

Fig. 10: Crack detected using point cloud analysis - (a) 360-degree image and (b) result of point cloud analysis.

Fig. 11: Defect on junction of two elements - (a) 360-degree image and (b) result of point cloud analysis.

Fig.12: Arch flattening visible on a 360-degree image.

Fig. 13: Comparison of detection rates in different bridges for each defect type - (a) considering all defects, (b) excluding repaired and tactile examination-related defects , and (c) considering the corrective actions.

Fig. 14: Defect count and detection status at different ranges of severity values - (a) considering all defects, (b) excluding repaired and tactile examination related defects, and (c) considering the corrective actions.

Fig. 15: Measurement of area covered by joint defects.

Fig. 16: Measurement of crack - (a) crack location, (b) length of crack, (c) width of crack.