6th European Conference on Computational Mechanics (ECCM 6)
7th European Conference on Computational Fluid Dynamics (ECFD 7)
11 – 15 June 2018, Glasgow, UK

PERFORMANCE EVALUATION OF BRIDGES USING VIRTUAL REALITY

MUHAMMAD OMER[1], SAM HEWITT[1], MOJGAN HADI MOSLEH[1], LEE MARGETTS[1] AND MUHAMMAD PARWAIZ[2]

[1]University of Manchester
University of Manchester, Manchester, M13 9PL, UK
Corresponding authors: eng.muhammad.omer@gmail.com, lee.margetts@manchester.ac.uk

[2]ABM Engineers Multidimensional Consulting Firm
C-68-D, 11th Commercial Street, Phase-II (Ext.) DHA, Karachi-75500, Pakistan
info@abmengineers.com and www.abmengineers.com

KEY WORDS: Visual Inspection, Bridge Inspection, Performance Evaluation, Bridge Performance, Structural Rehabilitation, Inspection Techniques, Virtual Reality

Abstract. There are approximately over 2.5 million bridges throughout the world, built to withstand massive forces and last for decades or centuries but very unlikely to last forever. According to a recent survey, there are more than 64,000 bridges in the US that have been declared as structurally deficient. Moreover, recent bridge collapse incidents in Italy, South Africa, United States and India have resulted in unplanned bridge closures affecting the economy of a state, traffic congestion, negative impact on day to day activities and in some extreme cases led to loss of life due to complete structural collapse. Therefore, law making agencies are pushed into paying greater attention to structural rehabilitation. Performance evaluation of bridges includes visual inspection, destructive and non-destructive testing. It is been stated that “Regardless of the fact that many structure testing methods have so far been developed, visual inspection is likely to remain the most significant aid for bridge condition assessment, especially for smaller typical structures”. Results from inspection serve as a foundation for engineers to suggest if further testing (destructive or non-destructive) is required. However, precision and accuracy greatly vary with qualification, motivation and equipment of persons conducting these inspections. This paper emphasizes the use of modern day technology by presenting a workflow of bridge inspection namely, visual inspection to address limitations and difficulties faced by engineers in assessing performance of bridges. It involves the use of lidar to capture, on-site, an image of the structure with all its imperfections such as cracks, corrosion, spalling, signs of corrosion, seepage marks, weathering, segregat-ion, honeycombing etc. The processed image is displayed in an immersive 3D virtual reality environment for assessment. Visual inspection through virtual reality (VR) promises to be a highly efficient and highly powerful inspection technique. Evaluation will become more reliable and accurate which will make engineers capable of effectively deciding the next step of rehabilitation. This technique is critically analyzed, interpreted and compared with traditional inspection methods to highlight the potentially improved efficiency of the proposed workflow. It is intended that the research findings will greatly contribute to the industrial development by raising standards and efficiency of bridge performance evaluation.

1 INTRODUCTION

Nowadays with current knowledge and technology, bridges can be built up to a span length of 2000 meters; made of concrete, steel, timber and different composites. They are built to withstand massive forces and last for decades or centuries, but will very unlikely last forever. Through-out history bridges have succumbed to deterioration causing many injuries or in some cases took with them many human lives. Over the last two decades, government authorities and society in general have been concerned about deficiencies in bridges as a consequence of aging and bridge collapses caused by natural disasters. In the United States, more than 70% of the bridges were built before 1935 [1], while in the United Kingdom the majority of bridges were constructed between the 1950s and 1960s [2]. Approximately 70% of bridges in New South Wales, Australia were built before 1985. Therefore, the focus of building authorities has moved from developing new structures to the rehabilitation of existing infrastructure [3]. Since 1968, the beginning of the United States federal bridge inspection program, visual inspection has been the primary technique for assessing serviceability and performace of the strucutres [4]. To efficiently maintain these structures and predict its remaining serviceable life, systematic periodic visual inspections are required [5]. However, the accuracy and reliability to find a remediation solution or allocate funds for repair and maintenance of a structure is highly questionable with current visual inspection techniques. Therefore, more advanced automated procedures are required to improve overall standards of inspection – the motivation of this current research.

2 BRIDGE INSPECTION TECHNIQUES

For Bridge Inspection Management (BMS), inspection of bridges is a key element especially for old and weary bridges. It is a pathway to the performance rating of a bridge. Historically, inspection of existing bridges was not considered as a priority and was conducted in a semi-random nature. They were only carried out as a result of an obvious incompetency of the bridge or as a consequence of warnings received from sources mainly outside the bridge network system [6].

Different types of bridge inspections may be required during the lifetime of a bridge. They mainly differ in frequency, duration and accuracy. Each inspection involves either destructive, non-destructive or both types of testing. Figure 1 shows different types of inspections performed on a bridge and elaborated in the following text.

Figure 1: Different types of inspection technique based on the Eurocodes

2.1 Initial (inventory) inspection

When a newly constructed or an existing structure is first entered into the database, initial inspections is performed. Its aim is to provide ground for all future inspections to be carried out. Initial defects occurring immediately after construction and changes in site conditions such as erosion, scour and regrading of slopes are noted [7].

2.2 Routine inspection

This inspection technique focuses on the bridge's most exposed areas by direct visual observation by the bridge inspector. Subjective evaluations are made. During an inspection, no significant structural defect is expected to be found and the work recommended falls within the range of regular maintenance. A period of fifteen months between routine inspections is recommended so that the influence of the weather on the general condition and degradation of the bridge can be clearly assessed [7].

2.3 Detailed inspection

In addition to detailed visual observation, non-destructive in situ tests are performed. This type of inspection is performed every five years and may replace routine inspection if dates coincide [7]. Based on the output of the inspection, one or more of the following actions are undertaken: arrangements for further structural assessment such as additional surveillance measurements; identification of specific aspects to check in the next inspection; planning the maintenance work needed and the definition of a maintenance plan for the medium term [6].

2.4 Structural assessment

A structural assessment is usually performed if a major structural or functional flaw is detected during routine or detailed inspection. It is also conducted in case of necessary bridge expansion or structural rehabilitation. In-situ destructive tests, static and dynamic load tests and laboratory tests are conducted. Care must be taken before performing these tests as apart from being expensive they cause traffic interuptions for a certain period of time [7]. A structural health index is determined which serves as a basis to suggest retrofitting measures required.

2.5 Special inspection

These inspections are accompanied by both detailed structural analysis and testing. They are implemented on the occurrence of conditions such as natural disasters or on the application of sudden intense loading.

Hence, the type of inspection required depends on the condition of the bridge. However, visual inspection remains a key element of each type of inspection. This paper mainly focuses on the use of virtual reality to address the limitations and difficulties faced by engineers in visually inspecting bridges. However, the industrial application of this concept is yet to be recognised, which is the key of motivation of the present study.

3 CONVENTIONAL PROCEDURE AND TOOLS REQUIRED TO CONDUCT VISUAL INSPECTION

Primarily, the aim of visual inspection is to observe and record areas of stress concentration using rough sketches, photographic evidence and drawings. The general procedure adopted before conducting an inspection is to study all relevant structural drawings available, any past inspections records or repair work on the bridge. While conducting an inspection, the use of structure when it was first constructed and now must be recorded. The condition of expansion joints, parapet walls, wing walls, drainage channels and bridge bearings must be evaluated. Any disparity in actual drawings and the structure constructed should be highlighted. Signs of concrete deterioration such as segregation, bleeding at the joints, honeycombing, spalling and crack patterns must be pointed out. Any surrounding soil settlements, excessive deflections in structural components, effects of freezing and thawing and other environmental conditions must be taken into consideration. After collection of all the data, all the information must be categorized and checked against National standards to determine the severity index of attention [8]. Figure 2 demonstrates equipment required to carry out visual inspection which is also elaborated in the following text.

Figure 2: Typical inspection equipment required to conduct visual inspection

To carry out visual inspection engineers must also have the right tools and a log book to keep records of observation. Accessories required include rulers and measuring tapes to measure the geometric dimensions of different components; markers to highlight important components; different types of binoculars and telescopes to access areas of difficulty; a crack width microscope to identify cracks and measure their length, width and penetration and a high-quality camera to collect photographs as evidence [8].

4 DRAWBACKS OF TRADITIONAL VISUAL INSPECTION TECHNIQUES

"Visual inspection is the default bridge inspection methodology; however, there are some limitations that might affect the efficiency of decision-making and resource utilization" [9]. In the FHWA report [8] these shortcomings are highlighted as being subjective in nature. The main contents of the report are summarized as follows:

- Timing: The static nature of inspection limits the continuous monitoring of structural deterioration. Hence, the understanding of structural behavior and the agility of response to undertake required precautionary measures is highly affected. A good practice would be to continuously monitor structural defects such as crack propagation rather than making an observation in a single point of time. Therefore, it is essential to efficiently estimate frequency of visual inspection based on structural deficiencies as a result of loading and environmental conditions [10].

- Interpretability: The fact that visual inspection is qualitative in nature and is based on an inspector's own judgment can lead to inappropriate and inadequate assessment of bridge performance. Moreover, inconsistency in inspector training methods employed and variations in inspection guidelines set by different organizations can also sum up to the subjectivity of assessment [10].

- Accessibility: The most important aspect of inspection is to assess the condition of connections and the intensity of distresses in critical areas of the bridge. These areas are often inaccessible or in some worst cases not even visible through a clear line of sight leading to incomplete or inaccurate evaluation. Also the internal defects or surface irregularities, if any, cannot be identified. Thus, accessibility becomes a major concern when conducting visual inspection [10].

"To date, the UK has no formal inspector training" [11]. No aptitude tests are carried out to check if inspectors suffer from fear of height, colour blindness, or debility of sight [9]. To address this, the UK Bridges Board has developed a Bridge Inspector Competence Scheme, which is a mandatory inspector qualification [12]. In contrast, Finland has a more rigorous scheme. Bridge inspectors are tested annually in a one-day session that includes two example inspections, a discussion of inspection results, and a written test that must be passed [11]. In the USA, to assure quality, three inspectors examine an identical bridge independently. Results are reviewed and checked for consistency. If results differ substantially, inspectors can lose their certification [13].

5 Methodology of Proposed Workflow using Virtual Reality

Inspections are performed to validate structures for safety, serviceability and to provide information related to future structural management. Considering all the drawbacks of current inspection techniques, a new workflow of visual inspection is proposed for performance evaluation of bridges using virtual reality; a 3D digital inspection environment. The general inspecting procedure is the same for all types of bridges. However, defects incurred in different bridges during their serviceable life may vary from one another. This paper uses visual inspection of masonry bridges as an example shown in figure 3. The entire bridge inspection workflow can be divided into three main categories namely, Pre-Inspection, During Inspection and Post Inspection.

Figure 3: Masonry Arch Bridge under Study

5.1 Pre- inspection

Before conducting an inspection, it is important to consider certain parameters to ensure an effective inspection plan.

5.1.1 Scheduling an inspection

Inspections must be scheduled to make the most efficient use of the resources and to minimize disturbance to the public. Factors such as availability of resources, traffic management, structures near or on railways or watercourses, weather conditions, environmental issues should be considered before conducting an inspection [14].

5.1.2 Preparation of method statement

During pre-inspection a method statement is to be prepared that summarizes all the relevant information and is agreed upon by the authorities concerned. Details of activities to be performed during the inspection are to be noted. Traffic management details and safety procedures for handling hazards, resources and staff carrying out the inspection are arranged. Additionally, planned working times, temporary works to be provided, protection from highway, railway or other traffic and any environmental impacts of the work are also taken into consideration [14].

5.1.3 Equipment required

The inspection technique proposed in this paper introduces 3D surface scanning equipment namely, Lidar, to scan the bridge and capture all its defects. A Lidar has been described as “a remote sensing technology which uses the pulse from a laser to collect measurements which can then be used to create 3D models and maps of objects" (3D Laser Mapping, 2008). Lidar captures a point cloud and corresponding photographic images by rotating 360 degrees both vertically and horizontally about its mean position. In masonry bridges, cracks less than 1 mm do not affect assessed structural capacity. Therefore, to capture critical cracks (greater than 1 mm), a Lidar with spatial resolution of at least 1 mm and high sensitivity is recommended. In this study, due to the limitations of currently available technology a spatial resolution of 2 mm with high sensitivity is used. Moreover, a tripod-stand to place and level the Lidar at a specified location is also required. A laptop or desktop computer is needed to process the data captured using the Lidar. This will preferably use the Windows operating system. The software used includes Cyclone 360 (for processing the Lidar point cloud data), MATLAB (for automatic defect detection from the captured point cloud and images), Blender (for building a virtual environment), a CAD Package, SDK manager (to manage and export apps to android devices) and Unity (a computer game authoring package used for building virtual reality applications). Finally, to present the data and inspect bridges, the proposed technique also requires an android smart phone device with sufficient computational power and a virtual reality headset with a remote control. Here we use the Samsung Galaxy S6 and Samsung Gear VR Oculus headset. Figure 4 shows the main hardware required to carry out visual inspection.

Figure 4: Lidar with a Tripod Stand, Samsung Galaxy S6 and Samsung Gear VR headset with Remote Controller

5.2 During inspection

Upon arrival on site, a careful check should be carried out to confirm the identity of the structure. Elements such as bearings and movement joints are correctly identified and the orientation of the drawings and the structure are clearly understood by the inspection team [14]. It must also be ensured that all necessary traffic measures are in place before commencing the inspection. Once all precautionary measures are confirmed, the Lidar is attached to the tripod stand and leveled on the specified location of interest. The height of the Lidar is measured and its position on the ground is recorded. The angle of scan is set between 0 - 360 degrees and the desired scan resolution and sensitivity is specified. It must be noted that high resolution and high sensitivity would yield accurate results but require larger computational power to process. To reduce time and excess data capture, the scan angle can be set to 0 – 180 degrees if the structure scanned is straight and not curved along its length. A point cloud and its corresponding image must be selected as the output options from the scanning. The point cloud is used to build the 3D-environment in the post-processing stage. For a masonry bridge, arch ring separation, loss of mortar, bulging and deformation, loss of bricks or stones, areas of cracking, seepage of water and deterioration of the bricks or stones are of special interest. To fully capture these defects in detail, the Lidar is placed at different locations and these elements are scanned.

5.3 Post- inspection

In the proposed workflow, most important stage is the post- processing stage. Once all the data has been captured and stored in a pen drive, the data is analyzed. Initially, the point cloud is saved in the proprietary *.bin* format and resulting images are captured in *.jpg* format which are processed using the Cyclone 360 software. General settings such as units and number of decimal places, link settings to customize the error threshold and cloud-to-cloud settings are set based on the accuracy of the point cloud captured. Using the height of the Lidar and its recorded location on the ground as reference points, the point cloud is superimposed with photographic images and surfaces are created as shown in figure 5. These surfaces are then

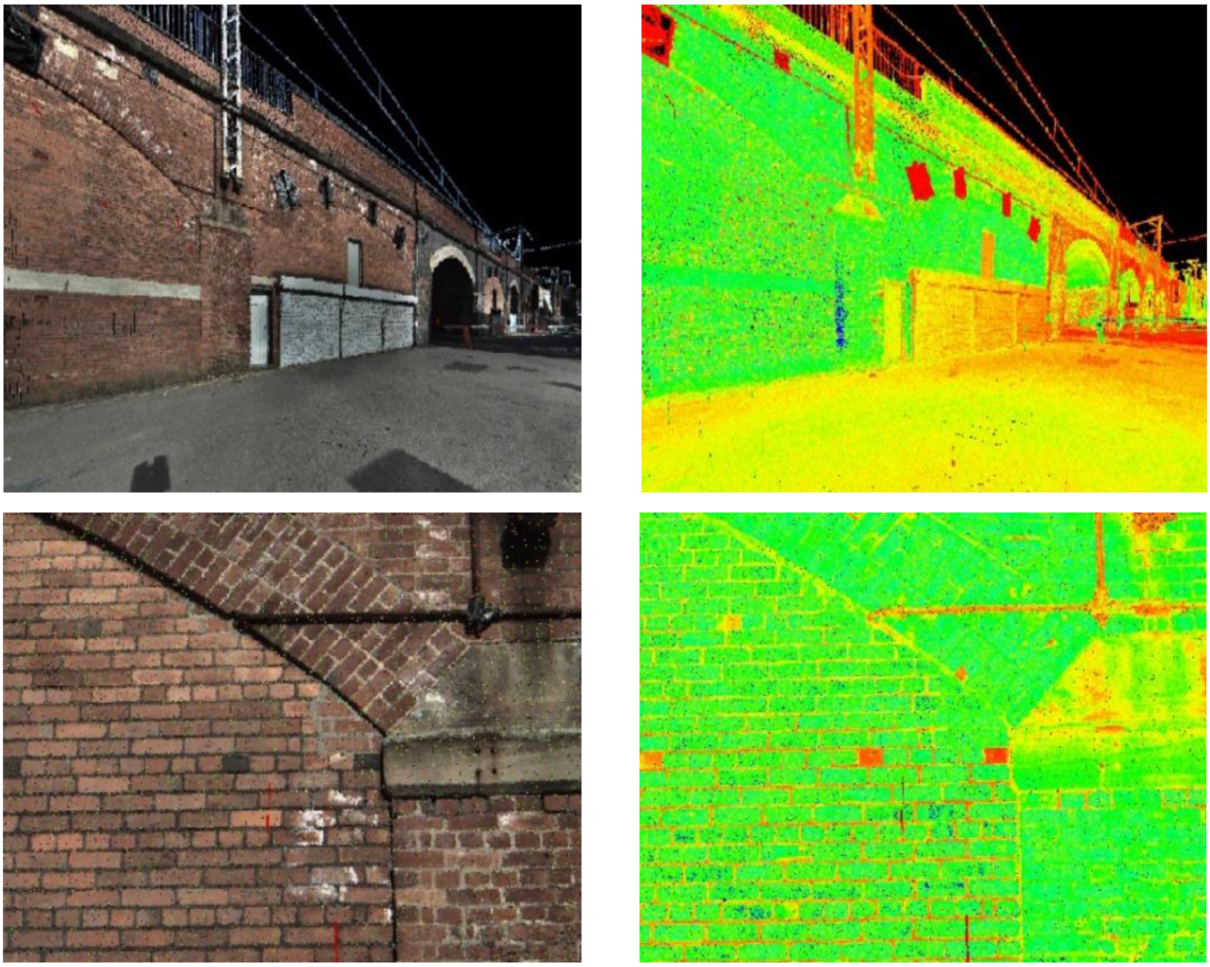

Figure 5: Point cloud superimposed on its corresponding images using Cyclone 360

exported to MATLAB to automatically detect bridge defects. Scripts are written to process the images. The locations of cracks and seepage marks are identified. Seepage severity, crack depth, crack length and crack width is calculated to perform element condition rating at a later stage. Processed MATLAB images are exported in the *.obj* file format to develop the 3D environment which includes the bridge and its surrounding areas, using the CAD package and blender software package. By applying various material properties and using rendering options a real world is depicted in the virtual environment. Additionally, supporting human characters as inspection crew are created, to provide a fully immersive 3D virtual environment inspection experience. This environment is then exported in the *.fbx* file format for further processing in the Unity software package. Navigational options in the VR environment, for example zooming features and teleporting are included. To measure on-site cracks and mark areas of special interest tools such as a measuring scale and colored highlighters are added. Audio scripts to describe the history of the bridge and any record of the previous inspection conducted are scripted using the Unity software. Finally, the entire package with all its features is ported to the Samsung Gear VR headset by applying appropriate export settings in Unity. A Samsung application in *.apk* file format is built and installed on a smart phone. To ensure its compatibility with the android operating system, the application is registered and licensed with the Oculus Store (an official Samsung mobile platform to transform Galaxy smart phone into a portable VR device.)

The bridge is then inspected in the Samsung Gear VR headset by multiple professional bridge inspectors. Results and conclusions from the inspection are drawn and evaluated using the element condition rating system as defined in the CSS Guidance Documents. These results are then reported to the authorities concerned for further action. Figure 6 summarizes and provides a pictorial representation of proposed workflow.

6 CRITICAL ANALYSIS OF PROPOSED WORKFLOW

Overall, bridge inspection using state of art Samsung Gear VR proves to be an efficient way of inspection as compared to traditional inspection methods. A Critical comparison between the proposed workflow and conventional visual inspection is summarized in table 1.

From the critical analysis of bridge assessment techniques, use of virtual reality unlocks new possibilities and highly raises standards of bridge evaluation. Instead of offices going to the bridges, bridges are coming to the office. Inspection is becoming more accurate and highly reliable in deciding the next step of rehabilitation. However, there are also some drawbacks associated with technology used in this inspection technique. It requires large computational power but as technology advances it becomes more and more powerful and readily available.

Figure 6: Pictorial representation of proposed workflow

Table 1: Critical comparison of visual inspection using virtual reality and conventional approach

Criteria	Visual Inspection Using Virtual Reality	Conventional Visual Inspection Approach
Effectives in term of rehabilitation	Highly Effective	Highly Effective
Practicality	Highly Practical	Highly Practical
Implementation in real-world	Industrial application is yet to be recognized	It's a defacto method of bridge inspection
Time Consumption	Less time consuming.	Depends on level of inspection
Cost Effectiveness	Neither expensive nor cheap	Depends on complexity of visual inspection
Accessibility to Critical Areas	All areas are accessible	Critical areas not accessible
Consistency in Interpretability of findings	Highly consistent as multiple inspectors can perform inspection at the same time	Highly dependent on inspector qualification

7 FUTURE WORK

For any assessment technique, opportunities for improvement always remain open. The resolution and sensitivity of the Lidar used can be improved to capture detailed and precise information. A drone based Lidar rather than tripod based, can be used to capture all faces of a structure with ease. Currently, the entire post-processing step is done manually, which can be automated by writing scripts. The proposed workflow can be applied to different bridges to evaluate its efficiency as an inspection technique.

8 REFERENCES

[1] Golabi, Thompson, Hyman. "A network optimization system for bridge improvements and maintenance", Technical manual, Publication number FHWA-SA_94-031: US Department of Transportation, Federal Highway Administration, (1993).

[2] Flaig, K.D. and Lark, R.J. "The development of UK bridge management systems", Proc. lnstn Civ. Engrs Transp., Vol. 141, (2000).

[3] Ariyaratne et., al, "Development of a model for assessment of future condition of bridges" University of Technology Sydney, Centre for built infrastructure research, (2009).

[4] Robert R., "Traditional Inspection Techniques: The Foundation of Structural Health Monitoring", McCormick School of Engineering and Applied Science, Northwestern University (2007).

[5] Emoto. H, A. Miyamoto. “Proposed verification of bridge evaluation system based on concrete core examination”, Proc. of the JCI 34 (2) (2012).

[6] Branco F.A, and Brito. J. “Handbook of Concrete Bridge Management”, ASCE Press, (2004).

[7] Andrey, D. “Bridge Maintenance: Surveillance Methodology” (in French), PhD Thesis, Lausanne, Switzerland, (1987).

[8] FHWA (Federal Highway Administration). “National bridge inspection standards”. 23 cfr part 650, Fed. Regist., (2004).

[9] Moore et al., Phares B., Graybeal B., Rolander D, and Washer G. “Rehabilitation of visual inspection for highway bridges”, Vol. I, (2001).

[10] Agdas D, Rice J, Martinez J, Lasa I. “Comparison of visual inspection and structural-health monitoring as bridge condition assessment methods”, Journal of Performance of Constructed Facilities, Vol. 30, (2016).

[11] Hüthwohl P, Lu R, Brilakis I. “Challenges of bridge maintenance inspection”, Proceedings of the 16th International Conference on Computing in Civil and Building Engineering, At Osaka, Japan, (2011).

[12] The Up and Under Group. “Bridge Inspector Certification Scheme” (NHSS31), (2015).

[13] U.S. Department of Transportation. Bridge Evaluation Quality Assurance in Europe, (2008).

[14] Inspection manual for highway structures, London: TSO, 2007