EVALUATION OF CRACK ON ARCH STRUCTURES USING THE DIGITAL IMAGE CORRELATION TECHNIQUE

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by

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ABSTRAK

Disertasi ini menyajikan penggunaan teknik Digital Image Correlation (DIC) dalam penentuan taburan regangan pada struktur lengkungan konkrit untuk mengesan dan meramalkan keretakan pada permukaan struktur. Kajian ini bertujuan untuk mengembangkan taburan regangan pada lengkungan konkrit dengan menerapkan beban pada struktur. Hasil projek ini diperoleh melalui karya eksperimen. Teknik korelasi gambar digital (DIC) adalah kaedah optik tanpa sentuhan berketepatan tinggi, tidak merosakkan, yang telah banyak digunakan dalam pelbagai bidang untuk mengukur ubah bentuk permukaan. Satu sampel kawalan dilemparkan dan diuji untuk mendapatkan kapasiti tertinggi lengkungan konkrit. Lengkungan gagal sekitar 22 kN muatan pekat pada jarak pertengahan. Tiga sampel eksperimen diuji pada tiga tahap beban, seperti 30% dan 60% dari beban maksimum, dan kemudian, pada tahap pemuatan akhir, sampel diuji hingga gagal. Pemuatan diulang tiga kali pada setiap peringkat pemuatan. Data dari LVDT dibandingkan dengan nilai yang diperoleh dari GOM Correlate, perisian DIC untuk mengesahkan hasil DIC sebelum menjalankan analisis DIC. Dengan data yang lebih tepat yang diperoleh dari DIC, ramalan lokasi dan corak retak dapat dilakukan pada permukaan struktur dan pekerjaan dalam pemantauan kesihatan struktur dapat lebih difokuskan pada penggunaan analisis gambar sehingga dapat mengurangi biaya, risiko, dan batasan untuk individu yang membuat karya. Dari hasil eksperimen, lokasi keretakan pada kegagalan dapat diramalkan dengan tahap ketepatan yang tinggi dengan menganalisis ketegangan pada permukaan spesimen. Taburan regangan pada struktur memberikan penglihatan yang jelas di mana regangan dan tegangan tertinggi terkumpul semasa proses ubah bentuk dan oleh itu ramalan jalan retak dapat dibuat. Hasil kajian juga menunjukkan bahawa ramalan yang dibuat pada 60% beban maksimum adalah lebih tepat daripada ramalan yang dibuat pada 30%.

ABSTRACT

This dissertation presents the usage of the Digital Image Correlation (DIC) technique in the determination of strain distribution on concrete arch structures to detect and predict the cracks on the structural surface. This study aims to develop the strain distribution on the concrete arch by applying a load on the structure. The results of this project are obtained via experimental works. Digital image correlation technique (DIC) is a high-precision, non-destructive, non-contact optical method that has been widely used in various fields for measuring surface deformation. One control sample was cast and tested to get the ultimate capacity of the concrete arch. The arch failed at around 22 kN of concentrated load at the mid-span. Three experimental samples were tested at three load stages, such as 30% and 60% of the maximum load, and then, at the final loading stage, the samples were tested until failure. The loading was repeated three times at every loading stage. Data from LVDT are compared with the values obtained from GOM Correlate, a DIC software to validate the DIC results before carrying out DIC analysis. With more accurate data obtained from DIC, the prediction of crack's location and pattern can be done on the structural surface and the work in structural health monitoring can be more focused on using image analysis so that it can reduce the cost, risk, and limitation to the individual who does the works. From the results of the experiment, the location of the crack at failure can be predicted with a high level of accuracy by analyzing the strain on the specimen surface. The strain distribution on the structure gives a clear vision of where the highest strain and stress are accumulated during the deformation process and hence the prediction of the crack path can be made. The results also showed that the prediction made at 60% of the maximum load is more accurate than the prediction made at 30%.

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DIC	Digital Image Correlation
NDT	Nondestructive testing
OPC	Ordinary Portland Cement
RC	Reinforced Concrete
SHM	Structural Health Monitoring

CHAPTER 1

INTRODUCTION

1.1 Background

Arch bridges are mostly known as structures employing masonry as the load-carrying system. There are also arch bridges using plain concrete, which relies on compressive strength characteristics of the concrete (Ozden Caglayan et al., 2012). Masonry bridges can be divided into three groups depending on the materials used in the construction: brickwork, stone, and plain concrete arch bridges (Yazdani and Azimi, 2020). Many countries use masonry arch bridges to cross river valleys or deep ravines for transportation purposes. However, many existing masonry arch bridges have exceeded their design service life and have some structural issues such as cracking but remain in service due to high construction costs and historical value.

According to previous research, most failures in arch structures are caused by discontinuity in the geometry of structures, such as cracking. As a result, considering the impact of crack presence is one of the primary concerns in analyzing arch structures (Panian and Yazdani, 2020). Cracking can reduce the durability and strength of the arch structure by allowing aggressive substances to penetrate the structure.

The assessment of the behaviour of concrete arch bridges has always been a great concern to both researchers and civil engineers (Panian and Yazdani, 2020). Concrete is a composite material composed of aggregate (fine and coarse), water, and admixture bonded together with cement that hardens over time. Concrete cracks easily when exposed to harsh environmental and loading conditions. Besides that, these cracks may develop into critical ones, causing severe structural damage to the structure. As a result, crack monitoring of concrete structures, especially arch structures, has become increasingly important (Zhang et al., 2016).

As arch structures age, structural assessment becomes increasingly important to determine their existing load capacity and provide recommendations for corrective treatments. The structural assessment of masonry arch bridges is based mainly on visual observation. However, several non-destructive techniques (NDT) can monitor their condition and performance (McCann and Forde, 2001).

While most techniques require direct access to the structure, which can be challenging in some locations, optical measurement techniques such as Digital Image Correlation (DIC) have become popular for measuring displacement and strain on the surface of the structure and detecting the cracks on the surface (Hasheminejad et al., 2018). DIC is a non-contact and non-destructive optical technique for measuring surface displacements and strain of an object subjected to loading (Fayyad and Lees, 2014). An image of the targeted area will be divided into many small subareas, and by comparing the small subareas and tracking their new locations after loading, we can obtain the full-field displacement of the area (McCormick and Lord, 2012). DIC is commonly used for varieties of structures, but its use for masonry arch structures is currently limited.

The deterioration of concrete is a gradual process that includes crack formation and propagation, aggregation, and unstable extension. Due to the nonlinear properties of concrete, concrete cracking is random and hard to predict. However, by using the DIC technique, we can evaluate and model the crack propagation by measuring the surface displacement and strains of the arch structure. DIC can also be used to evaluate the strain map of the surface of the arch structure and predict the location of crack initiation.

Growing concerns over the structural performance of increasingly ageing structures such as existing masonry arch bridges have prompted the development of condition assessment methods for existing structures. Current inspection technologies are typically based on traditional tools such as strain gauges and accelerometers. They need to be installed on the structure, which is time-consuming and costly. By using Digital Image Correlation (DIC) technique, inspectors can easily measure displacements and strains on large structures such as arch bridges with high accuracy to monitor and evaluate their structural condition.

1.2 Problem Statement

The masonry bridges are a major asset of transportation networks in Europe and the US (Fanning et al., 2001). While new materials like steel or reinforced concrete are becoming more and more common in bridge construction, masonry arch bridges still play a significant role in global infrastructure. For example, masonry bridges make up over 40% of all bridges in Europe. In 2013, there were around 1700 masonry bridges in the United States, as per the National Bridge Inventory (NBI). Like most bridges over 100 years, they may experience serious deterioration, lack of maintenance, and high traffic volume through the years (Pulatsu et al., 2019).

The nonhomogeneity of concrete in masonry arch bridges leads to randomness in the development and extension of cracks. Crack formation and development in concrete structures is one of the causes for the collapse of buildings (Rombach and Faron, 2019). Therefore, a method to study and model the crack development in concrete arch structures is essential to detect fracture failure at an early stage.

However, conventional methods such as strain gauges, crack gauges, and displacement metres, are commonly used in monitoring and analyzing crack behaviour in concrete. These methods are unable to provide full-filed measurements and physical contact is needed between the specimen and the equipment. These devices only provide the measurements on where they are installed, causing significantly fewer data to be analyzed. Using these conventional techniques on large scale structures such as arch bridges also significantly increases the cost as a large number of devices is required. The accuracy of the results will also be affected if the fracture happens away from where the devices are installed on the structure since no data can be measured.

1.3 Objectives

The objectives of this study are:

- To evaluate the crack behaviour of arch structures subjected to different loading conditions.
- To predict and model the crack development and growth of arch structures subjected to different loading conditions.

1.4 Scope of Study

The investigation of this study includes testing four concrete arch samples with grade 30 concrete under a concentrated load at the midspan. DIC will be used to capture and monitor the deformation around the critical shear cracks. Full-field displacements of the specimen surface will also be captured by using the DIC technique to evaluate the crack behaviour of the arches. Different stages involved in DIC analysis are (i) pre-processing such as preparation of specimens and image capturing, (ii) image analysis using GOM Correlate, and (iii) post-processing (extracting analysed images from GOM Correlate).

1.5 Layout of Thesis

In this dissertation, all the contents are divided into five chapters: introduction, literature review, methodology, results and discussions, and conclusions and future recommendations. In chapter 1, the background of the study, problem statements, objectives of the study, and scope of work were discussed and presented above. Chapter 2, which is the literature review, summarizes the findings of previous studies related to the topic of this project.

Furthermore, chapter 3 consists of the methodology of the project which describes the procedures and detailed steps used to achieve the objectives of this research. In chapter 4, the results and findings of the research were analyzed and discussed. Finally, chapter 5 concludes the project and provides several recommendations for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter aims to review the recent literature to understand the objectives of this study better. Structural health monitoring (SHM) determines the current condition of a structure by assessing the structural performance and service lifetime. The Digital Image Correlation (DIC) is an innovative, simple to use, cost-effective, and non-contact optical method for measuring strain and displacement. The basic principle of DIC, two-dimensional digital image correlation (2D DIC), and three-dimensional digital image correlation (3D DIC) technique is discussed in the section.

2.2 Structural Health Monitoring (SHM)

The number of large-scale and complex buildings is increasing considerably due to the continuous development of global civil engineering and related technology. Those existing structures are subjected to degradation over time, resulting in a situation where they no longer serve the function for which they were constructed (Gopinath and Ramadoss, 2020). The buildings are facing plenty of problems, including huge scale, complicated structure form, and environment. If these buildings fail, huge economic losses and deaths will be caused. As a result, in order to predict, diagnose and repair building defects before failure occurs, structural health monitoring (SHM) systems using a large number of advanced sensors have become an essential technology for evaluating the health of buildings. The SHM system primarily depends on the actual measurement information processing of the environment, load, and reaction to provide humans with early warning of major accidents and structural safety. While the effectiveness and safety of the SHM system are entirely dependent on a large number of advanced sensors, the traditional sensor detection technology completely relies on manual selfinspection, which has severe drawbacks such as high cost and time consuming (Yan et al., 2020).

The safety of a structure is assessed through SHM, which involves installing sensor networks in the structure and measuring certain reactions. Strain is measured using strain sensors such as electrical resistance strain gauges (ESGs) and fibre optic grating sensors (FBGs), which are then used to determine stresses and identify damages. Structural health monitoring technology is already being used in several high-rise structures, with strain sensor networks installed in critical structural elements, including columns and shear walls (Xia et al., 2014). However, strain sensor systems face issues such as data storage due to a large amount of measured data, sensors error, instability of the power supply, and difficulties in the maintenance and management of the systems. Furthermore, for long-term monitoring in large-scaled buildings, strains cannot be monitored due to temporary or permanent faults of numerous sensors. Therefore, an SHM system should be developed to account for errors caused by sensors, sensor break down, and loss of data during the long-term monitoring of a high-rise building (Oh et al., 2017).

SHM is referred to the process of implementing a damage identification plan for civil engineering infrastructure. This damage identification can be divided into four levels: predicting the presence of damage in structures, determining the geometric position of the damage, calculating the degree of the damage, and estimating the structure's remaining service life. However, it is critical to assess the damage as soon as the structure receives the initial signal to take the necessary procedures to ensure the structure's safety. As a result, it is important to keep detailed records of changes in critical members' stiffness and other mechanical properties. It is because damage above a particular threshold causes a safety threat, leading to a reduction in the use or even abandonment of the structure. An SHM system should have the ability to detect and interpret negative changes in a structure to increase reliability and lower life-cycle costs. Knowing what changes to look for and identifying them is the most challenging part of developing an SHM system. Visual inspection, surface hardness, penetration technique, rebound hammer test, acoustic emission test, and other methods are being used for SHM (Sharma and Mehta, 2016).

2.3 Digital Image Correlation (DIC)

Digital image correlation technique (DIC) is a high-precision, non-destructive, non-contact optical method that has been widely used in various fields for measuring surface deformation (Zhou et al., 2021). Displacements of the specimen surfaces can be measured by comparing the speckle images captured before and after deformation. DIC has many advantages, such as simplicity and flexibility, compared to conventional optical methods (Liang et al., 2021).

The calculation methods and the real-world applications of DIC have been studied and improved considerably in recent years. The calculation accuracy is influenced by many factors, such as the correlation criteria and the quality of the speckle images (Liang et al., 2015). However, the testing is mostly conducted in the laboratory, and the camera is fixed perpendicular to the specimen surface during the deformation, limiting the application of DIC outside of the laboratory (Crammond et al., 2013). As a non-interferometric optical method, DIC has many deformation and shape measurement applications in various areas, including measuring deformation and displacement of high-temperature objects (Lyons et al., 1996). Compared to other optical methods for measuring deformation, the DIC method seems to be more appealing because of the following advantages: simple experimental setup and specimen preparation; full-field measurement with adjustable spatial resolution; and suitable for both field and laboratory and measurements (Pan et al., 2010).

The application of DIC for displacement and strain analyses in two-dimensional and three-dimensional surfaces is becoming more and more important in research and industry, especially in the civil engineering field. Moreover, the technique becomes popular due to the improvement of the hardware, such as the computing performance and the quality of the cameras as well as the further development of the evaluation strategies. The basic requirement for the application of the DIC technique is the presence of a randomly distributed greyscale pattern, also known as a speckle pattern, on the surface of the object that is being assessed (Peretzki et al., 2019).

2.3.1 The basic principle of DIC

According to Tong (2005), the DIC technique obtains full-field surface displacements on a specimen surface by matching subsets of images taken before and after deformation using random speckle patterns as shown in Figure 2.1. For DIC to function effectively, the specimen surface must have a random grey intensity distribution as a carrier of deformation information that deforms along with the specimen surface. In general, a natural or white light source is adequate since DIC does not require laser sources, which are usually required by other optical methods (Liang et al., 2015).

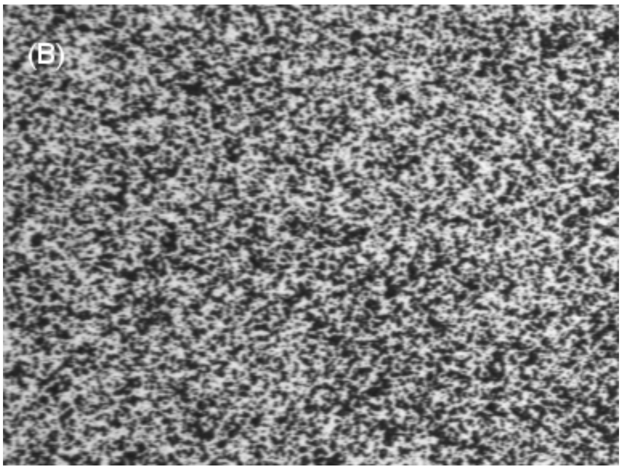

Figure 2:1: Random speckle pattern created using black and white spray paint (Pan et al., 2008)

The evaluation of DIC requires the formation of so-called facets that contain a defined number of pixels with greyscale values. During the loading of an object, the positions of the facets change, and the new positions are recognized. Thus, allowing the shifts of the facets to be determined. The finer the speckle pattern, the smaller the facets can be. Thus, a higher resolution can be achieved. For DIC, the speckle pattern must be very fine to produce a sufficient number of facets in the microscopic range. Typically, the patterns are created by spraying black and white paints using aerosol cans (Peretzki et al., 2019).

According to Hassan (2021), DIC requires a simple setup, as shown in Figure 2.1, that includes light sources which help to capture images of the specimen surface, camera to capture the images, which can be any highly accurate and stable camera with the least amount of image distortion, and computational device to analyse the captured images.

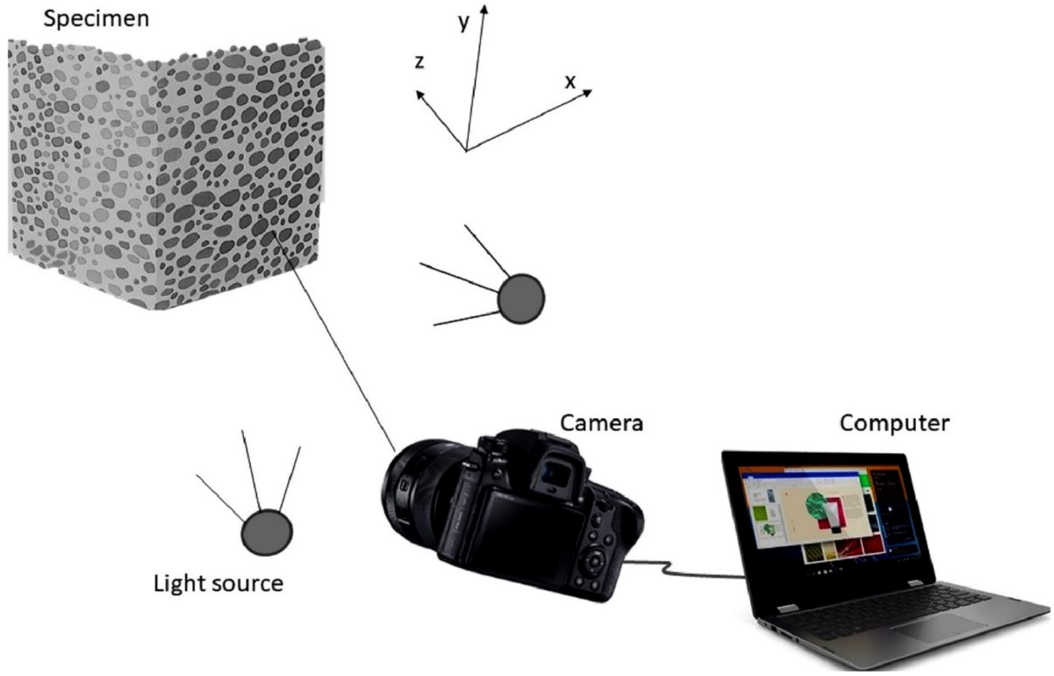

Figure 2:2: The general setup for DIC experiments to measure deformation on the specimen surface (Hassan, 2021).

Certain conditions must be satisfied to achieve accurate measurement results, such as the deformation occurring in the plane of the specimen surface and the optical axis of the camera being perpendicular to the specimen surface (Pan et al., 2010).

2.3.2 Two-dimensional (2D) Digital Image Correlation

Generally, the DIC technique can be divided broadly into two types: two-dimensional DIC (2D DIC) and three-dimensional DIC (3D DIC). The original DIC method is two-dimensional DIC (2D DIC) which tracks speckles in 2D images. It uses only one camera and is only valid for the in-plane deformation. The optical camera axis must be perpendicular to the specimen, and there must be no noticeable out-of-plane motions during the deformation of the specimen for 2D DIC to work (Lv et al., 2018). According to Suttan et al. (2008), the measurement accuracy of 2D DIC is unsatisfactory since the out-of-plane motions have a significant impact on the measured results in real-world experiments.

2.3.3 Three-dimensional (3D) Digital Image Correlation

To overcome the drawbacks of 2D DIC, 3D DIC, which is based on the principle of binocular stereovision, was developed. Using two synchronised cameras, 3D DIC can analyse not only the 3D shape but also the three displacement components of specimen surfaces. In particular, both the in-plane and out-of-plane displacements and deformations can be measured simultaneously. As a result, 3D DIC is commonly considered to be more precise and reliable than 2D DIC. While there are many benefits of using 3D DIC, the problems with computational efficiency and measurement accuracy in 3D DIC are much more severe than in 2D DIC. Since two cameras are employed, the computational amount of 3D DIC is about three times higher than 2D DIC (Gao et al., 2015).

2.4 Concrete Stress-Strain Characterization

Stress-strain diagrams are crucial in determining the behaviour of materials under loading as the diagrams show the elastic, plastic, and rupture part of materials. The stress-strain diagram can be obtained in a few ways, such as the invasive methods using physical tests such as the test-tube in which a little piece of the probe is placed, and a specific load is applied to it. After that, the deformation in displacement is measured. Optical methods are also used as an invasive way to determine residual stress, in-field displacements, and strain. Stress and strain are having a close relationship with each other in almost all case studies. Therefore, the stress-strain curve has been developed in understanding the relationship between them and towards the behaviour of the particular material under loadings such as elasticity, plasticity, and inelasticity (HA et al., 2015).

According to EC 2, the compressive strain for typical classes of concrete grade <C50/60 is given as 0.0035. A reinforced concrete usually fails in flexure with the assistance of reinforcement. Hence, the maximum strain value allowed is 0.0035 in concrete structures, and they will fail when the strain limit reaches the extra tensile strength provided by the reinforcement. For concrete structures without reinforcement, the allowable strain value is between 0.002 and 0.0035, which is smaller due to the lack of reinforcement.

2.5 Cracking Behaviour of Concrete Structures

Concrete is one of the widely used bridge construction materials. It is a quasi-brittle material with a relatively weak tensile strength than its compressive strength. As a result, it is prone to cracking. According to Kim et al. (2019), concrete cracking is often used as the main indicator for evaluating the degree of deterioration in reinforced concrete (RC).

There are two types of cracks in concrete arch bridges: loading cracks and non-loading cracks (Yehia et al., 2007). Non-loading cracks are mostly caused by environmental factors such as variations in moisture and temperature while loading cracks are caused by external loadings such as traffic and earthquakes. The formation of cracks in concrete could result in the corrosion of concrete reinforcements, which negatively affects the mechanical properties of concrete material and eventually reduces the durability of the concrete (Chen et al., 2021).

The presence of pre-existing defects causes cracks when the concrete is exposed to repeated load cycles, leading to the formation of a sizeable crack and, eventually, the final fracture. Concrete is a quasi-brittle composite material with a large size inelastic zone called fracture process zone (FPZ) ahead of the crack tip. Because of the heterogeneous nature of concrete, the formation of FPZ in concrete is extremely complicated. This inelastic zone controls the development of cracks in concrete in addition to the other material and geometrical conditions. This material behaviour has made the prediction of fatigue life and cracks growth rate in concrete difficult (Bhowmik and Ray, 2018).

The cracking process is associated with various phenomena, including crack formation, crack propagation, the presence of micro-cracks, and the concrete microstructure such as aggregate and cement particles (Hilerborg et al., 1976). Furthermore, various factors such as the concrete compressive strength, the bond between the concrete and the reinforcement, and the properties and the size of the concrete can affect the concrete cracking process (Fayyad and Lees, 2017).

A series of researches on the impact of aggregate size has been carried out on the fracture and fatigue behaviour of concrete structures. According to Nallathambi et al. (1984), the size and shape of the aggregates can significantly influence the crack propagation and development in concrete structures. According to their study, increasing the maximum size of the coarse aggregate improves the resistance to crack growth and, thereby, fracture toughness.

2.6 Masonry Arch Bridges

Masonry had been a choice of material in the past for building arch bridges in roads and railways due to its low cost, high durability, and availability of craftsmanship. Masonry arch bridges can be categorised into three types depending on the materials used in the construction: brickwork arch bridges, stone arch bridges, and plain concrete bridges (Yazdani