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MONITORING VERTICAL DISPLACEMENT OF REINFORCED CONCRETE BEAM BY DIGITAL PROCESSING TECHNOLOGY

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Abstract

Structural Health Monitoring (SHM) is a crucial scope of work in civil engineering specifically on monitoring the in-service and ageing coastal bridge deck concrete structure serviceability and limit state status performance. One of the possible natural process that pose detrimental effects to such structure performance monitoring is the steel rebar pitting corrosion problem. Progressive pitting corrosion process on the certain steel rebar area in low quality of concrete cover due to chloride ingression will cause local premature damage the steel rebar which obviously affect the serviceability performance of the structural element, i.e. displacement. However, the available displacement monitoring methods become an issue when it comes to engineering practicality and costs considerations. Therefore, the purpose of this study is to monitor and analyze the vertical displacement of an undamaged and damage reinforced concrete beam using the digital signal processing technology, Digital Image Correlation, (DIC) that use Sony camera and MATLAB scripts, and compared to a traditional method, Linear Variable Displacement Transducer (LVDT) at two points bending tests setup. It was concluded, that the quantified displacement for corrosion-damage RC via DIC method is higher than the normal reinforced concrete beam by 2 to 46 percent of error to LVDT measurements. Based on two tailed paired t-test analysis, DIC method was concluded to be as good as the LVDT method of measuring the beam's displacement. The developed method has the potential implementation on monitoring the any beam deflection on current real civil engineering related projects.

Keywords: rebar corrosion-damaged, Digital Image Correlation, displacement, structural health monitoring.

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Introduction

Complex, large and costly civil engineering coastal infrastructures i.e. bridges and jetty structures are designed to sustain specified loadings and protecting it from extreme coastal environment conditions (i.e. sea water, acid rain, carbonation, moisture and chloride ingression). Commonly constructed from reinforced concrete materials, those structures are used intensively by human beings and simultaneously exposed to the extreme conditions which possibly leads to material deterioration and create safety issues to the public. Coastal reinforced concrete materials have been traditionally designed for a specific design working life for stringent environmental exposure requirements as stated in BS EN 1992-1-1:2004 and BS EN 1992-2:2005. Despite of its stringent exposure requirement on design compliance, the current probability of reliability, safety and durability state of such aging structures will need to be reassessed by the structural engineer as these materials were gradually deteriorated over its service life and influence the structural limit state and serviceability limit state.

One of the most prominent and detectable structural serviceability limit state is the vertical deflection undergone by structural member when the member integrity property is lost and eventually leads to structural failure. There are various causes of this integrity lost in structures. For instance, the possible causes are the rebar corrosion (Michalopoulos and Koutsoukos, 2008), the existence of moisture and chloride (Senin and Hamid, 2016), the ocean acidification (Ragazzola et al., 2012), carbonation and chloride effects (Corina, Liviu, and Geert, 2015), existing void defects (Lavrov, Todorovic and

Torsaeter, 2016) and delamination (Gheitasi and Harris, 2014). However, pitting corrosion in steel and rebar is identified to be the significant deterioration problem in marine and offshore steel structures (Bhandari, 2015) and reinforced concrete structures (Pradhan, 2014). (Steward, 2008) concluded that steel rebar experience reduction in cross sectional areas up to 10 percent after undergone 50 years of pitting corrosion; leading to increased structural deflection.

Therefore, the present paper will investigate and compare the deflection characteristic of corrosion-damage damage and without corrosion damage beam using and sensors and camera. Both methods are very useful on diagnosing the "health" state of aging engineering structures.

Structural Health Monitoring: Integration of Image Processing Technology with Civil Engineering Monitoring works

Introduction

Structural Health Monitoring is a method that provide the means of assessing the effectiveness and continued performance of the rehabilitated structure, including the determination of serviceability, reliability, and remaining functionality of the engineering structures. One of the equally important information is the structural displacement assessment during its design life. This information has been successfully monitored by various available methods such as LVDT, target-based measurements, laser scanning, microwave interferometry and DIC.

A number of research works regarding the successful state of available displacement monitoring methods has been published within 10 years ago. (Ronnholm et al., 2009) stated that contacting sensors such as LVDT are capable of obtaining high accuracy measurements, the necessity that these sensors to be fixed at secure location greatly restricts their use in field applications. (Wilbur, 2011) indicate that target-based approach offers numerous advantages over contact sensors, but need for target affixed to the specimen surface will greatly increases the test set-up time. (Gordon et al., 2004) stated that the laser scanning offers the most dense data acquisition for three dimensional surface, but the cost of the necessary equipment is high due to the emergence technology. (Pieraccini, 2013) mentioned that radar waves at certain frequency used by microwave interferometry method is able to determine the small displacement and need high equipment cost for operation and interpretation. DIC uses a straightforward approach and has been widely used in many research projects. The surface of tested specimens requires little to no surface preparation before the testing and highly adapted on large range of sizes, which has advantages to be used for field engineering works.

Basic Principle of DIC

On measuring the strain and displacement of aging structure, the image processing technology has the potential to be used due to its non-destructive feature on structure, contactless method and low cost. Digital Image Correlation (DIC) is one of the image processing technology commonly used in the electrical engineering field that can be integrated in civil engineering monitoring work on quantifying the structural displacement and strain non-destructively (McCormick and Lord, 2010). In principle, DIC is a non-contact technique for measuring strains which compares a series of grey-scale images of a sample at different stages of deformation. This method tracks the movement of image pixels in the region of interest and thus compute the displacement by the use of numerical correlation algorithm. The method uses a digital camera, a light source and image processing software, MATLAB to capture the digital image of un-deformed (reference) and deformed structures. Prior the image capturing by camera, the sample surface needs to be sprayed or painted with certain random pattern in order to let the camera capture their movement, store and track them.

During the structural bending deformation by , two-dimensional consecutive images are taken by one or more cameras under a source light. It is assumed that the light source intensity distribution does not change during the deformation. Those images are later digitally processed by correlation algorithm using MATLAB. Figure 1 shows the reference (un-deformed) and deformed subset images from a specific region of interest on the sample surface. By referring to movement of point P, two important parameters, the gray level intensity,, and the normalized cross-correlation, , are computed based on reference and the deformed image, which can be expressed as follows,

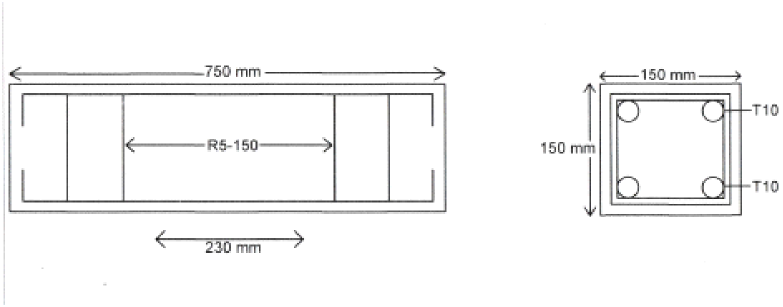

Figure 1. Location of reference point on reference image and deformed image

where P and P represent the gray levels within the subset of the reference and deformed images. and are the coordinates of a point on the subset before and after the deformation, respectively. Thus, the displacement components are computed by searching the best set of coordinates after deformation which minimize or maximize .

Materials and methods

Samples preparation

A total number of six (6) beams specimens of grade C25 were prepared in the Heavy Structure Laboratoty, UiTM Pulau Pinang. All concrete beams were designed in accordance to Eurocode 2 requirements with the size of 150 (width) x 150 (height) x 750 (length) mm. The first three beams specimens were considered as the undamaged beam (Figure 1) and the remaining beams were representing with damaged steel reinforcement (Figure 2). The main reinforcement were installed using 10 mm steel deformed bar diameter and the 5 mm diameter for shear link reinforcements. All beams were cured in normal tapped water inside the curing tank for 28 days to allow hydration process of the cement mix. Table 1 shows the sample mix composition of all beams.

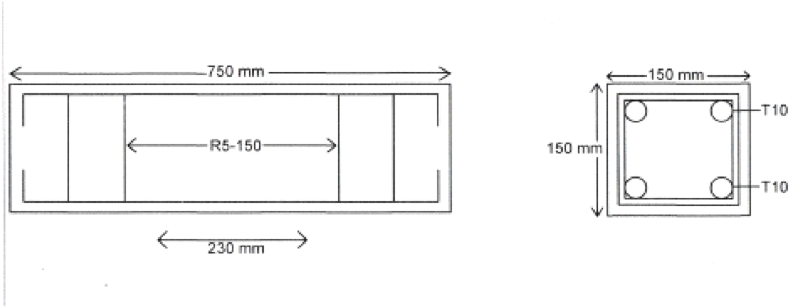

Figure 1. Undamaged beam with continuous bottom reinforcement

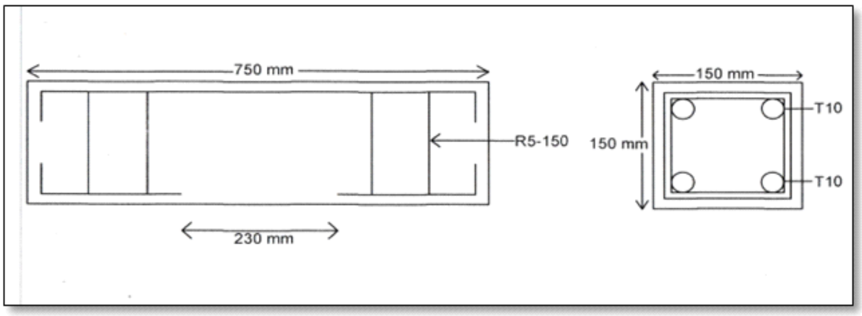

Figure 2. Damaged beam with discontinuous bottom reinforcement to simulate corrosion effect

Table 1. Sample mix composition

Materials	**Mix composition (kgm^{-3})**
Ordinary Portland Cement	453
Coarse aggregate (20 mm)	1070
Fine aggregates	782
Water	206

Cube compression strength test

In order to ensure all beam samples meets the minimum compression strength of 25 MPa, the compression strength of another three (3) cube samples of 150 x 150 x 150 mm were tested using similar mix composition as presented in Table 1. Figure 3 shows the cube and beam mould made of steel used for this study. Compression test machine was used to exert compression force on the cube surfaces until failed due to compression stress. The compression forces was recorded for each sample at 7, 14 and 28 days. The compression strength development of each cubes was monitored and recorded for checking the minimum compression strength compliance.

Figure 3. Steel mould used for the cube and beam samples

Beam's displacement data acquisition experimental setup

Beam surface treatment to locate reference configuration

After 28 days of curing, all beams were taken out from the curing tank and allowed to dry naturally within few hours duration. High density resolution camera is used for displacement monitoring on the beam's surface that was initially painted by white colour (Figure 4a) and random pattern black ink circle (Figure 4b). The use of artificial random pattern on concrete surface has been employed by Santos et al. (2013) as a promising technique to estimate the elasticity modulus of concrete by using image processing method. Adequate contrast of the patterns were established on the concrete surface to increase the degree of image resolution, which can be achieved by using black and white paint (Desai, 2016).

a b

Figure 4a. Painting the selected beam surface 4b. Black ink circles marked on the surface

Digital camera setup and LVDT installation

Before the bending test executed, the beam is supported at both ends by a simply support condition and placed in the right position (Figure 5) on the frame of tensile machine. A camera was used in this experiment where the camera was statically fixed using a tripod. The distance of the camera to the specimen is based on the space for flexural test available in the laboratory and the ability of the camera to be able to capture image for whole specimen.

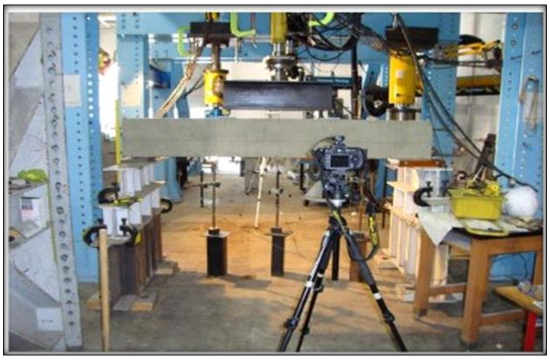

Figure 5. The camera setup and LVDT installation of the work

LVDT sensors were installed to the beams and connected to the data loggers to record the beam's displacement during the bending test.

Two-point bending test and beam displacement monitoring using LVDT sensor and camera

All beams were tested under two-point bending test using the Universal Testing Machine. The compression loading rate was set as 0.06 mm/s for all beam specimens. During the bending test, two point loads were applied on the top of the beam and the beam displacement were measured by LVDT and stored to the data logger. The camera recorded the black circle ink movement of the beam and will be processed by the in-house MATLAB script (Figure 6).

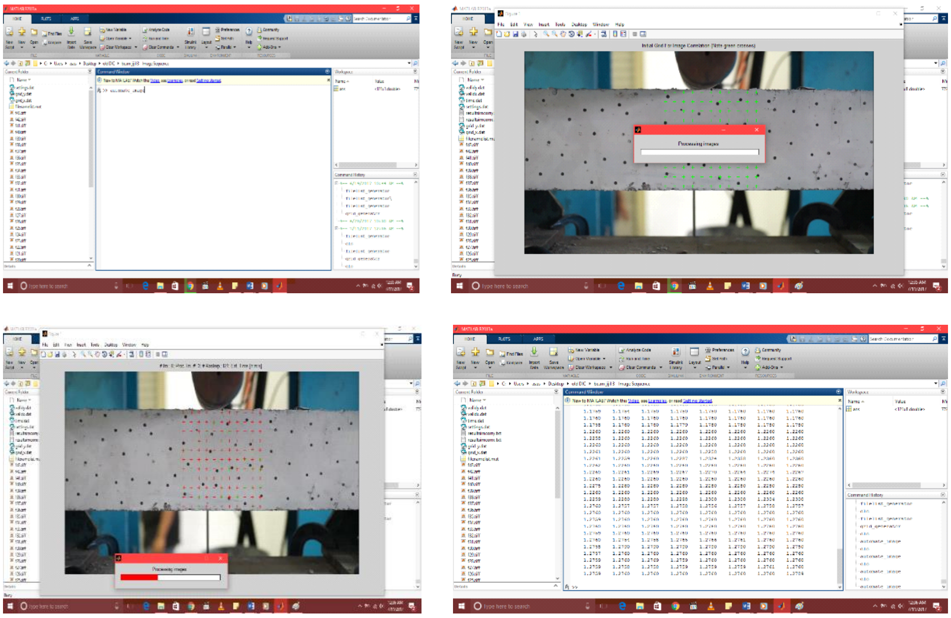

Figure 6a -d. The automated process done by MATLAB script on the captured data by camera

Results and Discussions

Compression stress of the cube samples

The average compression stress development of the concrete cubes at 7, 14 and 28 days of curing time is depicted in Figure 7. The required compression strength of the samples is the recorded average strength at 28 days.

Figure 7. The average compression stress development of cube samples

It is apparently that the average compression stress of cube samples showed increasing trend with the curing duration; inferring that the cement hydration process of the samples had occurred. The proposed mix proportion of the concrete was comply with the minimum compression strength requirement; as the measured compression strength is 46.64 MPa at 28 days. Therefore, the proposed mix composition is deemed satisfactory and is used for the beam samples production.

Vertical displacement of beams

Vertical displacement recorded by DIC method

In this study, the vertical displacement at the middle of the beams was measured and recorded by LVDT and DIC method. LVDT sensors detect the beam displacement and directly convert the electrical changes in sensors to actual displacement, however camera recorded the black circle movement based on image pixels. Therefore, the determination of actual length that corresponds to 1 pixel of recorded images of all beams were computed and shown in Table 2.

Table 2: Image length of 1 pixel (mm) for each type of beam

Type of beam	**Size grid (pixels)**	**Distance between 50 pixels**	**Length of 1 pixel**

		(mm)	**(mm)**
UB1	50	6.5	0.13
UB2	50	6.0	0.12
UB3	50	6.0	0.12
DB1	50	6.0	0.12
DB2	50	6.0	0.12
DB3	50	6.0	0.12

UB = Undamaged Beam DB = Damaged Beam

The actual vertical displacement at mid span of each beams using DIC method is presented in Table 3. The results obviously showed that the mid-span deflection of pre-induced corrosion-damaged beam was 1.1 to 2.2 times higher than those of undamaged beam. (Figure 8). It can be hypothesised that this scenario might attributed by the loss of rebar’s bonding strength with the concrete interface that significantly lowered the beam stiffness property; thus increasing the mid-span beam deflection of the damaged beams.

Statistical analysis on the vertical mid-span displacement of beams monitored by LVDT and DIC method

The mid-span displacement of all beams by both methods were recorded and shown in Table 4. In this preliminary study, due to financial constraint and time, only six beam samples were used to evaluate whether DIC method able to measure the displacement of all beams as good as LVDT method.

Table 3: Measured of Image displacement of beams using DIC method

Type of beam	**Black circle image displacement (pixels)**	**Length of 1 pixel (mm)**	**Actual displacement of the black circle (mm)**
UB1	3.0	0.13	0.390
UB2	5.6	0.12	0.672
UB3	5.9	0.12	0.708
DB1	10.4	0.12	1.248
DB2	11.8	0.12	1.416
DB3	13.9	0.12	1.668

Figure 8. Comparison of beam displacements

Both methods were approximately to be normally distributed in terms of skewness and kurtosis as the shown third and sixth row values of Table 5 were in between -1.96 and 1.96 (Doane and Seward, 2011). In order to test the effectiveness of DIC over LVDT method, two tailed paired t-test was implemented on both methods with 95 percent of confidence interval accompanied by null (H_0) and alternative (H_1) hypothesis as follows;

- H_0 = the mean mid-span displacement values of LVDT and DIC method is similar
- H_1 = the mean mid-span displacement values of LVDT and DIC method is not similar

Table 4: Displacement of beams measured by LVDT and DIC

Beam types	**Displacement value from LVDT (mm)**	**Displacement by DIC method (mm)**
UB1	0.382	0.390
UB2	0.825	0.672
UB3	0.535	0.708
DB1	1.532	1.248
DB2	2.064	1.416
DB3	1.720	1.668

Table 5: Skewness and kurtosis analysis of both methods

Method	**LVDT**	**DIC**
Skewness (1)	0.089	0.084

Skewness Standard Error (2)	0.845	0.845
• / (2)	**0.105**	**0.099**
Kurtosis (3)	-2.198	-1.889
Kurtosis Standard Error (4)	1.741	1.741
• / (4)	**-1.262**	**-1.085**

Table 6 shows the two-tailed significant value of the mid-span displacement mean measurement of LVDT and DIC method from the SPSS output. According to (Winter, 2013), the null hypotheses of similar mid-span displacement mean was accepted ($p > 0.05$). Thus, LVDT method was statistically significant equal to the DIC method of measuring the beam displacements. This findings proved that DIC, which is a relatively cheaper method of monitoring beam displacement, can be adopted by the engineers to perform the similar work done by LVDT method.

Table 6: Two tailed paired t-test on mean displacement of LVDT and DIC method

Parameter		**t**	**df**	**Sig. (2-tailed)**
Pair 1	LVDT - DIC	1.372	5	0.228

Conclusions

The vertical displacement of beam is significantly affected by the damage of the tensile reinforcement. Beam with pre-induced corrosion damaged rebar showed higher vertical displacement by 1.1 to 2.2 times higher than those beam without corrosion damage with DIC method. The quantified displacement for corrosion-damage RC via DIC method is higher than the normal reinforced concrete beam by 2 to 46 percent of error to LVDT measurements.

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