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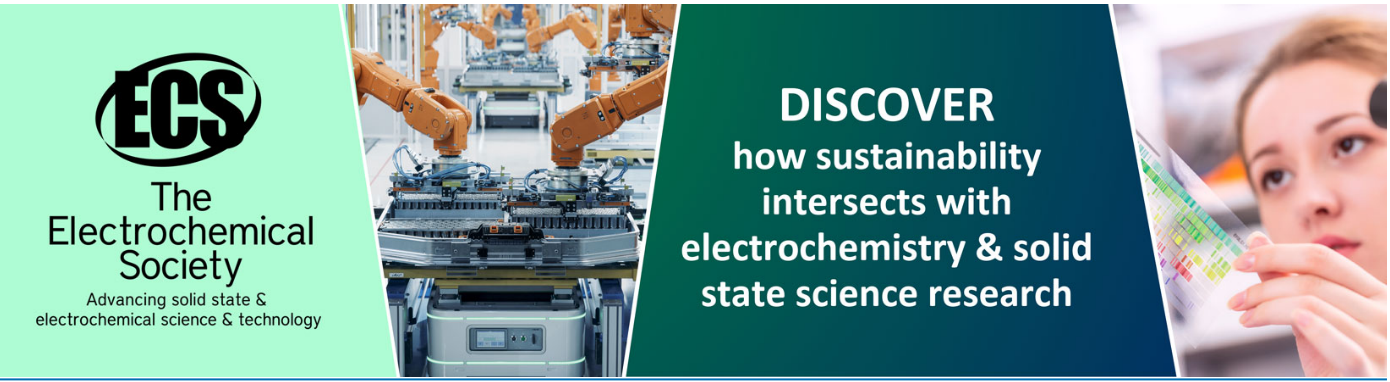

IOP Conf. Series: Materials Science and Engineering **274** (2017) 012045 doi:10.1088/1757-899X/274/1/012045

# Research on Damage Identification of Bridge Based on Digital Image Measurement

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**Abstract**. In recent years, the number of the damage bridge due to excessive deformation gradually increased, which caused significant property damage and casualties. Hence health monitoring and the damage detection of the bridge structure based on the deflection measurement are particularly important. The current conventional deflection measurement methods, such as total station, connected pipe, GPS, etc., have many shortcomings as low efficiency, heavy workload, low degree of automation, operating frequency and working time constrained. GPS has a low accuracy in the vertical displacement measurement and cannot meet the dynamic measured requirements of the current bridge engineering. This paper presents a bridge health monitoring and damage detection technology based on digital image measurement method in which the measurement accuracy is sub-millimeter level and can achieve the 24-hour automatic non-destructive monitoring for the deflection. It can be concluded from this paper that it is feasible to use digital image measurement method for identification of the damage in the bridge structure, because it has been validated by the theoretical analysis, the laboratory model and the application of the real bridge.

## 1. Introduction

The existing bridges around the world have varying degrees of security risks. In recent years, more and more attentions have been paid to the research of bridge structure health monitoring. Damage identification is the core of health monitoring because it can be used to assess the health of the bridge and give a reasonable maintenance advice[1]. Therefore, the many studies were focus on the damage detection and identification. As the core technology of the health monitoring, structural damage identification was to judge whether the structure was damaged by analyzing the relative indexes of the structure.[2-4] Moreover if the structure was damaged, the degree of damage and the residual capacity of the structure could be found out by the structural damage identification, and then the effective instructions for the maintenance of structure could be provided.

There are many conventional deflection measurement, such as total station[5], precision level instrument, dial indicator[6], communicating tubes[7] and GPS[8], etc. Obviously, manual measurement methods such as total station, precision level instrument, dial indicator were not suitable for long-term deflection monitoring of the bridge. GPS was not suitable for measuring the deflection of the bridge because it had high accuracy in the horizontal direction displacement measurement but low accuracy in the vertical displacement measurement, for which bridge deflection measurement was concern to the displacement in the elevation direction. Connected pipe, which was based on the principle of liquid balance, just could measure the displacement when the liquid was static so it could not achieve the dynamic deflection measurement requirements. In recent years, many new technologies and methods have the emerged. The accuracy of these methods has been improved to a certain degree and the automatic measurement has been achieved such as the measurement method based on inclinometer[9-11], laser spot[12], photoelectric imaging[13] etc. But there were still many deficiencies in the range, resistance from environmental influence and cost control. Moreover the accuracy of the automatic measurement method was generally in the order of millimeters to centimeters.

Aiming at the shortcomings, a 24-hour automatic non-destructive monitoring system based on digital image measurement technology is developed. The accuracy of this measurement has reached to sub-millimeter level, which provides a new means and method for bridge health monitoring. The system can be applied to the bridge health monitoring, which can identify the damage of bridge structure. This paper begins in the next section with a brief discussion of measurement principle and the testing system based on digital image measurement. The next section gives the theoretical analysis for the damage identification of bridge based on deflection. It also includes a discussion of the equation and the coefficients. The latter section is important both so that the effectiveness can be recognized by applying the digital image measurement method and the damage identification method based on the deflection to the laboratory experiment. This is followed by the application of the digital image measurement method to actual bridge.

## 2. Measurement principle and the testing system based on digital image

Digital image measurement method is the combination of the digital image and the measurement functions, in which the target image information for the measurement is changed into the digital form, and then the digital image information is analyzed in order to obtain the geometric characteristics of the measured object and the motion parameters of the measured object [14]. The main process is as follows.

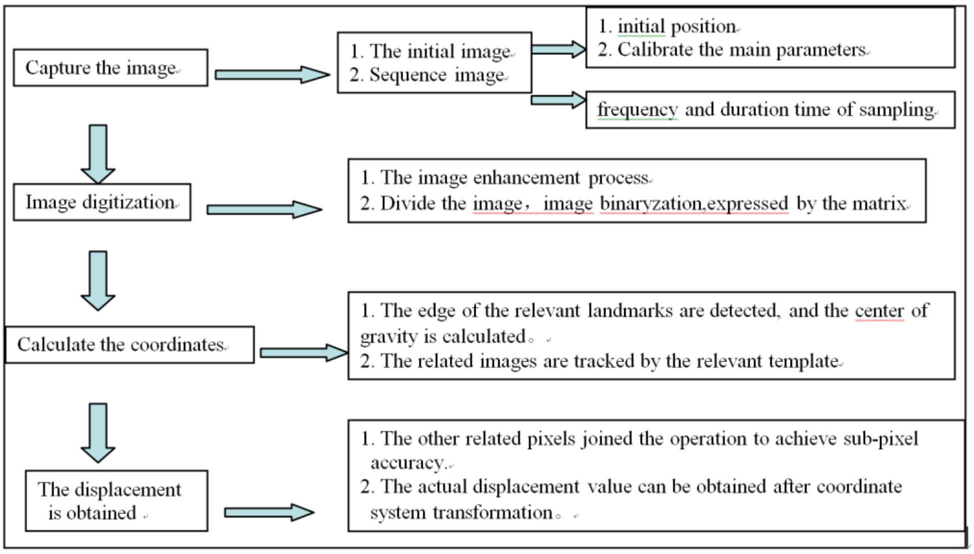



**Fig.1** The flow chart of the digital image measuring principle

The measurement accuracy is the key issue to be considered in the digital image measurement method. And many researchers have focused on how to improve the accuracy in the most economical way[15]. When the field of view is fixed by the distance from the measured objects and the resolution of the image acquisition device is determined by the system hardware, the only way to improve the measurement accuracy can only start from the software. The sub-pixel positioning technology is introduced to improve the measurement accuracy to sub-millimeter level. In order to identify and determine the location of the target, the image of the target needed to be analyzed by some processes such as filtering noise, highlight features, features and extraction of gray features, etc. In this paper, floating-point calculation is used to achieve the goal that the accuracy of the target positioning is better than that of the digital image pixel positioning. This analysis process is the sub-pixel positioning technology of the image object. This method first identified the characteristics of the observed target, which had certain characteristics that can be refined, and then started from the image search to find out the characteristics of the target location which met the refinement requirement.

The measurement error $\hat{\sigma}$ as shown in our previous work[16] can be simply estimated as

$$\hat{\sigma} \approx \frac{L}{m} \times \delta \times (1+\frac{\Delta}{L}) \times (1+\frac{\delta}{m})_{(mm)} \tag{1}$$

In which the extraction accuracy of image center is δ pixels, the sign board of the measured target is square with the length $L$ mm. The deviation of the actual size between two sizes is $\Delta$. The pixels between the upper and lower size, the right hand size and left hand size are both $m$.

## 3. Theoretical analysis for the damage identification of bridge based on deflection

The three-span continuous beam with damage is analyzed as shown in Fig. 2, in which the length of each span is $l$ and in the middle span there is one $\varepsilon$ long damage in the place $\varphi-\varepsilon$ distance from the middle support. The stiffness of the undamaged part is $EI$ and that of the damaged part is $EI'$. The origin is set at the left support.

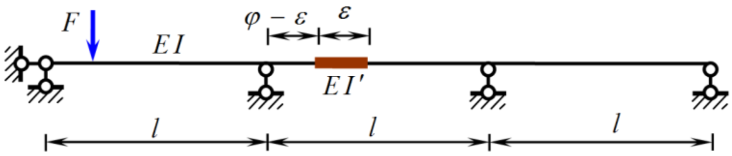



**Fig.2** continuous beam when the damage is in the middle span

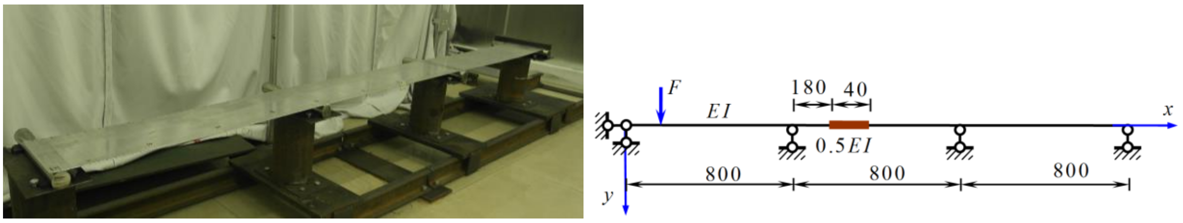
When a unit force applies on the bridge $x_0$ distance from the origin point, according to the basic principles of structural mechanics, the deflection in the middle of the bridge can be figured out as follows, which also called as the mid-span deflection influence line

$$\Delta H' = \begin{cases} \frac{M_B}{6EI\cdot l}\cdot x_0^3 - \frac{M_B}{6EI\cdot l}\cdot x_0 l^2, 0 \le x_0 \le l \\ \frac{(M_H - M_B)}{3EI\cdot l}\cdot x_0^3 + \frac{3M_B - 2M_H}{2EI}\cdot x_0{}^2 + C_1\cdot x_0 + C_2, l \le x_0 \le l+c-\varepsilon \\ \frac{(M_H - M_B)}{3EI'\cdot l}\cdot x_0^3 + C_3\cdot x_0{}^2 + C_4\cdot x_0 + C_5, l+c-\varepsilon \le x_0 \le l+c+\varepsilon \\ \frac{(M_H - M_B)}{3EI\cdot l}\cdot x_0^3 + \frac{3M_B - 2M_H}{2EI}\cdot x_0{}^2 + C_6\cdot x_0 + C_7, l+c+\varepsilon \le x_0 \le \frac{3}{2}l \\ \frac{(M_C - M_H)}{3EI\cdot l}\cdot x_0^3 + \frac{4M_H - 3M_C}{2EI}\cdot x_0{}^2 + C_8\cdot x_0 + C_9, \frac{3l}{2} \le x_0 \le 2l \\ -\frac{M_C}{6EI\cdot l}\cdot(\frac{1}{6}x_0{}^3 - \frac{3l}{2}x_0{}^2 + \frac{13l^2}{3}x_0 - 4l^3), 2l \le x_0 \le 3l \end{cases} \tag{2}$$

In which, the parameters $M_B$, $M_C$, $M_H$, $M$, $C_1$, $C_2$, $C_3$, $C_4$, $C_5$, $C_6$, $C_7$, $C_8$, $C_9$ are all included $\varphi$, $\varepsilon$, $l$, $EI$ and $EI'$

Equation(2) describes the deflection of the middle point of the middle span according to the applied place of the moving force. It can be concluded from Eq. (2) that the mid-span deflection influence line of the damaged structure showed as Fig. 2 is composed of six sections of cubic curve. The deflection influence line and its first derivative are continuous, but the second derivative of the deflection influence line is not continuous around the damaged place because the coefficients of $x^3$ are different. According to this property, wavelet transform can be used to find out the discontinuity point of the second derivative of the deflection influence line and determine the damage location. So the digital image measurement method and the damage identification method based on the deflection are applied to the laboratory experiment in the next step to test their effectiveness.

## 4. Laboratory experiment




a.the physical model b. computing model

**Fig.3** laboratory model

The three-span continuous beam is model using aluminum alloy plate in the laboratory experimental model shown as Fig.3 with 2400mm（3×800mm）long, 200mm wide and 2mm thick. Rigid round tubes with 40mm in diameter are chosen as the roller supports to restrict the vertical displacements of the bridge. A steel plate and rigid round tube are selected as the hinged support to restrict the vertical and horizontal displacements of the bridge. A graduation line is drawn every 20mm on the beam and the beam is divided into 120 units (totally 121 points). The force is applied on each graduation line and the observation point is set in the middle of the span (that is, the 61st test point). The mid-span deflection can be measured by digital image measurement.

The computing model of the structure is shown as Fig. 3.b The coordinate origin is set at the hinge support on the left and *x* direction is along the bridge, *y* direction is shown in Fig. 3.b The local damage is set at the place 180mm distance from the middle roller support (ie.980mm from the coordinate origin), with which the stiffness was 50% off.

The load moves in the *x* direction from 0 to 2400 mm and the mid-span deflection can be measured by the digital image measurement method as described in the second part of this paper. And the theoretical values of the influence line of the mid-span deflection are calculated according to Eq. (2). The experimental results and the theoretical ones are compared to find out that they are in consistent because the errors between them are less than 2%. Therefore the measurement results are reliable. The mid-span deflection of the theoretical results and experimentally measured values are taken under the Mexican wavelet analysis and the wavelet analysis coefficients varying with the *x* direction are shown in Figure 4. It can be clearly seen from Fig. 4 that except for the support places the wavelet coefficients have a sudden change in the damaged place. There is a mutation in the wavelet coefficients between 980mm and 1020mm away from the origin along the x-axis direction. It is just the where the damaged located. So from the mutation the damaged location can be clearly positioned. And it can be conclude that the damage is located between 980mm and 1020mm away from the origin and the damage is 40mm long. Both the theoretical results and the experimental results have similar results but the mutations in the theoretical results are more obvious than that of the experimental

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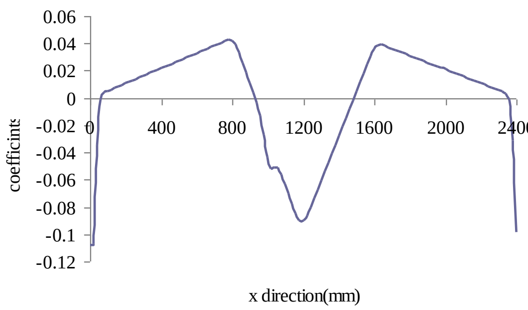
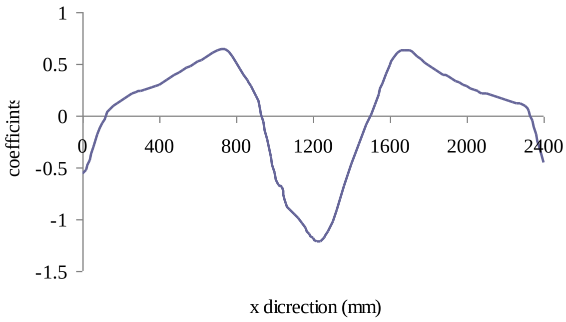
results. The measured data can be observed in the corresponding parts of the wavelet coefficient mutation. It can be seen that using the digital image measurement method described in this paper could well measure the deflection the structure and the accuracy is very high. Moreover the damage of bridge structure can be identified. The damage identification based on the deflection is effective under laboratory conditions. So this digital image measurement method and the damage identification method are applied to the actual bridge structure in the next step to see if the corresponding damage results can be obtained.




a. theoretical result

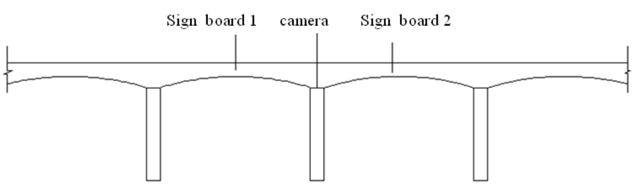



b. experimental result

**Fig. 4** Wavelet analysis coefficient of the results

## 5. Application of Digital Image Measurement Technology in Bridge Damage Analysis

The digital image measurement method and the damage identification method are also applied to the monitoring system of Pingtan strait bridge project. Pingtan strait bridge is a four-span (100m+2×180m+100m) prestressed concrete continuous rigid-frame bridge with variable cross-section. According to the previous theory and the laboratory model, it can be conclude that the position of the damage can be successfully identified by measuring the mid-span deflection. There are two middle spans in the four-span continuous rigid frame bridge, so two measuring points, set as sigh board 1 and sign board 2, are arranged in the middle point of the middle span as shown in Fig. 5. The camera and measurement system are set in the middle support of the bridge.



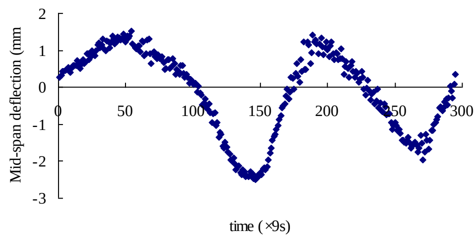




**Fig 5** the measuring point distribute of ping tan bridge Fig.6 The mid-span deflection varies with time

The damage of bridge structure is mainly due to cross-section cracking, prestress loss, concrete shrinkage and creep and other factors. These factors will directly affect the stiffness of the bridge structure, thus affecting the vertical displacement of the measuring point. The influences of prestress loss and concrete shrinkage and creep are on the overall rigidity of the bridge structure. However the cross-section cracking caused by the local damage just changes of the local stiffness of the bridge. It can be seen from the discussion of Eq.(2) that the second-order derivative of the deflection influence line is discontinuity caused by the change of the local stiffness. So the corresponding discontinuity point of the mid-span deflection can be obtained by the wavelet analysis and the damage can be identified. To avoid the interference of other vehicles and other factors, the data from sign board 1shown as Fig. 5 was selected when there was only one heavy vehicle crossing the bridge. The measurement frequency is one point every 9 seconds.

It can be seen from the results in Fig.6 that when the vehicle crosses the side span, the mid-span displacement of the sign board 1 is upward and when the vehicle goes through the middle span, the mid-span displacement is downward, which are in agreement with the calculated results. Moreover the maximum deflection is about 2.4mm for a 50t heavy vehicle, with which the results is close to the theoretical ones. It can be concluded that the measured data are reliable. Then the measured results are subjected to the Mexican wavelet transform as shown in the previous section to attempt to analyze the local damage of the bridge structure.

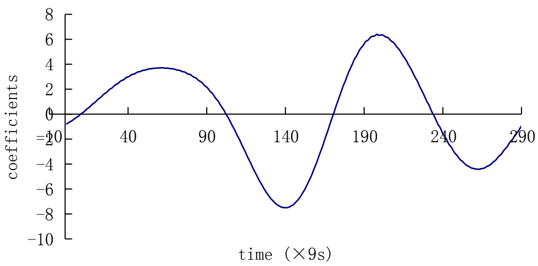



**Fig. 7** Wavelet analysis coefficient of the deflection

From the results of wavelet analysis (Fig. 7), the coefficient curve is nearly smooth, and there is no obvious transition point. It can be considered that there is no obvious damage for the bridge structure, and this result is also reasonable. Because the bridge has just completed and opened to traffic, normally there should be no cross-section damage caused by cracking, so the results are reasonable and credible.

## 6. Conclusion

In this paper, the damage of bridge structure is detected based on digital image measurement method, and the damage of bridge structure is identified by theoretical analysis, laboratory model and real bridge application. The conclusions are as followed,

The theoretical analysis of a three span continuous beam model with damage is carried out and it can be seen that the deflection influence line and its first derivative are continuous, but the second derivative of the deflection influence line is not continuous around the damaged place. According to this property, the discontinuity point of second derivative of the deflection influence line can be found out by wavelet transform and the damage location can be identified. Also in the laboratory test based on the digital image measurement, the mid-span deflection are captured and analyzed by the Mexican wavelet analysis. The wavelet coefficients have a sudden change in the damaged place which verifies this damage identification based on the digital image measurement.

The digital image measurement method and the damage identification method are applied to the Pingtan strait bridge and the real-time measurement data can be obtained. The measured results are in agreement with the calculated results. It can be concluded that the measured data are reliable. It can be considered that there is no obvious damage for the bridge structure, and this result is also reasonable. Because the bridge has just completed and opened to traffic.

It can be seen that it is feasible to use digital image measurement method for identification of the damage in bridge structural. It has been validated by the theoretical analysis, the laboratory model and the application of the real bridge. This 24-hour automatic non-destructive monitoring system based on digital image measurement method can reach the accuracy of sub-millimeter, which provides a new means and method for bridge health monitoring.

**Acknowledgments**
This work was financially supported by the Natural Science Foundation of China (11702067), Guangdong Province (2016A030313617), and the Foundation for Young Talents in Higher Education of Guangdong, China (20110172110031).

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