Vertical Displacement Measurements for Highway Bridge using Optical Devices/Sensors A Preliminary Study

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ABSTRACT:

In many bridges, the vertical displacement is one of the most relevant parameters to be monitored in both the short and long term. However, it is well known amongst bridge authorities all over the world that it is difficult to measure the vertical displacements of a bridge. Current methods are often tedious to use and require the intervention of specialised operators. Therefore it prompts the need to find a simple and practical method to measure vertical displacements. This paper presents two methods using either optical fiber (FBG) sensors or a charge-coupled-device (CCD) camera respectively for vertical displacement measurements of bridges. The FBG sensor method is based on the measurement of horizontal displacements together with the inclinations at various points along a bridge using FBG strain sensors and FBG tilt sensors. The CCD Camera method utilizes image processing techniques for edge detection. The image processing techniques include grayscale threshold consideration and brightness, contrast and gamma correction. The proposed methods were tested and compared in laboratory using a concrete beam and a steel beam separately. The comparisons include their installations, costs, degrees of accuracy, external factors affecting the measurement, etc. The theoretical background for both methods including the use of FBG sensors for structural health monitoring will be discussed in the paper. It is concluded that both methods could be used for vertical displacement measurement and they could be complementary to one another. With their implementations, a big advancement in the technology of Structural Health Monitoring is expected.

INTRODUCTION

In many bridges, the vertical displacements are the most relevant parameters for monitoring in both the short and long term. Strain monitoring, for example, yields only local information about material behavior, and too many such sensors would therefore be

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necessary to gain a complete understanding of the structure's behavior. However, as is well known amongst bridge authorities all over the world, it is difficult to measure the vertical displacements of a bridge. Current methods are often tedious to use and require the intervention of specialized operators. For example, traditional transducers need a reference base and most often the mechanical extensometers are impractical for most situations, e.g., over water. The disadvantages of the leveling method are that reference marks are lost, it is expensive in prescribed comparisons, and the swing of the compensator is difficult to control due to traffic. Attempts have been made in recent years to investigate the feasibility of applying GPS technology to monitor displacements [1-3]. However, these approaches are still far from being practical and effective, especially when GPS is applied to monitor dynamic structural deformation. Using dual frequency GPS receivers could give good results, but they are very expensive and cannot be applied to areas with congested buildings. Single-frequency GPS receivers may be cheaper, but they have problems with cycle slips [4]. Therefore, there is a need to find a simple and practical method to measure vertical displacements.

In civil engineering research, an optical method has been developed to measure vertical displacement using laser or camera devices for collecting measurement data for structural testing [5]. However, the method is very expensive. The method can be further developed to use CCD cameras instead, the price of which has dropped drastically in recent years. CCD cameras use a large number of pixels (dots) to form an image. The optical sensor used in these cameras is very sensitive to light. Thus, no artificial lighting is required to take an image of a bridge. However, although a CCD camera has an optical sensor with a large number of pixels, the resolution provided may not be adequate for displacement measurements for structural health monitoring. The sub-pixel displacement identification measurement (SPDIM) method has been developed to improve the accuracy of using digital cameras to levels comparable to those of traditional displacement transducers [6].

The experience gained from using Fiber Bragg Gratting (FBG) sensors for strain measurements [7-9] has demonstrated that FBGs can be practically used to measure strains accurately. This paper will further demonstrate how these sensors could be used to measure the bridge vertical displacements. The method developed would be superior to traditional methods, and yet is not perfect, as some installation work is still needed. Therefore, an alternate method using a CCD camera will also be developed for verifying/supplementing the FBG sensor technique.

VERTICAL DISPLACMENT MEASUREMENT USING FBG SENSORS

The vertical displacement, y, of any point along a beam is based on a double integration of radius of curvature, R, at that particular point, yielding:

$$y = \frac{x^2}{R} + Ax + B \tag{1}$$

Considering Figure 1, assuming the inscribed angle θ is small, the radius of curvature, R is given by

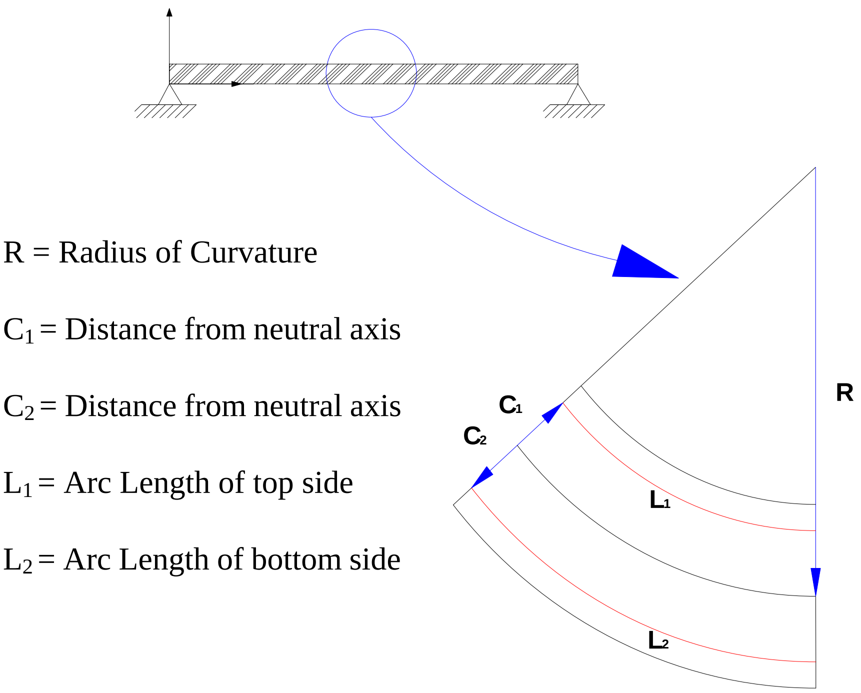


Figure 1: Definitions of Terms for Equation

$$R = \frac{C_2 l_1 + C_1 l_2}{l_2 - l_1} \qquad (2)$$

The two constants *A* and *B* in Equation 1 are then obtained using the boundary conditions at two ends and the measurements of the slope at any point along the beam using a tilt sensor.

VERTICAL DISPLACEMENT MEASUREMENT USING CCD CAMERAS

When a picture captured by a CCD is magnified, such as by eight times that of the original image, the picture is seem to be formed of many ‘dots’ or ‘squares’. These ‘dots’ or ‘squares’ are referred to as pixels (shown in Figure 2). The resolution of an image is determined by the number of rows and columns of pixels. If the image is composed of m columns and n rows, it is then represented as $m \times n$ resolution. This image has *m* pixels along its horizontal axis and *n* pixels along its vertical axis. For example, if the image is stated as 1280 × 1024, then the image has 1280 pixels along its horizontal axis and 1024 pixels along its vertical axis.

Ideally, when the images before and after displacement are obtained, the vertical displacement can be measured at any location of the bridge by calculating the displacement measured by the pixel difference before and after. The software LabView is used as a platform for calibrating and processing the image and calculating the vertical displacement subsequently. A special image processing program is developed, in which the background of the beam of interest will be erased using Brightness, Contrast and Gamma Correction as well as Grayscale Threshold and Morphology operations. The edge of the beam will then be generated using a developed edge detection program and the displacements could then be determined accordingly (Figure 3).

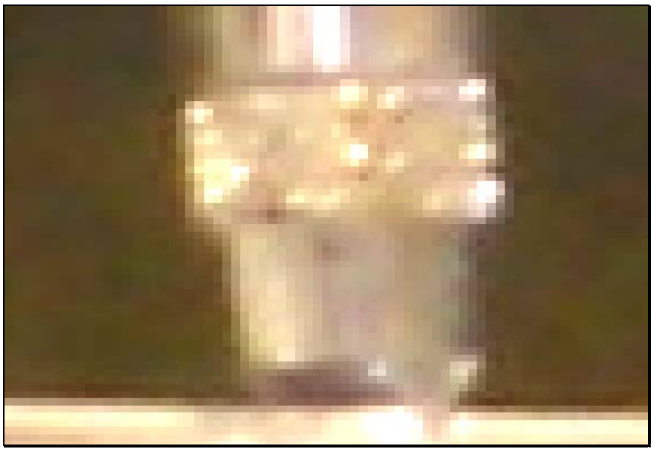


Figure 2: Pixels of a Photo

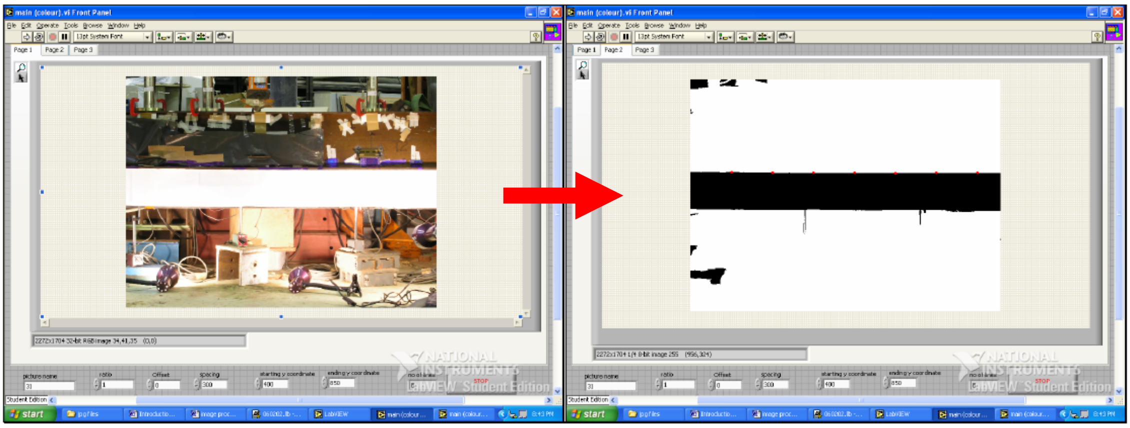
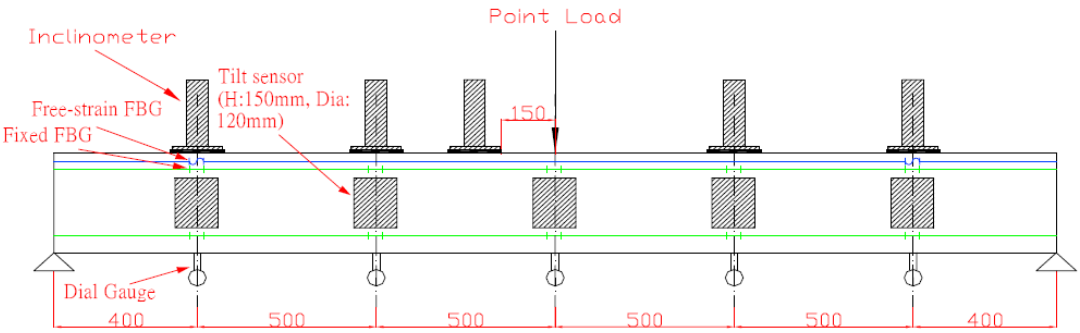


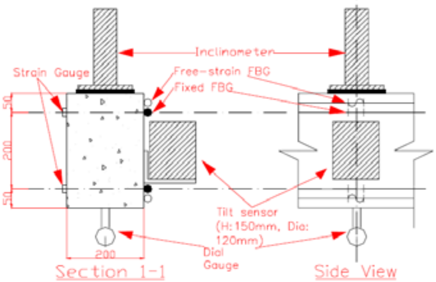
Figure 3: Example showing how a background could be erased leaving the beam only for displacement measurement

EXPERIMENTAL WORK

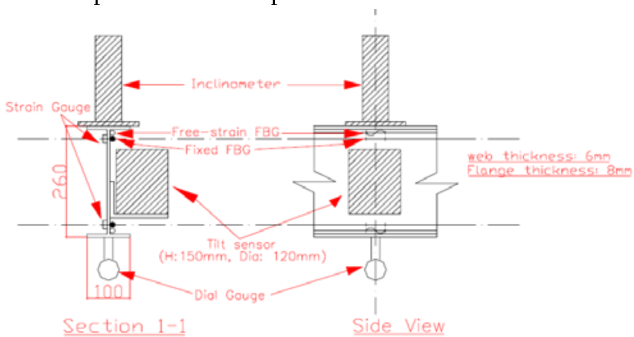
In the present study, two beams, one reinforced concrete beam and one steel I-beam beam, were used for experimental verification. The experimental set-up is shown in Figure 4. The span lengths for both beams are 2.8m. For the concrete beam, its depth and width are 300mm and 200mm respectively, while for the I-beam are 260mm and 100mm. For both of the beams, the inclinometers were bolted on the glued steel plank on the top of the beam. The strain gauges and FBGs were installed to two sides of the beam. The tilt sensor was set on an angle section which is on the same side as the FBGs. The transducers were then placed under the bottom of the beam. The locations of instruments in details are shown Figure 4. Regarding the measurement using CCD cameras, two cameras were tested, one monochrome and the other colour. The monochrome camera, having a 1280 × 1024 pixel array was controlled by a computer program using an i-link cable (IEEE 1394). The colour camera is just an ordinary digital camera with 2272 × 1704 pixel array. The two cameras were sited in front of the testing beam with their lenses at in the same level as the bottom of the beam. The test setup is shown in Figure 5.



(a) General Experimental Set-up



(b) RC Beam Set-up



(c) I-Section Steel Beam Set-up

Figure 4: Experimental Set-up (all dimensions are in mm)

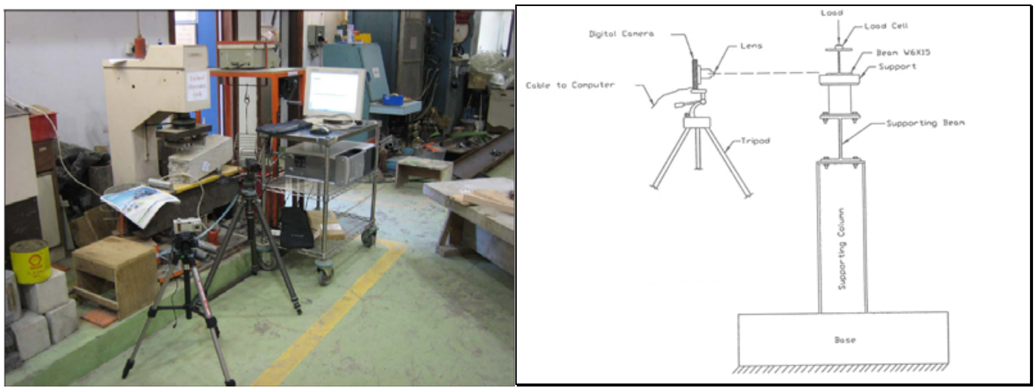


Figure 5: CCD Cameras Set-up

RESULTS

A series of test was conducted and the measurements of vertical displacement using traditional transducers, FBG sensors and CCD cameras were obtained and compared. Figure 6 shows one typical results obtained by different methods applying to the I-section steel beam. From the figure, it can clearly be seen that both the methods using

FBG sensors and CCD cameras could be used to measure the vertical displacement as compared to the traditional transducers with the CCD camera method being more accurate in the measurement when compared to the FBG methods.

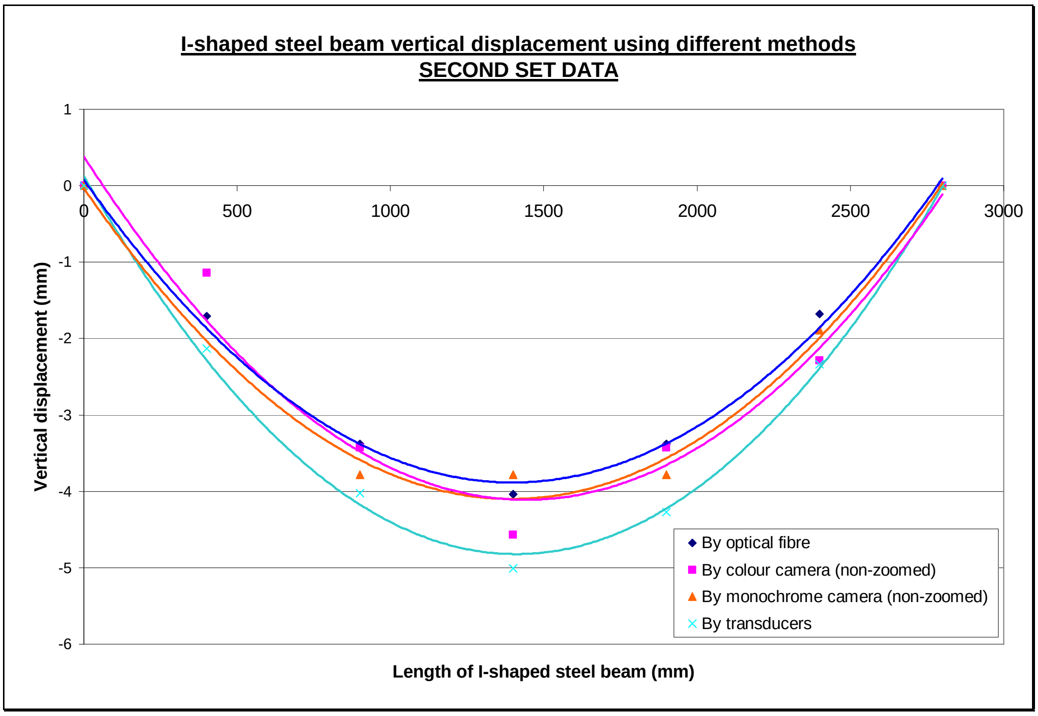


Figure 6: Vertical Displacement Measurement using different methods (Steel I-beam)

Regarding the test on the reinforced concrete beam, from the preliminary study, it is apparent that the vertical displacement of the reinforced concrete beam under a mid-span load cannot be obtained accurately using the CCD camera method. It may be due to the restriction of the magnification factor (pixel per mm) in measuring small displacement. For example, the magnification factor for a monochrome image is limited to 0.927mm/pixel which is much larger then the maximum vertical displacement of the beam (0.6mm) obtained in the test. Further tests would be required to test the feasibility in using CCD camera for small displacement either by using a camera with larger resolution or design a beam with larger displacement under other loading arrangement. For practical application, the displacement to be measured would be much larger, so it would still be acceptable to use the CCD camera method for vertical displacement measurement.

COMPARISON BETWEEN THE TWO DEVELOPED METHODS

From this preliminary study, it can be seen that the method using FBG sensors can measure comparatively small vertical displacements. However the vertical displacements of the reinforced concrete beam cannot be measured using the camera methods as the beam vertical displacement is smaller than the magnification factor of photographic images taken. Unlike the common vertical displacement measurement methods, stationary platforms are not required for the method using FBG sensors. Besides, comparing with the camera method, the FBG method will not be affected by the background or environment conditions of the beam. On the other hand, the installation and set-up of the camera method is much simpler than that of the FBG method and its accuracy is also higher than that of the FBG method. Table 1 below summarizes the comparison between the two developed methods.

Table 1: Summary of Comparison

	CCD camera method	**FBG measurement method**
Land requirement	Land is required for installing equipment	No land is required for installation
Weather condition	Affected by bad weather (low visibility).	Not affected by weather.
Capital cost	Increased with the points of interest and dependent on the price of cameras. (capital cost: cameras and computers)	Approximately fixed. (capital cost: interrogator)
Equipment installation process	Simple (setup the tripods and cameras)	Complex (glue the FBGs and fix the tilt sensors on the bridge surface.
Degree of accuracy	Suitable for measuring bridges with vertical deflection > 10mm then accuracy > 95%. (Resolution: 1280 x 1280 and the bridges are enlarged to 500mm, magnification factor = ±0.488mm)	Suitable for measuring bridges with span length >3m and vertical deflection > 5mm (accuracy after correction = 99% or ± 0.05mm)
Experimental preparation before measurement	Installing distinguishing marks on the bridge surface for the calibrations and as points of interest.	Finding the correction factors for the deflection measurements in a laboratory
External effects on the measurement	Affected by the vibration of tripod and background of the bridges	No external effects

CONCLUSIONS

From the preliminary study, it is proved that it is feasible to use the FBG sensor method or the CCD camera method for vertical displacement measurement. Both methods developed are superior to traditional methods, solving a major problem of bridge managers who are always looking for a simple, inexpensive, and yet practical method to measure bridge vertical displacements. Further study is still required for its practical application. A successful outcome will not only help to solve an important problem for bridge management, but also prepare the way for better structural health monitoring techniques, which would be much improved if vertical displacements could be practically measured continuously in real-time. For example, the detection of damage together with the identification of its location and determination of the loss of prestressing force in a prestressed concrete bridge will be two such techniques that could be explored using the methods developed.

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REFERENCES

1. Roberts, G. W., Dodson, A. H., and Ashkenazi, V. (1999). "Twist and Deflection: Monitoring Motion of Humber Bridge." *GPS World*, 10(10), 24-34.
2. Duff, K., Hyzak, M., and Tucker, D. (1998) "Real-time Deformation Monitoring with GPS: Capabilities and Limitations." *SPIE 3330, Smart Structures and Materials 1998: Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials*, pp. 387-395.
3. Ogaja, C., Rizos, C., Wang, J., and Brownjohn, J. (2001) "Toward the implementation of online structural monitoring using RTK-GPS and analysis of results using the wavelet transform." *Deformation Measurements and Analysis, 10th International Symposium on Deformation Measurements*, Orange, California, USA, pp. 284-293.
4. Young, C. (1998) “Single Frequency OTF Kinematics GPS Bridge Delfection Monitoring,” MSc thesis, University of Nottingham, Nottingham.
5. Fu, G., Moosa, A.G., and Peng, J., (1998). "Probabilistic Pattern Recognition Using Coherent Laser Radar for Bridge Inspection", Final Report to FHWA, USDOT, for Contract DTFH61-97P00549, Department of Civil and Environmental Engineering, Wayne State University.
6. Fu, G. and Moosa, A.G. (2002) "An Optical Approach to Structural Displacement Measurement and Its Application", *ASCE Journal of Engineering Mechanics*, 128 (5) pp. 511-520.
7. Chan, T.H.T., Tam, H.Y., Ni, Y.Q., Liu, S.Y., Cheng, W.H., and Guan, B.O., (2004a), “Using Optical Fibre Sensors for Structural Health Monitoring of Tsing Ma Bridge” Proceedings of the *First Workshop on Smart Materials and Structures Technology*, Hawaii, U.S.A., pp. 539-546.
8. Chan, T.H.T., Yu, L. Yu, Tam, H.Y., Ni, Y.Q., Liu, S.Y., Cheung, W.H. Cheng, L.K., (2005a) “Use of FBG Optical Sensors for Structural Health Monitoring: Practical Application”, Proceedings of Bragg Gratings, Poling & Photosensitivity/30th Australian Conference on Optical Fibre Technology, Sydney, Australia.
9. Tam H.Y., S.Y. Liu, B.O. Guan, W.H. Chung, T.H.T Chan, and L.K. Cheng, “Fiber Bragg Grating Sensors for Structural and Railway Applications,” (Invited Paper), Photonics Asia 2004, Beijing, 8-12 November 2004.