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THE MEASUREMENT OF FULL SCALE STRUCTURAL BEAM-COLUMN CONNECTION DEFORMATION USING DIGITAL CLOSE RANGE PHOTOGRAMMETRY TECHNIQUE

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Abstract: Measurement and monitoring of structural components such as beams and columns under loading are important in structural analysis and design assessment. Presently, the assessment on structural components on deformation or displacement measurement is carried out through LVDTs or dial gauges. The LVDTs or dial gauges were installed in contact with the structural components, also known as contact method. However, present contact method is subjected to some limitations such as s displacement points of measurement are highly depend on the position of LVDTs available, reliability of LVDTs and dial gauges to measure during the experiments due to possibility of damage sensors and consumption of time on the installation the sensors. Due to the limitations of contact method, this study demonstrates the use of a non-contact method using digital close range photogrammetry technique to measure the deformational behaviour of full-scale structural beams and columns. In this study, a full-scale load tests on structural components were performed under laboratory conditions. A series of digital images of the structural beams and columns under various loads were captured using Nikon DSLR cameras. The digital images then processed and analyzed using digital close range photogrammetric technique to measure and extract the magnitude of the structural beam and column displacements. The deformation and displacement of beam and columns have been validated by comparing the photogrammetric outputs against the results obtained from the LVDTs. The statistical analysis shows the differences obtained between the photogrammetric technique and contact method used were not significant.

Keywords: *Photogrammetry, Structure, Beam, Displacement and Deformation*

1.0 Introduction

In general, the use of photogrammetry techniques in civil engineering practices has been successfully applied for various measurements such as a three dimensional structural vibration measurements (Chang and Ji, 2007), to study the evolution of cracks in concrete structure (Barazzeti and Scaioni, 2007 and Hampel, 2010), beam displacements (Psaltis and Ionindis, 2004, Mushairry et. al. 2009, Mushairry et. al. 2012, Radzuan et. al. 2011, Radzuan et. al. 2012), surface deformation on concrete structures (Benning et. al., 2005), to monitor soil erosion (Rieke-Zapp and Nearing, 2005), to monitor construction project progress (Zubair et. al., 2006), road pavement crack classification and quantification (Othman et. al.,2007), tracking excavation activities of soil removal at construction site (Quinones-Rozo et. al., 2008).

Measurement and monitoring the structural component such as beams deformation have an essential role in structural management (Benning et. al., 2005). While, the results was obtained from the structural deformation displacement measurement are very useful for the theoretical design of material behaviour modelling (Psaltis and Ioannidis, 2004) and also can be used as an indicators pertaining to its failure (Mushairry, et. al. 2004). At present, the measurement of structural components deflection or displacement is typically undertaken using contact method by using linear variable differential transformers (LVDTs). The LVDTs are employed for structural deflection experiments because of their high precision spatial measurement capabilities at a point or point wise of a structure with an accuracy of 1/100mm.

However, the contact methods face numbers of major drawbacks such as: the measuring instruments may be damaged during the experiment, and the points measured cannot be dense and well distributed (Psaltis and Ionindis, 2004;Gordon et. al., 2004). In other word, deformations can only be measured at points where gauges or LVDTs sensors are fixed and in many cases would not cover the entire surface (Mushairry et. al. 2004; Gordon and Lintchi, 2007). In addition, when the large numbers of points of displacement are required or desired, the using of the sensors becomes prohibitively expensive and laborious task (Fu and Moosa, 2002). Due to the numbers of limitation faced by contact method, this study demonstrates the use of digital close range photogrammetry as a supplementary method in determination of structural component displacement behaviour under laboratory conditions. The main objective of this study is to employ the photogrammetric technique in detecting the full scale concrete beam and column connection behaviour under loading. The deformations result obtained via photogrammetry technique then compare against deformation results obtained using LVDTs.

2.0 Photogrammetry

Photogrammetry is a technique to obtain the position, size and shape of physical object using two dimensional photograph or digital images of the same object captured from difference camera stations. The new era of digital photogrammetry is more convenient in comparison to traditional photogrammetry because all photographs now are in digital format. Furthermore, due to the dramatic drop in the cost of on the shelf digital cameras, storage media, computer hardware and phorogrammetry processing system, that is why photogrammetry was recently being widely used in various applications in various field. Moreover, the most important feature is the fact, that the objects are measured without being touched. Therefore, the term “remote sensing“ is used by some authors instead of “photogrammetry“ (Mushairry, et.al. 2009).

In general photogrammetry can be divided into two namely aerial photogrammetry and terrestrial photogrammetry (Wolf and Dewitt, 2000). Aerial photogrammetry is widely used for public and private land development, exploitation of natural resources and production of topography maps (Luhman et. al. 2006). On the other hand, terrestrial photogrammetry is used at ground level for small scale surveying, manufacturing and industrial applications. Terrestrial then may be further defined as close range photogrammetry (Luhman, et. al. 2006). The term close range photogrammetry (CRP) is used to describe the technique when the size of the object to be measured is less than about 100 m and the camera is positioned close to it. However, Kennert and Torlegard (1980) claimed the minimum distance is a fraction of a micrometer and millimetre range to 300m as a maximum limit also falling within the scope of CRP. Recently, all photos can be captured and stored in digital format using digital cameras the close range photogrammetry now is known as digital close range photogrammetry (DCRP) (Luhman et. al. 2006).

DCRP technique is a method where three-dimensional measurements are made from two or more digital images taken on one object. Generally, digital images are taken of an object from at least two camera positions. From each camera position, there are lines that run from each point on the object to the perspective centre of the camera. Using a principle of triangulation, the point of intersection between the different lines of sight for a particular point is determined mathematically using collinearity equation to identifying the spatial or three-dimensional locations of the object points. Generally, there are five basic steps in the photogrammetric process: (1) calibration of cameras (2) layout of the control or reference coordinates systems; (3) planning and image gathering; (4) images processing and (5) point measurement using the digital images. Detail discussion of each photogrammetric process can be found in many photogrammetry text book (i.e Aktkinson, 1996; Wolf and Dewitt, 2000; Luhman et. al. 2006).

2.1 DCRP Measurement - Fundamental Steps

A digital image is a perspective projection and the optical centre of the camera is the perspective centre. The region between the perspective centre and the sensors is called the image space. The region occupied by the object to be imaged, including the reference coordinate system used, is called the object space. The measurements are involves the transformation from two-dimensional data to three-dimensional output through some perspective relationship. The geometry and the relative positions of each cameras or sensors are required before any measurements of the images could be taken. This could be achieved by performing the following three vital steps, namely, interior orientation, relative orientation and absolute orientation (Mushairry & Mitchell, 2001). For more detailed explanation of three camera orientation, readers are advised to refer to any photogrammetry text book (e.g. Wolf and Dewitt, 2000).

2.2 Computation of Object Space Coordinates (X,Y,Z)

For an image point whose coordinates are (x, y), the collinearity equation, which can be found in most photogrammetric textbooks (e.g. Wolf and Dewitt, 2000), they are given by:-

$$x - x_o = -f\left(\frac{m_{11}(X - X_o^T) + m_{12}(Y - Y_o^T) + m_{13}(Z - Z_o^T)}{m_{31}(X - X_o^T) + m_{32}(Y - Y_o^T) + m_{33}(Z - Z_o^T)}\right) \quad \ldots (1)$$

$$y - y_o = -f\left(\frac{m_{21}(X - X_o^T) + m_{22}(Y - Y_o^T) + m_{23}(Z - Z_o^T)}{m_{31}(X - X_o^T) + m_{32}(Y - Y_o^T) + m_{33}(Z - Z_o^T)}\right) \quad \ldots (2)$$

where,

m_{11} .. m_{33} are elements of the rotation matrix (ω, ∅, κ), x_o,y_o are the image coordinates of the principal point, X,Y,Z are the corresponding object space coordinates of (x,y) and X_0^T, Y_0^T, Z_0^T are the object space coordinates of the perspective centre (see Figure 1).

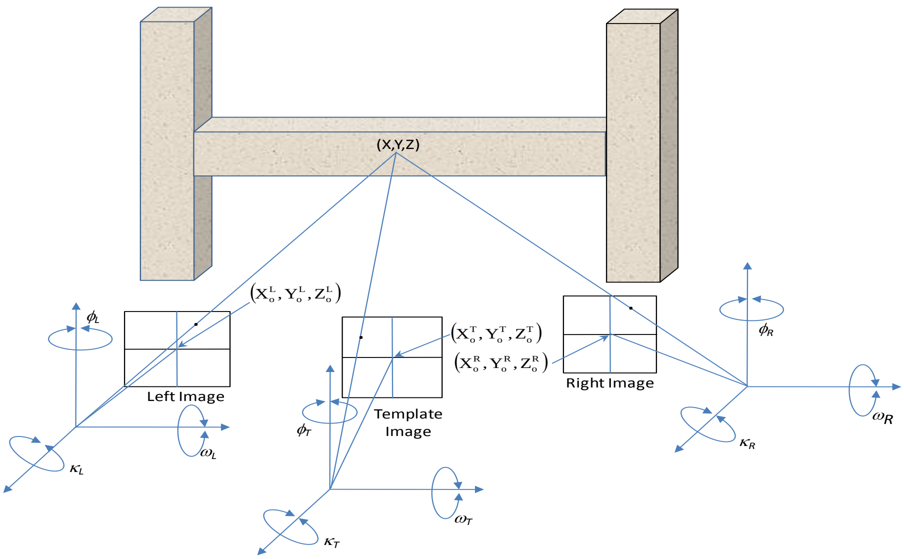


Figure 1: Intersection of object space coordinates from three camera station

Equations (1) and (2) can be formed for a point in the image. Supposing a pair of corresponding image points is available, then four collinearity equations can be formed and the object coordinates (X,Y,Z) can be directly computed using any of these three equations. If the position of the middle camera is held fixed during the relative orientation process (as in a one-projector relative orientation) then the rotations will result in an identity rotation matrix, i.e. :-

$$\begin{bmatrix} m^T_{11} & m^T_{12} & m^T_{13} \\ m^T_{21} & m^T_{22} & m^T_{23} \\ m^T_{31} & m^T_{32} & m^T_{33} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \mathbf{I} \qquad \ldots (3)$$

Assume that the object space coordinates are based on the left-hand perspective centre, then $X_o = Y_o = Z_o = 0$ and, for simplicity sake, adopting the coordinates of the principal point $x_o = y_o = 0$. (In practice however, the origin of the image's coordinate system is normally at the top or bottom left corner). Eqns. (1) and (2) are simplified as follows:-

$$x_T = -f_T \frac{X}{Z} \quad \ldots (4a) \qquad\qquad y_T = -f_T \frac{Y}{Z} \quad \ldots (4b)$$

If the rotation matrix for the right and left camera respectively is given by :-

$$R^R = \begin{bmatrix} m^R_{11} & m^R_{12} & m^R_{13} \\ m^R_{21} & m^R_{22} & m^R_{23} \\ m^R_{31} & m^R_{32} & m^R_{33} \end{bmatrix} \quad \ldots (5a) \qquad L^L = \begin{bmatrix} m^L_{11} & m^L_{12} & m^L_{13} \\ m^L_{21} & m^L_{22} & m^L_{23} \\ m^L_{31} & m^L_{32} & m^L_{33} \end{bmatrix} \quad \ldots (5b)$$

and the object space coordinates of the perspective centre of right and left images are $\left(X^R_o, Y^R_o, Z^R_o\right)$ and $\left(X^L_o, Y^L_o, Z^L_o\right)$ respectively, then the collinearity equations for the corresponding point on the right and left images are given as :-

$$x^R = -f_R \left(\frac{m^R_{11}\left(X - X^R_o\right) + m^R_{12}\left(Y - Y^R_o\right) + m^R_{13}\left(Z - Z^R_o\right)}{m^R_{31}\left(X - X^R_o\right) + m^R_{32}\left(Y - Y^R_o\right) + m^R_{33}\left(Z - Z^R_o\right)} \right) \quad \ldots (6)$$

$$y^R = -f_R \left(\frac{m^R_{21}\left(X - X^R_o\right) + m^R_{22}\left(Y - Y^R_o\right) + m^R_{23}\left(Z - Z^R_o\right)}{m^R_{31}\left(X - X^R_o\right) + m^R_{32}\left(Y - Y^R_o\right) + m^R_{33}\left(Z - Z^R_o\right)} \right) \quad \ldots (7)$$

$$x^L = -f_L\left(\frac{m_{11}^L(X - X_o^L) + m_{12}^L(Y - Y_o^L) + m_{13}^L(Z - Z_o^L)}{m_{31}^L(X - X_o^L) + m_{32}^L(Y - Y_o^L) + m_{33}^L(Z - Z_o^L)}\right) \quad \text{... (8)}$$

$$y^L = -f_L\left(\frac{m_{21}^L(X - X_o^L) + m_{22}^L(Y - Y_o^L) + m_{23}^L(Z - Z_o^L)}{m_{31}^L(X - X_o^L) + m_{32}^L(Y - Y_o^L) + m_{33}^L(Z - Z_o^L)}\right) \quad \text{... (9)}$$

It can be readily seen that the object coordinates (X,Y,Z) could be computed by using Eqns. (4a), (4b), (6) and (7), i.e. 6 equations against 3 unknowns. In other words, a least squares could be performed to solve for the unknowns. However, as explained by, e.g. Wolf and Dewitt (2000) the computations of the object space coordinates *X* and *Y* can be reduced by substituting either Eqn. (4a) or (4b) into Eqns. (6), (7), (8) and (9). Since good determination of parallax is achieved in the *x* direction (i.e. better intersection of the rays) it is best to use Eqn. (4a), (6), (7), (8) and (9) for computing the object space coordinates. The *Z* component is then obtained by back substitution into either Eqn. (4a) or (4b). In this experiment, the latter approach is adopted for the computations of the object space coordinates. It should be reminded that the pair image coordinates (x,y) used in the collinearity equations must be corrected for lens distortions. The lens distortion correction can be performed during inner orientation stage.

3.0 Laboratory Experimental Set-up

The load test on full scale structure component in this experiment was carried out at Structure and Material Laboratory, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai. The following part will discuss in the preparation of digital close range photogrammetry system thus includes the camera calibration process and structural laboratory set-up prior to the structural components load test experiments.

3.1 DCRP Cameras

The digital cameras used in this research were a pair of Nikon D70 fitted with AF Nikkor 18-50mm lenses and a Nikon D300 fitted with a 18-50mm lens. The CCD sensor sizes of the cameras are 3008 by 2000 pixels (6 megapixels for Nikon D70) and 4288 by 2848 pixels (12 megapixels for Nikon D300). The size of each square pixel for the D70 and D300 is 0.008mm and 0.005mm respectively. All digital cameras used in this experiment were calibrated prior to experiments to determine the characteristics of the camera parameters. The camera calibration is required to determine the camera parameters such as the focal length of camera (f), image coordinate of the perspective centre (x_o, y_o), radial distortion parameters (K_1, K_2, K_3) and tengential distortion parameters (P_1 and P_2) for each camera used. The camera parameters are very important for correction of the lens systematic errors if precise measurements are required.

A calibration plate that consists of 88 points of retro-reflective targets is use prior to the test whose spatial coordinates were determined using a Leica TCR 1200 total station. The standard errors in the positioning of the targets are ±0.2mm in xyz directions. The target plate was tilted and rotated into different orientations while images were acquired. The images were then used in the camera calibrations process to determine the camera parameters using bundle adjustment technique. The bundle adjustment used was Australis software.

3.2 Description of Structural Beam-Columns Specimen

The full scale experimental test of monolithic conventional reinforced concrete was carried out with H-shape cut-out beam and columns (subframe). The size of the beam and column is 300 mm x 300 mm. The H shape sub-frame has a 3300 mm clear span and also the total columns' height. Beam longitudinal reinforcement consists of two 16 mm high tensile steel bar embedded in upper and bottom of section of beam. Longitudinal bars of columns are considered as 8 numbers of 16 mm steel bars. Steel stirrups are assumed as 1T10 mm@100 mm of beams length. The longitudinal bars have standard hooks at their ends continued in column section to satisfy the rigid connection between beam and columns. The longitudinal steel bars grade is 460. The grade of stirrups steel is 250. Concrete Compression strength is 30 MPa. The support conditions at the ends of the columns are arranged to shape it as hinged.

3.3 Load Test Experiment Set-Up

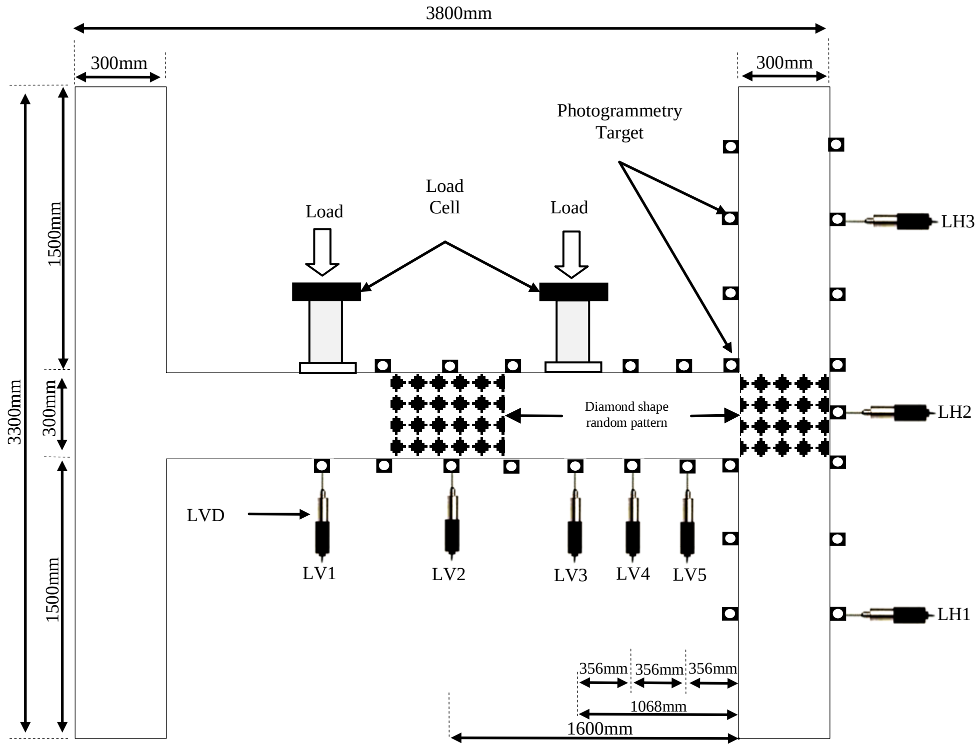
Reinforced concrete beam and column connection of structure specimens were fabricated at structure and material laboratory by Industrial Industrialise System Research Group, Faculty of Civil Engineering, Universiti Teknologi. These structural components were mounted on the Magnus frame as shown in Figure 2. Images of the structure component were captured at each load applied. A pair unit of Nikon D70 and single unit of Nikon D300 were mounted on a stainless steel bar located 3.4m from the structure component as shown in Figure 3. Total of 81 target points used as controls in order to determine camera positions (x,y,z) and camera orientation (ω,ϕ,κ) respectively. The spatial coordinates of control points were determined via intersection method using Leica TCR1200 robotic total stations.

A total of five unit LVDTs (LV1, LV2, LV3, LV4 and LV5) were placed at the bottom of beam (including one at mid point and two exactly under two load point) where the beam vertical displacement was measured. An additional of three LVDTs (LH1, LH2 and LH3) were placed on the column where the column horizontal displacement will be measured. While the photogrammetry targets were placed/aligned with the LVDTs sensor location so that the LVDTs readings could be directly compared to those obtained photogrammetrically. The locations of the LVDTs and photogrammetry targets are as shown in Figure 4.

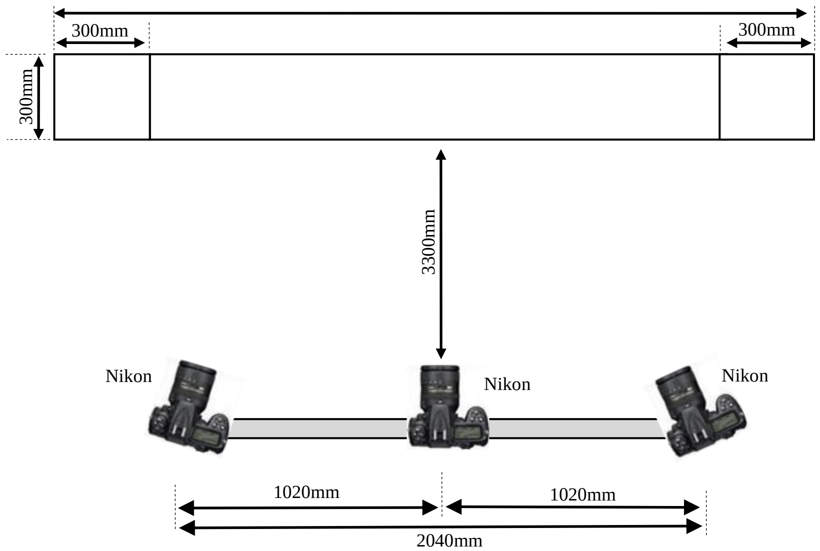
Loads were applied at two points at 1/3 and 2/3 beam length respectively. A ten percent (0kN – 8kN) and thirthy percent (0kN – 26kN) of the total load were applied on the structure and decreased to zero before the loading continue until the structure failed (predicted at 80kN). The final loading steps were increased at every 5kN and the actual breaking point of the structural beam was at 100kN. At each step after the deformation had stabilised, both LVDTs and photogrammetry data was collected simultaneously. The digital images captured via DCRP technique then processed using image processing technique to measure the displacement magnitude.

Figure 2: Full scale concrete beam-column

Figure 3: DSLR cameras fixed on steel bar



(a) Front view

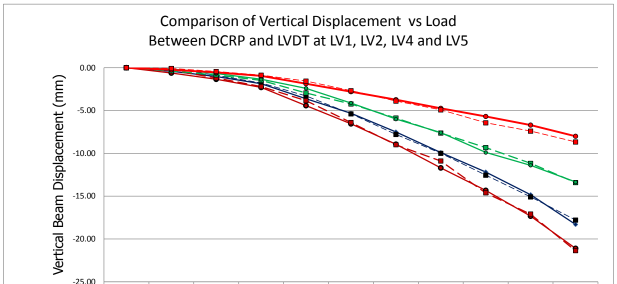


(b) Plan view

Figure 4: Schematic diagram illustrates the DCRP set-up for the load test experiment

4.0 Results and Discussion

Figure 5 and Figure 6 show the vertical and horizontal displacements behaviour of structural beam and column respectively. Adopting the displacements given by the LVDTs as baseline data, it can be readily seen that the average differences for the vertical displacement between DCRP and LVDTs techniques at LV1, LV2, LV3, LV4 and LV5 are 0.24mm, 0.30mm, 0.31mm, 0.22mm and 0.32mm respectively.



	0 KN	10 KN	20 KN	30 KN	40 KN	50 KN	60 KN	70 KN	80 KN	90 KN	100 KN
LVDT LV-1	0.00	-0.41	-1.03	-1.86	-3.63	-5.32	-7.51	-9.92	-12.19	-14.84	-18.31
DCRP LV-1	0.00	-0.10	-0.90	-1.80	-3.30	-5.40	-7.80	-10.00	-12.55	-15.10	-17.80
LVDT LV-2	0.00	-0.61	-1.34	-2.29	-4.43	-6.55	-8.93	-11.70	-14.32	-17.33	-21.10
DCRP LV-2	0.00	-0.30	-1.20	-2.20	-3.85	-6.40	-9.00	-10.90	-14.63	-17.10	-21.38
LVDT LV-4	0.00	-0.38	-0.85	-1.47	-2.95	-4.24	-5.88	-7.63	-9.34	-11.17	-13.42
DCRP LV-4	0.00	-0.15	-0.68	-1.35	-2.40	-4.13	-6.00	-7.58	-9.90	-11.40	-13.35
LVDT LV-5	0.00	-0.24	-0.54	-0.95	-1.86	-2.81	-3.73	-4.75	-5.70	-6.71	-8.01
DCRP LV-5	0.00	-0.10	-0.44	-0.88	-1.56	-2.68	-3.90	-4.92	-6.44	-7.41	-8.68

LV5

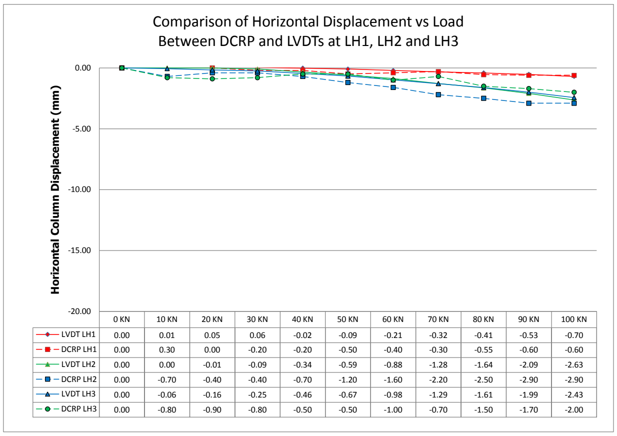
LV4

LV1

LV2

Figure 5: Beam vertical displacement comparison between DCRP and LVDT at LV1, LV2, LV4 and LV5

The horizontal displacements at LH1 obtained by DCRP and LVDTs only differ by 0.17mm. The differences at LH2 and LH3 are rather substantial, i.e. 0.6mm and 0.37mm respectively. The differences obtained were statistically tested to determine whether they are significantly different or otherwise. Applying at t-test with the confident level of 5% revealed that the difference between the two sets of results is not significant.



	0 KN	10 KN	20 KN	30 KN	40 KN	50 KN	60 KN	70 KN	80 KN	90 KN	100 KN
LVDT LH1	0.00	0.01	0.05	0.06	-0.02	-0.09	-0.21	-0.32	-0.41	-0.53	-0.70
DCRP LH1	0.00	0.30	0.00	-0.20	-0.20	-0.50	-0.40	-0.30	-0.55	-0.60	-0.60
LVDT LH2	0.00	0.00	-0.01	-0.09	-0.34	-0.59	-0.88	-1.28	-1.64	-2.09	-2.63
DCRP LH2	0.00	-0.70	-0.40	-0.40	-0.70	-1.20	-1.60	-2.20	-2.50	-2.90	-2.90
LVDT LH3	0.00	-0.06	-0.16	-0.25	-0.46	-0.67	-0.98	-1.29	-1.61	-1.99	-2.43
DCRP LH3	0.00	-0.80	-0.90	-0.80	-0.50	-0.50	-1.00	-0.70	-1.50	-1.70	-2.00

LH1
LH2
LH3

Figure 6: Column horizontal displacement comparison between DCRP and LVDT at LH1, LH2 and LH3

5.0 Conclusion

This experiment has demonstrated the DCRP technique in measuring structural beam and column connection displacements under laboratory conditions. The DCRP technique has been successfully applied for civil structural component such as beam and column displacement measurement. This is clearly indicated by the small differences in the deflections. DCRP could provide additional information to structural engineers in structural beam and column displacements analysis. DCRP method can be used to measure deformational behaviour of beam-column under loading. The statistical test show insignificant differences between LVDT (contact) and DCRP (non-contact). Relevant data which was acquired by using DCRP will facilitate in the undertaking in-depth analysis on deformational behaviour of structural components.

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