

MEASUREMENT OF DEFLECTIONS IN CONCRETE BEAMS BY CLOSE-RANGE DIGITAL PHOTOGRAMMETRY

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Abstract

This paper describes the use of digital photogrammetry for measurement of deflections in concrete beams during destructive testing. A two-video camera system was used to measure vertical deflections with a precision of $\pm 0.25\text{mm}$ (1σ). The system, network design and processing methods are described in detail. Results are presented from several tests of different types of beams. Some of the advantages over contact methods including three-dimensional measurement of deformation components, unrestricted measurement range and immunity to non-linear systematic errors are demonstrated. Comparison is made of photogrammetric and linear-variable-differential transformer deflection measurements.

Key words: digital photogrammetry, deflection measurement, structural testing.

1. Introduction

Load testing of structures and individual structural elements (e.g., beams, columns, slabs, etc.) is performed for both assessment of strength and for refinement of theoretical finite element models. Assessment testing of bridges, for example, is made necessary by strength deterioration over time (due to cracking, creep, shrinkage, poor concrete quality and corrosion of steel reinforcing and pre-stressing tendons) and/or less stringent standards at the time of design and construction (Mehrkar-Asl and Brookes, 1997). A testing regime might consist of *in situ* tests in which the bridge is subjected to both static and dynamic loads and destructive testing of individual members to estimate their ultimate strength.

A number of concrete beams have been destructively tested at Curtin University for flexural and shear strength estimation. These include inverted U-shaped reinforced concrete beams and rectangular pre-stressed concrete beams. The beams were taken from bridges around Western Australia that have been replaced and subsequently dismantled. However, a number of bridges that utilise members of similar construction still exist around the state. The inverted U-shaped beams were designed for single axle truck traffic and constructed in the late 1950s. The concern that motivated the testing was the beams' ability bear the load of heavier, multiple axle truck traffic. If beam strength was found to be insufficient, then reinforcement with steel tendons or carbon fibre strips would be necessary.

Beam deflection measurements—critical to structural assessment—are typically obtained with contact instrumentation such as dial gauges and linear-variable-differential transformers (LVDTs). In short, an LVDT yields an induced voltage signal proportional to the displacement experienced by its iron core that resides within a set of coils. A more concise description of LVDT operation can be found in Doebelin (1990). Whilst very precise, these sensors provide only one-dimensional information and are best suited to laboratory use as their response can be biased by external electromagnetic fields. Furthermore, LVDT travel (i.e., measurement range) is limited and accuracy degrades significantly outside its linear range, which restricts the magnitude of deflection that can be measured. An additional concern in destructive testing is damage to instrumentation that necessitates its removal, thus prohibiting deflection measurement when the beam is close to failure.

Digital photogrammetry offers several advantages over conventional instrumentation for deflection measurement. Photogrammetry is non-contact, requires no manual reading of dials, yields three-dimensional measurements and provides visual records of the testing. It is ideally suited for destructive testing since only a set of inexpensive targets is lost or damaged rather than expensive LVDTs or dial gauges. Digital photogrammetry has been successfully applied for similar

metrology tasks including testing of concrete slabs and columns (Woodhouse *et al.*, 1999), thermal deformation of steel beams (Fraser and Riedel, 2000), pavement deformation under rolling load (Mills *et al.*, 2001) and deformation of a coal dredger (Fraser and Shortis, 1995).

Destructive testing of numerous beams was conducted in a laboratory at Curtin University. Beam deflections were measured using both conventional methods (dial gauges and LVDTs) as well as digital photogrammetry. This paper describes the photogrammetric system, network design and methods used to measure the beam deflections. A comparison of results from the photogrammetric system and LVDTs highlights the advantages of the optical method for such a project.

2. Testing Lab Facilities

The Curtin University Civil Engineering heavy testing laboratory is pictured in Figure 1. The image shows an inverted U-shaped reinforced concrete beam undergoing flexural testing. Load was applied near the mid-span of the beam with two hydraulic jacks suspended from the two heavy steel frames. The beam was simply supported at both ends. Numerous retro-reflective targets on and around the beam are visible in the scene.

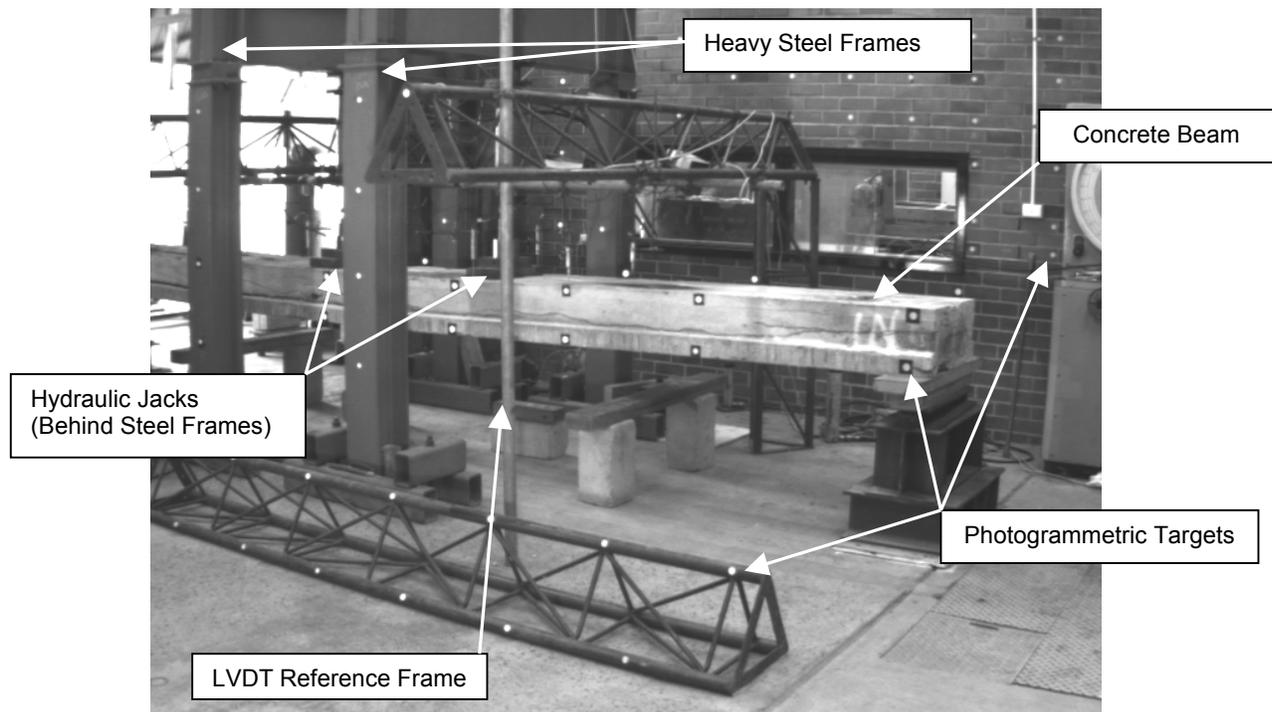


Figure 1. An inverted U-shaped reinforced concrete beam undergoing flexural testing.

The layout of the testing area, shown schematically in Figure 2, was relatively confined with approximate dimensions of 7m x 7m. The crowded confines of the lab posed a challenge at the photogrammetric network design stage in terms of the trade-off between camera station placement, field of view (FOV), convergence angle and attainable positional precision. However, acceptable precision was achieved, as detailed in forthcoming sections. Target placement had to be carefully considered due to the numerous obstacles in the lab that included:

- The supporting frames for the hydraulic jacks;
- The hydraulic lines to the jacks and the jacks themselves;
- The reference frame and supports for the LVDTs;
- The end supports for the beams;
- The beam being tested; and
- Other equipment not used for the destructive testing.

Some of these occluding objects can be seen in Figure 1.

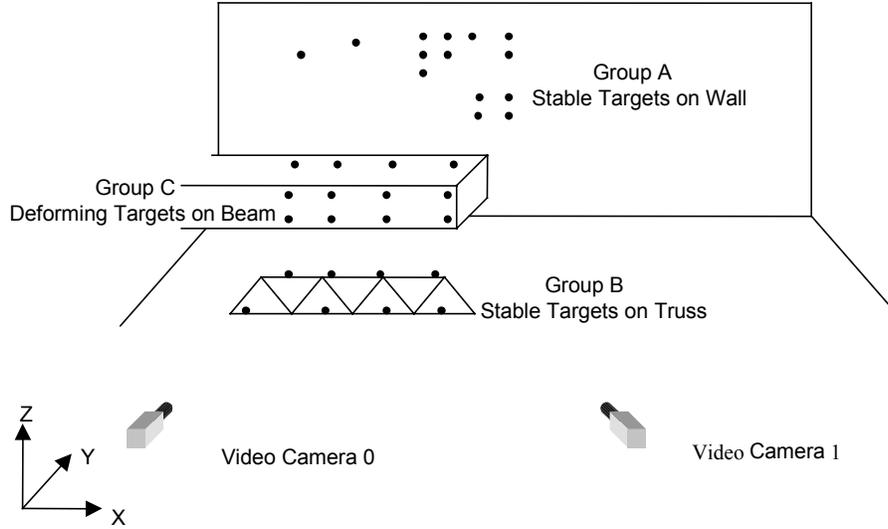


Figure 2. Schematic diagram of the heavy testing laboratory layout and photogrammetric network.

3. Imaging System

Since cost was the limiting factor in the purchase of equipment for the photogrammetric system, low-resolution video cameras were acquired. Two JAI CV-M50 1/2" CCD video cameras, each fitted with an 8 mm C-mount lens, were used. Images were captured with a two-channel Imaging Technology IC-ASYNCR frame grabber card and accompanying software. The grabbed image size was 768 x 574 pixels.

Prior to testing, the cameras were self-calibrated to determine their principal distance, principal point offset and additional parameters (APs). The following AP set was chosen

$$\Delta x = \bar{x}(k_1 r^2 + k_2 r^4 + k_3 r^6) + p_1(r^2 + 2\bar{x}^2) + 2p_2 \bar{x}\bar{y} + a_1 \bar{x} \quad (1a)$$

$$\Delta y = \bar{y}(k_1 r^2 + k_2 r^4 + k_3 r^6) + p_2(r^2 + 2\bar{y}^2) + 2p_1 \bar{x}\bar{y} \quad (1b)$$

where

$\Delta x, \Delta y$ are the corrections to the observed image point co-ordinates;
 \bar{x}, \bar{y} are the image point co-ordinates reduced to the principal point;
 r is the radial distance given by

$$r = \sqrt{\bar{x}^2 + \bar{y}^2} ; \quad (2)$$

k_1, k_2, k_3 are the coefficients of radial lens distortion;
 p_1, p_2 are the coefficients of decentring lens distortion; and
 a_1 is the x-axis scale factor that arises due to electronic digitising bias.

Sixteen images of an indoor, retro-reflective target field were captured with each camera. The standard design measures of convergent imaging geometry and orthogonal exposures were incorporated into the calibration network. *Australis* version 5.02 (Fraser and Edmundson, 2000) was used for both camera self-calibration and off-line co-ordination of targets on the concrete beams during the testing campaign. The high degree of radial distortion in the lenses is evident in both the curvature of the brickwork at the top of Figure 2 and in profile shown in Figure 3. For Camera 0, the distortion, δr , reached a maximum of 413 μ m at a radial distance, r , of 4mm. Camera 1 exhibited a similar distortion profile.

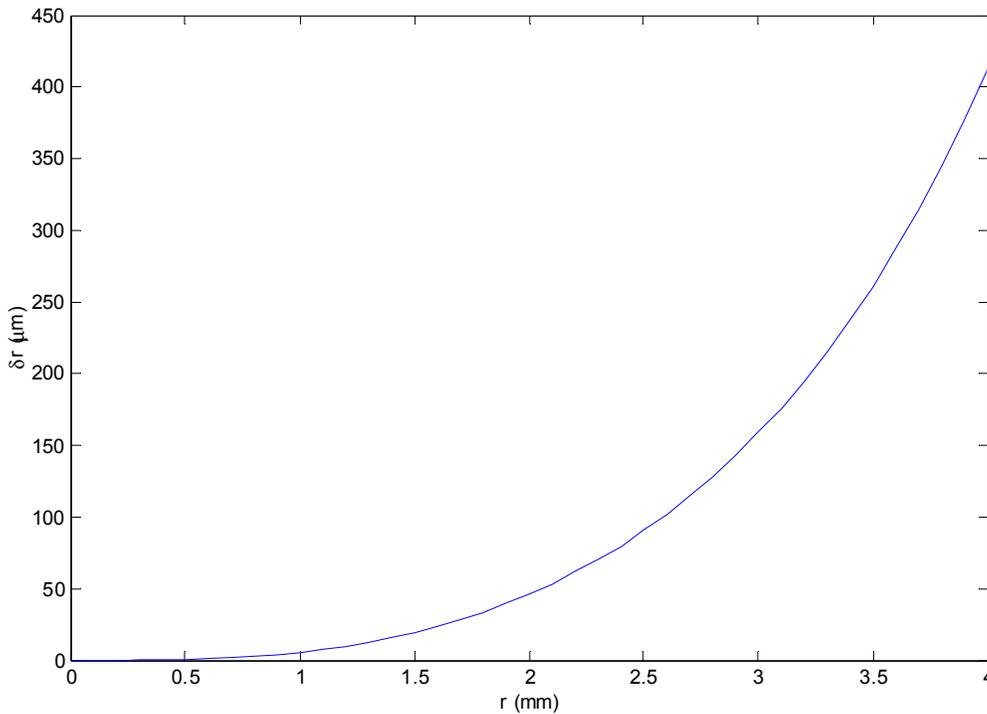


Figure 3. Camera 0 radial lens distortion profile.

Targets placed on the concrete beams were a composite of a punched circle of silver 3M Scotchlite retro-reflective film centred on a square, black background. To ensure that each target image spanned at least four pixels, various circle diameters (20 to 40 mm) were used as appropriate. The need for such large targets was the low resolution of the video cameras. Small lens apertures and artificial lighting were used to ensure high contrast between target materials.

4. Network Design

Images of the targeted beam were acquired from two camera locations at regular intervals of applied load, with each epoch of imagery being captured a few minutes apart. The cameras remained stationary throughout the duration of the testing since their movement between epochs was not feasible primarily due to the video camera cabling and other testing equipment in the laboratory and the short time interval between load applications. This constraint prohibited optimisation of precision and reliability through a multi-station network design.

As shown in Figure 2, the network of object space points was divided into three groups: A, B and C. Group A points were mounted on the laboratory wall behind the beam and therefore stable throughout the duration of the testing campaign. These were co-ordinated by close-range surveying methods using electronic total station and invar subtense bar. The targets of group B were mounted on a heavy steel truss placed in front of the concrete beam to add geometric strength to the network. These points were stable during a beam test, but were moved between tests to allow forklift access to the concrete beam. The points of groups A and B were included in the inner-constraints datum definition in the bundle adjustment. Group C consisted of the targets on the concrete beam (known to be deforming) and points on the steel frames (possibly deforming in reaction to the applied hydraulic load). Initial approximate co-ordinates for both Groups B and C were determined by photogrammetry.

In order to exploit the stationarity of object point groups A and B, all epochs of imagery for a given beam were simultaneously adjusted. Group C points (deforming) were given different identifiers in *Australis* to distinguish the individual epochs. Table 1 presents a typical example of the object point precision obtained with this approach. Mean object point precision was determined from 25 group C points for a flexural strength test of a pre-stressed concrete beam. As would be expected, the Y-axis (depth) precision worse than that for the X- and Z-axes by a factor of two. Of primary interest, though, were the Z-axis (vertical) measurements, for which mean precision was $\pm 0.24\text{mm}$ (1σ).

Table 1. Mean Object Point Precision.

$\bar{\sigma}_X$ (mm)	$\bar{\sigma}_Y$ (mm)	$\bar{\sigma}_Z$ (mm)
± 0.27	± 0.54	± 0.24

The relatively low object point precision can be attributed to two sources: camera resolution and intersection geometry. Only low-resolution video cameras were available, as indicated previously, and each point in group-C was estimated with only two intersecting rays with a relatively low convergence angle ($\approx 47^\circ$). Though much greater digital photogrammetric precision has been achieved in industrial settings (see for example, Fraser and Shortis, 1995), the precision attained was deemed adequate for this project since deflections on the order of several tens of millimetres were expected.

5. Test Results

Three pre-stressed concrete beams and thirty-four reinforced concrete beams with reinforcing materials were tested for flexural and shear strength at the Curtin lab over the course of several weeks. Deflection measurements were logged continuously by LVDTs and at recorded at discrete intervals by dial gauge and digital photogrammetry. Some of the more interesting results are presented herein.

5.1 Pre-Stressed Beams

Three pre-stressed concrete beams were tested for flexural strength. The rectangular beams were 6.6m long, 0.29m high and 0.6m wide. Pre-stressed beams are able to withstand large deflections at high loads due to their high tensile strength resulting from the pre-stressed steel cables.

Testing of the pre-stressed beams began by applying load to the beam in equal increments of hydraulic line pressure until first flexural cracking occurred. The load was then removed and the beam allowed to elastically rebound. The load was then reapplied until failure of the beam occurred. The load-reload test strategy was adopted to identify the forces in the steel tendons. The increments of load application varied and depended upon the type of test and amount of load already applied. In general, the increments were smaller for shear tests and when the beams were close to failure. Typically, the increments were 2 or 4GPa.

Figure 4 is a load-deflection curve for one of the pre-stressed beams determined by both digital photogrammetry and an LVDT. The residual 0.7mm displacement at zero load represents the permanent, plastic deformation of the beam from the initial load application. The load-displacement curve resulting from load reapplication parallels the original curve. The non-linear behaviour of the curve indicates a gradual change in beam stiffness due to cracking of the concrete (Warner *et al.*, 1989). Note the large deflection of this beam: nearly 55mm at 247kN, the last measurement obtained prior to failure.

The loci of photogrammetric and LVDT data points follow similar patterns but parallel each other due to an offset between the target and LVDT that could not be accurately co-located for these tests. However, results and analyses from tests conducted on other beams, in which co-location was possible, are presented below. The LVDT locus deviates significantly from the photogrammetric data trend at 21mm deflection, which highlights one of the drawbacks of this technology. The measurement range of this particular short-travel LVDT was limited to 25mm, of which only 20mm could be considered to reliably lie within the instrument's linear range.

Figure 5 is a vector plot of total deflections in the X-Z plane for the same beam at a load of 247kN. The mid-span of the beam, where the largest Z deflections occurred (77mm at point 11), was located mid-way between the two hydraulic jacks. This figure illustrates one of the advantages of photogrammetry for structural testing: three-dimensional measurement of point displacements that gives the complete picture of how the beam was deforming in response to the applied loads. The vectors in Figure 5 point toward the beam's mid-span due to bending, an expected phenomenon not captured by the LVDTs. Points 15 and 25 were located above one of the end supports and, thus, experienced no vertical displacement. However, point 15 did experience some horizontal displacement due to bending of the beam. In other tests, significant displacements in Y—that could not be detected by LVDT—were observed photogrammetrically. These displacements were believed to be due to non-centric loading of the beam.

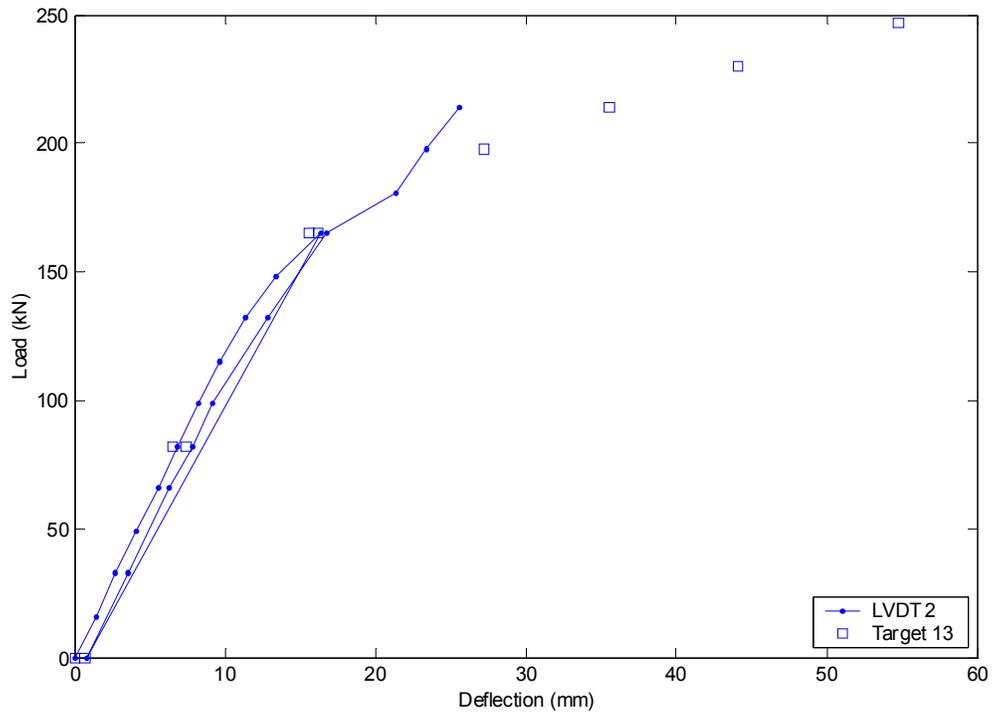


Figure 4. Load vs. deflection for pre-stressed beam 2 measured by LVDT and photogrammetry

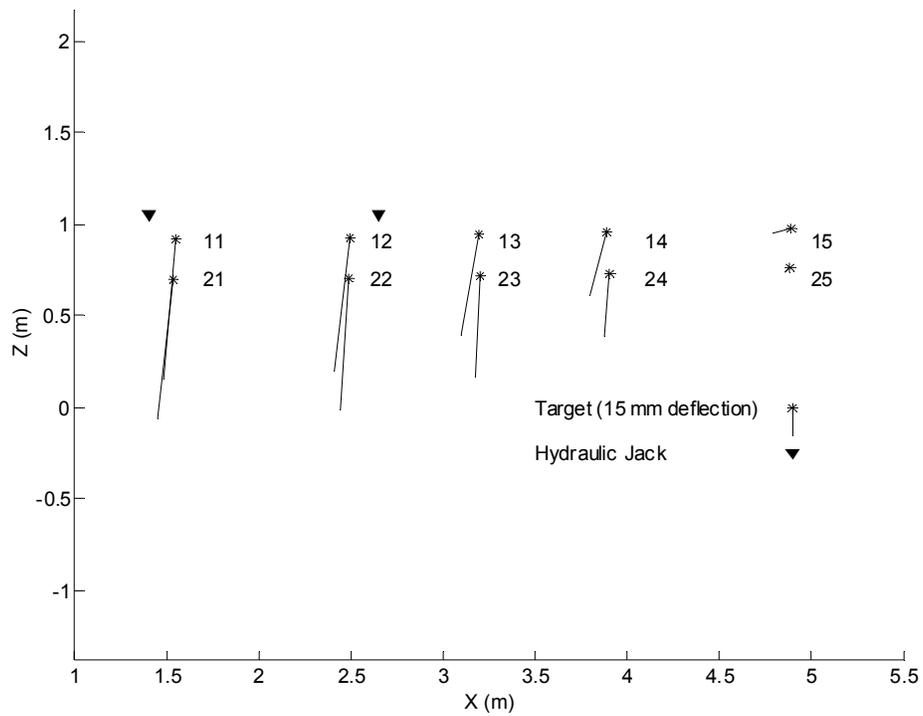


Figure 5. X-Z displacement plots for pre-stressed beam 2 measured by photogrammetry.

5.2 Carbon Fibre Reinforced, Inverted U-Shaped Beams

Tests were conducted on the inverted U-shaped beams reinforced with carbon fibre strips. The beams were 6.4m long, 0.94m wide and 0.41m high with long strips of carbon fibre material bonded to their underside to improve their tensile strength. The goal of this testing was to ascertain whether the carbon fibre reinforcement would improve the strength of the 40+ year-old beams to adequately bear the load of modern truck traffic.

Co-location of LVDTs and photogrammetric targets that facilitated direct comparison of the two methods was possible in these tests. The image in Figure 6 shows the co-location of target and LVDT on a beam after shear failure, which is indicated by the large diagonal crack. Generally, shear testing involves application of greater load closer to an end support and results in smaller deflections. Thus, it was an ideal opportunity to test the photogrammetric system's ability to measure deformations of smaller magnitude.

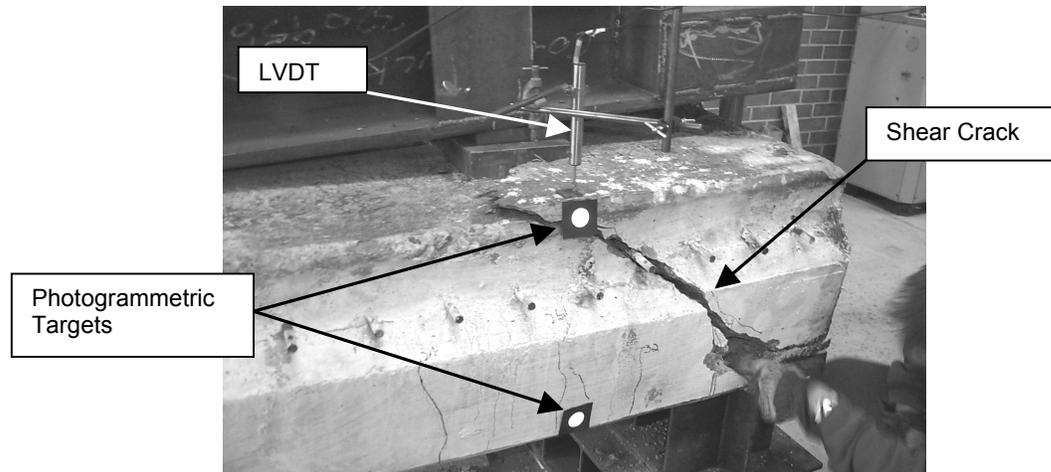


Figure 6. Shear crack of carbon-fibre reinforced concrete beam and co-located photogrammetric target and LVDT.

A load-deflection diagram from the shear testing is plotted in Figure 7. Note the smaller overall deflection (8.9mm at 389kN) than that realised in the flexural test. Also note the different deflection axis scale than that of Figure 4. The LVDT data series ends at 5 mm since the contact instruments were removed prior to failure of the beam to prevent damage. Failure in this case occurred shortly after the last set of images was acquired. The photogrammetric and co-located LVDT measurements coincide fairly well, with the maximum and RMS differences being 0.16mm and ± 0.10 mm, respectively.

5.3 Kerb Section of the Inverted U-Shaped Beams

A kerb section inverted U-shaped beam was also tested for flexural strength. This beam was not reinforced with additional materials and had roughly the same dimensions as the previously described U-shaped beam save for the kerb on one side of its top face. Due to the asymmetric cross-section, some torsion of the beam was expected in response to the centric loading. Results from this test are included here to further demonstrate the advantage of photogrammetry over LVDTs for measuring three-dimensional deformations.

Figure 8 shows photogrammetrically measured displacements in the X-Y plane. The vectors have both a small X-component due to bending and a more significant Y-component due to the torsion. Again, a more complete picture of the deformation mode is obtained with photogrammetry than with the LVDTs.

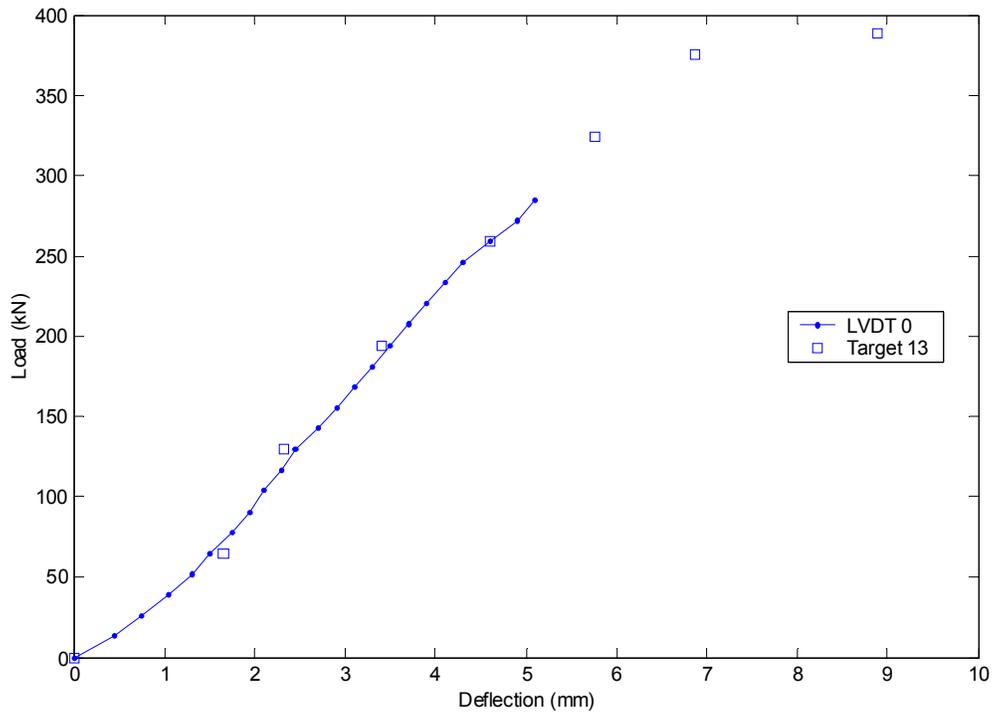


Figure 7. Load vs. deflection for carbon-fibre reinforced beam undergoing shear testing measured by LVDT and photogrammetry.

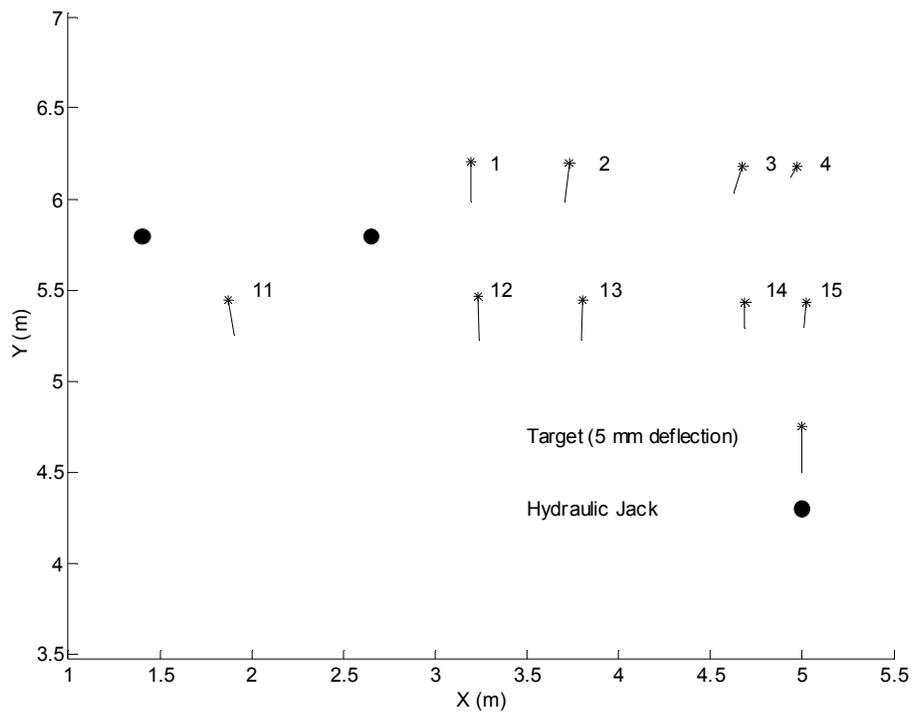


Figure 8. X-Y displacement vectors for a kerb section of a reinforced concrete beam undergoing flexural testing.

6. Conclusions

In summary, measurement of deflection in concrete beams during destructive testing using low-resolution video cameras has been successfully demonstrated. Sub-millimetre object point precision was achieved in all three co-ordinate dimensions, giving complete information about the mode of deformation that the contact sensors could not deliver. The study has also highlighted some of the problems with LVDTs that include limited range, non-linearity of response and the ability to measure only in one dimension. Comparison of co-located targets and LVDTs indicated close agreement between deflection measurements obtained from both data sources.

Though the precision attained was modest relative to what can be achieved with higher resolution CCD cameras, it was adequate for the testing described herein. The success of this project has led to new collaborative projects, one of which will involve *in situ* testing of wooden bridge sections under static loading conditions.

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