

AN AUTOMATIC TECHNIQUE FOR ACCURATE NON-CONTACT STRUCTURAL DEFORMATION MEASUREMENTS

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ABSTRACT:

This paper presents an automatic, close-range photogrammetric process developed to measure point-wise 2D deformations of a concrete beam during a loading experiment. Required accuracy was better than 1 mm. A non-contact method is proposed, which is simple to implement and provides almost online results that meet the accuracy requirements fully. This technique requires only one known distance between two signed points, and the use of specifically designed targets. First, a stereopair is acquired by a calibrated digital camera. The camera stays still in its last position, while images are taken periodically during the load epochs. When data collection is completed, the relative orientation of the stereopair is calculated automatically. The image point coordinates are measured using a template matching algorithm, based on normalized cross-correlation, and the homologous points between the two images are located by automatic recognition of the code number of each signed point. Next, 3D point coordinates are calculated by a photogrammetric intersection solution using the known relative orientation parameters in an arbitrary reference system. As all monitored points of the front side of the beam remain practically on the same plane during the load epochs (2D deformations), the image-point coordinates are measured automatically for each epoch, and their 2D-coordinates are calculated. Using the known distance, the scale of the system is defined and all deformations are transformed into the object space.

The inner accuracy is determined by comparing consecutive images of each epoch, while the outer accuracy through the comparison of the results with measurements using dial gauge. The results in both cases show that the overall accuracy of the method is approximately 1.5 pixels, or better than 1 mm in object space.

1. INTRODUCTION

Structural assessment is mainly based on information about the materials, which is usually obtained experimentally. Deformation monitoring of construction objects, like beams, in laboratory conditions, are very useful for the theoretical design of material behaviour modelling. Deformation monitoring is typically undertaken using point-wise measurements. The observation techniques include two basic methods: contact and non-contact.

In contact methods, dial gauges, LVDTs (Linear Variable Differential Transformers) and fibre optics are used to measure 1D or 3D displacements with an accuracy of 0.01 mm – 1 mm. These methods face two major problems: the measuring instruments may be damaged during the experiment, and the points measured cannot be dense and well distributed.

Non-contact methods include geodetic techniques, terrestrial laser scanning, close-range photogrammetry and videometry. All the above methods can achieve results comparable with those of the contact methods, in terms of accuracy, but they don't share their limitations and they are more flexible. Consequently, non-contact methods are dominant in the field of accurate deformation measurements.

Geodetic techniques implement spatial intersection for the determination of the 3D coordinates of specific points, by acquisition of high accuracy angle measurements. It is impossible to monitor dynamic deformations by manual measurements, because the measuring procedure is very time consuming (Tsakiri et al., 2004). There is a possibility to speed up the procedure by employing robotic theodolites, yet their

price is very high considering the fact that at least two of those are needed.

Terrestrial laser scanning is a new and promising technique, which is not thoroughly tested yet. Laser scanners can capture an enormous and dense 3D data set in a small period of time. Even though their single point accuracy is relatively small, with proper modelling techniques the accuracy achieved can be high (Gordon et al., 2003). The main disadvantage of these methods is the still extravagant cost of such sensors.

Videometry is using video sequences that provide 3D information in real time and is ideally suited for monitoring dynamic deformations. In order to achieve accurate results by this method, the use of expensive very high definition synchronised camcorders is required.

Close-range photogrammetric techniques implement photo-triangulation using bundle adjustment to determine 3D coordinates of a large number of points in a single adjustment. This can be done automatically in various ways, but off-line, providing very accurate results (Fraser et al., 2000). Special exterior orientation devices are used as well as complex testing arrays. To complete the whole procedure in real time, more than two synchronised cameras are required a fact that also limits the use of such techniques.

Recently, the Laboratory of Photogrammetry of N.T.U.A. contributed to a deformation monitoring experiment on a concrete beam reinforced with FRP (Fibre Reinforced Polymers) bars. It was decided that the selection of the appropriate technique should take into account four basic parameters:

- Simplicity, so that even a non-expert could do the measurements;
- On-line or almost on-line calculation of results;
- Use of low-cost equipment;
- Accuracy better than 1 mm.

From the above, it is evident that none of the methods mentioned completely satisfies the four basic requirement needs, mainly in terms of cost and simplicity. Yet, the geometric characteristics of the object allowed the use of an alternative close-range photogrammetric technique. The selected approach involves an easy and quick data mass collection without the need for geodetic measurements. The only instruments needed are a digital camera, in this case a Canon EOS-1D Mark II 8 Mp, and a measuring tape. The results are calculated almost on-line due to the automation of the whole measuring process and their accuracy is in fact better than 1 mm.

2. AUTOMATIC MEASUREMENTS

Automatic photogrammetric measurements require less time and effort, while in many cases their results are of equal accuracy and reliability of those achieved manually. In the case presented here, the automation was necessary in order to simplify the process and increase its speed. The measurement process includes two stages: localisation based on template matching, and recognition of coded targets based on point tracking techniques (Psaltis, 2005).

2.1 Automatic localisation

Automatic localisation is achieved by various matching techniques. When data are collected in a controlled environment, a-priori knowledge can be used to make matching more effective. Strategies employing such knowledge and especially the shape and size of the template to be localised, are referred to as template matching (Schenk, 1999). Template matching is usually executed in two phases, approximate and precise localisation. In the first phase, by using a method to reduce search space and a matching method, approximate positions of possible templates are located. These are used as initial values for the next phase, where the final position of the template is defined with sub-pixel accuracy. In general there are many combinations of methods that can be implemented depending on the conditions of the experiment and the accuracy needs. The combined method used here is a normalised cross-correlation and image pyramids for the approximate localisation and the perimeter method for the precise localisation. In normalised cross-correlation the template lays on every possible position on the image, and then the value of the coefficient ρ (Equation 1) is calculated for every position. The final position of the template is that where ρ has the maximum value.

$$\rho(u, v) = \frac{\sum_{i=u}^{u+R} \sum_{j=v}^{v+C} [g(i, j) - \bar{g}_{uv}] [t(i-u, j-v) - \bar{t}]}{\sqrt{\sum_{i=u}^{u+R} \sum_{j=v}^{v+C} [g(i, j) - \bar{g}_{uv}]^2 \sum_{i=u}^{u+R} \sum_{j=v}^{v+C} [t(i-u, j-v) - \bar{t}]^2}} \quad (1)$$

where
 g = image function of the reference
 t = image function of the template
 R = rows of the template
 C = columns of the template

In the perimeter method, four points on the perimeter of the template and on opposite directions are located through an edge extraction technique. The final coordinates of the target are given by the Equations (2).

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i, \quad \bar{y} = \frac{1}{n} \sum_{i=1}^n y_i \quad (2)$$

where $x_i, y_i = x, y$ coordinates of the points on the perimeter
 $n =$ total number of points on the perimeter.

These methods are all easy to develop and flexible in use, maintaining a satisfactory accuracy of about 0.5 pixels. Knowing that the normalised cross-correlation is affected seriously by geometric distortions (Trinder et al., 1992), the only prerequisite is to avoid importing such distortions to the images collected, which in laboratory conditions can be easily achieved. Because the coefficient is normalised, it absorbs radiometric distortions (Ulrich, 2002) so there is no need of certain lighting conditions.

2.2 Automatic recognition

Automatic integration of data related to the same points and derived from various sources is frequently needed to accomplish a variety of tasks, such as automatic relative and exterior orientation, or even automatic bundle adjustment. To achieve this, automatic point recognition is required. There are two major approaches for that. First, to recognise the points, the geometric constraints of the data and the relations between the points are exploited. Second, each point is signed with a unique target to be recognised by the appropriate software (Fraser, 1997). The major difference between these two approaches is that the first approach is suitable both for signed and unsigned points, whereas the second is only suitable for signed points. The second approach has no need for any constraint. Considering the fact that the points to be measured will be signed, the second approach is chosen to be the most appropriate. The targets were developed together with the decoding software and the localisation algorithms to achieve maximum compatibility and fine tune the procedure of automated measurements.

Target size, shape and encoding strategy are the major concerns. In many cases the size of the coded targets is considerably large (Knyaz, 1998). If such targets are placed on a small object, like a concrete beam, it will be a major drawback. The shape of the target plays a key role for localisation and recognition, as it must be resistant to geometric distortions, scale and rotation. The encoding strategy must ensure a great number of unique codes, since some applications, such as calibration, require a lot of points to be measured.

The above problems are solved by the design shown in Figure 1. After testing various sizes and proportions between the features of the target (Psaltis, 2005), the dimensions shown, allow robust localisation of the template with the method mentioned above. The targets are small and invariant to rotation and scale due to their circular shape.

The target has a rectangular shape, and the position of the point is determined by the centre of a black circle; the code of the point is defined by the small black circles that appear in some of the 16 fixed positions in a circular coding strip arrangement (Figure 1b). According to the coding strip, the use of two consecutive black dots signifies the beginning of the code. This way the coding can be invariant to rotation κ , but in the same time there are less maximum unique codes, since there can't be

any other directly successive black dots in the coding strip. Using this encoding strategy, 79 unique codes were produced, but their number can be further increased if necessary.

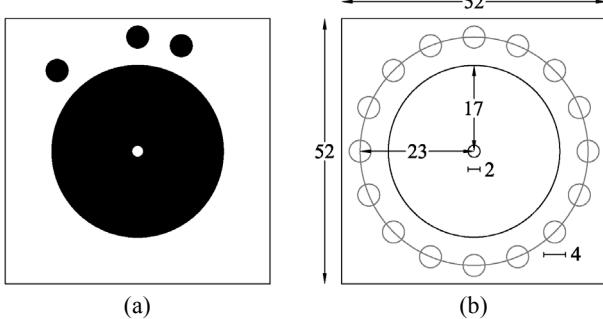


Figure 1. (a) The target coded as "number 1",
(b) The targets' design (dimensions refer to pixels)

Automatic recognition of the aforementioned targets includes:

- Edge detection of the main black circle;
- Extraction of its radius;
- Calculation of scale;
- Calculation of the coding strip's radius;
- Development of the strip;
- Adaptive calculation of the strip's threshold with the Otsu method (Otsu, 1979);
- Transformation to binary;
- Detection of each coding dot;
- Detection of two consecutive dots, beginning of the code;
- Assertion of the code number.

The above methods for localisation and recognition were implemented in C++ programming language. Using the libraries developed, tests were conducted in laboratory conditions. The accuracy of localisation was determined to be 0.5 pixels. The recognition was totally successful, but in cases where the lighting conditions weren't stable and the geometric distortions were relatively high, the failure of the algorithm was frequent.

3. PROPOSED PROCEDURE

The techniques mentioned, allow the almost real-time measurement of a large number of pre-signed control points placed on the front side of the beam, at several load epochs starting from still mode, up to failure. In order to meet simplicity requirements and to use low cost equipment with high accuracy results, the following were decided:

- Use of only one digital camera during the experiment; thus there is no possibility of acquiring simultaneous multiple images of the object at any epoch of the load test.
- All points that are situated on the front surface of the beam belong to one plane, and they will continue to stay on that during the whole load test. Theoretically this convention is valid, since during loads the beam will deform only along two directions; the vertical deformation is the one of main interest and the one that is recorded through the conventional technique of dial gauges.

Under these circumstances point coordinates cannot be calculated by a bundle adjustment triangulation method, not even through a stereo-restitution. At each load epoch only one image will be available, so the parameters of the exterior orientation must be known in advance, and the mathematic surface on which the points lie must be spatially defined.

The proposed procedure requires:

- The use of a calibrated digital camera; simultaneous camera calibration during the experiment will increase the equipment requirements;

- The selection of the particular locations on the front surface of the beam, where the coded targets will be placed. At least two (2) of these targets must be placed along the longest side of the beam, and the distance between them must be measured; for example distance D between targets A and B in Figure 2a.

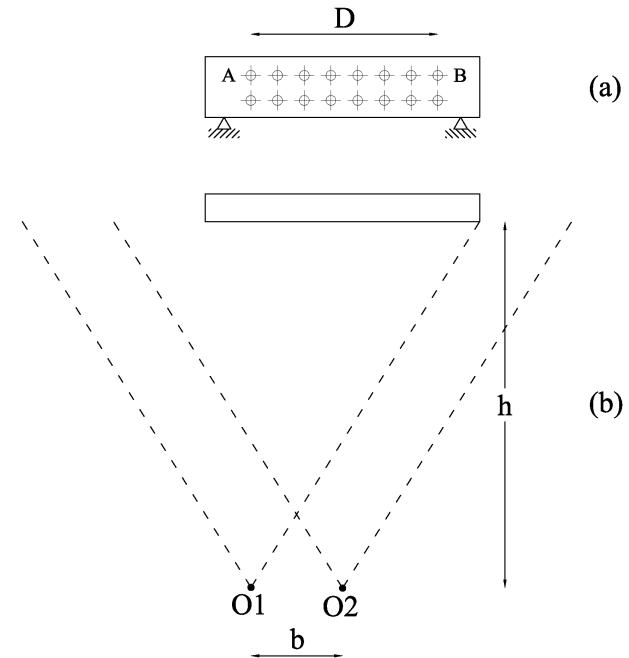


Figure 2. Measuring layout (a) Front-side view of the beam
(b) Planimetric view

Before the beginning of the loads, an image stereo-pair is acquired. The image base should be almost parallel to the direction of the longest side of the beam. At least six (6) targets, including those that the distance between them is measured, must be shown at this stereo-pair. It is preferable that the left image's angles ω and ϕ have zero values. The right image (the second one) must be taken from a stable location, e.g. using a tripod, and after that the camera must remain absolutely still during the whole experiment (Figure 2b).

The image-acquisition stage is followed by the calculation of:

- Relative orientation parameters of the stereo-pair, using the coplanarity equation, after the automatic measurement (localisation and recognition) of all common targets. So, the parameters of the exterior orientation of the right image ($X_o = 1$, $Y_o = by$, $Z_o = bz$, $\omega = d\omega$, $\phi = d\phi$, $\kappa = dk$) are calculated in a arbitrary reference system, assuming that those of the left image have zero values;
- X, Y, Z coordinates of the targets, in the arbitrary reference system, through intersections;
- Transformation parameters from the arbitrary reference system into the final reference system in which the displacements will be calculated. This right-handed coordinate system is defined to have:
 - X axis parallel to the long dimension of the beam
 - Y axis vertical to X axis and lying on the front surface of the beam
 - Z axis vertical to the front surface of the beam (XY plane) and away from the beam.

The practical determination of the above reference system is related to the targets arrangement:

- The target which is on left end of the measured distance on the beam, is determined to be the origin of the system (target A in Figure 2a);
- +X axis is along the measured distance direction (distance D between targets A and B in Figure 2a);
- All targets at the front surface of the beam have the same stable Z coordinate (e.g. Z=0).

The unknown parameters of the system are:

- The 7 parameters of the spatial similarity transformation (three translation, three rotation and one scale parameters);
- The Y coordinate of the target, which is the right end of the measured distance on the beam (target B in Figure 2a);
- The X, Y unknown coordinates of the rest targets.

For the adjustment, the measurement of more than 4 targets on the front surface of the beam is needed.

An alternative approach is the acquisition of more than two overlapping images of the beam, having always as last image the one taken from the location that the camera is planned to stay during the whole load experiment. All images should have approximately the same scale. In this case a bundle adjustment photo-triangulation is made using the colinearity equations, with reference system the arbitrary system of the first image. The 3D similarity transformation parameter determination follows. Yet, the system becomes more complicated, with higher risk of errors in the automated measurements and more calculations which delay the operation.

Through the above described calculations the preparation phase of the experiment is completed and the beam load procedure starts. The following steps repeat in each load epoch:

- Acquisition of one image, keeping the camera unmoved. The exterior orientation of these images is considered to remain stable and known. To increase the reliability of this condition, it is preferable to acquire the images using a remote control. Obviously more than one images can be taken, to control the stability and the accuracy of the results
- Determination of the 2D coordinates of the targets at the arbitrary system of the initial stereomodel, since the exterior orientation of the image is known and the third dimension of the points remains the same for all loads.
- Determination of the 2D coordinates of the targets at the final reference system.

By the end of the load phase (at beam's failure) dx and dy displacements are calculated for each target.

For each step of the above procedure, a programming library in C++ was developed and tested with real and simulated data to ensure its functionality.

These libraries combined with the libraries for automatic localisation and recognition mentioned before, are used for the development of the "Automaton" software, capable of automatically determining the displacements of signed points during a load experiment.

4. LOAD TEST

4.1 Data collection and processing

The procedure described earlier is developed for the deformation monitoring of a concrete beam, reinforced with FRP bars. FRP bars are made from filaments of fibres held in a polymeric resin matrix binder. Their major advantages compared to steel are that they are not affected by corrosion and

can be used in situations where electrical and magnetic transparency is needed. However the stress-strain behaviour of these bars is different than steel and this experiment intended to specify some of its parameters. In order to do this, it was necessary to monitor its deformation under load.

The geometry of the beam used for the particular experiment is shown in Figure 3; it is reinforced with 3 FRP bars of V-ROD type of a diameter of 8mm, at a distance of 1cm from the lower surface of the beam and 2 FRP bars at the upper part of the beam. It is placed symmetrically on a structural testing machine. The beam's construction and the load test are accomplished at the Laboratory of Structural Mechanics and Technical Works by a research group under the supervision of Assistant Professor M. Kattis.

Ten points on the left part of the front surface of the beam are chosen to be monitored and they are signed with the appropriate targets; these are placed in two rows, one close to the upper and the other close to the lower edge of the long side of the beam (Figures 3 and 4). Ten more targets are placed in stable positions around the beam to be used later for the assessment of the inner and outer accuracy of the method (check points in Figure 4). In the position where the maximum deformation is expected, the middle of the lower surface of the beam, a dial gauge with 0.1 mm accuracy is placed to acquire control deformation measurements (showed in Figure 7). Two of the targets (named T6 and T10 in Figure 3) are placed parallel to the lower edge of the beam and the distance between them is measured with a measuring tape and an accuracy of 0.5 mm.

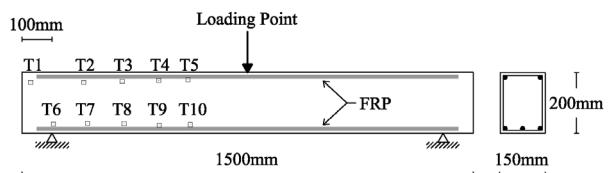


Figure 3. Geometry of the beam and target arrangement

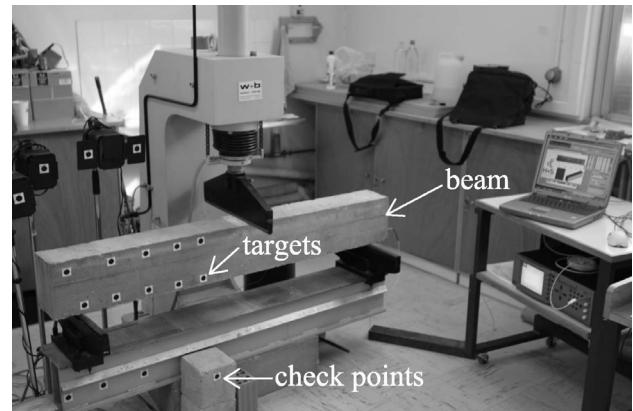


Figure 4. Laboratory test setup

The next step is the image acquisition. The camera used is a calibrated Canon EOS-1D Mark II with 8Mpixel resolution and a 35mm lens. To achieve a small groundel size, thus higher measuring accuracy, the image scale should be large and so the camera is placed near the beam, about 1.8 m from its front surface.

Before the load two images forming a stereopair with 70% overlap are acquired with their base almost parallel to the beam. The camera remains in its second position and the load begins. Images are acquired at four selected epochs: when the load

reaches 19kN, 39kN, 60kN and 85kN. In order to check the stability of the system, two images are acquired for each epoch. The beam finally fails at 87kN, and the last images are taken at this stage; in total, images are acquired for five epochs.

Collected data are processed by the "Automaton" software. Automatic processing takes about 5 min for a computer with a Pentium4 2.0GHz processor and 512Mb RAM. Two-dimension coordinates are calculated at the beam surface plane, for all targets (those on the beam, and those on stable positions) and for both images of each epoch. Horizontal and vertical displacements of each point are determined.

4.2 Results

Control of consecutive images at the same load epoch shows that the repeatability in the determination of coded targets is of an average of 0÷0.25 pixels for each one of the 5 epochs; the maximum difference in the determination of coordinates of the targets is 0.5 pixels. The pixel size for the configuration of this experiment is 0.42 mm.

The inner accuracy of the system is determined from the coordinate differences of the check points (targets in stable positions) which are derived for the load epochs. The experiment results show a displacement of 0.25±1 pixel per coordinate, systematic along the vertical axis. This total error includes repeatability errors, errors in target localisation and the impact of external factors during image acquisition.

Besides inner accuracy, the outer accuracy includes the impact from the scale (created by the error in the measurement of the distance) and the determination of the coordinate reference system (from a possible rotation of its materialized axis in correlation with the ideal). Checking shows that, for the configuration of this experiment and for the errors inserted into the targets' displacements by the two latter factors are less than 0.2 mm at object space. The total outer accuracy is much better than 1mm, which is the accuracy demand of this application.

Next, the behavior of those targets which are on the beam surface is investigated for various loads. The most important measurements are the vertical displacements of the targets. They are nearly linear for all points, except in the epoch of failure of the beam. Then all the points move abruptly downwards, something that can be explained by the intense fragmentation of the beam at that time. Considering the measurements from the dial gauge, all points are less displaced than the point where the deformation is expected to be the maximum (Figure 5).

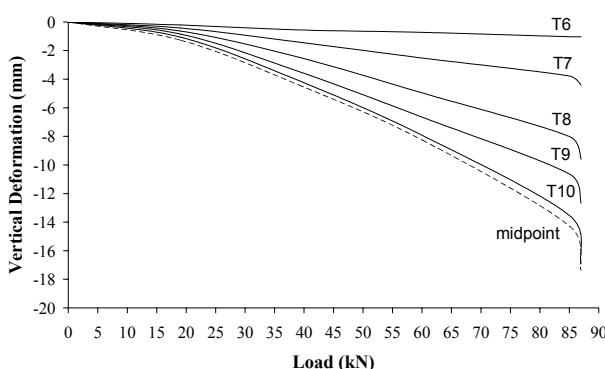


Figure 5. Vertical displacements of the targets placed on the lower row, and measurements from the dial gauge (in dot line).

Investigating the vertical and horizontal displacements of the targets, an evident difference between the top row of points and

the bottom row is observed. Theoretically all the points should move vertically with their displacement increasing as they approach the middle of the beam. This is exactly the case for the top row of points. However, the behaviour of the points at the bottom row is different as they show a considerable horizontal displacement together with the vertical, especially during the latter phases of the experiment (Figure 6).

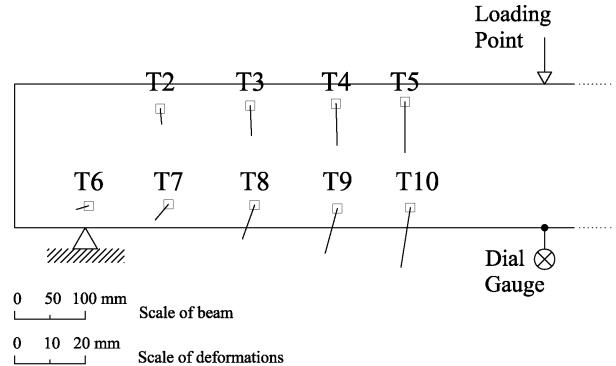


Figure 6. Displacements between zero load and after the beam's failure

The explanation is that when the load reached 60kN the beam started to crack and gaps are formed only in the lower region of the beam (Figures 7 and 8). This results in the significant horizontal displacements of the lower row points only. The same conclusion about the cracks can be reached from Figure 9. This diagram shows the vertical displacements of the points through the load epochs. The top points follow an almost linear deformation and so do the lower ones until the load of 60kN (3rd epoch). In the next epoch, two big cracks are formed, one between points T7-T8, and one between points T9-T10 (see Figure 6). These cracks have a profound impact on the linearity of the deformations.

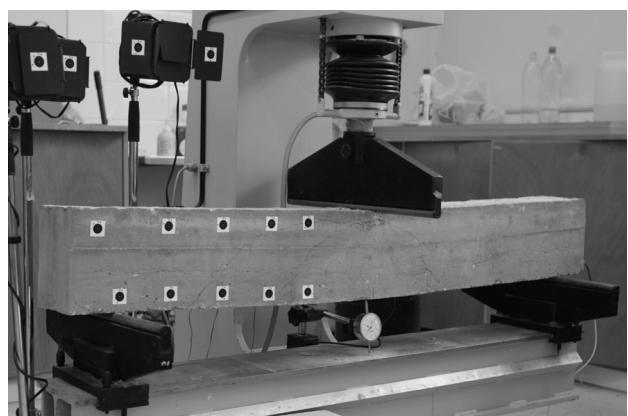


Figure 7. The beam after its failure. The position of the coded targets and the dial gauge are shown

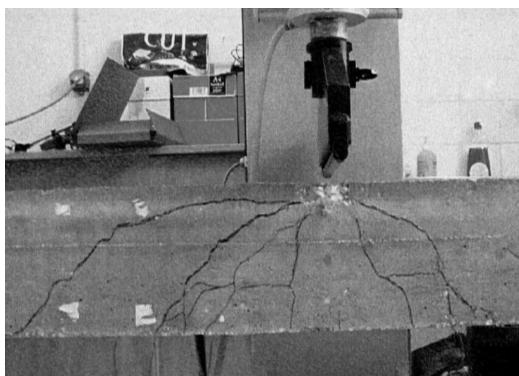


Figure 8. Detail of the central part of the beam, showing the cracks

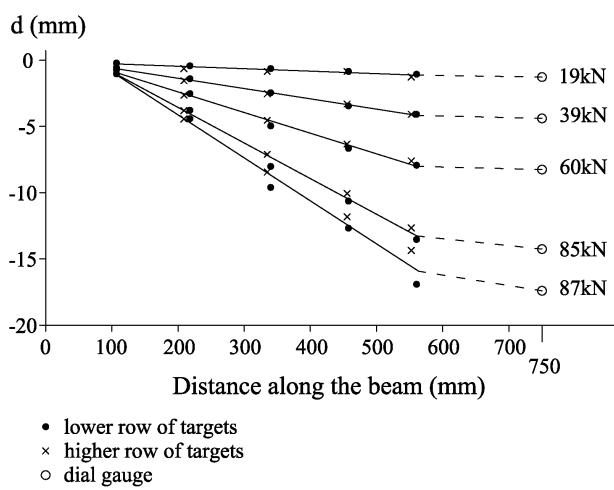


Figure 9. Vertical displacements during the experiment

5 CONCLUSIONS

Results show that the proposed procedure fully meets the standards of an automatic, simple, inexpensive, almost on-line calculation of displacements with accuracy better than 1 mm in the object space. It requires a calibrated digital camera and a minimum of one measured distance between two points-targets; the required computation time is less than five minutes, after data acquisition. The two most important factors defining the final accuracy of the method are the accuracy of the localisation algorithm and the accuracy of the measured distance. Keeping the first at about 0.5 pixels and the second at 0.5 mm, the final accuracy achieved is better than 1 mm in object space. This can be further improved mainly by the implementation of a more accurate localisation method, such as the centroids method. To achieve real-time calculations it is necessary to develop software capable of retrieving data directly from the camera. However, the current problem does not require such an approach.

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