APPLICATION OF PHOTOGRAMMETRY TO BRIDGE MONITORING

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ABSTRACT
Photogrammetry is a method developed in the early XIXth century. Nowadays, with digital photography associated to the development of image processing, this technique presents new fields of application with several advantages in relation to traditional methods. In this paper, the authors describe the use of photogrammetry in on-site monitoring of a pedestrian bridge, during load-tests. The proposed methodology was first validated by comparing results with values measured with linear-variable-differential transducers at reference points in the following laboratorial tests: monitoring of two long span RC beams, one loaded until failure and other subjected to creep tests; and laboratorial monitoring of steel beam-to-column connections, submitted to monotonic tests until failure. It was concluded that photogrammetry can be used in structural monitoring without loosing accuracy and exhibiting additional advantages in relation to traditional methods: (1) an almost unlimited number of measuring points can be considered and automatically processed, contrarily to topographic methods; (2) hardware is unnecessary and, therefore, it can be used under nearly any situation LVDTs are unviable, due to difficulties in positioning, as in the case of bridges, or due to extreme load conditions, such as in laboratorial tests under fire conditions, or even due to space restrictions, for small testing zones.

INTRODUCTION

The behaviour of great structures such as bridge needs to be continuously assessed, implying monitoring. Normally, displacements are measured using linear-variable-differential transducers (LVDTs). However, these procedures reveal important disadvantages: LVDTs can only be positioned in a limited number of points, conditioned by the number of available devices and by the space occupied by each one. In cases of difficult access and in extreme situations, such as in fire tests, the use of LVDTs can even be unviable.

The objective of the study described in this paper is the development of an application methodology of this technique to structural monitoring. In the first two given examples, results are validated by comparison with the methods traditionally used in laboratorial tests. In the remaining three examples, the proposed methodology is used in situations where the application of traditional methods is difficult or even unviable.

PHOTOGRAMMETRY

Historical Synopsis

Photogrammetry is the science that makes possible to obtain three-dimensional measurements of objects from photographs taken from different perspectives. The word photogrammetry has its origin in three Greek words, *photos*; *gramma*; and *metron*, which mean, respectively, *light*; *description* and *measurement*. The American Society of Photogrammetry describes photogrammetry as the “art, science, and technology of obtaining reliable information about physical objects and the environment, through processes of recording, measuring, and interpreting photographic images based on standard tests of electromagnetic radiant energy and other phenomena” (American Society of Photogrammetry, 1980).

The transformation of a plan image to a 3D reality involves the knowledge of the camera intrinsic characteristics (focal length and rotation angles) and information concerning one point of the global coordinates system. The algorithms used are based on the principles of the image geometry, allied to the adopted camera calibration (Fu et al, 1987).

The recent wide spread use of digital cameras and of personal computers has expanded the number of possible applications of photogrammetry. Structural monitoring, namely in the cases previously referred to and for the reasons also mentioned before, is one of the potentially most interesting new applications of this technique in civil engineering problems.

Previous research, conducted by Whiteman (Whiteman et al, 2002), Fraser (Fraser, 2001) and Fraser and Riedel (Fraser & Riedel, 2000), revealed that photogrammetry can be used to monitor laboratorial tests of short span beams. With the study herein described, the main objectives were: (1) to compare the accuracy of photogrammetry with the one obtained with LVDTs, in long span beams and in major structures in general; (2) to assess the reachable accuracy in small zones of test specimens; and (3) to define a methodology to use this technique in structural monitoring.

Equipment

Two cameras were used in the considered case studies: a Single Lens Reflex (SLR) digital photographic camera, Nikon D70, with an image size of 3008x2000 pixels; and a compact digital camera, Olympus C8080, with an image size of 3264x2448 pixels.

With Nikon D70, two lenses were used: a 24*mm* and a 50*mm* focal length. The adopted Olympus C8080 has a fixed zoom lens, with a focal length range between 28 and 140*mm*; which was always used with the highest value, 140*mm*. Cameras were first calibrated at the laboratory and internal parameters were determined, such as: radial distortion constants (K_1, K_2); principal point (X, Y); sensor size (W, H); and exact focal length (λ) of each adopted lens (Valença, 2006).

Methodology

The protocol adopted for structural monitoring uses the sub-pixel target mode and consists on the following steps:

1. Positioning of fixed targets in the neighbourhood of the structure, named control points, to serve as reference points;
2. Positioning of targets on the structure to monitor displacements; being redundant data important to the photogrammetric procedure, contributing to increase the method's accuracy;
3. Taking of convergent photographs, at all stages considered relevant for the analysis, including both sets of targets, stable and movable, in each one;
4. Building of photogrammetric projects for each stage considered, using specific software; input data must be processed and cross checked in order to detect possible errors; this is an iterative procedure that can be refined with the introduction of new data;
5. Attribution of a scale factor to the model, which can be done using control points; this procedure, associated to a rigorous calibration of the photographic equipment, results in a fast convergence to the correct solution;
6. Attribution of constraints to the model, when applicable; the data referent to the control points can also be used with this purpose;
7. Orientation of the model by defining a set of coordinate axes;
8. Exporting the generated 3D model to drawing exchange format files to be manipulated with a CAD software;
9. Overlapping of the photogrammetric models generated for each stage, using the static targets, to assess the deformation of the structure by quantifying the displacement of targets positioned on the structure.

Accuracy and Control Points

The success of a photogrammetric project depends mainly on the correct positioning of the camera station. It is necessary to follow a set of rules in order to guarantee that the principal control parameters, namely, intersection angle, rays per point, photo coverage and residual, assume adequate values during the project's construction.

The *intersection angle* is defined as the angle between any two light rays that identify a point. The ideal situation to define a 3D point corresponds to a 90 degrees angle between the two light rays but it is acceptable to have angles between 30 and 90 degrees. Below 30 degrees, the software can not correctly compensate errors and this can reduce the accuracy of the 3D model.

Rays per point is defined as the number of light rays that identify a 3D point. In other words, this indicates the number of photographs each target has been marked on. Every target must be marked on, at least, two photographs and preferably on three. The higher the number of rays per point, the higher the redundancy obtained and, hence, the higher the precision for that.

Photo coverage is defined as the percentage of area with relevant data, i.e., the area covered by marked points, in each photograph. A higher value indicates a higher precision since the software can determine more accurately the position of the camera station associated to that photograph.

Residual is defined as the distance between the marked position of a given point in each photograph and the corresponding assumed true position, defined after computation and convergence of the project. This can be quantified considering the maximum value or the root mean squared value in pixels. All projects must have the largest residual below 10 pixels. For projects with calibrated cameras, the largest residual should be less than 3 pixels and, when sub-pixel targets are used, the largest residual should be less than 1 pixel.

EXPERIMENTS AND RESULTS

Working Plan

To calibrate and validate the photogrammetric method, first the following laboratorial situations were considered: (1) tests of long span RC beams; and (2) tests of steel beam-to-column connections. In the first case, the major problem researchers normally have to overcome is related to the limited number of LVDTs available at the testing facilities. Therefore, the use of photogrammetry with acceptable accuracy would represent an important benefit since practically an unlimited number of points can be considered and automatically processed. In the second case, the tested zone has a reduced area and, for this reason, there is a physical difficulty in placing several LVDTs on the latter. Being very small the spots necessary to identify the relevant points of the testing area, the photogrammetric procedure also presents obvious advantages in this case, provided as well that at least the same accuracy is obtained.

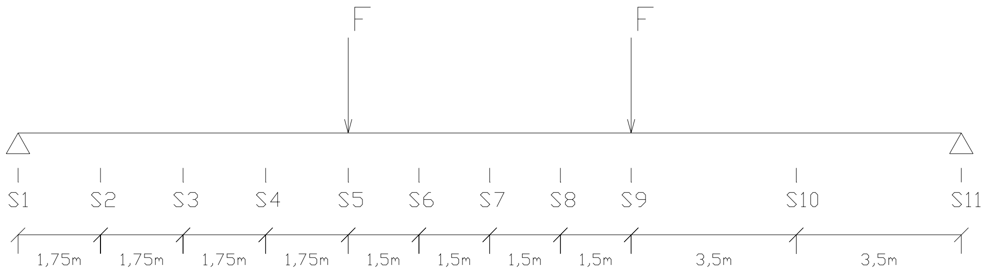
Subsequently, due to the excellent results obtained with the laboratorial tests, it was decided to use this technique in monitoring of a pedestrian bridge in Aveiro, Portugal. This bridge has the particularity of having a circular configuration in plant, connecting three different margins of a "T" shaped estuary arm. In this case, LVDTs can not be used because there are not any fixed points and the use of topographic methods would be extremely work-intensive and time consuming. Therefore, this was considered to be a good case study to test the advantages and the efficiency of the photogrammetric method applied to structural monitoring.

Validation Tests

Tests of Long-Span Beams

Four RC beams with a span length of 20*m* and an I cross-section with a width of 0.30*m* and a height of 0.50*m* were tested in the scope of a PhD thesis (Fernandes, 2006). Two of these were monotonically tested until failure and the remaining two were subjected to a permanent load to study the time-dependant behaviour, mainly due to creep.

For failure tests, the beams were able to withstand large deformations, with more that 700*mm* of maximum vertical deflection. Photogrammetric surveying was performed at 0, 150, 250, 425, 500 and 700*mm* of imposed displacement at the actuator. For creep tests, photogrammetric surveying was performed before applying the load; 2.5 hours after loading; and every 15 days from that day on. Both types of tests were monitored with LVDTs: creep tests in sections S3, S5, S7, S9 and S10; and failure tests in sections S2, S3, S4, S5, S6, S7, S8, S9 and S10 (Fig. 1). These sections were considered as control points, i.e., results obtained with the photogrammetric procedure and LVDTs were compared at these points.



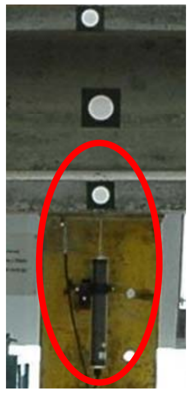


Fig. 1 Creep test; and failure test.

It is important to mention that failure and creep tests were performed in different laboratories, with distinct constraints. Due to the long span of the beams and reduced space available at the laboratories, the conditions for photo coverage were quite different in each case, resulting in different photo overlapping and intersection angles. There were physical constraints, mainly due to materials stored in the laboratory, and due to the vicinity of walls for one end of the beams in both tests, which affected the ideal camera station position to take convergent photos. Most of the constraints were overcome by a well planned surveying and by considering more photos. In creep tests between 8 and 9 photos were taken and in failure tests between 13 and 18 photos, since there were more severe physical constraints (Fig. 2).

The photogrammetric projects were built with the following average values of control parameters: intersection angle of 78º; photo coverage of 38%; and RMS residual of 0.30 pixels, for creep tests; and intersection angle of 76º; photo coverage of 30%; and RMS residual of 0.32 pixels, for failure tests.

For creep tests, the differences observed in displacements at control points, determined by photogrammetry and measured with LVDTs, at both stages considered, 2.5 hours and 88 days after loading, were: 0.52*mm* on average, varying between a maximum of 1.13*mm* and a minimum of 0.07*mm* (Fig. 3). In percentage, the average difference between the two methods was 0.83%.

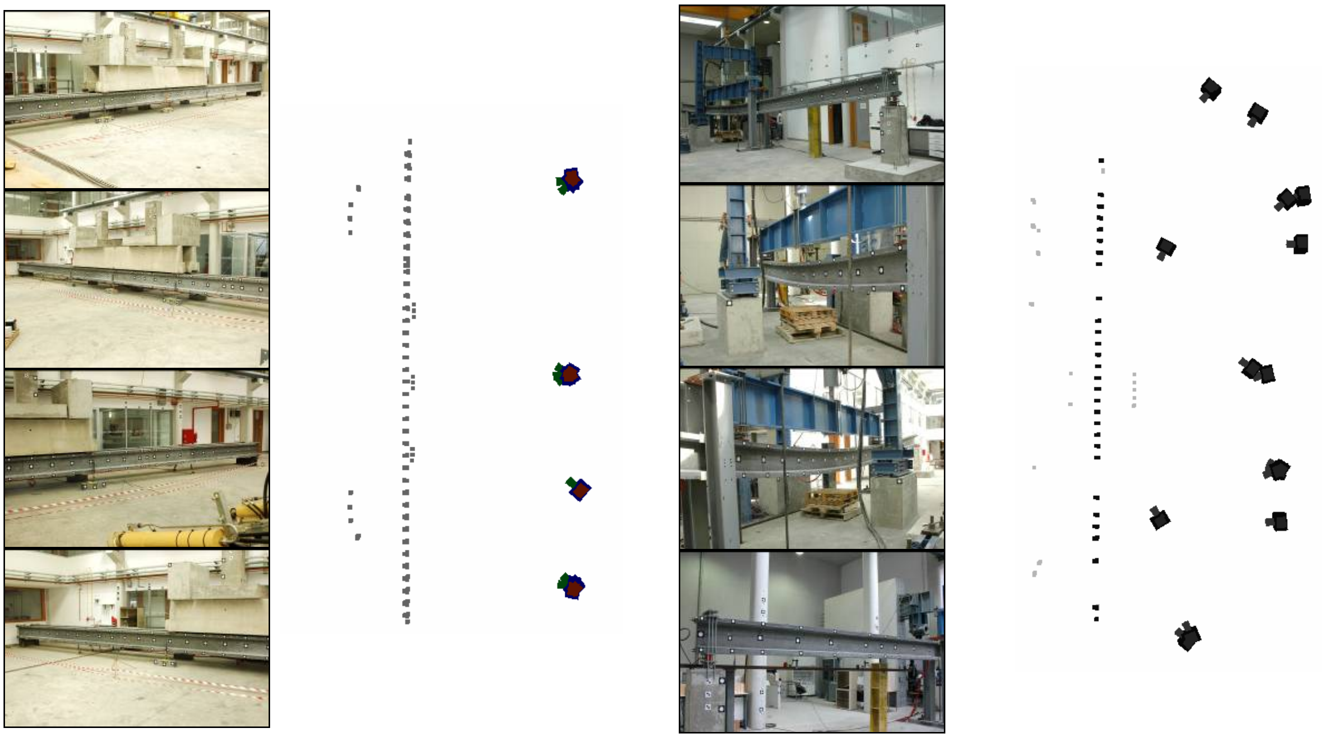


Fig. 2 Creep test; and failure test.

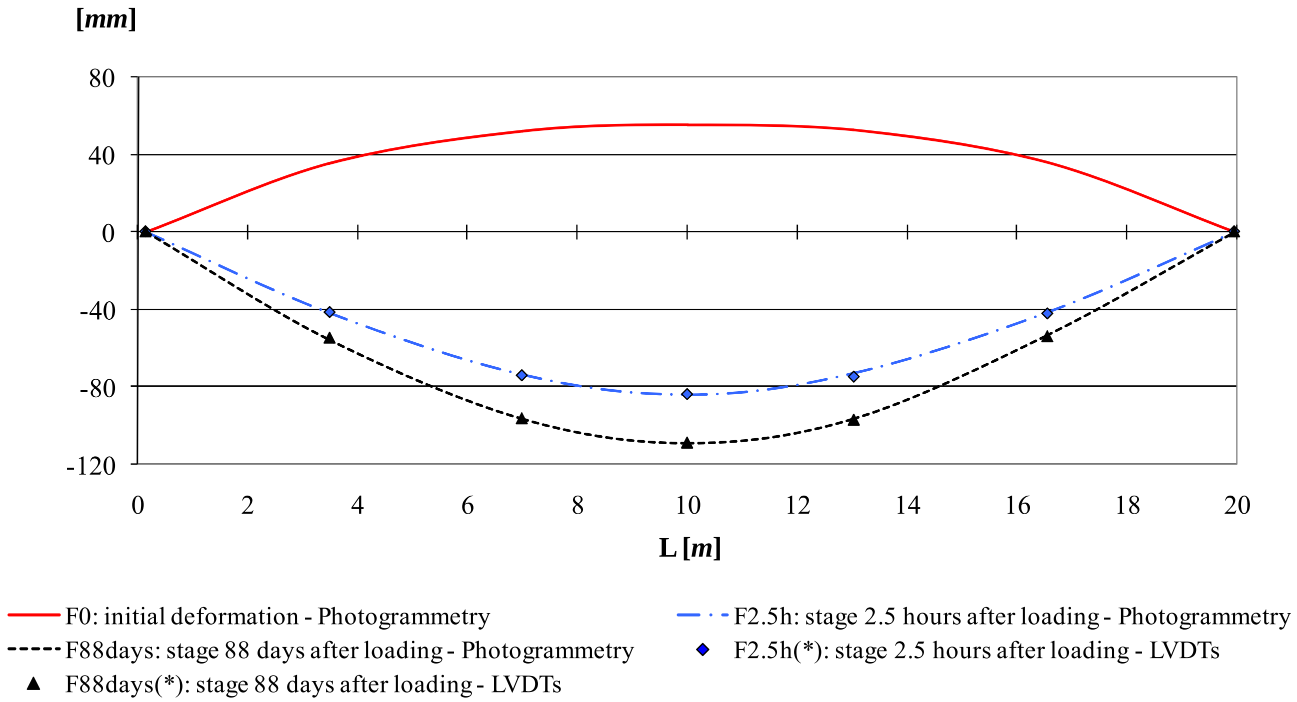
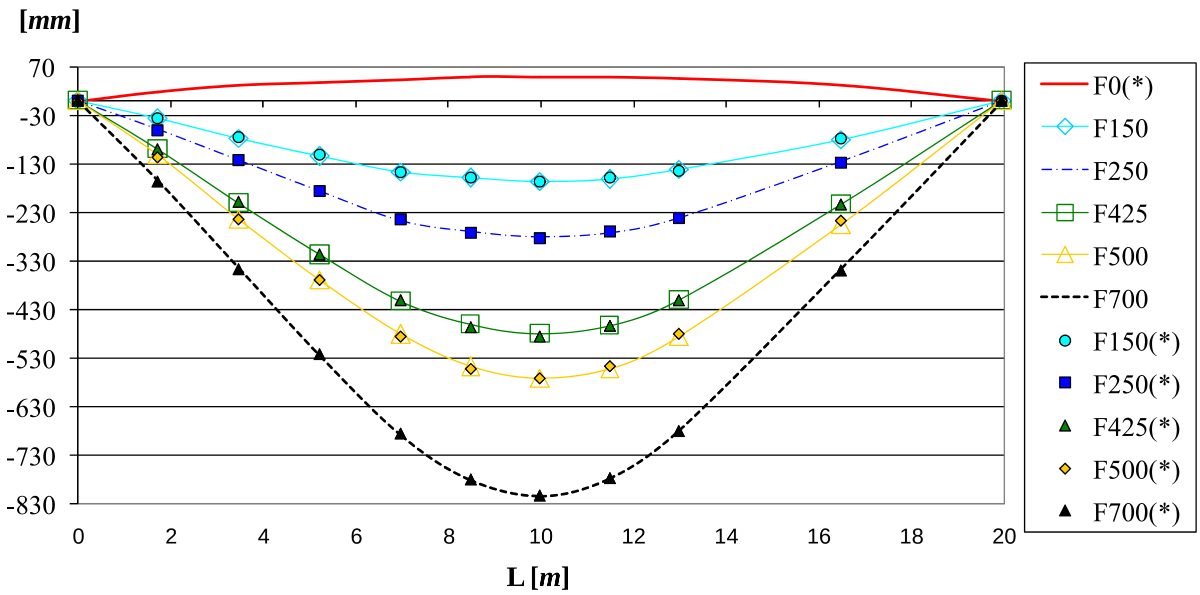


Fig. 3 Photogrammetric *versus* LVDTs results for creep test.

For failure tests, nine sections at five stages were compared (Fig. 4). The average difference between photogrammetric and LVDTs results was 2.19*mm*, varying between a maximum of 7.50*mm* and a minimum of 0.00*mm*. In percentage, this corresponds to an average difference of 0.96%.



F*n* (*): *n* mm induced deformation in the jack – Photogrammetry
F*n*: *n* mm induced deformation in the jack – LVDTs

Fig. 4 Photogrammetric versus LVDTs results for failure tests.

Test of Steel Beam-Column Connection

Several steel "strong beam / column / weak beam" connections were tested, until failure, in the scope of a PhD thesis (Jordão, 2008). After performing ten tests, all monitored with LVDTs and strain gauges, it was concluded that important data was not obtained accurately. It was observed that when the steel node exhibits a plastic behaviour, LVDTs can no longer be assumed to be perpendicular to the plate in relation to which measurements are registered. For this reason, it was decided to use photogrammetry to monitor the last two experimental tests. The main objective was to determine the displacements in the imaging plan. The methodology used consisted in framing the steel connection, considering 60 static targets used as control points, and monitoring movable targets – over 70 – glued to the flanges and web of the column, within the space available between strain gauges. A photogrammetric surveying was performed at five distinct stages using 6 convergent photos in each one (Fig. 5).

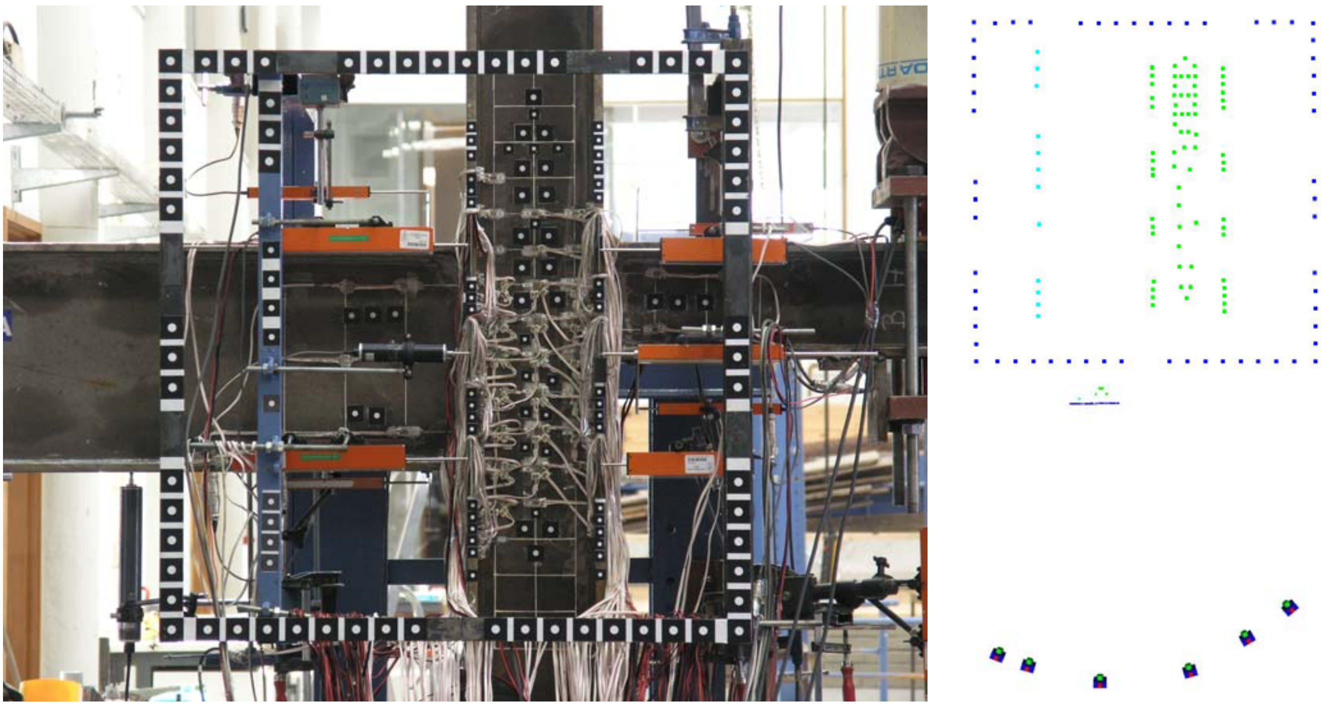


Fig. 5 (a) First test before loading; (b) Static and movable targets; and (c) Camera stations.

These tests presented the following principal constraints: (1) light variation during tests, that lasted over five hours; (2) electric instrumentation, namely wires to which strain gauges were connected that limited the targets positioning; and (3) column flange and steel plates used for LVDTs measurements, which hindered the visibility from extreme camera stations of web targets located next to the column flange.

The generated 3D models presented the following average values of control parameters: angle intersection of 61º; photo coverage of 49%; and RMS residual of 0.12 pixels. Since all control points and movable targets were in the same photogrammetric surveying conditions – focal length, angle intersection, photo coverage, residual and illumination – the difference between the coordinates of control points in each project was assumed to be within the accuracy of the photogrammetric survey.

For the first test, an accuracy of 0.04, 0.03 and 0.08*mm* was obtained in the horizontal direction of the image plan (X), in the vertical direction of the image plan (Z); and in normal direction in relation to the image plan (Y), respectively, and a maximum displacement of 41.64*mm* was registered in the horizontal direction. For the second test, the corresponding values were: 0.02, 0.02 and 0.05*mm* of accuracy and a maximum displacement of 41.24*mm* (Fig. 6). Although the objective was to determine displacements in the imaging plan, displacements in the direction perpendicular to the imaging plan (Y) were also obtained, however with half the accuracy achieved in the other directions.

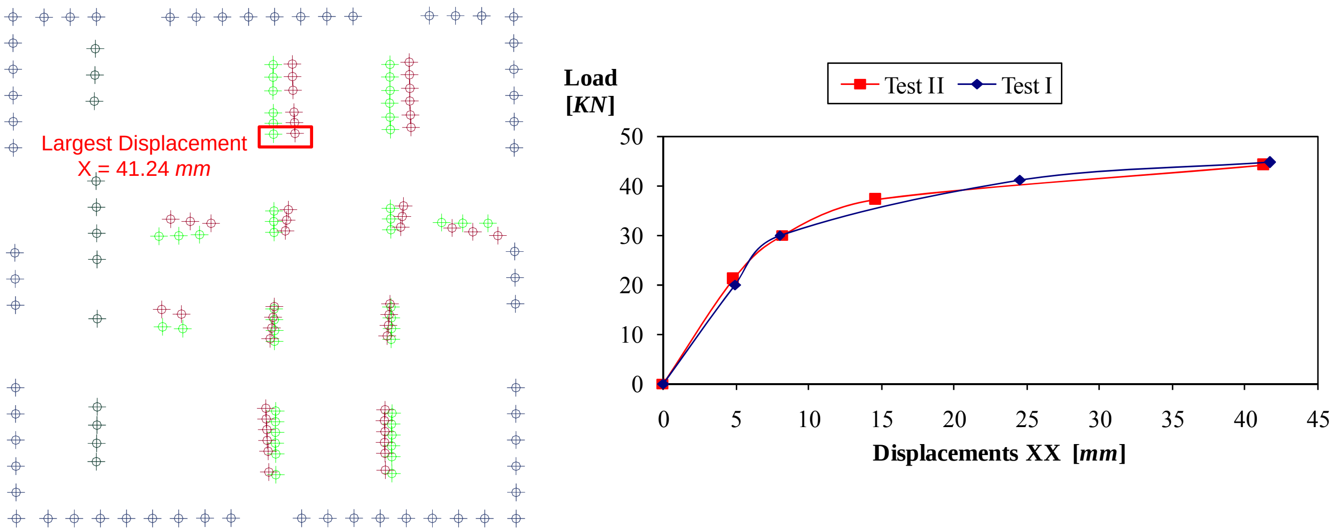


Fig. 6 (a) Overlapping of first and last photogrammetric models - test 2;
(b) Largest horizontal displacements.

Structural Monitoring of a Pedestrian Bridge

The pedestrian bridge linking São Roque channel to both sides of Botirões channel in Aveiro's Estuary was completed in 2006. The bridge deck presents an unusual circular configuration in plant. It is supported at the three margins and at eight symmetrically distributed cables, connected to a mast (Fig. 7a). Before opening the bridge to the public, its structural behaviour had to be assessed. With that aim, static and dynamic tests were conducted. Monitoring with LVDTs would only be possible at few points and therefore this option was discarded. The use of topographic methods would take too long and/or only few targets would be monitored. For these reasons, it was decided to use photogrammetry to measure the deformation of the bridge subjected to static load tests.

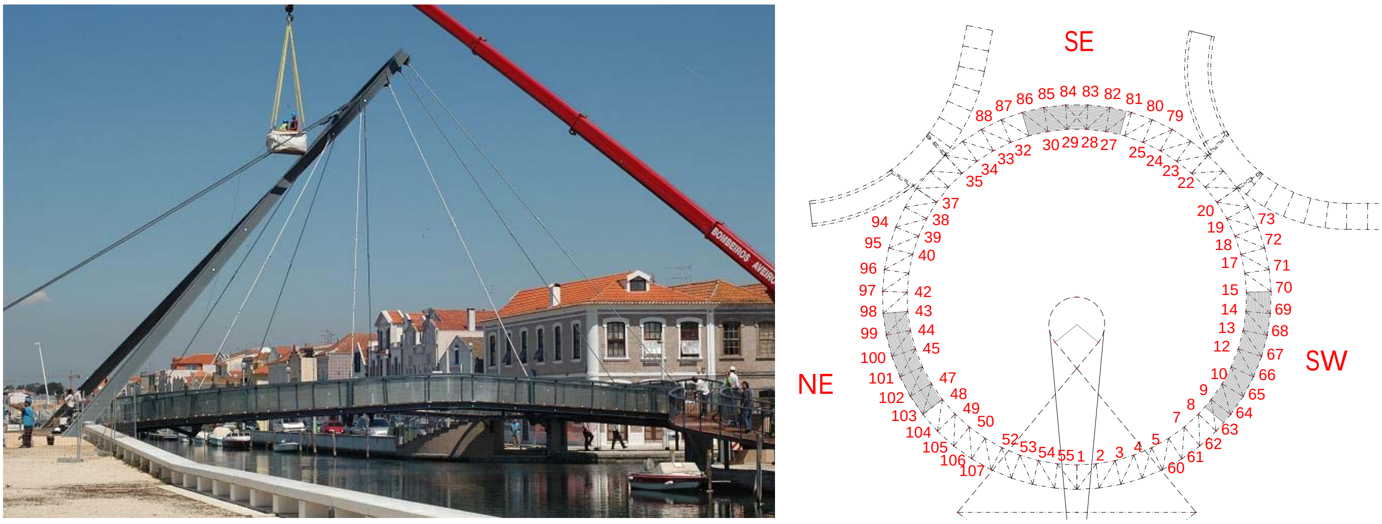


Fig. 7 (a) Circular steel pedestrian bridge; (b) loaded areas.

The photogrammetric survey, with a total of 83 targets glued to the web of the external steel beam, consisted in three distinct stages: (a) before loading; (b) with the bridge loaded; and (c) after unloading. The load was materialized with students from the University of Aveiro, previously weighted, and successively positioned in three distinct areas of the bridge (Fig. 7b). With the bridge loaded, to ensure good illumination conditions, only loaded views were photographed, using between 11 and 14 photos. For the remaining stages, before loading and after unloading, all the structure was surveyed, using between 30 to 32 photos.

During this test were registered constraints that affect the photographic surveying; and constraints that affect the photogrammetric project, such as: images in backlighting; inadequate convergent angles between photos from some points of view; structure vibration caused by the wind and by people; and distance and unfavourable light conditions of the static reference targets. These factors have inevitably introduced errors in the results. The photogrammetric projects control parameters assumed the following average values: intersection angle of 38º, photo coverage of 39%; and RMS residual of 0.48 pixels, that can be considered acceptable results.

Results from bridge load tests were obtained by comparing the photogrammetric projects built. The average vertical difference in targets positions, determined from the stages before loading and after unloading, were 2.54*mm* (3.13*mm*, in SE side; 2.70*mm*, in SW side; and 1.80*mm*, in NE side). The maximum vertical displacements registered in each of the three loading situations considered were the following: 23.17*mm*, in SE side (Fig. 8); 29.71*mm*, in SW side (Fig. 9); and 27.78*mm*, in NE side (Fig. 10).

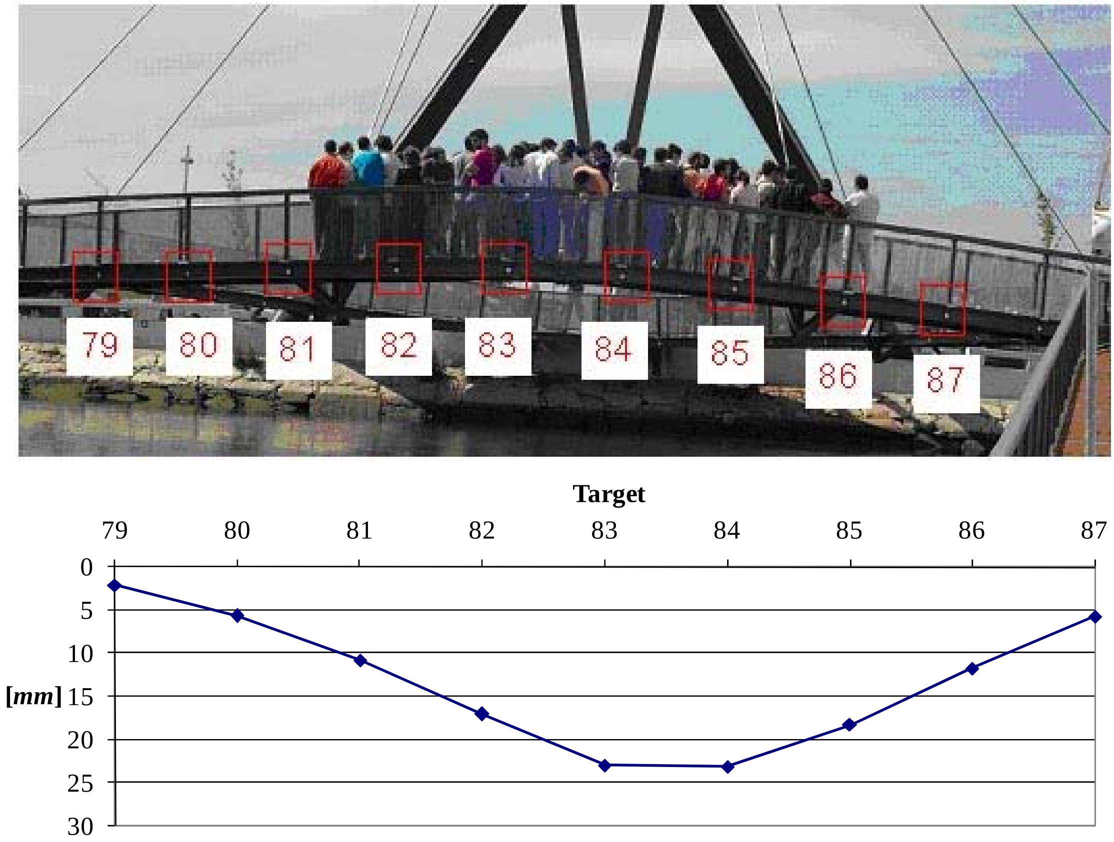


Fig. 8 Vertical displacements for SE loading situation.

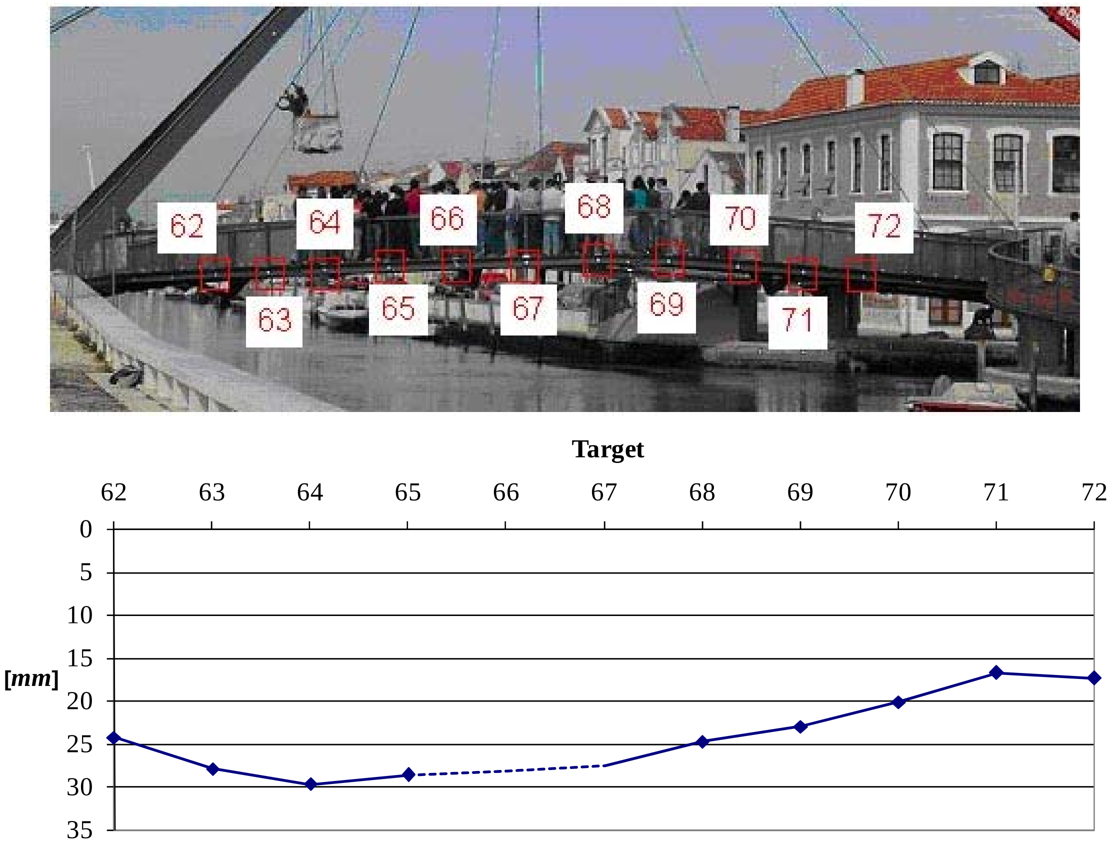


Fig. 9 Vertical displacements for SW loading situation.

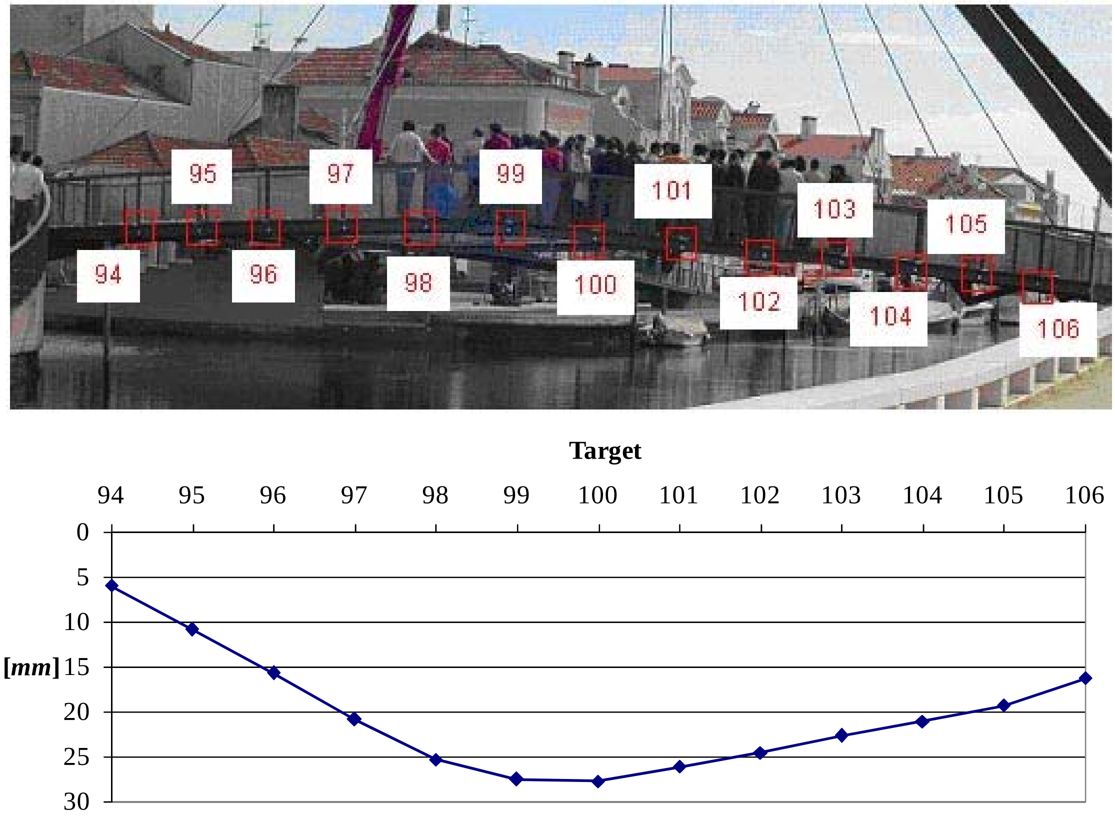


Fig. 10 Vertical displacements for NE loading situation.

CONCLUSIONS

From the studies herein described, it can be stated that photogrammetry can be used in monitoring of great structures. It was also proven that high accuracy can be obtained in laboratorial tests; in the steel connection tests, an average accuracy of 0.1*mm* was obtained in the three directions of space.

The difference of precision between this technique and the traditional methods is irrelevant, presenting photogrammetry several additional advantages, mainly: (1) accurate and fast results are obtained and automatically processed at an almost unlimited number of targets, contrarily to topographic methods; (2) hardware is unnecessary and therefore, the number of devices available, space restrictions and positioning difficulties do not exist; (3) it is not sensible to large displacements and does not have range limits; and (4) it is a low cost technique since non-professional digital cameras can be used.

Constraints are well identified and it was demonstrated that these can be overcome with a well planned surveying. It is important to point out that, to get reliable results, the presented methodology should be carefully followed, and especially control points and/or fixed points must be cautiously defined.

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