# APPLICATION OF DIGITAL PHOTOGRAMMETRY FOR MEASURING DEFORMATION AND CRACKS DURING LOAD TESTS IN CIVIL ENGINEERING MATERIAL TESTING

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**ABSTRACT**
Methods of digital photogrammetry depict a suitable tool for the automatic measurement of two- and three-dimensional displacements fields, deformations and surface defects such as cracks of test objects and structures during short and long time load tests. The paper gives an overview on recent research and development activities in the field of civil engineering material testing, conducted by the Institute of Photogrammetry and Remote Sensing and the Institute for Structures and Materials at Dresden University of Technology. It also describes the adaptation of photogrammetric techniques to special requirements from the civil engineering point of view. Results obtained in mass experiments are discussed, and suitable techniques for a compact visualization of complex results are presented.

## 1 INTRODUCTION

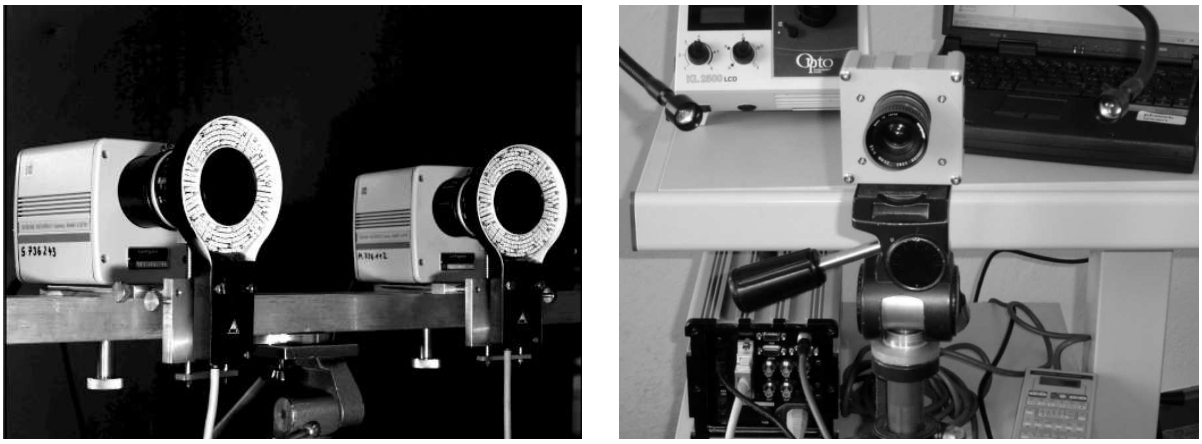
An essential topic in civil engineering research is the verification of theories and mechanical models. This can often be achieved by static, quasi-static and dynamic short and long time load experiments on test objects and structures. During these load tests parameters such as load, strain, stress, displacement, deformation, cracks and other defects have to be monitored (Opitz, 2000, DGZfP, 2001, Opitz, 2002). At present, displacement and deformation measurements are typically acquired by wire strain gauges or inductive displacement transducers. Those supply on-line results with a high precision, but only point-wise and one-dimensional, and they are generally not suitable for a large number of measurement points or the detection of cracks during load tests. For these purposes or for complete surface measurements, methods of digital closed range photogrammetry are usually better qualified (Maas, 1992, Hampel, 1997, Luhmann, 2000), because they allow automatic measurements of two- and three-dimensional displacement fields, deformations and defects. The accomplished photogrammetric measurements in civil engineering material testing with test objects of concrete, wood, brickwork, steel and composite materials indicate the wide range of requirements to systems and methods of the digital closed range photogrammetry. Often the essential measurement parameters (precision, measuring range, surface of measuring objects, etc.) pose challenges to the design of efficient photogrammetric measurement procedures. Sometimes problems at the planning stage give impulses to adapt existing techniques or to develop special methods (Hampel et al., 1997–2003).

## 2 PHOTOGRAMMETRY IN CIVIL ENGINEERING MATERIAL TESTING

Planning and efficiently performing photogrammetric measurements in a wide range of civil engineering material testing tasks requires a systematic approach to the technique and the definition of task-oriented measurement concepts. In the following, we will discuss hardware configurations for photogrammetric data acquisition, methods for the application of these systems to different tasks and algorithmic aspects in the automation of whole measurement procedures in mass experiments. Each experiment can be subdivided in the tasks of planning, preparation, data acquisition and processing as well as post-processing. Defining measurement procedures for new measurement tasks, these individual steps require expert knowledge in civil engineering as well as in photogrammetry.

### 2.1 Photogrammetry System

The developed photogrammetry system is an open modular system. It combines commercial and proprietary hardware and software modules to achieve efficient solutions for different measurement tasks in civil engineering. The software modules include project management tools, image acquisition modules, commercial and own data processing modules, control units for data synchronization with other measurement techniques and some additional modules (for example a high precision displacement table and a deformation model for verification purposes). Figure 1 shows some digital cameras used for on-line measurements during load tests. The sensor of Kodak Megaplus (Figure 1(a)) is a CCD with 2k x 2k Pixel (1-2 Hz) and a radiometric resolution of 10 bit. The high speed camera FastCam Ultima (Figure 1(b)) has an CMOS-sensor and can acquire image sequences with a geometric resolution between 256 x 32 Pixel (16 kHz) up to 1k x 1k Pixel (0.5 kHz). This high temporal resolution is needed for detection of dynamical or crash situations.



(a) Kodak Megaplus 4.2i / 10

(b) Fast Cam Ultima (High Speed Camera)

Figure 1: Digital camera systems for on-line measuring.

### 2.2 Methods of Photogrammetry

Table 1 gives an overview about some photogrammetric methods used for taking photographs and for evaluation. The typical methods of 2-D and 3-D are well known (Luhmann, 2000). But the potential of 2.5-D is very important for an efficient photogrammetric measurement of deformation, cracks etc. in material testing (Hampel, 2002). Section 3 presents some applications for all cases.

| | Methods of photogrammetry for taking photographs and evaluation |
|---|---|
| 2-D | Deformation analysis in image space |
| 2.5-D | Deformation analysis in image space |
| | (dynamic projective transformation, mirror photogrammetry) |
| 3-D | Stereo- and multi image photogrammetry, mirror photogrammetry |

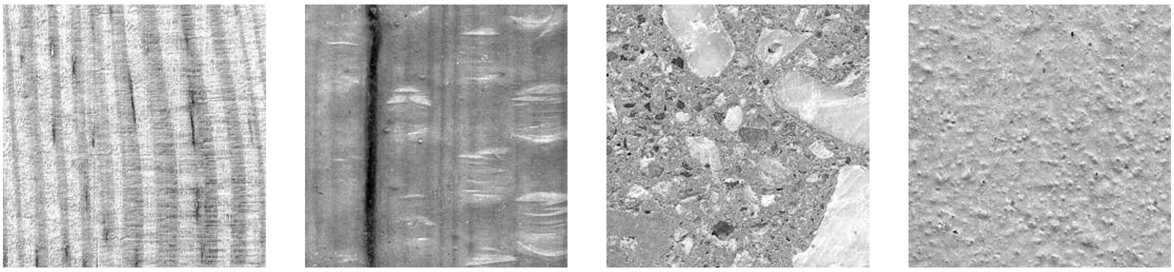
Table 1: Methods of photogrammetry for taking photographs and evaluation.

**Dynamic Projective Transformation (DPT):** In case of test bodies, where the surface describes a plane, a 2-D acquisition is sufficient for the detection of deformations, cracks etc. The 2-D acquisition allows a correct detection of in-plane displacements with respect to the reference state only, but no acquisition of out-of-plane displacements and 3-D total object movements. In case of in-plane displacements and 3-D total object movements an independent natural or artificial reference system can be used for a dynamical correction of object movements (Hampel, 2002). The reference system has to be in a defined position to the object during the time of load test. Figure 5 shows an example with an artificial reference frame for a mass experiment.

**Mirror Photogrammetry (MP):** An other possibility for the detection of 2.5-D or 3-D displacements etc. is offered by mirror photogrammetry (Hampel, 2002). The example in section 3.2 shows an efficient calibration of fiber-bragg-grid-sensors based on one camera and mirror photogrammetry.

### 2.3 Image correlation

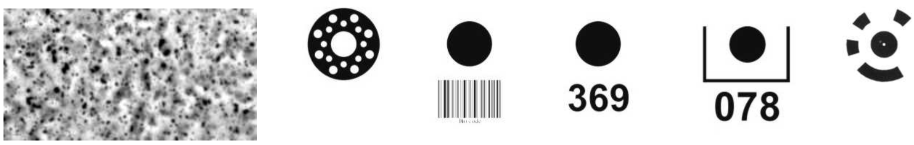
In material testing subpixel accuracy image correlation techniques form a very important tool for a high precision detection and measurement of deformations, cracks etc. on surfaces of test objects. Figure 2 shows some typical textures of natural surface structures on test bodies in civil engineering material testing.



(a) wood (b) textile reinforced wood (c) concrete (d) textile reinforced concrete

Figure 2: Textures of natural surfaces on test objects in civil engineering material testing.

The textures of some natural surface-structures are often not qualified for high precision image correlation. In this case the surface of test bodies has to be prepared with an artificial object signalization. Figure 3 shows some different artificial object signalizations for discrete points and for surfaces. The suitable methods of image correlation in sequences are different algorithms, which are based on least-squares-matching and cross-correlation. These methods reach a precision of up to 1/50 pixel for natural textures and up to 1/100 pixel for artificial signalization. Targets with varying intensity are qualified for a high precision deformation-analysis of discrete points (Hampel, 1998). Some tests and verifications of this kind of targets confirm a precision up to 0.008 Pixel (Hampel, 1999b).




(a) surface signalization (b) coded targets (with constant intensity)

(c) targets with intensity gradients

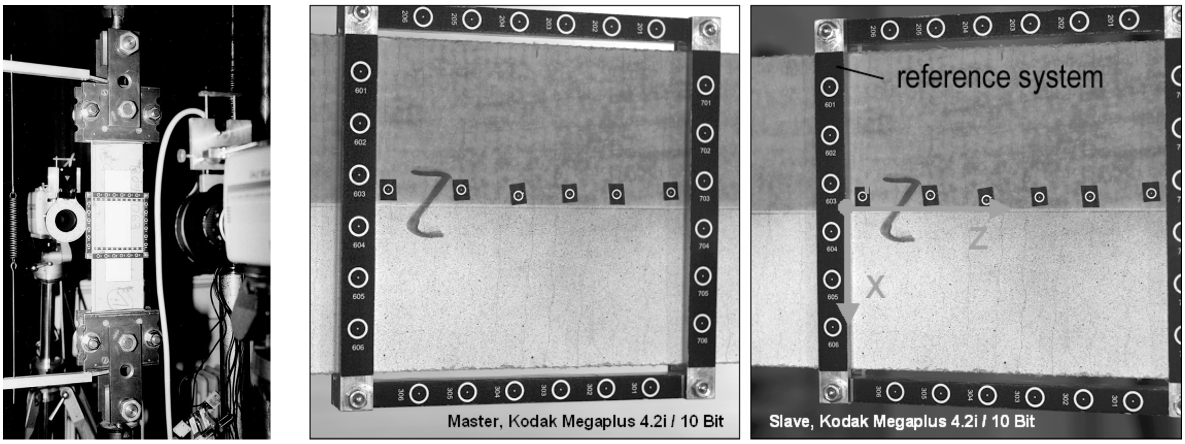
Figure 3: Artificial signalization of discrete points and surfaces.

The signalization of objects with a large number of targets can be very time-consuming (and for example very difficult for small test bodies). In some cases a fix target-grid is not desired for the evaluation in post-processing, because the interesting areas and points may change dynamically during the evaluation process. Typical examples are the verification of FEM-evaluations with different grid-structures and the dynamical adjustment of cracks (crack-position, crack-width and distance between cracks).

## 3 EXAMPELS FOR MEASURING DEFORMATIONS AND CRACKS

### 3.1 Tension and shear tests of concrete test bodies with textile reinforcement (2.5-D, 3-D)

The research project D3 of the *Center of Research Excellence in Science and Technology 528* (promoted by the *German Research Foundation*) realizes high precision measurements with digital photogrammetry for the detection of deformations and cracks for tension- and shear-tests of textile rein-




(a) 2.5-D with 2 cameras (b) 3-D with 2 cameras for one side

Figure 4: Tension tests of textile reinforced concrete bodies with two cameras (Kodak Megaplus 4.2i / 10 bit) and a reference system (frame) for 2.5-D and 3-D image acquisition.

forced concrete (Curbach, 2002). The main problem is the required precision of $1\ \mu m$ for displacements and up to $3\ \mu m$ for crack detections (width). The great number of experiments requires semi- or fully-automated methods for image correlation (section 2.3), deformation- and crack-analysis and complex data-handling. The experiments of research projects on crack detection can be efficiently realized in 2.5-D (section 2.2). Figure 4(a) shows the test stand with two cameras for a 2.5-D acquisition per object side. The connection of the two separate 2.5-D measurements was realized over a two-faced reference frame. The defined position of that reference system at the object is realized with a three-point-mounting. Figure 4(b) also shows the reference-system (frame) in case of a 3-D measurement. The two cameras acquire one object side in 3-D.

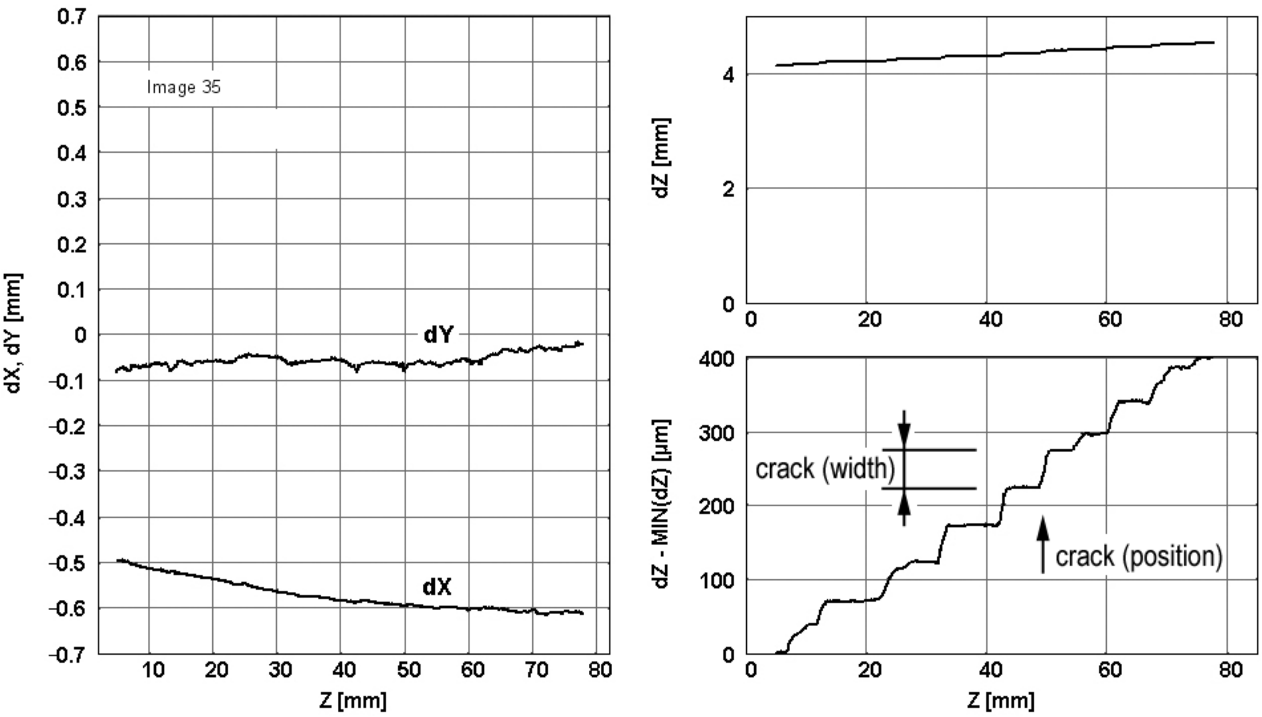



Figure 5: Results of 3-D deformation analysis.

Figure 5 shows only one profile in tension-direction (Z) of the absolute or relative displacements in 3-D. The in-plane deformations show significant cracks and insignificant out-of-plane deformations. Here the 2.5-D approach allows an efficient acquisition of both sides of test bodies by only two cameras. Very interesting are the detection of in-plane deformations, the relative crack-positions and the crack-width for several profiles or for complete surfaces.

### 3.2 Calibration of fiber-bragg-grid-sensors by mirror photogrammetry (2.5-D, 3-D)

Another research project used fiber-bragg-grid-sensors (FBGS) for measuring expansions inside of textile reinforced concrete test bodies (Curbach, 2002). The use of fiber-bragg-grid-sensors requires a calibration of these. The required precision for extension measuring was defined with $0.01\ \%$ for a fiber with a diameter of approx. $100 \mu m$ over a length up to $60\ mm$. Some constraints – the diameter of the fibers and the fiber-bragg-grid-sensor twisted itself during the load test – caused more difficulties at the planning phase. In the planning phase of the photogrammetry measurement some object signalizations for the small fibers were tested. The best results for the automatic detection obtained a cylindric hull, which is invariant against the twist moving of the fiber during the load test. The design of the measurement space was a long tube. In this case the mirror photogrammetry obtains a very efficient measurement. In the minimum case a 3-D measurement can be realized with only one camera and one mirror. To cover the measuring itself, it is possible to add more than one mirror. Regarding the costs of high quality digital cameras special silver mirrors obtain very cost efficient measurements. The case of mirror photogrammetry with one camera will also circumvent any synchronization problems. Figure 6 and 7 show the realized test stand and the results of the verification. The results of the photogrammetric measurement correlated very well with the load characteristics (Hampel, 2002).

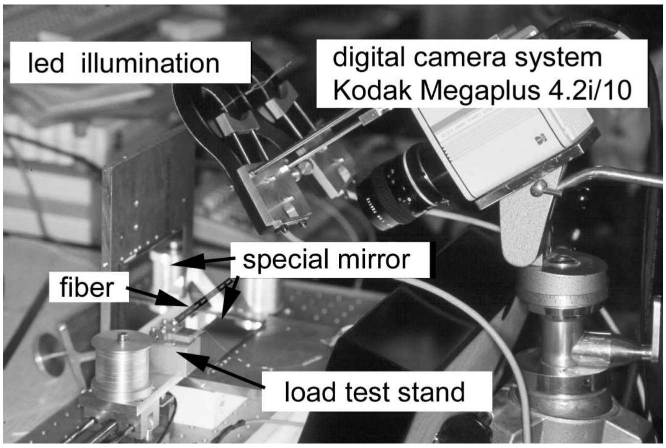



Figure 6: Test stand for calibration of fiber-bragg-grid-sensors with digital photogrammetry (mirror photogrammetry).

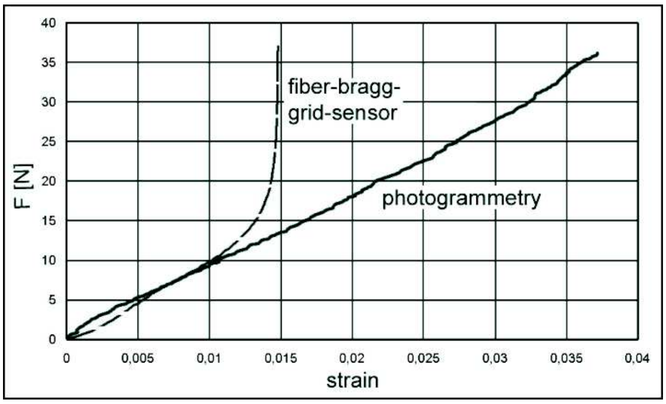
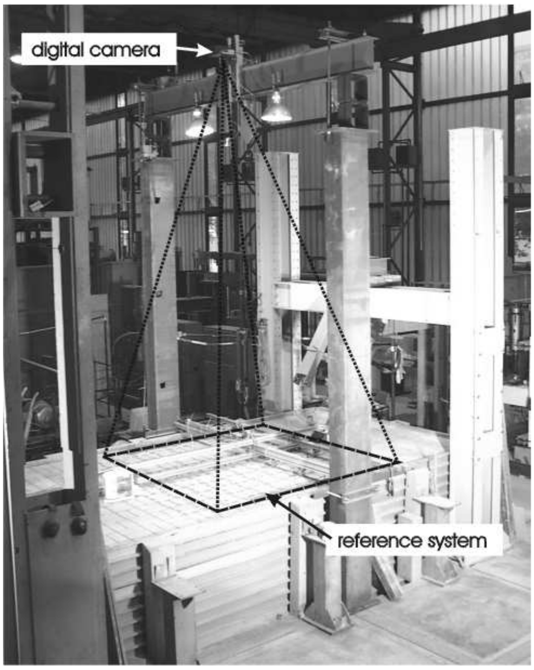



Figure 7: Verification of values of a fiber-bragg-grid-sensor and photogrammetry.

### 3.3 Dynamical load tests of road pavement during long-term experiments (2.5-D)

Some research projects deal with the tasks in road construction, analyzing for example deformations of different road pavement surfaces. The experiments include dynamic load tests over approx. one million load test cycles. Figure 8 shows the load test stand and the measurement area with a typical pavement and the installed reference system, measurement points, inductive displacement gauges etc.




(a) Test stand


(b) Measurement area

Figure 8: Dynamical load tests on pavement

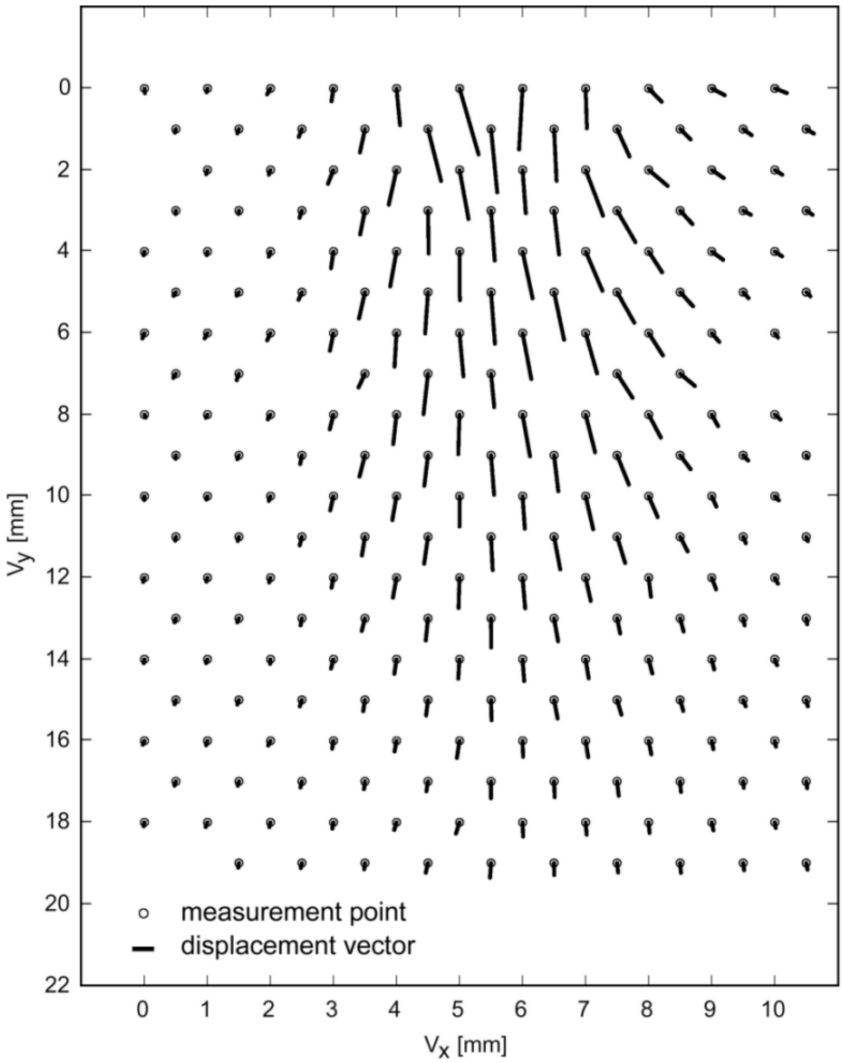



Figure 9: Field of displacements

The first load tests confirmed an insignificant out-of-plane displacement of pavement. In this case a 2-D measurement is sufficient. A long focal length in combination with a large distance of the camera to the measurement area reduces a possible effect as a result of out-of-plane displacements. During the long time load test the temperature changed significantly and influenced the exterior orientation of the digital camera continuously. This effect had a large influence on the measurement, because the errors had the same size as the real in-plane-displacements. In this case a reference system, which is defined mounted on a controlled frame, may help (2.5-D, section 2.2). The 2.5-D evaluation delivers very good results. The verification was verified at selected points on pavement with inductive displacement gauges. Figure 9 shows an example for displacements of the centre of gravity of the paving stones in a standardized coordinate system (Hampel and Wellner, 2002).

## 4 CONCLUSION

The applicability of digital photogrammetry as a measurement tool in civil engineering material testing has been proven in many different and difficult measurements. The high requirements to the systems and the methods of the digital photogrammetry were the entrypoint to develop some special methods and systems for the efficient measurement of deformations, cracks etc. during short and longtime load-tests. Future work will look at the application of computer tomography (CT) to overcome the limitation of photogrammetry to surface-visible effects. Here the data fusion of photogrammetry measurements and CT data processing results poses an interesting challenge. As further option of data fusion we intend to integrate thermal (sub-)surface measurements.

## 5 ACKNOWLEDGEMENTS

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