MONITORING CRACK ORIGIN AND EVOLUTION AT CONCRETE ELEMENTS USING PHOTOGRAMMETRY

W. Benning [a], J. Lange[a], R. Schwermann[a], C. Effkemann[a], S. Görtz[b]

[a] Geodetic Institute, RWTH Aachen, Templergraben 55, 52062 Aachen, Germany, lange@gia.rwth-aachen.de
[b] Zerna, Köpper & Partner, Industriestraße 27, 44892 Bochum, Germany

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ABSTRACT:

Controlling and monitoring of crack origin and evolution of concrete elements is an important task in research of building materials. The efficiency of the reinforcement to the bearing capacity depends among other on the limited crack evolution. Regarding the research of crack evolution at the surface of the element, photogrammetry is approved, because it allows an expanded investigation of larger objects with high precision.

With the presented experiments different structural elements of prestressed, reinforced and textile concrete are investigated. These are tension, shear beams and plate elements. For the photogrammetric measurements the surface is prepared by a grid of targets. Up to three digital cameras (Kodak DCS Pro 14n) are used as a multi exposure assembly or as a static one-camera-system. Cracks are causing local changes to the displacements between the targets. Repeating the measurement in time intervals the crack evolution can be observed. The digital images are evaluated by the photogrammetric software PHIDIAS; it yields a precision of the target coordinates up to 3µm.

For analysing deformation, a software is developed to detect crack structures. Hereby the measurement data and the parameters of material are probabilistically regarded in the existence probability of a crack. The values are improved by intensification methods and then single cracks are automatically traced. Detail information like crack width and crack edge displacement are also calculated.

In addition a Finite- Element- Module is developed, which simulates the test. Thus the results of photogrammetric measurements can be compared with the numeric tension calculation and iteratively improved.

The described measurement and analysis system is developed at the Geodetic Institute of RWTH Aachen, University (Germany). The tests are realised at the Institute of Structural Concrete, the Institute of Building Material Research and Institute of Textile Technique, all RWTH Aachen. The work is part of the research activities referring to the "Sonderforschungsbereich 532 - Textilbeton" (Collaborative Research Centre financed by the DFG (German research association) for textile concrete) .

KURZFASSUNG:

Die Kontrolle und Beobachtung der Rissentstehung und Rissentwicklung von Betonbauteilen ist eine wichtige Aufgabe in der Bauforschung. Die Wirksamkeit der Bewehrung im Hinblick auf die Tragfähigkeit der Bauteile hängt unter anderem von der begrenzten Rissbildung ab. Bei der Untersuchung des Rissbildungsverhaltens an der Bauteiloberfläche hat sich die Photogrammetrie bewährt, da sie als einziges Verfahren die hochgenaue, flächenhafte Untersuchung eines größeren Objektbereiches ermöglicht.

In den hier vorgestellten Versuchen wurden unterschiedliche Bauteile aus Spann-, Stahl- oder Textilbeton untersucht. Es handelt sich um Zug- oder Biegeträger sowie um Scheibenkörper. Für die photogrammetrischen Messungen wird die Oberfläche der Versuchskörper mit rasterförmig angeordneten Messmarken präpariert. Die Aufnahmen werden mit bis zu drei Digitalkameras (Kodak DCS Pro 14n) als Mehrbildverband oder als statisches Einkamerasystem erstellt. Risse bewirken lokale Änderungen in den Abständen zwischen den Messmarken. Durch die Wiederholung der Aufnahmen in zeitlichen Abständen kann auf diese Art die Rissbildung verfolgt werden. Die Aufnahmen werden photogrammetrisch mit der Software PHIDIAS ausgewertet, wobei die Koordinaten der Messmarken mit einer Genauigkeit von bis zu 3 µm ermittelt werden.

Für die Deformationsanalyse wird eine eigene Software zur Ermittlung der Rissstrukturen entwickelt. Hierbei werden die Messdaten und die Parameter des Materials probabilistisch in der Existenzwahrscheinlichkeit eines Risses berücksichtigt. Die Messwerte werden mittels Verstärkungsmethoden verbessert, um danach einzelne Risse automatisch verfolgen zu können. Detailinformationen wie Rissbreiten und Rissuferverschiebungen werden zusätzlich in der Berechnung ermittelt.

Außerdem wird an einem Finite-Elemente-Modul gearbeitet, das die Versuche parallel simuliert. Auf diese Weise kann das aus der photogrammetrischen Messung gewonnene Ergebnis mit den numerischen Spannungsberechnungen verglichen und iterativ verbessert werden.

Die Entwicklung des hier beschriebenen Mess- und Analysesystems findet am Geodätischen Institut der RWTH Aachen (Deutschland) statt. Die Versuche werden am Institut für Massivbau (IMB), Institut für Bauforschung (IBAC) und Institut für Textiltechnik (ITA), alle RWTH Aachen, durchgeführt. Die Arbeiten sind Bestandteil der Forschungsaktivitäten im Rahmen des Sonderforschungsbereiches 532 „Textilbeton".

1. INTRODUCTION

A crack in the composite material concrete activates a complex redistribution between concrete matrix and reinforcement. Only by cracks the ultimate load can be reached. Knowing cracks by number, destination, width and edge displacement, conclusions about the load reaction of the concrete structure can be drawn and finally dimensioned.

Photogrammetry is used to observe targets at the surface of a structure during a deformation test.

A grid of targets is the base for the calculation of crack position, crack width and crack edge displacement. In comparison with conventional strain gages and position encoders a two-dimensional surface can be measured. In addition a grid of deformations allows transmitting the displacements of a real test to a numeric simulation.

The aim of the research is therefore the measurement of deformations at the surface of concrete structures with photogrammetry to observe crack pattern, crack width and crack edge displacement. The research is part of the “Sonderforschungsbereich 532- Textilbeton” specialized for the new textile reinforcement.

2. APPLICATION AREAS

Structures of concrete are usually broken. The whole crack width is distributed to many very narrow cracks so that the appearance and the protection against corrosion can be fulfilled. Concrete breaks at a low tensile stress. The load is taken in the crack totally by the reinforcement and is transmitted in the neighbourhood from reinforcement to concrete by bond (figure 1). The tensile stress in concrete rises with the distance to the crack, till the tensile strength is reached again and a new crack opens. A strong bond generates many tiny cracks.

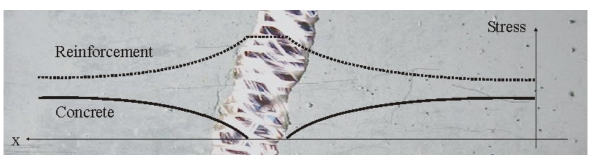
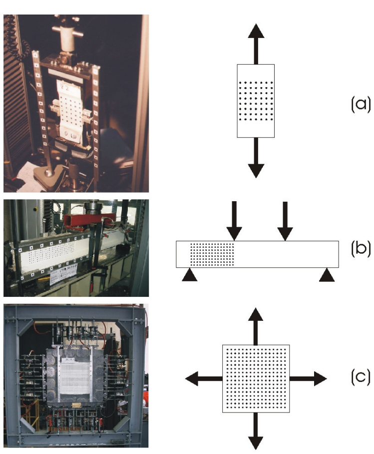


Figure 1: Stress of concrete and reinforcement in the region of crack

Otherwise the bond behavior is recognizable by the way and the width of cracks. By different types of tests the properties of material and bond is analyzed (figure 2) and are used for the assessment of several concrete structures.



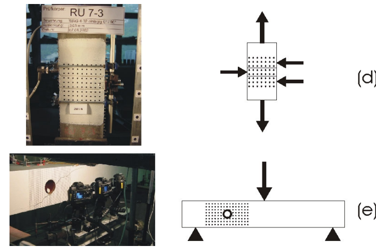


Figure 2: Diverse types of tests (in cooperation with the Institutes of structural concrete Aachen and Kaiserslautern)

(a) Tension, (b) shear, bending, (c) plate tests and other special tests like (d) for the research of crack edge displacement or (e) of a recess are performed. All test specimens are continuous loaded and are observed by a photogrammetric multi-camera system.

The crack width depends on the used reinforcement. At the researched textile reinforced (reinforced with fibres of glass or carbon) specimens starts the crack width with about 20 µm, the human eye can detect cracks starting with about 40 µm. It is also not possible to observe all cracks simultaneously and measure detail information like crack width or crack edge displacement. A wide application area arises for the technique of photogrammetry.

3. PHOTOGRAMMETRY

Photogrammetry is known as a contactless measurement technique. Before starting the test the specimens are prepared in the area of interest with a regular grid of targets (target diameter holds 3 mm and distance between targets 5 mm, see figure 3). During the test the field of targets is simultaneously photographed by up to three digital cameras (Kodak DCS Pro 14n with 35 mm or 28 mm lenses) with a time interval of 10 seconds. Due to the increasing load cracks are arising and, to this, the distances between related targets are changed. Figure 4 shows the arrangement of the cameras during a plate test.

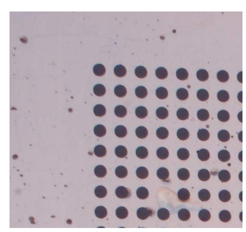


Figure 3: Detail with targets

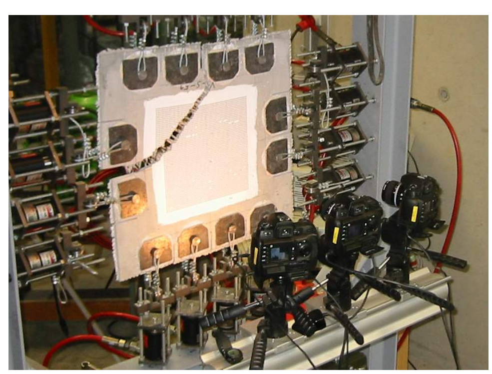


Figure 4: Test assembly with cameras and plate test specimen after failure

The images are evaluated with the digital photogrammetric system PHIDIAS. At the beginning of any test a portable field with control points is photographed from various directions to perform the orientation of the camera assembly (figure 5). The field of control points contains several points, whose distances are previously determined using an interferometer. These distances guarantee superior accuracy and are introduced to the calculating of the orientation as additional observations. The orientation parameters are determined by bundle adjustment in combination with self-calibration.
The targets are measured automatically using image processing with PHIDIAS. The centres of the targets are determined with a standard deviation of about 0.4 microns. The three-dimensional coordinates of the targets are subsequently calculated by forward intersection using the image coordinates of two or three cameras. The scale of the images is 1 : 7 to 1 : 10, that means the targets on the specimens may be determinable with an accuracy up to 3 microns (perpendicular to exposure direction).

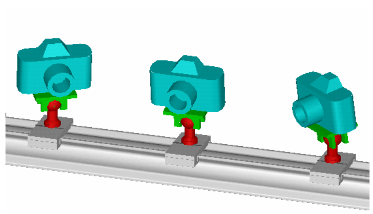


Figure 5: Assembly of measurement cameras

3.1 Use of cameras

Up to three cameras are available for the test series. For a rapid overview *one camera* perpendicular in front of the measured object is sensible. But a displacement of the specimen perpendicular to the measured plane cannot be recognised.
Thus at least *two cameras* are used. A second camera allows to determine three-dimensional coordinates. Then in opposite to the one-camera-measurement deformations perpendicular to the surface can be detected.
The assembly of *two cameras* has an important effect to the quality of result, as well as using *three cameras* instead of two. The difference between a measurement with the outer two cameras (assembly of all cameras see figure 5) to a measurement of one outer and the middle camera is between 4 microns and 6-8 microns to the measurement of three cameras.
In the border area far from the cameras the noise raises (figure 6)

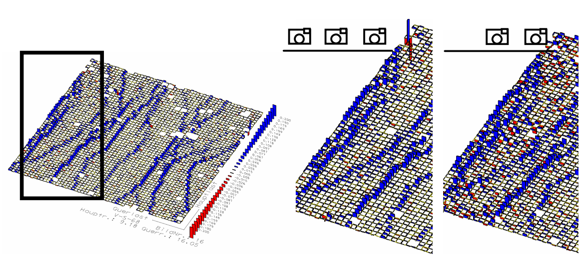


Figure 6: Measurement of deformation with 2 and 3 cameras of a plate test

4. MEASUREMENT OF DEFORMATIONS AND AUTOMATIC CRACK ANALYSIS

I. The evaluation software PHIDIAS calculates from the images in every epoch three-dimensional coordinates of the targets and its standard deviations. The deformations can be determined by the difference of two measurement epochs. They show global displacements like the deflection of a beam (figure 7a). Only the difference of two adjacent displacement vectors focus attention on the cracks (figure 7b).

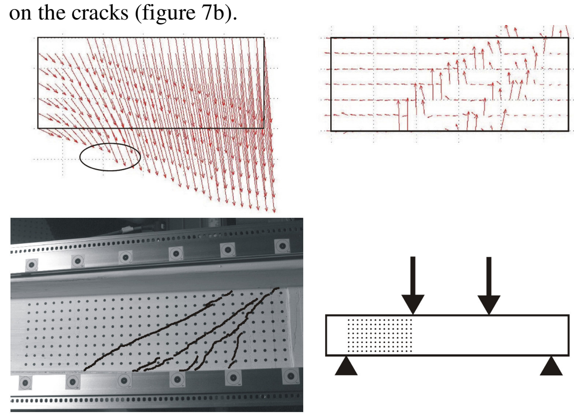


Figure 7: a) Displacement of targets of a shear test
b) Difference of neighboured vectors (vertical direction)
c) Original image (cracks drawn)
d) Schematic drawing

Cracks are extracted from the displacements. For this the following method is developed and implemented. An overview shows figure 8.

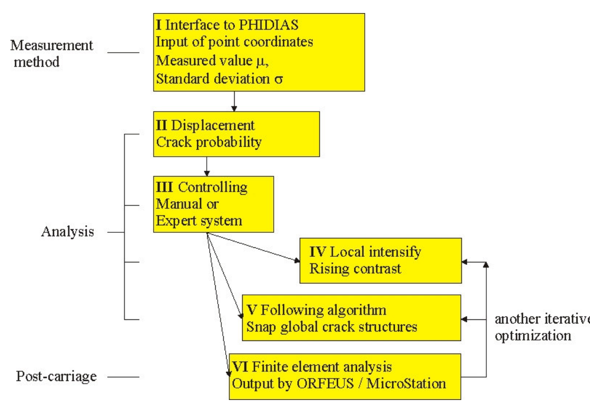


Figure 8: Way of crack analysis

II. By the comparison of the measured change of length between two targets with the statistically distributed material parameter, which is necessary for the creation of a real crack (primary crack width), the existence of a crack can be calculated as a stochastic value (figure 9).

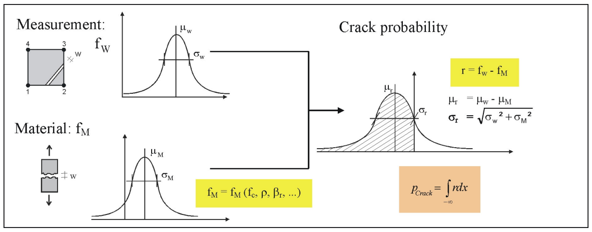


Figure 9: Calculation of crack probability from measured displacement and crack width at the material

The crack probabilities are the basis for the following calculation of crack structures.

III. A controlling module uses the crack probabilities and controls the process of extraction of cracks. It decides about the sequence and use of analysis methods and defines defaults. The controlling is manual, but as an alternative it research is done on automation with an expert system. This uses the knowledge about optimisation with the decision of analysis methods in the program.

IV. The first revision of data aims at the intensification of the contrast between cracked and not cracked areas.

These are displayed by the crack probabilities, which are between 0% (not cracked) and 100% (cracked). The use of intensification methods extracts cracked areas. For the intensification the following methods are used:

- Rules from mechanics (i.e.: dispersion length)
- Filter methods from image processing
- Crack history over the load steps
- Iterative correction by finite element analysis

After the local calculation of crack probability and intensification, crack ways, which belong together, must be tracked.

V. The algorithm for tracking of crack structures follows a contour tracking method by WAHL (1987). It starts at an initialisation edge and searches the way of highest crack probability. There it marks located edges and a surrounding area of dispersion length. Is the crack probability lower than a limit the tracking is stopped and a new initialisation edge for a new crack is searched. The way of crack is weighted in the direct and indirect neighbourhood with the crack probability.

In addition at special specimen, i.e. tension and shear tests cracks do not change the direction large scale, which constrains the choice of crack ways.

VI. The graphic output is done by the finite element program ORFEUS (CHUDOBA & KONRAD 2003) or by the CAD- System MicroStation. The display of crack pattern allows cracked edges on a grid, but also difference displacements. The result of the crack extraction can be controlled by optical comparison (figure 10).

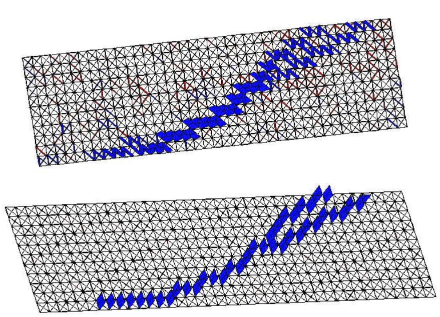


Figure 10: Displacement pattern and extracted crack pattern (displayed by ORFEUS)

4.1 Detailed investigations

As an additional module a routine for the calculation of crack width and crack edge displacement exists. For this the following method by GÖRTZ (2004) was used (figure 11).

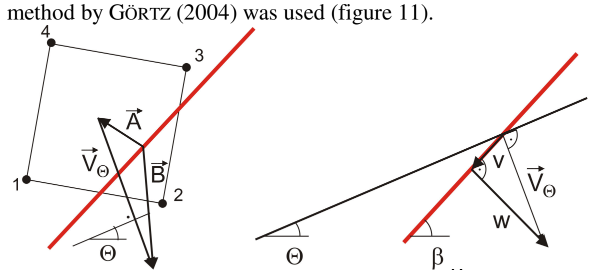


Figure 11: Calculation of crack opening vector $\vec{V}_\Theta$, crack width w and crack edge displacement v from the displacement vectors $\vec{V}_1$ to $\vec{V}_4$ of one element

A broken element, which consists of four neighboured targets, is separated by the crack into two parts (figure 11**,** crack in the example between the targets 1, 3, 4 and 2). The displacement of the targets ($\vec{V}_1$ to $\vec{V}_4$) are summarized in both parts to a mean value ($\vec{A}, \vec{B}$):

$$\vec{A} = (\vec{V}_1 + \vec{V}_3 + \vec{V}_4)/3 \quad , \qquad \vec{B} = \vec{V}_2 \tag{1}$$

The difference ($\vec{V}_\Theta = \vec{A} - \vec{B}$) is the relative displacement of the crack. Because of the difference between the angle Θ and the real crack angle β, the relative displacement can be converted by using trigonometric functions in crack width w and crack edge displacement v:

$$w = \left|\vec{V}_\Theta\right| \cdot \cos(\beta - \Theta) \quad , \quad v = \left|\vec{V}_\Theta\right| \cdot \sin(\beta - \Theta) \tag{2}$$

The calculation of crack width and crack edge displacement can also be done using the difference displacements between two crack-divided targets (figure 12).

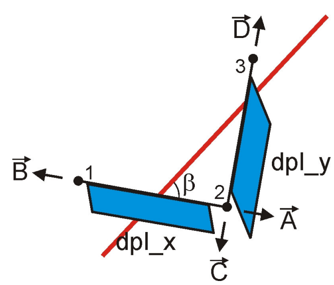


Figure 12: Displacement at two edges

Crack width w and crack edge displacement v can be derived from the formulas (1) (2).

$$w = \left|\begin{pmatrix} dpl\_x \\ dpl\_y \end{pmatrix}\right| \cdot \cos\left(\beta - \arctan\left(\frac{dpl\_x}{dpl\_y}\right)\right)$$
$$v = \left|\begin{pmatrix} dpl\_x \\ dpl\_y \end{pmatrix}\right| \cdot \sin\left(\beta - \arctan\left(\frac{dpl\_x}{dpl\_y}\right)\right) \tag{3}$$

4.2 Finite Element Analysis

The numerical simulation of a concrete structure with finite element software is a usual approach in civil engineering. At this the structure is divided into small elements (finite elements) and their interaction is simulated.

The photogrammetry allows the connection between finite element simulation and a real test. The displacements of the targets are used as displacements of the connections. In addition the crack tracking is used to define cracked elements with discrete or distributed basic approach functions (figure 13).

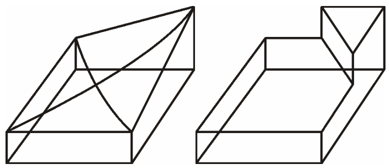


Figure 13: discrete or distributed basic approach functions

The finite element system allows calculating with material laws stress in the concrete element. If they exceed the maximum tension stress of the concrete at a location, the crack probability is there increased and a new iterative program step is to run.

Knowing cracks as well as displacement, the used material laws of the finite element software can be checked and calibrated by controlling stresses.

5. EXAMPLES

The presented method was tested on different specimen types, which are shown in the following chapter. Therefore different grids of targets, camera positions and number of cameras are used.

5.1 Tensile Test

The tensile test is basically used as a pre-test before a complex test can be realised. The tensile strength of concrete and reinforcement are the most important values. The following example comes from a test series for the effect of inclined inlaid reinforcement. The specimen was prepared with a grid of targets (76 x 17 targets) and the photos are made by a one-camera-system in an interval of 15 seconds. The calculation delivers the change of distance between the targets and at the same time directly the crack width for the horizontal cracks. The experiment set-up, the crack pattern at the end of test, and a schematic drawing is presented in figure 14**.**

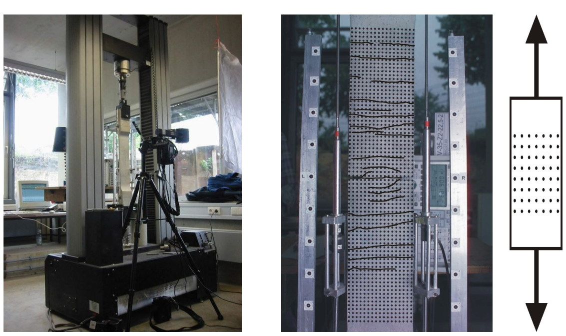


Figure 14: a) experiment set-up with one camera b) crack pattern at the end of test c) schematic drawing

In figure 15 the crack pattern evolution is shown. The basic crack in the centre was generated by cuts and is dominant till failure. Neighboured are the evolutions of secondary cracks. The width of the basic crack is more than 1 mm at the end and the width of the secondary cracks are between 0.2 and 0.4 mm.

In addition an overturning of the specimen can be detected, which makes it necessary to change the restraint.

During the tests it was recognized, that the plane representing the target field is unstable in relation to the camera. The specimen changes its distance to the fixed camera under increasing load, so that the attitude varies marginally. Therefore the method was extended by one or two cameras to be able to determine three-dimensional displacements.

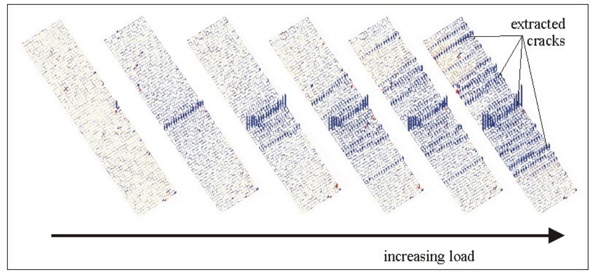


Figure 15: Crack pattern evolution at a tensile test (display PHIDIAS)

5.2 Shear Test

The next test presented is a 4-point loading test in form of an I-beam with the length of 1 meter. The measurement was made at one side to research the area of shear cracks. The grid of targets (76 x 16 targets) was measured with two or three cameras (Figure 16).

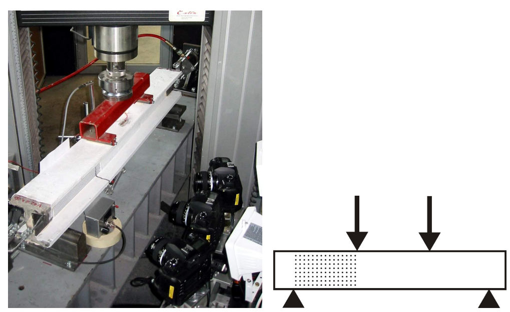


Figure 16: a) configuration of a 4-point loading test with three cameras b) schematic drawing

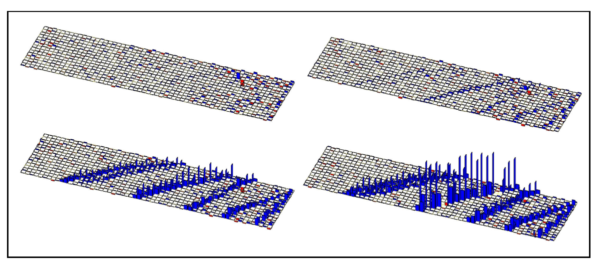


Figure 17: Crack pattern evolution at a shear test (showing four selected epochs, displayed by PHIDIAS) starting crack width about 0.02 mm (image above right) failure crack width about 0.20 mm (image below right)

The testing configuration set-up of a 4-point loading test is usual in civil engineering to generate bending and shear cracks. The shear cracks are parallel to the diagonal load pressure between support and bearing (figure 17). The first crack width starts with about 0.02 mm, and ends a short time before failure with about 0.20 mm.

5.3 Plate Tests

More complex to assess and, to this, more difficult to estimate are plates, which are loaded biaxial by tensile or compressive force from one or two sides.
The measurement area with 30 x 30 cm² was prepared with 59 x 59 targets (figure 18). Figure 19 shows the evolution of the crack pattern.

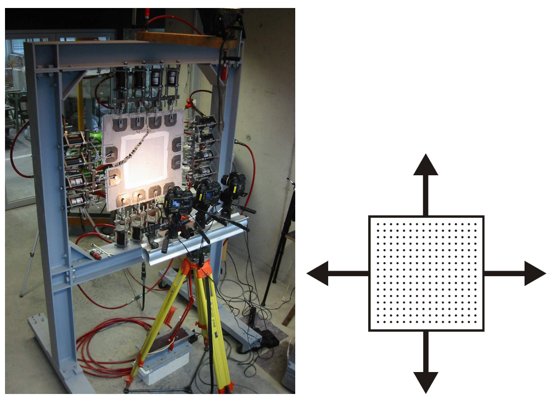


Figure 18: Testing configuration and schematic drawing

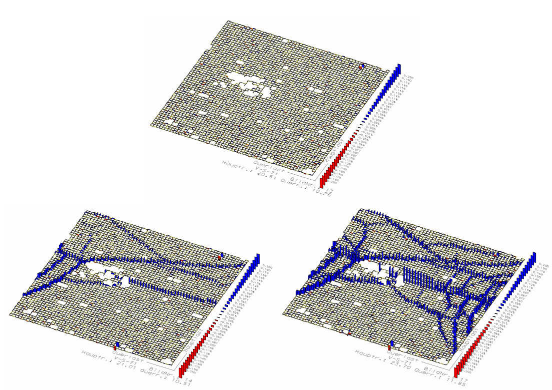


Figure 19: Crack pattern of a plate test in selected epochs

The method is robust against missing targets. Figure 19 shows a measurement display with blank areas. There the concrete was too defective to fix all targets. It is possible to interpolate the missing targets without a strong smearing of the crack structures (figure 20).

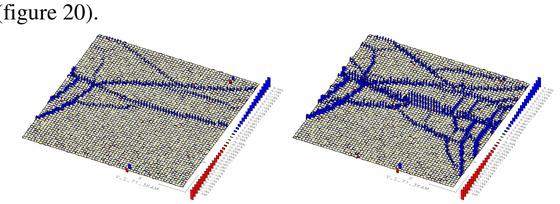


Figure 20: Interpolated targets

6. CONCLUSIONS

The paper describes several applications of digital photogrammetry for monitoring cracks at concrete elements during research experiments. The specimens are prepared with circular targets and photographed with up to three digital cameras simultaneously. The cracks are causing a variation in the distance between adjacent targets, which is measured photogrammetrically. Thus the evolution of the cracks can be observed as soon as the width of the cracks exceed at least 5 – 10 µm. The above-mentioned examples show, that digital photogrammetry as non-contact measurement technique is useful in research projects of civil engineering.

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