High sophisticated full field interferometry (ESPI) on concentrate loaded concrete

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Abstract

The maximum load of shear loaded anchors close to the edge is accompanied by cracks of huge length. The initiation of these cracks starts already at a low load level. In contradiction to reinforced concrete in this case the load transfer is achieved by the partial already cracked structure which cannot be neglected.

Electronic Speckle Pattern Interferometry (ESPI) is used to analyse the distribution of strain near shear loaded expansion anchors. Superficial micro cracks can be made visible directly after their initiation and their crack width can be quantified in the range of micrometers.

Difficulties and possibilities for a two-dimensional application are shown. Due to the low deformation, various outer influences can falsify the results. A satisfactory output only can be guaranteed with the knowledge of the behaviour of concrete surface, impact of vibration and outer light etc.

Micro cracks often don't grow to visible macro cracks because of the big spreading of concrete tensile strength. They lead already to a relocation of stress distribution and therefore they change the flow of forces.

Consequently the localisation of invisible micro cracks is important for understanding the whole crack process.

1. Introduction

Anchorage in concrete is applied frequently because of its flexible use in all kinds of structures. Especial for anchors close to the edge the tensile strength of the surrounding concrete is the deciding failure criterion.

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For this reason it’s important to have an exact knowledge of the real stress near the concentrated loading and of the development of micro cracks.

The maximum anchor load is accompanied by already visible cracks. Hence the detection of micro cracks and their mode of operation are researched by using a non-contact measuring method.

2. Optical and finite element methods

In the research of Lendenhoff [1] an optical microscope was used to detect micro crack processing by elaborate preparation technology. Also in this research it was attempted to compare the results of ESPI to the crack width measured by microscope.

On the one hand it was a problem finding the micro cracks and not knowing if they had already been there in advance. On the other hand there was no exact definition of the edge because of superficial spalling, which caused insufficient results.

Supported by finite element method model simulation using non linear material models (Červenka et al. 2001 [2]) the qualitative crack process could be estimated.

ESPI already was used by Eberhardsteiner [3] at the research of biaxial stress of fir wood. According to the producer of ESPI, in this research this type of interferometer is used the first time for analysing concrete cracks.

3. Test facilities

3.1 Material testing machine Zwick Z100

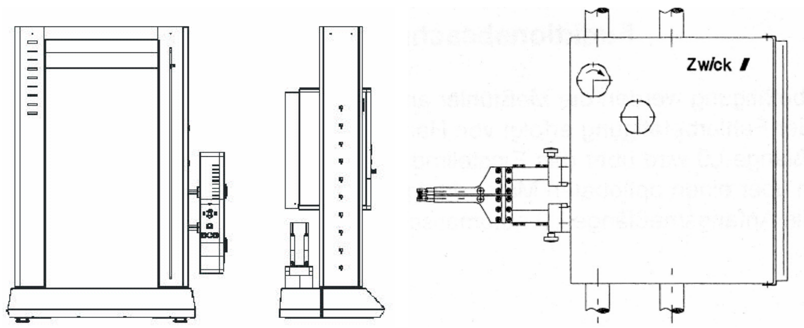

Fig. 3.1:** **L: Testing machine Zwick Z100; R: elongation measure system Makro; *[4]*

The horizontal traverse is moved by an electro mechanic spindle drive with shaft joint. Although tension or compression loads up to 100 kN can be achieved, the actuation velocity can be adjusted between 0.5 µm/min and 300 mm/min.

Because of its vibration-free bedding the testing machine is not influenced by outer vibration. Displacements can be measured by the traverse position or by an external elongation measure system “Makro”. The change of position of the unloaded traverse was verified by Makro and ESPI and can be made in the range of micrometers.

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3.2 Electronic Speckle Pattern Interferometry (ESPI)

The principle of a Michelson interferometer is enhanced to measure the displacement of each pixel at the observed surface (ca. DIN A4, 800x600 pixels) in all three directions (in plane IP and out of plane OOP) with accuracy up to 10 nm.

The illumination by widened LASER light has to be uniform, and the influence of environmental light is reduced by shading and optical filters.

Fig. 3.2: Speckle interferometer with 4 reflector arms

3.2.1 Formation of speckle pattern

- Use of monochromatic LASER light as a measurement tool for displacement
- Each speckle results from overlaying laser rays in the particular pixel
- Brightness of each pixel depends on phase offset of incoming rays caused by surface
- These subjective speckles represent the rough surface like a fingerprint

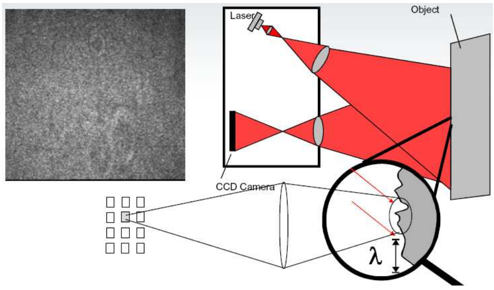

Fig. 3.3: Characteristic speckles, like fingerprint *[5]*

3.2.2 Changing of speckles due to deformation

- Wavelength ($\lambda < 1$ µm) of light forms the scaling
- Reference beam for interferometry:
  Change of distance between interferometer and surface causes difference of brightness of each speckle
- Full field interferometry:
  Each speckle in the whole field of vision delivers results caused by deformation
- Capturing speckle picture of all three directions by CCD camera

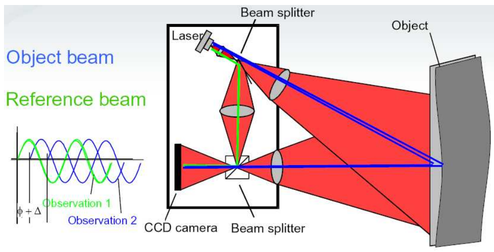

Fig. 3.4: Changing of brightness of Speckles due to deformation *[5]*

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3.2.3 *Measuring of one load step*

- Reference state:
  Capturing speckles of all three directions (2x in plane, 1x out of plane) of unloaded object
- Loading first load step (LS)
- Deformed object:
  Capturing speckles without further movement by CCD camera
- Subtracting speckle pictures:
  Relatively changing of brightness of each speckle is made visible
- Fringes show deformation of surface of one load step
- Points at the same fringe have nearly same deformation in the particular direction
- About 3 µm difference of deformation between fringes (IP)

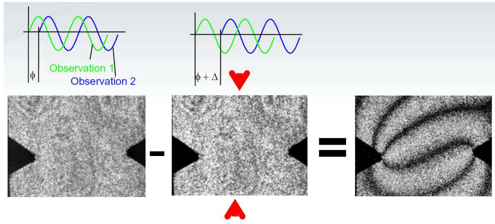

Fig. 3.5: ***reference state - deformed object = correlation fringes*** *[5]*

3.2.4 *Unwrapping of correlation fringes*

- Although perturbation is minimized, superposition of objective and subjective speckles and other influences require software filters
  So fringes are processed by filters and algorithms
- Getting brighter means getting more deformation
- Definition of a start point
- Detection of discontinuities in grey value
- Adding an offset (n • 2π)

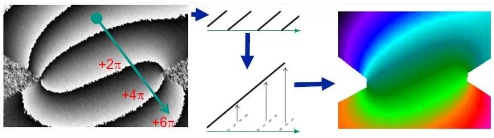

Fig. 3.6: Wrapped phase map → unwrapped phase map (miscoloured)

3.2.5 *Sensitivity vector*

- Calculating sensitivity vector S for each pixel out of trigonometry
- Computing 3D deformation by using phase maps and sensitivity vectors of all three directions
- Highest sensitivity for out of plane deformation

The final deformation is arisen by summing the load steps.

For further information: Gingerl [6].

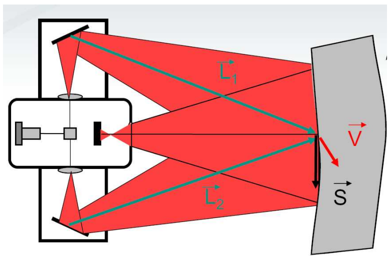

Fig. 3.7: In plane sensitivity vector S *[5]*

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4. General setup

Vibrations and offset relating to the speckle interferometer have to be minimized. Besides the vibration-free bedding of the testing machine a stiff connection between the observed surface and the interferometer is implicated by aluminium profiles. Without this preparation every human step made near the trial could be noticed by the interferometer.

The influence of outer light and airflow are minimized, and the surface condition is adjusted by powder spray.

***Fig. 4.1:** Stiff connection between interferometer and concrete, shading to reduce outer light*

5. Verifying crack width

ESPI provides deformations only relatively to a chosen point in the field of view. Therefore an analysis across discontinuities (e.g. cracks) is not possible, so crack width just can be quantified using "crack bridges". These crack bridges can be made by elastic films connecting both crack edges. Another possibility is to use the non cracked concrete aside like a continuous connection between the edges.

In basic experiments a concrete cuboid is charged at its inlying centric reinforcing bar.

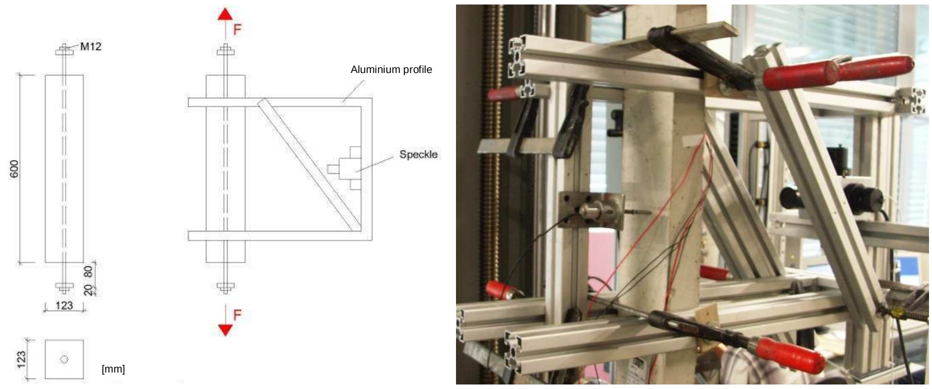

***Fig. 5.1:** Tensile loading at reinforcement bar, position of interferometer*

In the speckle picture (Fig. 5.2 L) vertical deformation is shown by grey values and fringes. Cracks are made visible by discontinuities of the brightness. The crack starts at the left side and ends close to the right concrete border (white arrows). The vertical

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speckle picture shows a clockwise rotation of the upper and a contrary rotation of the lower part, which also can be seen in the vertical deformation image in Fig. 5.2 R.

The results of ESPI were compared with applied strain gages and inductive displacement transducer. So besides strain the crack width could be verified in the range of micrometers.

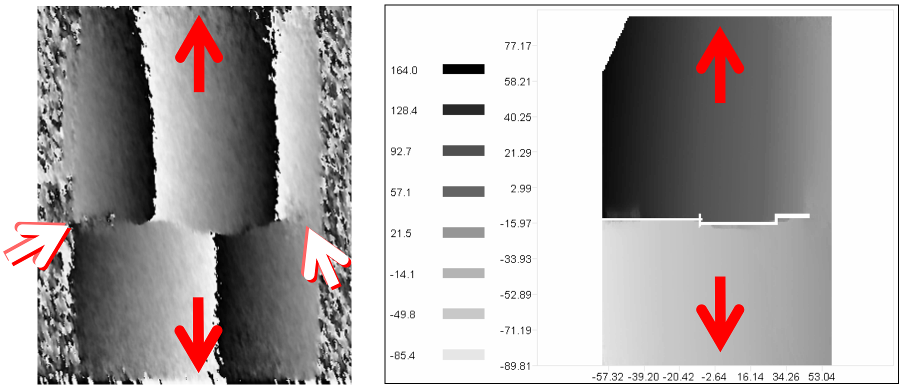

Fig. 5.2: L: fringes of vertical speckle picture (clockwise rotation of upper part); R: deformation image

6. Crack initiation of shear loaded fasteners close to edge

6.1 Experimental setup

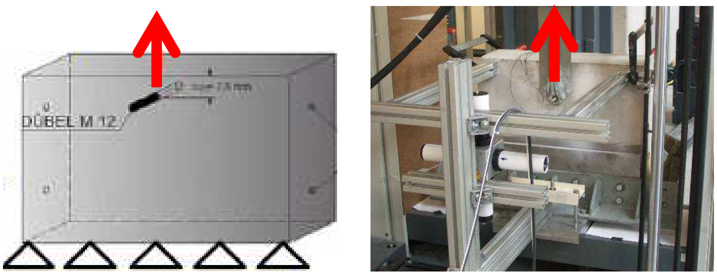

Fig. 6.1: Test setup: shear loaded anchor close to edge, bonded steel plate as uniform support

The concrete cuboid is not reinforced. It is supported at the bottom by a bonded steel plate. That way there is no influence of global stress near the anchorage during the trial and the setup also represents practical application.

The area around the anchor is observed by ESPI which is connected to the surface by stiff aluminium bars.

6.2 Results and interpretation

At shear loaded anchors the cracks are initiated at the surface. So superficial deformation measurement by ESPI detects crack initiation in the beginning and the whole cracking process can be analysed. Furthermore each formation of cracks causes a qualitative

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relocation of the stress and strain field. By ESPI it's also possible to have a look at the real superficial deformation and strain during the crack process.

1.) The first cracks arise at the local loading. The concrete at the load transfer next to the anchor is under high compressive stress what produces orthogonal tension and causes local radial cracks and superficial failure at a very low load level. Thereafter the leading−in of the main load is relocated deeper. Here a zone of very high three dimensional compressive stress is developed.

Some trials have shown that large local spalling, as a result of drilling, shifts the leading−in deeper and so it can delay these radial cracks and also enlarge the breaking load V_{max} and ductility.

2.) The second group of cracks starts beginning from the anchor orthogonal to the load direction (Fig. 6.2 L and Fig. 6.4 L) because of concrete tension failure.

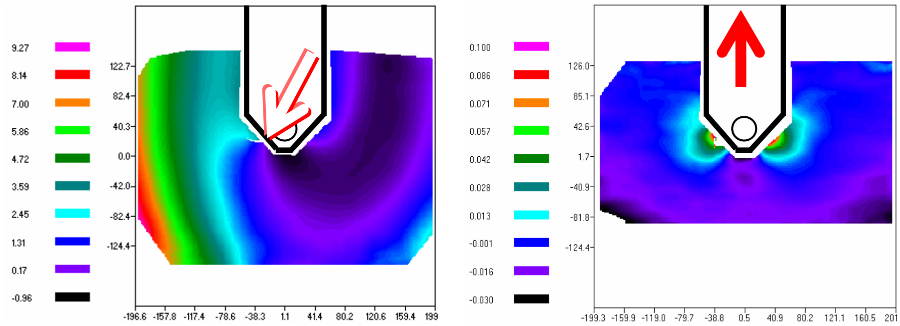

Fig. 6.2: Vertical, ½ V_{max}: L: deformation [µm], first micro crack; R: concentrated strain [‰] near anchor

The vertical strain at ½ V_{max} in Fig. 6.2 R shows the strain concentration near the anchor with a maximum of 0.1 ‰ which is the breaking elongation of concrete. From this point on, cracks are initiated and shown by discontinuities in the speckle pictures (Fig. 6.4 L). They just can be quantified till both edges are still connected by non cracked concrete in the field of vision.

On account of the direction of the laser rays the ESPI method is more sensitive to out of plane (OOP) deformation. Although the main crack direction is in plane, crack initiation can be best seen in OOP speckle pictures. So during the trial this direction is observed.

Also vibration, offset and other perturbation can be detected best this way.

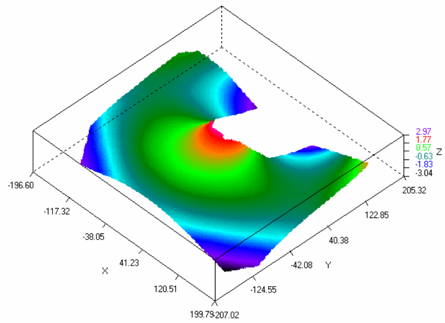

Fig. 6.3: 3D- OOP- deformation [µm] at ½ V_{max}

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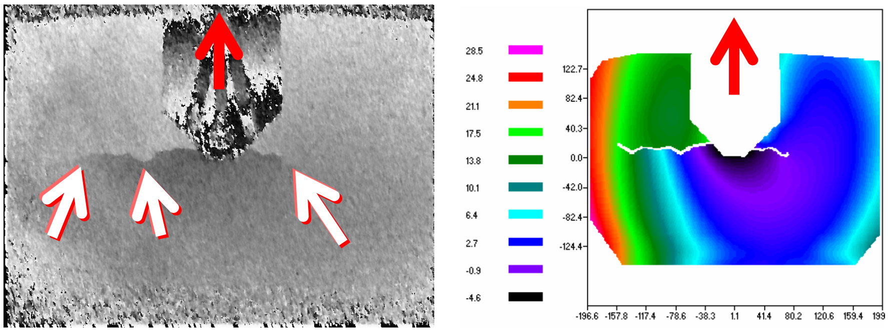

Fig. 6.4: ¾ of V_{max}: L: speckle picture of one load step; R: vertical deformation [µm]

3.) Finally a mechanism analogue to a simple beam is built which produces bending tension stresses at the edge. This causes one crack starting from the edge which could be made visible by ESPI in other trials using a different adaptor.

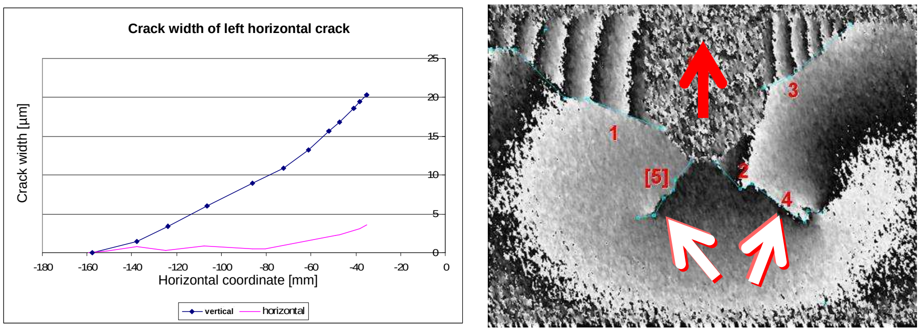

Fig. 6.5: L: Course of left horizontal crack width; R: example of cracks also opposite load direction

Many trials also show that the first crack isn't always the decisive one and/or the final macro crack has the same origin but a different direction. Also sometimes many cracks appear in the beginning, and in the end just one of them is visible to the naked eye, and betimes cracks occur opposite to the load direction like in Fig. 6.5.

This depends not only to the geometry but also to coincidental material behaviour around the anchor.

7. Summary

Highly sensitive Electronic Speckle Pattern Interferometry (ESPI) is adjusted for concrete as a new field of application. An experimental setup is developed for maximal accuracy of the results. Cracks create discontinuities what complicates analysing the crack width. As a result of basic trials, cracks not only can be analysed qualitatively but also can be quantified.

So it's possible to observe crack initiation near the concentrated leading-in as well as its growth precisely even far before maximal load is reached. Furthermore the real

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deformation of the observed surface in all three directions in the range of micrometers and the strain concentration around the anchor are made visible.

All these effects improve a better understanding of the flow of forces in the cracked concrete and will be worked out by cracking modes in following research.

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