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Application of distributed optical measurements to structural concrete experiments

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ABSTRACT: This paper explores the combined application of digital image correlation (DIC) and high-resolution fibre optical (FO) measurements to structural concrete elements. These novel distributed optical instrumentation techniques allow measuring virtually continuously and without affecting the mechanical behaviour (i) displacements on the concrete surface and (ii) elastic as well as plastic strains in reinforcing bars, respectively. The results of an experimental study consisting of two reinforced panels subjected to diagonal tension show the ability of DIC to successfully detect complex crack patterns and their kinematics. The reinforcement strains recorded by FO correlate perfectly with the position and opening of the cracks. The results prove the great potential of DIC and FO to measure phenomena like bond, crack behaviour and shear transfer that hardly ever have been directly measured in detail until now. Transforming the large amount of collected data into useful structural information is an important challenge for these techniques.

1 INTRODUCTION

The growing number of ageing structures, combined with increasing traffic loads, leads to a rising need and interest in the assessment and monitoring of concrete structures. The knowledge in structural concrete is perfectly developed for the dimensioning of new structures, which can be designed to provide sufficient ductility for a safe application of lower bound limit analysis methods. However, there is a lack of sound mechanical models for the assessment of existing structures. Many of these structures were built following older design codes and do not satisfy the prerequisites for using actual design methods. Hence, research is required to develop assessment methods accurately predicting the actual capacity of existing structures and reducing the need for retrofitting measures. Novel instrumentation techniques allowing distributed measurements on the surface of, and inside the concrete will be essential for the development of such detailed analysis methods, as they can provide insight into the mechanical behaviour of structural concrete that hardly has been possible up to now. The present work addresses the potential of combining the application of two of these novel techniques, i.e. full field digital image correlation (DIC) and distributed fibre optic strain measurements (FO), as schematically illustrated in figure 1. These instrumentations are able to monitor crack kinematics on the concrete surface and strains along reinforcement bars quasi-continuously, which makes it possible to determine the internal forces of the specimen and the stresses transferred across cracks directly from equilibrium at the crack locations (Kaufmann et al. (2017)). Compared to conventional strain gauges or displacement transducers these innovative measuring systems have the advantage of providing thousands of closely spaced sensor points, leading to virtually
continuous measurements. Moreover, these techniques do not disturb the behaviour of the structure, since DIC measurements are contactless and FO uses tiny fibres as sensors, with almost no impact on bond. While the present work focuses on the application of DIC and FO to structural concrete experiments aiming at improving assessment models, both techniques have also great potential as monitoring systems for existing structures.

Strain sensing with optical fibres is based on light backscattered either at artificial distortions in the fibre (e.g. Bragg gratings) or at natural local defects of the fibre itself, such as the variation of the refractive index. Changes in a fibre’s temperature or strain cause an alteration in the properties of the reflected light, which can be detected with a suitable reflectometer and processed to localise and quantify the relative changes (Samiec (2011)). While an optical time domain analysis of the Brillouin backscatter allows measuring strains over tens of kilometres with a sensor spacing of about one meter, an optical frequency domain analysis of the Rayleigh backscatter is very promising for monitoring concrete structures since it increases the spatial resolution up to 1 mm for a maximum sensing length of about 50 m providing a sensitivity of a few µm/m (Samiec (2011); Henault et al. (2012)). The high cost of the sensing device (patented technology) contrasts with the inexpensive sensors used (standard telecom fibres).

Digital image correlation is a novel but already well-established optical instrumentation that tracks the displacement field of a surface based on pattern recognition of digital images. Stereoscopic applications of DIC allow tracking three-dimensional displacements and avoiding errors due to out-of-plane displacements inherent to two-dimensional DIC applications with a single camera. DIC is very promising to measure crack kinematics in complex concrete structures, as shown recently in several studies for single cracks (Cavagnis et al. (2015); Huber et al. (2016)). However, the quality of the results is highly dependent on the user’s expertise and diligence, as well as on the use of appropriate procedures to correct lens distortions.

This paper presents the results of an experimental study consisting of two square, orthogonally reinforced panels subjected to diagonal tension with the objective of exploring the combined application of DIC and FO to reinforced concrete elements with biaxial load and complex cracking behaviour. To the authors’ knowledge, the presented work is the first one where DIC and FO are applied together in structural concrete experiments with complex crack patterns.

![Figure 1. (a) General setup of possible structural concrete experiment with rebars instrumented with optical fibres and speckled surface; (b) data acquisition and post-processed data of FO measurements along one rebar; (c) speckle pattern and strain field calculated with DIC (extracted from Kaufmann et al. (2017)).](image-url)
2 EXPERIMENTAL PROGRAMME

2.1 Test specimens

The two square panel specimens with 600 mm side length and 125 mm thickness are shown in figure 2a together with the reinforcement layout. The specimens were reinforced orthogonally with stirrups of diameter 10 mm parallel to the $x$-direction and either stirrups of diameter 6 mm (specimen FODIC-10-6) or 8 mm (specimen FODIC-10-8) in the $y$-direction. For the load introduction two rebars of diameter 22 mm with anchor plates were placed over one diagonal. The stirrups consisted of hot-rolled steel, but lacked a distinct yield plateau. Table 1 shows the main properties of the reinforcement obtained from standard tensile tests. The concrete, with maximum aggregate size of 16 mm, had a nominal characteristic compressive cylinder strength of 40 MPa. The specimens were tested deformation controlled under diagonal tension by pulling the diagonal rebars in a universal testing machine at a speed of 0.06 mm/min that was increased in the post-peak phase of the test. With the stirrups oriented at 45° to the direction of the applied force, a combined loading in shear and biaxial tension was obtained with respect to the reinforcement directions. Besides recording the applied load and displacement, the specimens were instrumented by fibre optic sensors and digital image correlation.

2.2 Distributed fibre optic strain measurements

To measure the strains of the stirrups, a fibre optic measurement system based on the Rayleigh backscatter technology was used, with standard telecom fibres as sensors. The fibres, with an inner core of 9 $\mu$m and total diameter of 250 $\mu$m, were glued with epoxy in 1x1 mm grooves which were carved along the length of every stirrup. This procedure minimises the impact on bond behaviour and maximises the protection of the fibres inside the specimen. A total number of 24 measuring lines resulted per specimen, as both legs of every stirrup were instrumented. Outside the glued section, the fibres were put into small rubber tubes to protect them during casting (see figure 2b). In the transition zone between glued and unglued sections, the fibres need additional protection, e.g. by silicon, which might bias bond in this local area. However, the length of this zone is negligible comparing the undisturbed measuring length for bigger specimens. The protection of the fibre segments inside the concrete worked very well; only 8% of the transition zones were damaged. As a reflectometer, the commercial system ODiSI-A was used, allowing to measure up to 13 millistrains (‰) over a sensing length of 50 meters with a maximum sampling frequency of 1/3 Hz (Polytec (2013)). Sensor spacing and virtual gauge length were chosen equally to 5 mm. The maximum observed noise at the beginning of the test was 0.02 ‰ and increased when reaching the strain limit of the measuring device. Stresses and forces were calculated using the stress-strain-relationship of every type of rebar obtained from the steel tensile tests and considering the nominal cross sectional area.

Table 1. Material properties of the reinforcement

<table>
<thead>
<tr>
<th>Diameter [mm]</th>
<th>Steel type [-]</th>
<th>Yield stress $f_y$ [MPa]</th>
<th>Ultimate stress $f_u$ [MPa]</th>
<th>Strain at peak load $A_{gt}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø6</td>
<td>B500A</td>
<td>505</td>
<td>535</td>
<td>31</td>
</tr>
<tr>
<td>Ø8</td>
<td>B500B</td>
<td>522</td>
<td>574</td>
<td>36</td>
</tr>
<tr>
<td>Ø10</td>
<td>B500B</td>
<td>519</td>
<td>584</td>
<td>36</td>
</tr>
</tbody>
</table>
2.3 Digital image correlation measurements

The displacement field of one side of each specimen was full field tracked using three-dimensional digital image correlation. The concrete surface was speckled to reduce the uncertainty of the pattern-matching algorithm. The speckle pattern consisted of a white background and circular black dots of approximately 3 pixels diameter (see figure 2c). Two Allied Vision Prosilica GT6600 monochrome cameras (28.8 Megapixel, 36x24 mm sensor) were used at 2400 mm distance to the specimen with a stereo angle of 28º. The use of 28 mm lenses (Carl Zeiss Distagon-2/28 Z-M42-I) resulted in a field of view of 2000x2800 mm and a scale of 0.45 mm/pixel. The field of view is much larger than the size of the specimens, because the experimental campaign aimed at evaluating the performance of the measuring system for larger specimens (Kaufmann et al. (2017)). The correlation was performed with VIC-3D software (Correlated solutions (2014)) with the main parameters defined in figure 2c. The strain field was computed from the measured displacement field and the cracks were detected as peaks in the principal tensile strains, as indicated in figure 1. Once the crack location and orientation is known, the crack kinematics are calculated as relative displacements of the crack lips.
To overcome the user-dependent uncertainty of DIC measurements, before each structural test a check to evaluate this uncertainty was performed, consisting of a movement of the panel without load (so-called zero strain test). All deviations in strains and relative displacements computed in this test with respect to the reference state are uncertainties of the DIC measurement. Table 2 shows the standard deviation of the uncertainties in strains ($\sigma(\varepsilon)$) and in relative displacements ($\sigma(\Delta d)$) for two different intervals of movement. The uncertainty increases with the applied movement showing that, apart from random noise, small systematic deviations are present.

### Table 2. Uncertainties of DIC measurements depending on the magnitude of movement ($d$)

<table>
<thead>
<tr>
<th></th>
<th>$d &lt; 20\text{ mm}$</th>
<th>$20\text{ mm} &lt; d &lt; 150\text{ mm}$</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$\sigma(\varepsilon)$ [%]</td>
<td>$\sigma(\Delta d)$ [mm]</td>
</tr>
<tr>
<td>FODIC-10-8</td>
<td>0.257</td>
<td>0.007</td>
</tr>
<tr>
<td>FODIC-10-6</td>
<td>0.265</td>
<td>0.014</td>
</tr>
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</table>

3 RESULTS OF DISTRIBUTED OPTICAL MEASUREMENTS

DIC measurements correlated properly over the whole experiments. The FO system lost the correlation to the baseline at around 130 kN for FODIC-10-6 and 180 kN for FODIC-10-8. The high measured strains towards the end of FODIC-10-6 imply that the loss in correlation occurred because the maximum detectable strain range was exceeded. In contrast, in FODIC-10-8 the correlation was affected by a damage of the fibre. Table 3 summarizes some results of the optical measurements for different load steps. In FODIC-10-6 elastic and plastic strains in the stirrups up to 14.6\% were recorded. For FODIC-10-8 only elastic strains were observed.

Figure 3 shows the combined results of DIC and FO for two different load steps. The detected cracks are shown as black lines with the line thickness indicating their opening. The colours along the stirrups indicate the stresses measured at the front layer and the line thickness corresponds to the forces for both stirrup layers. Since the optical fibres left the specimen at the boundary area, the detection area of DIC and the tracked cracks do not reach the specimen’s edge. The measured strains in the first centimeters of the stirrups have to be interpreted carefully as they are taken in the transition zone between the glued and unglued section (see figure 2b) and might be underestimated. In FODIC-10-6 the stirrups of diameter 10 mm stayed elastic over the whole monitoring time whereas the stirrups of diameter 6 mm reached the yield point at approximately 110 kN. In FODIC-10-8 the stresses in most of the stirrups are close to yielding at 150 kN. The location of the cracks can clearly be identified in the FO measurements.

### Table 3. Maximum strains ($\varepsilon_{\text{max}}$) and stresses ($\sigma_{\text{max}}$) in the stirrups as well as maximum ($w_{\text{max}}$) and average crack opening ($w_{\text{avg}}$) for several load steps (last row corresponds to the peak load)

<p>| | | | | | | | | |</p>
<table>
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</thead>
<tbody>
<tr>
<td>$F$ [kN]</td>
<td>$\varepsilon_{\text{max}}$ [%]</td>
<td>$\sigma_{\text{max}}$ [MPa]</td>
<td>$w_{\text{max}}$ [mm]</td>
<td>$w_{\text{avg}}$ [mm]</td>
<td>$F$ [kN]</td>
<td>$\varepsilon_{\text{max}}$ [%]</td>
<td>$\sigma_{\text{max}}$ [MPa]</td>
<td>$w_{\text{max}}$ [mm]</td>
</tr>
<tr>
<td></td>
<td>$\odot 6$</td>
<td>$\odot 10$</td>
<td>$\odot 6$</td>
<td>$\odot 10$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>2.4</td>
<td>2.0</td>
<td>442</td>
<td>372</td>
<td>0.37</td>
<td>0.14</td>
<td>70</td>
<td>1.3</td>
</tr>
<tr>
<td>110</td>
<td>4.3</td>
<td>2.4</td>
<td>502</td>
<td>442</td>
<td>0.57</td>
<td>0.16</td>
<td>110</td>
<td>2.4</td>
</tr>
<tr>
<td>125</td>
<td>14.6</td>
<td>3.2</td>
<td>525</td>
<td>493</td>
<td>1.37</td>
<td>0.25</td>
<td>150</td>
<td>3.6</td>
</tr>
<tr>
<td>134</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.66</td>
<td>0.35</td>
<td>201</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 3. Crack locations and openings, steel stresses and forces in front layers of stirrups for FODIC-10-6 at (a) 80 kN and (b) 110 kN as well as for FODIC-10-8 at (c) 90 kN and (d) 150 kN.

except for those localised in the transition zone, and match very accurately with the crack tracked independently with DIC on the surface.
Figure 4. Results of steel strains and crossing cracks for stirrup A (Ø10, y = -50 mm) of FODIC-10-8: (a) measured strains for different load steps with position, orientation and opening of cracks; (b) continuous results for crack 3 (x = 20 mm).

Strains of both legs of stirrup A (Ø10, y = -50 mm) in FODIC 10-8 (see figure 3d for exact location) are shown in figure 4a for different load steps together with the measured openings and inclinations of the cracks crossing the stirrup. Cracks 1 and 2 close to the edge of the specimen are occurring before or slightly after 90 kN, whereas crack 3 is formed at a load of approximately 120 kN. As observed in figure 3, the location of the cracks can be detected independently with both optical systems and the positions match very accurately. The FO strains of the front and back leg of the stirrup are very similar. It has to be noticed that in the first and last 50 to 100 mm of the FO measurement length the fibres are crossing the transition zone from the glued to the unglued section (see figure 2b) and therefore the curves might not represent the true strains. This can be observed for the region around crack 1, where much higher strains in the reinforcement would have been expected to be consistent with the existing large opening of the crack. For the other cracks, the component of the crack kinematics in the direction of the stirrup can be calculated by integrating the FO strain data if the tensile strains in concrete are neglected. With the integration length defined by dotted vertical lines in figure 4a, the results are in the same order of magnitude as evaluated with DIC (e.g. for crack 2 & 3 at 170 kN: DIC: 0.07 mm & 0.13 mm, FO: 0.08 mm & 0.16 mm). Figure 4b shows the continuous evolution with the applied force of the opening of crack 3 and the steel strains for both stirrup legs at this position. The sudden formation of the crack at 120 kN lead to a significant drop in the load. A jump in the strains and in the crack opening of about 1‰ and 0.2 mm respectively was tracked successfully in this fast process, demonstrating the capability of optical measurements to monitor the cracking phase of concrete structures.

4 CONCLUSIONS

Two reinforced concrete panels under diagonal tension with complex crack patterns were tested to assess the joint application of digital image correlation (DIC) and distributed fibre optic (FO) measurements. This allowed computing elastic and plastic strains, stresses and forces in every section of all the reinforcement, as well as location and opening of the cracks all over the
concrete surface, and represents a significant step forward in current testing and monitoring of concrete structures. The measurement of crack location and opening of both measurement techniques matched very accurately. Several aspects should be further investigated for future applications, such as (i) the necessity of a very careful installation of the fibres because of their fragility; (ii) the difficulty of measuring with FO high gradients of strains in space and time, produced at cracking or at yielding for steels with a distinct yield plateau; (iii) the user dependent accuracy of DIC and (iv) how to handle the huge amount of data generated. Obtaining much more information than with traditional instrumentation can paradoxically lead to a lower understanding of the behaviour or to more biased interpretations. Therefore, a big effort should be put by the research community to develop automated and objective post-processing tools as well as standards about data reliability and data sharing for distributed optical measurements. If these aspects are properly addressed the combined use of DIC and FO has a great potential to increase knowledge in structural concrete in the field of bond, load carrying and load deformation behaviour as well as crack behaviour. A better understanding of these topics is essential for the development of sound mechanical models leading to accurate assessments and optimal rehabilitations of existing civil structures. The combined use of distributed optical measuring systems is also very promising to monitor and understand the behaviour of structures, as well as to predict and prevent potential failures.

5 ACKNOWLEDGMENTS

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