Application of fiber optic measurement in textile-reinforced concrete testing

Henrik Becks | Jan Bielak | Benjamin Camps | Josef Hegger

Institute of Structural Concrete, RWTH Aachen University, Aachen, Germany

Correspondence
Henrik Becks, Institute of Structural Concrete, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany.
Email: hbecks@imb.rwth-aachen.de

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Abstract
In research on concrete constructions, fiber optic sensor technology is becoming increasingly important. It enables high-frequency and quasi-continuous measurement of temperature and strain distribution. Furthermore, this technology offers the opportunity to determine the crack width within the cross section of specimens and not, as with conventional instrumentation, only from the outside. While experience for application of fiber sensors in steel-reinforced concrete research already exists for several years, only few findings are available for textile-reinforced concrete (TRC). This article gives a short overview of the principle of fiber optic sensor technology, presents possible concepts for utilization in TRC testing, and explains the necessary post-processing steps for the preparation of the measurement results by means of an example from current research. Finally, the results are validated with conventional measuring methods and the applicability and further challenges are discussed.

KEYWORDS
CFRP, crack width, fiber optic measurement, instrumentation, strain, textile reinforced concrete

1 | INTRODUCTION

While research on textile-reinforced concrete (TRC) gained momentum in the last 30 years and numerous publications were produced, adequate answers for essential topics are still lacking and the innovative construction material remains a niche product. Insufficient measurement methods in TRC testing might be one part of an explanation for this situation. Japanese researchers utilized “lattice reinforcement of continuous carbon fibers bonded together with resin” as early as the late 1980s in construction works for a research base in Antarctica. Yet, it took years of fundamental research on the subject until application examples for facades, bridges or shell structures in Germany were reported. One reason for this are the fundamentally different construction strategies enabled by the non-metallic, textile reinforcement materials with its robustness to corrosion. While construction with fiber-reinforced polymer (FRP) reinforcement bars is very similar to conventional reinforced concrete, construction with TRC is different and requires a rethinking of established production methods. While this offers many advantages, for example, additional protective coatings in severe exposions become obsolete, more emphasis needs to be put...
on fulfillment of architectural aspects in serviceability limit state (SLS). As external elements such as bridge decks are no longer covered with an additional coating and thin cross sections are generally less robust to unplanned impacts, cracks and crack width control become increasingly important. For example, full vertical cracks in the non-prestressed bridge deck of the trough cross section in Reference 13 were expected and are no threat to load-bearing capacity but pose a visual deficiency to some users, especially in the state of drying after rain.

Previous research in TRC mainly focused on ultimate limit state (e.g., References 14–16), and generally accepted models for verification of crack width in SLS are not yet available. Meanwhile, it is assumed that the distributed textile reinforcement guarantees a fine crack pattern. This might be true for non-impregnated textiles with low efficiency and for high reinforcement ratios. Newer, fully impregnated high-strength textiles, however, often require additional sand coating to ensure small crack width and crack spacing.\(^\text{15,19}\)

To determine crack width and stress levels in the reinforcement in SLS, adequate test methods are required. Especially the internal measurement of strains at multiple locations in the vicinity of cracks is nearly impossible with conventional measurement techniques, as the individual yarns are of small diameter. The application of strain gauges directly on textile reinforcement is therefore challenging and prone to errors in execution, and the instrumentation (cables, adhesive) significantly influences bond characteristics. Generally, crack width can be measured from the outside using digital image correlation (DIC) tools. This might be adequate in uniaxial tensile tests on thin layers,\(^\text{20}\) which are often used for strengthening. For thicker elements in bending or shear test, the local stress state in the longitudinal and transversal reinforcement cannot be determined by external measurements alone.\(^\text{21}\) For those tests, internal measurement with fiber optical sensors (FOS) is predestinated and promising. This method is increasingly used in reinforced concrete research, and test systems are widespread.\(^\text{22–24}\) For steel-reinforced concrete, determination of the crack width using FOS has already been successfully practiced.\(^\text{25,26}\) For TRC testing, however, existing test concepts need to be adapted. This article presents application concepts and highlights the particular challenges when utilizing small-scale textile reinforcement with high tensile strength combined with state-of-the-art high-strength concrete.

## 2 | FOS IN REINFORCED CONCRETE RESEARCH

To derive design concepts based on physical models for structural concrete, or to validate nonlinear finite element models, precise knowledge of the load transfer and the related deformations of structural components is essential. While applied loads and deformations have always been recorded in experimental investigations, strains in the reinforcement and the surrounding concrete are also of paramount relevance. For strain measurements, usually only local values using strain gauges or smeared values using linear sensors (LVDT) are recorded. A valuable complement to the conventional measurement technologies is a fiber optic measurement system, which allows continuous strain measurement. This enables to deepen the knowledge of physical effects and underlying load-bearing principles and consequently the improvement of design approaches.

Since the early 1990s, various types of reliable sensors based on fiber optic technologies are available for a broad application range. Nowadays, fiber optic sensing is used for structural monitoring in aerospace, marine, or civil engineering as well as for applications in the medical field. FOS can be fundamentally classified by their field. FOS can be fundamentally classified by their measurands or the technology on which they are based. A variety of physical measurands can be gauged today, such as strain, temperature, or pressure. The most common technologies are fiber gratings and scattering sensors.\(^\text{27}\) Although the measuring techniques differ, both are based on the recording of the frequency shift due to external effects on the measuring fiber. The main distinction is the number and distribution of the separate measuring points along the measuring fibers. While fiber gratings (e.g., Fiber Bragg Grating (FBG))\(^\text{28}\) are applicable for point measurement, systems based on the backscattering of a signal are used for quasi-continuous measurement along the entire fiber. In the construction industry, FBGs are of particular importance for structural health monitoring. They are encoded on short sections of an optical fiber using UV light to create a discrete measuring point.\(^\text{29}\) By multiplexing FBGs, it is possible to construct sensors which allow quasi-continuous distributed measurements at several points along the optical fiber.\(^\text{30}\) The a priori definition of measurement points remains often futile, as for example cracks in concrete structures emerge randomly. Thus, for research purposes it is advantageous when measuring points are continuously distributed along the fiber with a very high spatial resolution. As the description suggests, scattering sensors use backscattered parts of the light (Brillouin, Raman, or Rayleigh scattering) of the glass fiber to detect strain or temperature variations. Systems based on the Brillouin or Raman backscatter are suitable for long ranges (e.g., applications in pipeline or dam constructions) while systems based on the Rayleigh backscatter are suitable for shorter distances.\(^\text{31,32}\) A particular advantage of Rayleigh systems is the very high spatial resolution of the
measuring points along the sensor, which is millimeter-scaled.\textsuperscript{33} Conventional single-mode optical fibers can be used to construct measuring sensors. Different coatings enhance robustness but may have a negative influence on the measuring results, respectively, strain transfer losses.\textsuperscript{34} In combination with an optical frequency domain reflectometer (OFDR\textsuperscript{35}), high spatial resolution measurements and simultaneously high sampling rates become possible. The functionality of measuring systems with ODFR and Rayleigh backscatter has already been described in various publications.\textsuperscript{32,33,36}

Recently, systems based on OFDR and Rayleigh backscatter of an optical fiber have been applied successfully in reinforced concrete research to record strain or temperature changes. Frequently, fiber optic measurements are conducted for crack detection, where FOS is advantageous compared to conventional instrumentation.\textsuperscript{37} The measuring fibers can be attached directly to the concrete surface\textsuperscript{38,39} or they can be embedded in the concrete. Since glass fibers without additional coating are very fragile, a free placement in the concrete is nearly impossible without additional supporting structures. In unreinforced concrete, these supports for the sensors can be realized for example by adding additional structures of metal or plastic.\textsuperscript{40} In reinforced concrete, the application of the fibers on the surface of the reinforcement is convenient.\textsuperscript{41,42} An even better protection can be achieved by inserting the fibers into a notch milled into the steel reinforcement.\textsuperscript{39}

After successful application of the measurement technology in laboratory-scaled tests, real-scale applications on existing bridge structures\textsuperscript{43,44} or concrete slabs of an industrial building\textsuperscript{45} followed. Fiber optic sensing systems can significantly simplify measurements both on existing structures and on new constructions so that a more precise prediction of the service life in the context of structural health monitoring (SHM) can be ensured.

The general concept of fiber application for strain measurement in an experimental setup is shown exemplarily for a reinforced concrete beam in 4-point bending in Figure 1. Local strain gauges (orange squares) were utilized to validate the results. In this example, a single measuring fiber (cyan dotted line) passes along the upper reinforcement in a protection tube to the beginning of the measuring area (cyan line). In this region, the optical fiber was attached to the reinforcement to record the strains of two stirrups and the lower and upper longitudinal reinforcement (Figure 1). In Section 2–3, the measured strains of the lower reinforcement show various peaks, which indicate the location of individual cracks. In contrast, the strain gauge only provides a single recording, which serves merely as a first orientation value of occurring stress, since other sections along the longitudinal reinforcement with higher strains exist. Section 4–5 is located in the compression zone of the specimen and is characterized by a constant strain level. In this section, the results of the fiber optic measurement match the results of the strain gauges, as expected.

3 | APPLICATION CONCEPTS FOR FOS IN TRC RESEARCH

Reinforcement in TRC consists of anisotropic fibers, bundled in yarns, impregnated, and arranged in multiple grid-type reinforcement layers. While this distributed arrangement of individual yarns is advantageous in terms of reduction of local stress concentration due to multiple crack bridging, the experimental determination of stress and strain state is more challenging compared to larger FRP reinforcement bars. The application of local strain sensors to thin FRP elements is state of the art not only

![Figure 1](image-url)
for longitudinal but also for pre-formed shear reinforcement (e.g., References 46,47) and even fiber optic measurement has already been used in concrete structures with FRP and textile reinforcement (e.g., References 48–50). The problem with local strain sensors is that each sensor might locally disturb the stress–strain state inducing premature failure and, more importantly, changing the local bond behavior of the yarns. The smaller the cross section of the reinforcement element, the more pronounced the effect, as cables, connectors, and protection elements do not scale. Therefore, the application of FOS as distributed strain sensors in TRC is especially promising. The measuring fibers themselves are very small and thus influence on local bond behavior is reduced. However, direct transfer of established application techniques presented in Section 2 to TRC proves difficult. Grooving of the yarns similar to milling steel rebar is no option, as the cross sections are too small and typically vary along their length. Thus, longitudinal notches might severely damage the yarn and influence its stress–strain behavior, especially if fibers are not perfectly aligned parallelly. Theoretically, measurement fibers could be incorporated in the textile production process and embedded in the interior of the fibers. While this is possible on a laboratory scale with careful handling and manual impregnation, the yarns assembled in this manner might differ substantially regarding their mechanical properties from industrial-produced textile fabrics. Especially the introduction of the FOS termination and the connection to the sensor controller is a major hurdle. Even more important is that later replacement of damaged fibers or manual adjustment is not possible, reducing the range of applications. Consequently, attaching the measurement fibers to the surface of the yarns is the remaining application method.

Figure 2 shows different examples for application concepts of FOS in TRC testing. A straightforward idea is the application in test direction in uniaxial tensile tests (Figure 2a) for determination of reinforcement stress and strain in the vicinity of transverse cracks. This example will serve as first proof of concept and is discussed in more detail in this paper. The helix (b) or wave (c) layup aims at measuring strain in the concrete surrounding the textile reinforcement in uniaxial tension. Due to their undulating shape and mechanical interlock, yarns in TRC might introduce concentrated ring stresses which eventually lead to splitting cracks as governing bond failure mechanism. 51,52 Internal measurement is a prerequisite for better understanding the local mechanisms and for validation of numerical modeling. For the layouts (b) and (c), however, minimized supporting structures for the FOS are required to reduce possible influences on concrete strain and crack localization.

FOS is ideally suited for continuous measurement along the longitudinal reinforcement in bending tests (Figure 2d), just as in steel-reinforced concrete. Finally, glass fibers might allow for continuous measurement along grid-type shear reinforcement (Figure 2e). This enables accurate measurement of activation and anchorage of vertical reinforcement elements crossing each emerging shear crack, which is typically impossible with localized strain gauges. As the fibers can be arranged in...
continuous loops, it is no longer necessary to install a multitude of individual strain gauges to enhance the chance of measuring near the critical shear crack (e.g., Reference 53).

Figure 3 shows a first example of strain measurement according to concept (a) on a thin TRC specimen in laboratory scale with the test setup described in Reference 54. The measurement fiber is arranged in two loops on the three yarns with a fiber cross-sectional area of 3.62 mm² in test direction, so that it crosses each transverse crack three times. The application method for this example is discussed in detail in Section 4.3, while the employed materials are listed in Section 4.2. The comparison with a conventional strain gauge glued directly on the other side of the middle yarn proves that the strain measured with both methods is of the same magnitude and leads to plausible results. Note that a comparison to external load is possible because the crack localized next to the strain gauge, probably because of the local reduction of concrete cross-sectional area due transverse yarns and cables leading to the sensor. It should be mentioned that from four specimens prepared for this proof of concept, only two of the FOS were functional on the day of testing despite the simple layout.

Encouraged by the results of the implementation of concept (a), we directly tried to transfer the application method utilized for the uniaxial tensile tests in Figure 3 to the most complicated example following concept (e). In three slab segments \((l/b/h = 2300 \text{ mm}/200 \text{ mm}/200 \text{ mm})\), FOS were attached to planar shear reinforcement and to c-shaped vertical shear reinforcement, respectively (Figure 4). Details on the test setup are given in Reference 55. Despite using exactly the same procedure as before, none of the sensors was operational on the day of testing. In fact, the sensors were functioning prior to casting and directly after casting. Exposure to physical stresses (concrete shrinkage) and chemical attack (alkaline environment in the concrete) during casting, demolding, early strength development, and further hardening might have damaged the fragile fibers. Note that the number of bends and turns in this second example was significantly larger, each posing a possible threat to fiber breakage.

In order to further refine possible application and evaluation techniques, we went back to the uniaxial tensile test, scaling it up to a more realistic depth used in actual TRC constructions. The aim was to find more robust fiber application methods adapted to the necessities of TRC testing which would eventually be applicable in real constructions. The following section presents the results of this experimental campaign.

4 | EXPERIMENTAL INVESTIGATION ON REAL-SCALE TRC SLAB SEGMENTS USING FOS

4.1 | Test setup

In a test program investigating the influence of tensile normal forces on shear resistance of TRC slab segments \((l/b/h = 800 \text{ mm}/190 \text{ mm}/70 \text{ mm})\), the FOS system ODISI 6108 was utilized for an internal measurement

![Figure 3](image)  
**Figure 3**  Strain distribution of three cracks in uniaxial tensile test on TRC specimen, measured directly after formation of the third and last crack at 26 kN axial force
on six specimens in addition to conventional external instrumentation (Figure 5). In the present paper, the possibilities of these FOS-measurements will be presented in detail using one of the specimens. The loading scenario comprised of two phases: in phase A, first, the axial load was increased until a stabilized cracking stage was achieved, and then the specimens were fully unloaded; in phase B, the slab segments were loaded to a target normal force and subsequently tested in single span three-point bending until failure. The aim of utilization of FOS was to determine the strain distribution of the carbon fiber-reinforced polymer (CFRP) reinforcement along the full specimen length throughout the test, especially in the pre-loading phase A. With this measurement, calculation of reinforcement stress distribution in the vicinity of vertical cracks and investigation of bond behavior becomes possible.

4.2 | Materials

As longitudinal reinforcement, a bidirectional warp-knitted grid made of epoxy resin-impregnated carbon fiber yarns with a center-to-center spacing of 38 mm and a cross-sectional area of 95 mm²/m per layer and per direction was used. The modulus of elasticity in longitudinal direction was 244,835 MPa and an ultimate tensile strength of 3221 MPa was determined in uniaxial tensile tests on individual yarns taken from the grid. Further material characteristics are given in Reference 14. The concrete was self-compacting and of high strength, with a maximum crushed aggregate size of 4 mm.

Modulus of elasticity and splitting tensile strength were determined on cylinders cast together with the specimens (h/d = 300 mm/150 mm) to 41,750 MPa and 4.8 MPa, respectively. Compressive strength of cubes (a = 150 mm) was 123 MPa on the day of testing. The mixture was developed explicitly for use in TRC and is presented in more detail in Reference 14.

4.3 | Application methods for the measuring fiber

Since the FOS has only been used to a limited extent in TRC, in the present test series three different techniques to externally attach the fiber to the yarns were employed and evaluated (Figure 7). As first step in each method, the reinforcement was cleaned with an isopropyl alcohol. For method 1, the measuring fiber (polyimide-coated with a diameter of 150 μm) was subsequently attached to the yarns with the cyanoacrylate adhesive Z 70 from Hottinger Baldwin Messtechnik (HBM) approximately...
every 10 cm (Figure 6, left) and then fully covered with the two-component polyester adhesive PS from Tokyo Measuring Instruments Laboratory Co. (Figure 6, right). This procedure aimed at protecting the measuring fiber against mechanical impact during concreting works and to achieve a continuous, full bond between measuring fiber and reinforcement. In method 2, the two-component polyester adhesive was not applied and the measuring fiber was continuously bonded to the reinforcement with cyanoacrylate adhesive instead.

In methods 1 and 2, the fiber is situated between two layers of reinforcement, whereas in method 3 it was attached to the bottom of the textile (Figure 7). The latter method leads to a vertically undulating path of the measuring fiber, since the transversal yarns need to be crossed at each intersection. One fiber was attached to three yarns for simultaneous measurement of three locations over the cross section at each vertical crack (Figure 7, bottom). This reduces the effort required to manufacture the measuring fibers. To allow the observation of crack initiation phenomena, the measurement was performed at a frequency of 20 Hz. Yet, to reduce the total data set, only the first 10 results per second were stored. A measuring point distance of 0.65 mm in the fiber was chosen for all tests.

5 | PREPARATION AND EVALUATION OF TEST RESULTS

5.1 | Post-processing of raw data

The axial tensional loading in phase A induced vertical separation cracks in the specimens, which occurred...
abruptly due to the high tensile strength of the concrete and led to a significant increase in local strain in the reinforcement. From the differential strain of fiber and concrete and its characteristic shape, information about anchorage length and crack width can be derived. To determine this differential strain from raw measurement data, several post-processing steps are necessary, which are briefly explained in the following. Figure 8 exemplifies strains measured by FOS at 75 kN axial force, which corresponds to stabilized cracked stage. The horizontal axis ranges from the fixed support (relative coordinate 0 cm) to the free support (44 cm). The black dashed lines represent the separation cracks on the upper side of the specimen. Although some peaks can be observed, neither the location of the vertical cracks nor the local strain distribution can be clearly determined from the unprocessed data.

To obtain the differential strains, the strain measurement immediately before the formation of each separation crack is subtracted from this measurement after the formation of the separation crack (Figure 9). Repeating this procedure for all separation cracks leads to Figure 10.

5.2 | Evaluation of crack location and crack width

5.2.1 | General

Figure 10 allows for localization of separation cracks using solely the strain measurement data. Furthermore, first statements about the bond between reinforcement and concrete become possible. On average the reinforcement needs about 6–7 cm to re-introduce its stress into the concrete. Compared with the results from Reference 51, this length appears to be relatively large: In the uniaxial anchorage tests in that study, lengths as small as 3.8 cm transferred tensile stresses of up to 1650 MPa. In contrast to those anchorage tests with free yarn ends, the yarns were continuous in the present study, and in combination with their high longitudinal stiffness, longer sections of transfer length are activated at smaller relative displacement between concrete and reinforcement.

As the cracking load increases, no significant increase in the length of the stress introduction can be seen, which means that the transfer length is approximately the same for both 44 kN (crack 1) and 75 kN (crack 7).
tensile force. Neighboring cracks set a natural limit to transfer length. If a crack develops in the immediate vicinity of an existing crack, the transfer lengths of the two cracks will overlap. A greater transfer length than half the crack spacing is therefore not possible.

The theoretical reinforcement strain at initiation of crack 1 \( (44,000 \text{ N}/(20 \times 3.62 \text{ mm}^2 \times 244,835 \text{ MPa}) = 2480 \text{ μm/m}) \) corresponds well with the measurement results of the FOS. The nearly constant slope of the strain trend line in its ascending and descending sections indicates a constant local bond force. Although Preinstorfer et al. chose a discrete modeling approach for the same type of reinforcement that resulted in a staggered transfer of bond forces with each global “wave” of the yarns, a simplifying assumption of a constant local bond force similar to steel-reinforced concrete might be justified.

The differential strain shortly before formation of a separation crack (Figure 11) shows a strain increase in the reinforcement prior to full opening of the crack. This indicates micro-cracks that precede the formation of the separation crack.

5.2.2 Influence of the application method

Taking into account results from all specimens, application method 2 without additional protection of the fiber with an adhesive provided the best results in determination of local reinforcement strain distribution. This finding corresponds well with the investigations of Reference 60. While method 2 resulted in comparatively few measuring point losses, for method 1 several centimeters of measuring fiber yield no results. In the presented specimen, the measuring fiber was applied to the middle yarn according to method 2 and to the two outer yarns according to method 1. This allows for direct comparison of the application methods in one separation crack (Figure 12). As can be clearly seen, method 1 provides only very few measurement results, leaving the strain distribution open to speculation. Furthermore, negative strains are often measured when positive strains should actually be present. One explanation could be the
inelastic behavior of the two-component adhesive layer. It might crack or delaminate from the yarn at several locations along the measuring fiber with sudden transfer of stress to the reinforcement after opening of cracks in the concrete. This local detachment or local cracking might change the strain state of the fiber compared to the yarn strain, which in turn leads to the measured fluctuations in the strain distribution. Furthermore, the thick protective two-component polyester adhesive cover of method 1 influences local bond behavior of the yarns. Method 2 did not have this thick cover and in uniaxial tensile tests with and without measuring fiber, no influence on crack spacing, tendency for longitudinal cracking, and fracture behavior could be detected.

Of all fibers attached to the bottom reinforcement according to method 3, half of the measuring fibers failed before testing. Also, the few sensors which initially provided measurement results failed much earlier than the measuring fibers attached according to method 1 or 2. One explanation might be the waviness of the fiber caused by crossing the transversal yarns with small bending diameter, which might result in local stress concentrations eventually breaking the fiber. However, this does not explain why the measuring sensors failed even before the test, especially since a control measurement immediately after stripping the formwork showed that all measuring fibers were operational. Reason for this could be the physical stresses and/or chemical attack described in Section 3.

5.2.3 | Comparison with conventional measurements

Although the general shape of the strain distribution in Figure 11 seems plausible, the obtained results need to be validated. One approach is to compare the crack width \( w \) determined with different measurement methods to the integral of strain measured by FOS along the transfer length (Equation (1)). To integrate the strain distribution, a polynomial approximation can be utilized (Figure 11).

\[
\int \varepsilon(x) = w = s_t + s_l + \Delta l \\
\Delta l = \Delta l_{\text{pre}} + \Delta l_{\text{post}} \tag{2}
\]

\( \Delta l \) results from the elastic strains of the yarn (Equation (2)). The elastic strains before crack formation \( \varepsilon_{l,\text{pre}} \), which result in \( \Delta l_{\text{pre}} \), were neglected, since they disappear when calculating the differential strain. The
calculation of $\varepsilon_{t,\text{pre}}$ with Equation (3) reveals its small share of only 3.1% of the total strain (at cracking load $F_{cr} = 44$ kN). $A_c$ in Equation (4) refers to the gross cross-sectional area of the concrete.

$$\varepsilon_{t,\text{pre}} = \varepsilon_{c,\text{pre}} = \frac{F_{cr}}{A_t \cdot E_c}$$  \hspace{1cm} (3)

$$A_i = A_c + \left( \frac{E_t}{E_c} - 1 \right) \cdot A_t$$  \hspace{1cm} (4)

The crack width was measured manually with a crack width ruler after formation of each crack at one side of the specimen at the level of longitudinal reinforcement.
Additionally, the crack width was determined by means of DIC (Figure 13).

The calculated (Equation (1)) and measured crack widths are in very good accordance (Figure 14). In this exemplary application, FOS seems to provide realistic measurement results. However, it should be noted that the strain distributions of cracks 3 and 6 had only few measuring points and approximated trend lines are subject to assumptions. Manual measurement and DIC measurement were carried out on opposite sides of the specimen, and crack width might differ over the width of the specimen even if the reinforcement layout was symmetric.

By integrating the measured strains, it is also possible to evaluate the crack width of laboratory-scaled uniaxial tensile tests, from Section 3, Figure 3. In these tests, the measuring fiber was arranged according to application method 2. Figure 15 compares the determined crack widths. As in the other tests, the crack width assessed by DIC and by manual measurement could be determined very well using the FOS results.

6 | SUMMARY AND CONCLUSIONS

Based on a state-of-the-art review of FOS in structural concrete testing this paper investigated the special requirements of testing structural components with distributed non-metallic textile reinforcement and introduced possible utilization concepts. While two smaller experimental studies served as proof of concept, one larger experimental campaign on uniaxial tensile tests allowed for assessment of different fiber application methods on the reinforcement and subsequent evaluation techniques. The conclusions and further challenges can be summarized as follows:

- With FOS on carbon textile reinforcement, plausible results for strain distribution along the fibers can be generated, with continuous as well as with intermittent attachment. The comparison of crack width calculated from FOS measurements with conventional measurement served as validation of the strain distribution along the reinforcement at a crack bridge in this study.

- From three methods evaluated in this study, the continuous attachment with a cyanoacrylate adhesive without additional protection of the fiber led to the best measurement results with a minimal loss of data points along the fiber. While this method succeeded for simple uniaxial tensile tests, its limitations in terms of fiber protection became apparent in more complicated application concepts such as for textile shear reinforcement.

- The measuring fibers are very sensitive compared to conventional instrumentation. A large proportion of measuring fibers in this study failed prior to testing. Therefore, compared to steel-reinforcement, even more emphasis needs to be put into proper application and protection of the sensors. Possible reasons are assumed to be physical tension (concrete shrinkage) or chemical attack (alkaline environment in the concrete). Finding a good balance of fiber protection and minimizing local disturbance of bond and material properties is key to successful application of FOS in TRC. The more complicated the layout of the fiber and its path in the specimen, the higher the risk for premature failure.

- With continuous strain measurement in textile reinforcement it is possible to determine the detailed stress state near macroscopic cracks, experimentally obtain the transfer length, determine local bond behavior, and calculate crack width also within specimens near the reinforcement and not only on the surface.

The results of the presented investigations are independent of the fiber material and can therefore also be applied to glass, aramid, or basalt reinforced concrete. Further experimental investigations are necessary to extend the range of applications of FOS in TRC research and to gain deeper insights regarding serviceability limit state and local bond behavior of yarns. To fully exploit the potential of FOS in TRC, a simple transfer of established application techniques from steel-reinforced concrete to TRC is not recommended. New fiber variants with different protective covers and new manufacturing techniques for installing the sensors in the laboratory should be investigated in future studies.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Henrik Becks ♦ https://orcid.org/0000-0002-4123-3092
Jan Bielak ♦ https://orcid.org/0000-0002-3219-655X
Benjamin Camps ♦ https://orcid.org/0000-0002-8594-
REFERENCES

1. Hirai T. Use of continuous fibers for reinforcing concrete. Concr Int. 1992;14(12):58–60.
2. Hegger J, Kulas C, Horstmann M. Realization of TRC façades with impregnated AR-glass textiles. Key Eng Mater. 2011;466:121–30. https://doi.org/10.4028/www.scientific.net/KEM.466.121
3. Kulas C, Schneider M, Will N, Grebe R. Hinterlüftete Vorhangfassaden aus Textilbeton. Bautechnik. 2011;88(5):271–80. https://doi.org/10.1002/bate.201101462
4. Hegger J, Goralski C, Kulas C. Schlanke Fußgängerbrücke aus Textilbeton. Beton-Stahlbetonbau. 2011;106(2):64–71. https://doi.org/10.1002/best.201000081
5. Helbig T, Unterer K, Kulas C, Rempel S, Hegger J. Fuß- und Radwegbrücke aus Carbonbeton in Allstadt-Ebingen. Beton-Stahlbetonbau. 2016;111(10):676–85.
6. Michler H. Segmentbrücke aus textilbewehrtem Beton – Rottachsteg Kempfen im Allgäu. Beton-Stahlbetonbau. 2013;108(5):325–34. https://doi.org/10.1002/bate.201300023
7. Ehlig D, Schladitz F, Frenzel M, Curbach M. Textilbeton - Ausgeführte Projekte im Überblick. Beton-Stahlbetonbau. 2012;107(11):777–85. https://doi.org/10.1002/bate.201200034
8. Scholzen A, Chudoba R, Hegger J. Thin-walled shell structures made of textile-reinforced concrete: part I: structural design and construction. Struct Concr. 2015;16(1):106–14. https://doi.org/10.1002/suco.201300071
9. Beckmann B, Bielak J, Scheerer S, Schmidt C, Hegger J, Curbach M. Standortübergreifende Forschung zu Carbonbetonstrukturen im SFB/TRR 280. Bautechnik. 2021;98(3):232–42. https://doi.org/10.1002/bate.2020000116
10. Hegger J, Curbach M, Stark A, Wilhelm S, Farwig K. Innovative design concepts: application of textile reinforced concrete to shell structures. Struct Concr. 2018;19(3):637–46. https://doi.org/10.1002/suco.201700157
11. May S, Michler H, Schladitz F, Curbach M. Lightweight ceiling system made of carbon reinforced concrete. Struct Concr. 2018;19(6):1862–72. https://doi.org/10.1002/suco.201700224
12. Bielak J, Will N, Hegger J. Zwei Praxisbeispiele zur Querkrafttragfähigkeit von Brückenplatten aus Textilbeton. Bautechnik. 2020;97(7):499–507. https://doi.org/10.1002/bate.202000037
13. Rempel S, Kulas C, Will N, Bielak J. Extremely light and slender prestressed pedestrian-bridge made out of textile-reinforced concrete (TRC). In: Hordijk DA, Luković M, editors. High tech concrete: where technology and engineering meet: proceedings of the 2017 fib symposium. Cham: Springer International Publishing; 2017. p. 2530–7.
14. Bielak J, Adam V, Hegger J, Classen M. Shear capacity of textile-reinforced concrete slabs without shear reinforcement. Appl Sci. 2019;9(7):1382. https://doi.org/10.3390/app9071382
15. Rempel S, Ricker M, Hegger J. Biegebemessungsmodell mit einer geschlossenen und iterativen Lösung für Textilbetonbauteile. Beton-Stahlbetonbau. 2020;115(3):218–30. https://doi.org/10.1002/best.201900086
16. Scheerer S, Zobel R, Müller E, Senckpiel-Peters T, Schmidt A, Curbach M. Flexural strengthening of RC structures with TRC—experimental observations, design approach and application. Appl Sci. 2019;9(7):1322. https://doi.org/10.3390/app9071322
17. Sharei E, Scholzen A, Hegger J, Chudoba R. Structural behavior of a lightweight, textile-reinforced concrete barrel vault shell. Compos Struct. 2017;171:505–14. https://doi.org/10.1016/j.composites.2017.03.069
18. Morales Cruz C, Gohil U, Quadflieg T, Raupach M, Gries T. Improving the bond behavior of textile reinforcement and mortar through surface modification. In: Bramshuber W, editor. Proceedings of the 11th international symposium on Ferrocement and textile reinforced concrete 3rd ICTRC. Bagneux, France: RILEM Publications S.A.R.L.; 2015. p. 215–24.
19. Rempel S, Erhard E, Schmidt H-G, Will N. Die Sanierung des Mariendomdaches in Neviges mit carbonbewehrtem Spritzmörtel. Beton-Stahlbetonbau. 2018;113(7):543–50. https://doi.org/10.1002/best.201800016
20. Morales Cruz C, Raupach M. Influence of the surface modification by sanding of carbon textile reinforcements on the bond and load-bearing behavior of textile reinforced concrete. MATEC Web of Conferences. 2019;289(6):04006. https://doi.org/10.1051/matecconf/201928904006
21. Kulas C. Zum Trageverhalten getränkter textiler Bewehrungselemente für Betonbauteile (Dissertation). Aachen: RWTH Aachen University; 2013.
22. Brault A, Hoult NA. Distributed reinforcement strains: measurement and application. ACI Struct J. 2019;116(4):115–27. https://doi.org/10.14359/5714483
23. Davis MB, Hoult NA, Bajai S, Bentz EC. Distributed sensing for shrinkage and tension stiffening measurement. ACI Struct J. 2017;114(3):755–66. https://doi.org/10.14359/51689463
24. Regier R, Hoult NA. Concrete deterioration detection using distributed sensors. Proc Inst Civil Eng – Struct Build. 2015;168(2):118–26. https://doi.org/10.1680/stbu.13.00070
25. Berrocq CG, Fernandez I, Rempling R. Crack monitoring in reinforced concrete beams by distributed optical fiber sensors. Struct Infrastruct Eng. 2020;1;16:124–39. https://doi.org/10.1080/15732479.2020.1731558
26. Brault A, Hoult NA. Assessment of reinforced concrete structures with distributed fibre optic sensors. In: Delong JM, Schooling JM, Viggianni GM, editors. International conference on smart infrastructure and construction 2019 (ICSIC). ICE Publishing; 2019. p. 541–8. https://doi.org/10.1680/isic.64669.541
27. Lee B. Review of the present status of optical fiber sensors. Opt Fiber Technol. 2003;9(2):57–79. https://doi.org/10.1016/S1066- 5200(02)00527-8
28. Hill KO, Meltz G. Fiber Bragg grating technology fundamentals and overview. J Lightwave Technol. 1997;15(8):1263–76. https://doi.org/10.1109/50.618320
29. Melz G, Morey WW, Glenn WH. Formation of Bragg gratings in optical fibers by a transverse holographic method. Opt Lett. 1989;14(15):823–5. https://doi.org/10.1364/OL.14.000823
30. Jin W. Multiplexed FBG sensors and their applications. In: Lieberman RA, Asundi AK, Asanuma H, editors. International symposium on photonics and applications. International Society for Optics and Photonics; 1999. p. 468–79. https://doi.org/10.1117/12.369343
31. Muena Y, Oton CJ, Di Pasquale F. Application of Raman and Brillouin scattering phenomena in distributed optical fiber sensing. Front Phys. 2019;7:1–14. https://doi.org/10.3389/fphy.2019.00155
32. Soga K, Luo L. Distributed fiber optics sensors for civil engineering infrastructure sensing. J Struct Integr Maint. 2018;3(1):1–21. https://doi.org/10.1080/24705314.2018.1426138
33. Samiec D. Distributed fibre-optic temperature and strain measurement with extremely high spatial resolution. Photon Int. 2012;1:10–3.
34. Weisbrich M, Holschemacher K, Bier T. Comparison of different fiber coatings for distributed strain measurement in cementitious matrices. J Sens Sens Syst. 2020;9(2):189–97. https://doi.org/10.5194/jsss-9-189-2020
35. Eickhoff W, Ulrich R. Optical frequency domain reflectometry in single-mode fiber. Appl Phys Lett. 1981;39(9):693–5. https://doi.org/10.1063/1.92872
36. Froggatt M, Moore J. High-spatial-resolution distributed strain measurement in optical fiber with rayleigh scatter. Appl Optics. 1998;37(10):1735–40. https://doi.org/10.1364/AO.37.001735
37. Liu T, Huang H, Yang Y. Crack detection of reinforced concrete member using Rayleigh-based distributed optical fiber strain sensing system. Adv Civil Eng. 2020;2020:1–11. https://doi.org/10.1155/2020/8312487
38. Henault JM, Salin J, Moreau G, Delepine-Lesoille S, Bertand J, Taillade F, et al. Monitoring of concrete structures using OFDR technique. In: Thompson DO, Chimenti DE, editors. AIP conference proceedings: Vol. 1335. Review of progress in quantitative nondestructive evaluation. Volume 30. American Inst. of Physics; 2011. p. 1386–93. https://doi.org/10.1063/1.3592094
39. Kirpal E, Stempniewski L. Einfluss chloridinduzierter Spannstahlkorrosion auf das Trageverhalten von Brückenbauwerken – Numerische und experimentelle Untersuchungen an vorgespannten Trägern: Numerische und experimentelle Untersuchungen an vorgespannten Trägern. Bauingenieur. 2020;95(7/8):279–88. https://doi.org/10.1155/2020/8312487
40. Speck K, Vogel F, Curbach M, Petryna Y. Faseroptische Sensoren zur kontinuierlichen Dehnungsmessung im Beton. Beton-Stahlbetonbau. 2019;114(3):160–7. https://doi.org/10.1002/best.201800105
41. Fischer O, Thoma S, Crepaz S. Quasikontinuierliche faseroptische Dehnungsmessung zur Rissdetection in Betonkonstruktionen. Beton-Stahlbetonbau. 2019;114(3):150–9. https://doi.org/10.1002/best.201800089
42. Schmidt-Thrö G, Scheufler W, Fischer O. Kontinuierliche faseroptische Dehnungsmessung im Stahlbetonbau. Beton-Stahlbetonbau. 2016;111(8):496–504. https://doi.org/10.1002/best.201600026
43. Gehrlein SP, Fischer O. Full-scale shear capacity testing of an existing prestressed concrete bridge. Civil Eng Des. 2019;1(2):64–73. https://doi.org/10.1002/cend.201900003
44. Regier R, Hoult NA. Distributed strain behavior of a reinforced concrete bridge: case study. J Bridg Eng. 2014;19(12):1–9. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000637
45. Henault J-M, Moreau G, Blairon S, Salin J, Courivaud J-R, Taillade F, et al. Truly distributed optical fiber sensors for structural health monitoring: from the telecommunication optical fiber drawing tower to water leakage detection in dikes and concrete structure strain monitoring. Adv Civil Eng. 2010;2010(8):1–13. https://doi.org/10.1155/2010/930796
46. Miyata S, Tottori S, Terada T, Sekijima K. Experimental study on tensile strength of FRP bent bar. Proc JCI. 1989;11(1):789–94.
47. Tottori S, Wakui H. Shear capacity of RC and PC beams using FRP reinforcement. ACI Spec Publ. 1993;138:615–32. https://doi.org/10.14359/3944
48. Mufti AA, Tennyson RC, Cheng JIR. Integrated sensing of civil and innovative FRP structures. Prog Struct Eng Mater. 2003;5(3):115–26. https://doi.org/10.1002/pse.150
49. Zikalla SH, Shehata E, Abdelrahman AA, Tadros G. Design and construction of a highway bridge with CFRP - the new generation. Concr Int. 1998;20(6):35–8.
50. Saidi M, Gabor A. Experimental analysis of the tensile behaviour of textile reinforced cementitious matrix composites using distributed fibre optic sensing (DFOS) technology. Construct Build Mater. 2020;230:117027. https://doi.org/10.1016/j.conbuildmat.2019.117027
51. Bielak J, Spelter A, Will N, Claßen M. Verankerungsverhalten textiler Bewehrungen in dünnen Betonbauteilen. Beton-Stahlbetonbau. 2018;113(7):515–24. https://doi.org/10.1002/best.201800013
52. Preinstorfer P, Kollegger J. New insights into the splitting failure of textile-reinforced concrete. Compos Struct. 2020;243:112203. https://doi.org/10.1016/j.comstruct.2020.112203
53. Gleich P, Maurer R. Querkraftversuche an Spannbetondurchlaufträgern mit Plattenbalkenquerschnitt. Bauingenieur. 2018;93(2):68–72. https://doi.org/10.37544/0005-6650-2018-02-31
54. Schütze E, Bielak J, Scheerer S, Hegger J, Curbach M. Einaxialer Zugversuch für Carbonbeton mit textilier Bewehrung. Beton-Stahlbetonbau. 2018;113(1):33–47. https://doi.org/10.1002/best.201700074
55. Bielak J. Shear in slabs with non-metallic reinforcement (dissertation). Aachen: RWTH Aachen University; 2021. https://doi.org/10.18154/RWTH-2021-09163
56. Becks H, Bielak J, Hegger J. Interaction of normal and shear loads in carbon reinforced slab segments. In IABSE (Chair), IABSE Congress. Symposium conducted at the meeting of IABSE, Netherlands, Ghent. 2021.
57. Bielak J, Becks H, Hegger J. Effect of tension forces on shear capacity of thin slab segments. In Tudalit e.V. and C3 - carbon composite e.V (Chair), Proceedings of 12th Carbon and Textile Reinforced Concrete Days, Dresden. 2020.
58. Luna Innovations Incorporated. Data sheet of the Optical Interrogator (ODiSI) 6000 Series. 2020. Available from: https://lunainc.com/sites/default/files/assets/files/Data-sheet-LUNA-ODiSI-6000-Data-Sheet.pdf
59. Preinstorfer P, Pinzek A, Kollegger J. Modellierung des Verankerungsverhaltens getränkter textiler Bewehrungen. Beton-Stahlbetonbau. 2018;113(7):515–24. https://doi.org/10.1002/best.201800013
60. Barrias A, Casas JR, Villalba S. Embedded distributed optical fiber sensors in reinforced concrete structures – a case study. Sensors. 2018;18(4):980. https://doi.org/10.3390/s18040980
AUTHOR BIOGRAPHIES

**Henrik Becks, M.Sc.**, Research Associate, Institute of Structural Concrete, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany. 
hbecks@imb.rwth-aachen.de

**Dr. Ing. Jan Bielak**, Research Associate, Institute of Structural Concrete, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany. 
jbielak@imb.rwth-aachen.de

**Benjamin Camps, M.Sc.**, Research Associate, Institute of Structural Concrete, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany. 
bcamps@imb.rwth-aachen.de

**Prof. Dr.-Ing. Josef Hegger**, Head of Institute, Institute of Structural Concrete, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany. 
jhegger@imb.rwth-aachen.de

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