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DOI
10.1016/j.cscm.2025.e04493

Publication date
2025

Document Version
Final published version

Published in
Case Studies in Construction Materials

Case Studies in Construction Materials 22 (2025) e04493

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Smart sensing of concrete crack using distributed fiber optics sensors: Current advances and perspectives

Xuehui Zhang [a,b], Luyuan Long [b], Wout Broere [b,*], Xiaohua Bao [c,d,**]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Ho, Kowloon, Hong Kong
[b] Geo-Engineering Section, Department of Geo-science and Engineering, Delft University of Technology, Delft, the Netherlands
[c] State Key Laboratory of Intelligent Geotechnics and Tunnelling, College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, Guangdong 518060, China
[d] Key Laboratory of Coastal Urban Resilient Infrastructures (Shenzhen University), Ministry of Education, Shenzhen 518060, China

ARTICLE INFO

Keywords:
Concrete crack
Smart crack sensing
Distributed fiber optic sensing (DFOS)
Quantitative crack sensing
Crack width

ABSTRACT

Monitoring of cracks and crack growth rates is a crucial aspect of structural health monitoring for concrete infrastructure, and multiple manual and automatic monitoring techniques have emerged over the years. This study focuses on an in-depth review of concrete crack sensing using distributed fiber optic sensing (DFOS) technology. DFOS provides the option to sample distributed data points through dedicated optical fibers or cables, thereby effectively addressing the spatial limitations associated with conventional discrete point sensors such as foil strain gauges and transducers. The main findings include that (1) smart concrete crack sensing generally involves three objectives: detecting crack initiation, identifying the crack location and determining the crack width and its evolution; (2) for DFOS used for crack sensing, the three main sensing principles are to measure localized strain spikes in optical fibers or cables that span across cracks, to detect signal intensity losses caused by micro-bending of optical fibers in proximity to cracks and to measure precise local temperature variations within the crack areas; (3) strain-based crack sensing has become the predominant method due to its superior sensing performance and application versatility. This dominance is supported by extensive experimental demonstrations and successful implementations in field monitoring practices; (4) the sensitivity of optical fibers or cables to concrete cracks depends on the installation method, while quantitative crack width measurements require the precise determination of crack locations followed by a subsequent integration or exponential fitting of strain along the length at fiber-concrete interface. This study helps to advance the application of the smart DFOS for structural health monitoring and maintenance of concrete infrastructures.

1. Introduction

Concrete is recognized as the dominant material in contemporary construction due to its cost-effectiveness, robustness, the ability to design any geometry and excellent compatibility with steel reinforcement. It is extensively employed across a variety of infrastructure projects including, but not limited to, residential buildings, bridges, tunnels, dams, and others [26,3]. Nonetheless, concrete

* Corresponding author.
** Correspondence to: College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, Guangdong 518060, China.
E-mail addresses: W.Broere@tudelft.nl (W. Broere), bxh@szu.edu.cn (X. Bao).

https://doi.org/10.1016/j.cscm.2025.e04493
Received 17 October 2024; Received in revised form 17 February 2025; Accepted 3 March 2025
Available online 5 March 2025

is characterized by a notable weakness in tensile strength, making it susceptible to cracking over its operational life. Such cracks may arise from a range of internal and external causes, including unqualified construction quality, temperature change, external loading, uneven settling of foundations, and chemical reactions [30]. These cracks compromise the concrete's ability to safeguard the embedded steel reinforcement from deterioration, leading to issues like reinforcement corrosion [46,52], diminished structural load capacity, and in severe cases, catastrophic failures that entail significant human and financial losses. Consequently, the practice of crack monitoring has emerged as a crucial component of the structural health monitoring for concrete infrastructures.

However, crack monitoring in concrete is fraught with significant technical difficulties. These challenges stem, in part, from the diverse causes of crack formation, which often render the prediction of their future locations a complex task. Since cracks in concrete are closely related to tensile strain, traditional crack monitoring often relies on strain measurement using point sensors, such as (foil) electric strain gauges, linear variable differential transformers (LVDTs), or fiber Bragg gratings (FBGs) [75,10]. It is important to note that point sensors can only monitor strain at specific locations where they are installed, and therefore for monitoring actual concrete structures, thousands of strain measurement points would need to be deployed, which is often not feasible due to the prohibitive cost and impracticality in terms of labor.

Moreover, the initial stages of crack development are characterized by exceedingly fine crack widths (frequently at the sub-millimeter or micrometer level), complicating their detection through standard visual inspection methods. This necessitates the utilization of sensing devices and monitoring techniques with exceptionally high-resolution capabilities for effective crack detection. Additionally, the detection of internal cracks within the concrete matrix, prior to their extension to the surface, poses a considerable challenge, sometimes proving to be unfeasible with mere visual assessments. Although crack monitoring based on machine vision can enhance detection efficiency through artificial intelligence algorithms [27,57], this method typically can only monitor surface cracks and is primarily limited to crack identification. Recently other innovative techniques such as ultrasonic horizontal shear waves have been explored and validated to detect the depth of concrete surface cracks [34,53], but this only offers advantages in monitoring a limited number of major crack spots rather than for integral monitoring of large-scale linear infrastructure. To summarize, traditional practices of crack monitoring, which rely on localized strain sensors or manual visual assessments, are time-consuming, inefficient, and susceptible to inaccuracies [45], and inadequate to address the modern demands of structural health monitoring. Within this realm, distributed fiber optic sensors (DFOS) provide a potential solution, both from a technical and economical point of view.

DFOS is a sophisticated sensing technology known for its ability to accurately measure distributed strain and temperature across vast distances [36,41]. A fully integrated DFOS setup comprises a fiber optic (FO) cable, often termed the sensing cable, and a terminal device for analyzing the signals. Capable of extending over lengths of up to one hundred kilometers, this technology is particularly well-suited for the surveillance of large-scale infrastructure projects [64,76,77]. The primary benefit of these techniques is their potential to acquire highly densely spaced (with millimeter-order interval) data sampling points at a reduced cost and manual labor workload compared to traditional sensing techniques, thus improving the accuracy and efficiency of crack detection in concrete structures.

This study provides an overview of the latest advances in concrete crack monitoring using DFOS. The remainder of this study is divided into three main sections: Section 2 delves into the working principles of DFOS and the three typical light backscattering phenomenon that occur within optical fibers, as well as the underlying working principles for crack sensing; Section 3 conducts a systematical review of laboratory and field studies conducted over the last two decades on smart crack sensing with various DFOS systems; Section 4 performs a summary on currents advances and a critical evaluation of different crack sensing principles and their suitability, with special focus on quantitative crack sensing issues; and finally some key conclusions are presented in Section 5.

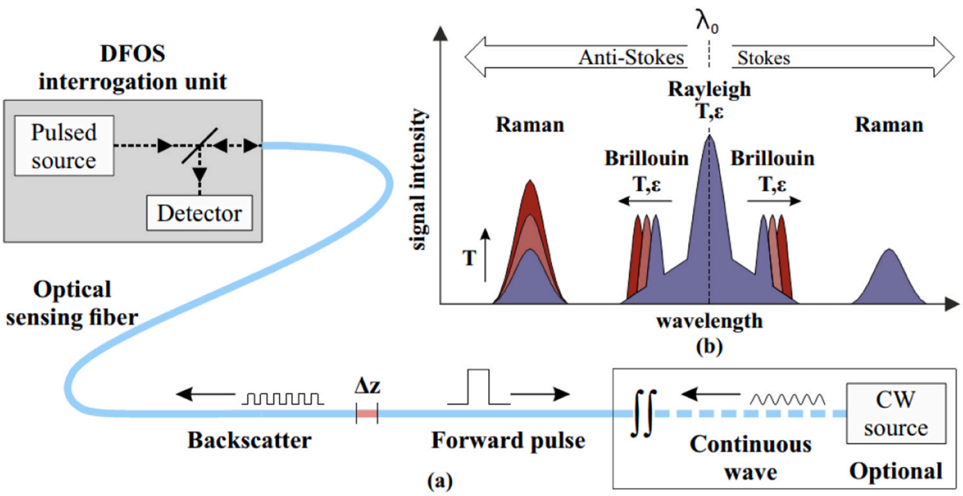

Fig. 1. Schematics of distributed fiber optic sensor technology [40].

2. DFOS for crack sensing

2.1. General information of DFOS systems

A distributed fiber optic sensor (DFOS) primarily functions through the backscattering of light within an optical fiber or cable, which encompasses (linear) Rayleigh scattering and the non-linear phenomena of Brillouin and Raman scattering [22,32,36]. A comprehensive DOFS system typically consists of an optical fiber or cable, serving as the sensing element, alongside a terminal interrogator (or read-out unit) that can facilitate the initiation and analysis of the light signals, as depicted in Fig. 1.

Of the various types of optic fibers available, generally, single-mode fibers are favored over multi-mode fibers in distributed sensing applications due to the latter's higher signal attenuation and shorter sensing range. In the optical fiber manufacturing industry, a commonly produced basic product is the 0.25 mm diameter bare fiber (D-0.25 mm), as depicted in Fig. 2(a). This bare fiber consists of an internal silica core with a diameter of 8–9 μm, a cladding with an outer diameter of 125 μm, and an external protective coating with a diameter of 250 μm. Typically, the core and cladding together form the primary pathway for light transmission, and thus serve as the actual "sensing" components of the fiber [71]. The basic D-0.25 mm bare fiber is typically too fragile and not used for direct sensing, and thus is further processed to make stronger reinforced optical fibers or cables as examples shown in Fig. 2. Different fiber products exist with different mechanical and optical properties. Notably, so-called silica fiber core generally has a limited bending resistance and elongation capacity (limited to about 1 %), while other types, such as polymer optical fiber (POF), consists of a larger core, as shown for example in Fig. 2(e) [78]. This fiber type is with a core made of acrylic polymer polymethyl-methacrylate (PMMA), a cladding layer of fluorinated polymer and a polyurethane coat and is more resistant to external impacts and elongation (up to as high as 40 %). In this way POF exhibits higher intensity loss and sensitivity to micro-bends triggered by cracks, and hence is preferred in crack sensing based on signal loss observations.

Backscattering of light travelling within a fiber is caused by the heterogeneous microstructure of the fiber core, including variations in glass composition that lead to changes in the fiber core's refractive index [58], and the light that is backscattered falls apart in three distinct sets of frequency shifts, compared to the original wavelength of the source light. Of these, Rayleigh scattering is dependent on the strain and temperature in the fiber. For Rayleigh scattering, the interrogator generally works on either of two principal methods for processing signals, in the frequency domain or the time domain, named Optical Frequency Domain Reflectometry (OFDR) and Optical Time Domain Reflectometry (OTDR). Of these, OTDR generally achieves a spatial resolution of around 1 m [32,43] over several decade kilometers length and is mainly used for measuring signal loss of long cables that may result from aspects such as local bending or poor physical connections. In the context of distributed strain and temperature sensing, commercial interrogators are predominantly based on OFDR, which assesses frequency shift changes of light between reference and disturbed states. A Rayleigh scattering OFDR interrogators generally feature a superior spatial resolution of sub-millimeter but with a significantly reduced sensing distance of around 100 m, more suitable for laboratory tests or small-scale field monitoring [76].

Brillouin scattering is again dependent on both the strain and temperature in the fiber and results in a Brillouin frequency shift (BFS) [36,41]. By measuring the BFS at various sampling points on the fiber, the spatially resolved strain or temperature changes occurring longitudinally along the fiber can be acquired. Different technical implementations exist to resolve the frequency shift, again either in the time domain or in the frequency domain, and commercially available Brillouin scattering-based interrogators based on

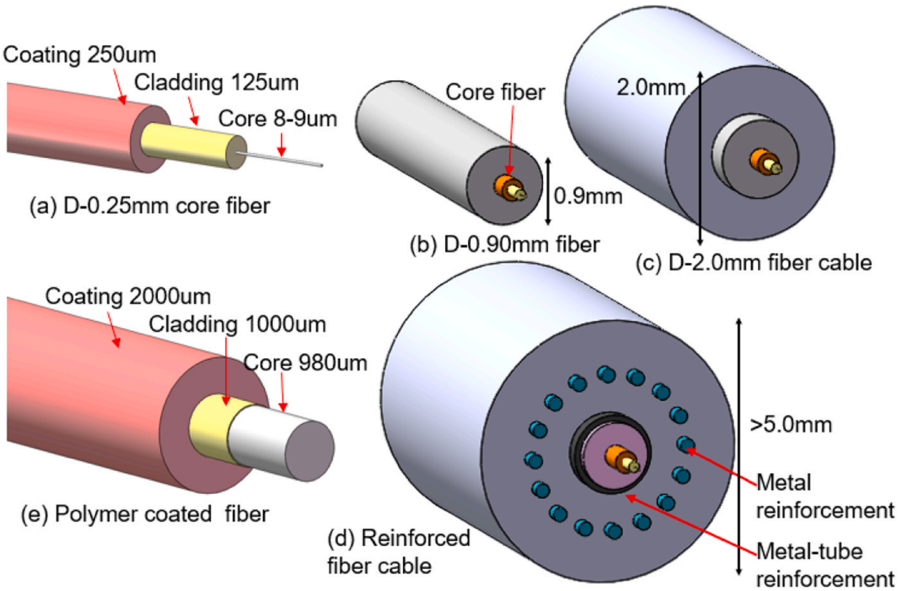

Fig. 2. Illustration of different sensing fiber types.

Brillouin Optical Time-Domain Analysis (BOTDA) and Brillouin Optical Frequency-Domain Analysis (BOFDA) are available. These two interrogator types generally feature a spatial resolution of 2–100 cm with a sensing distance of above a hundred kilometers and are therefore potentially appliable for field structure monitoring [74,76].

For Raman scattering, the intensity of anti-Stokes scattering light is temperature dependent. By analyzing the intensity ratio of anti-Stokes to Stokes light (see Fig. 1), the temperature distribution can be measured. The interrogator processes and demodulates the temperature at each spatial position, reconstructing the spatial temperature distribution information based on the OTDR principle. Research in Raman scattering is relatively mature, offering a variety of products, and stands as the most significant distributed temperature sensing (DTS) technology [60].

2.2. Cracking sensing principles using DFOS

Smart concrete crack sensing generally involves three objectives: detecting crack initiation, identifying the crack location and determining the crack width and its evolution, and the degree of fulfilling these three objectives depends on the DFOS type. Currently, crack monitoring in concrete using DFOS is fundamentally based on three primary sensing principles:

(1) Crack monitoring based on tensile strain measurement. Upon the formation of a crack, the segment of the optical fiber that spans the crack undergoes localized stretching, resulting in a pronounced strain peak along the fiber axis as illustrated in Fig. 3(a). This strain peak can be detected by the fiber signal interrogator, thereby facilitating the identification of the crack. In this context, not only can crack detection be achieved, but also the quantitative monitoring of crack characteristics. In this case the adopted interrogator types for strain sensing are mostly Rayleigh scattering based OFDR, and Brillouin scattering based BOTDA and BOFDA.

(2) Crack monitoring based on signal loss induced by micro or macro bending of the optical fiber. In an undeformed fiber, light entering the core at a slight angle undergoes total internal reflection at the core-cladding boundary, ensuring propagation within the core. The fiber intersecting the crack has to be bent to stay continuous, thus two micro bends will be formed on both sides of the crack (shown in Fig. 3(b)). Bending loss in the optical fiber occurs at curved sections, primarily due to the optical phenomena of spatial filtering, mode leakage, and mode coupling [78]. These signal losses are usually quantified using Rayleigh scattering-based OTDR [32]. The thicker polymer coated fiber with large core size (seen in Fig. 2(e)) shows a higher sensitivity to micro-bends, and is therefore a preferred choice for this type of application [64].

(3) Crack monitoring based on temperature anomalies. Concrete cracks, particularly in early-age concrete, induce localized changes in heat transfer characteristics. Since cracked areas exhibit distinct temperature fields compared to adjacent non-cracked regions, detecting these localized temperature variations potentially enables the identification of crack formation (as illustrated in Fig. 3(c)). Because both Brillouin and Rayleigh scattering are related to coupled strain and temperature effects, temperature anomalies in concrete crack sensing mostly use Raman scattering based OTDR technique.

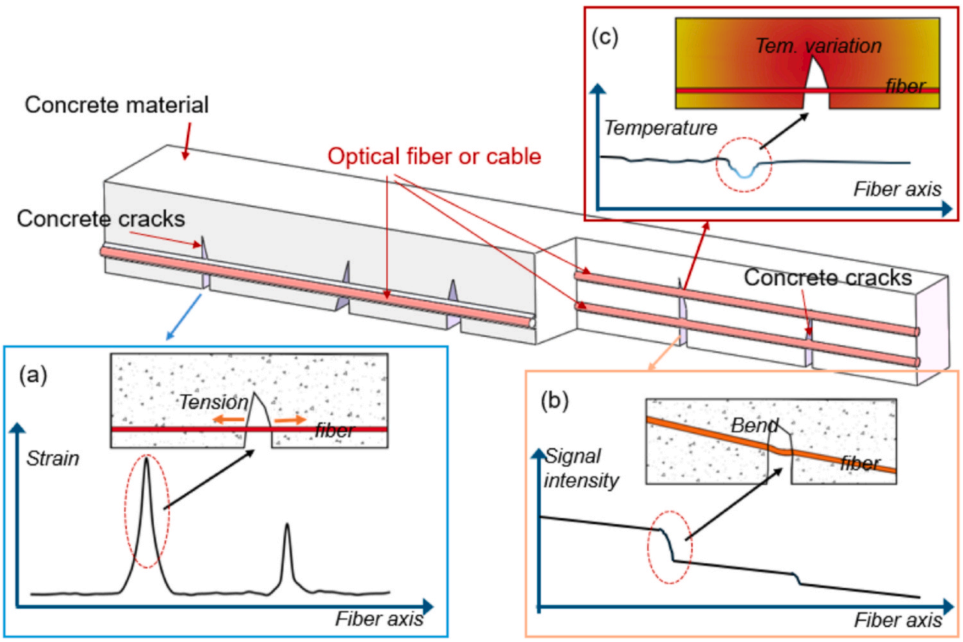

Fig. 3. The crack sensing principles with DFOS.

3. Systematic review of DFOS for cracking sensing

A total of 81 publications, including journal papers and conference contributions published between 2003 and 2024, have been identified that discuss DFOS applications for monitoring of concrete cracking. Notably, 63 of these have been published after 2019, or within the past five years, showing a significant increase in the number of publications, indicative of the increased uptake of these techniques and their effectiveness for crack monitoring.

3.1. Strain-monitoring based cracking sensing

3.1.1. Concrete specimen tests

Investigations on the applicability of DFOS for crack detection started with laboratory tests of small concrete specimens. In these small-sized specimens, the optical fibers or cables are typically embedded in the concrete mixture at the fabrication stage and are firmly bonded to it after hydration. The strain data are mostly collected using Rayleigh scattering based OFDR instruments, since these exhibit a better spatial resolution and hence strain sensitivity than Brillouin scattering based BOTDA or BOFDA instruments.

Depending on the monitoring needs, the optical fibers can acquire strain readings through the hydration period of the concrete and speculate the possible shrinkage cracks. For example, in the study by Tan et al.[59], the optical fibers are used to test the shrinkage cracks of ultra-high-performance concrete (UHPC) specimens during the hydration stage; in the work by Zhang et al. [69], the optical fibers are delicately embedded into the 3D printing concrete to sense the potential cracks during its hydration stage. In the follow-up laboratory specimen tests, optical fibers can monitor the crack evolution during compression tests, such as in the studies by Howiacki et al. [26]. It is worthy of mentioning that due to the very tiny size of optical fiber (a bare fiber of around 0.25 mm in diameter), it can be arranged conveniently to extend along various routes which allows to detect strain evolution along multiple directions, such as the axial (Fig. 4(a) and (b)), circumferential (Fig. 4(c)) or diagonal direction (see Fig. 5). Zdanowicz et al. [66] analyzes the advantages of optical fiber strain monitoring in triaxial concrete tests using small specimens, and particularly highlights the application of 150 μm fine fibers and their superior performance in crack monitoring (as in Fig. 5). Rather than measuring axial strain, Alj et al. [1] installs the fiber circumferentially to sense the loop strain developed within the cylinder specimen test (shown in Fig. 4(c)). Bassil et al. [6] conducted a laboratory wedge splitting test to investigate the cracking sensing performance of DFOS, where the FO cables are integrated by internal embedding and surface bonding into a precut groove, and additionally a theoretical formula is developed to characterize the strain transfer at interfaces and calculate crack width. In these studies, the optical fiber sensors employed typically have a diameter of 0.9 mm, allowing them to be flexibly attached to small-scale concrete specimens through continuous gluing. The distributed strain information is primarily obtained using a Rayleigh OFDR interrogator, which provides millimeter-order spatial resolution. Therefore DFOS significantly enhances the volume of strain data available for analyzing the strain-stress behavior of concrete materials, offering advantages over conventional spot strain gauges or LVDTs.

3.1.2. Bond-slippage tests

The capacity of acquiring a continuous strain profile of the small optical fiber makes it well-suited for rebar strain sensing in bond tests. Bado et al. [2] investigates the interfacial bond stress and slip phenomena occurring between concrete and steel reinforcements within reinforced concrete (RC) tensile members of varying crack dimensions, including those without any cracking. Their research delineates that optical fiber cables affixed to the reinforcing steel presents an optimal solution for the identification of cracks as well as for the accurate derivation of strain profiles in the experimental rebars. Similar experimental research has been performed in Galkovski et al. [19], Zhang et al. [67] and Saidi and Gabor [50]. In addition, when the optical fiber is firmly bonded to the rebar, it is possible to detect sudden strain variation of the rebar in the case of weakening of the cross-section due to various external factors (e.g., corrosion, perceived grooving, etc.). Notably, in these bond tests, the fiber is typically embedded within a pre-cut groove in the rebar rather than

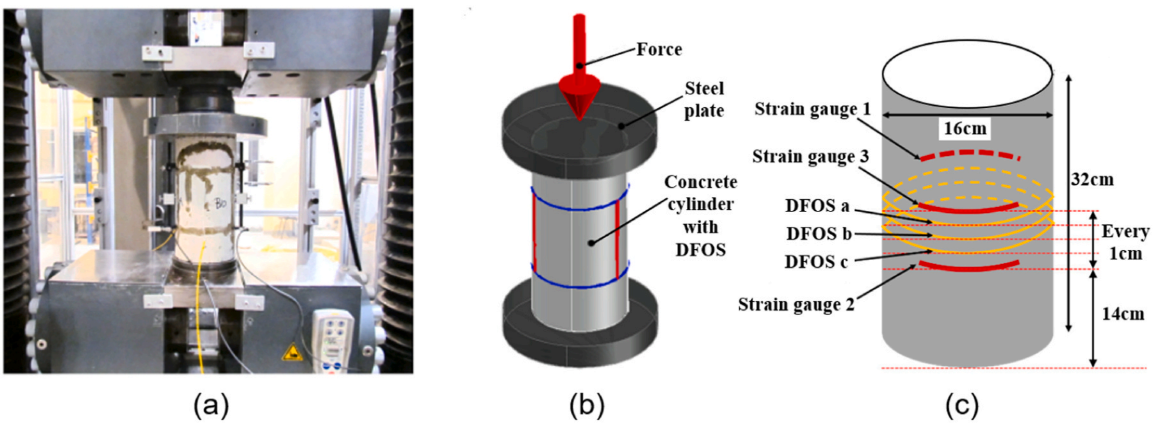

Fig. 4. Schematic of concrete specimen compression tests using DFOS: (a) specimen loading setup; (b) cylinder specimen; (c) specimen with instrumented fiber cable (based on [26] and [1]).

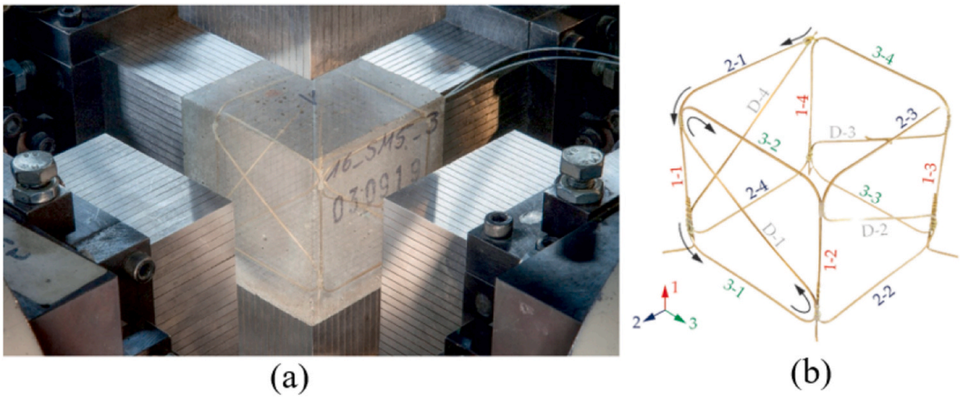

Fig. 5. Instrumentation the DFOS for multiple directional strain sensing in concrete cubic specimen test [66].

being attached to the surface. This approach provides enhanced protection for the fiber, minimizing the risk of damage at the rebar-concrete interface due to the transfer of large shear forces, compared to surface bonding (as shown in Fig. 6).

3.1.3. Beam flexural tests

Concrete beams mainly withstand bending moments and are prone to crack, although the tension area of cross-section is usually fitted with reinforcements. The flexural characteristics and progressive failure modes of beams are typically investigated via a three-point or four point bending tests, and conventionally the strain information is sensed by spot strain gauges usually bonded to the rebars, or LVDTs attached on the concrete surface. However, these point sensors only detect localized strain information, and the acquired discrete strain data fails to accurately capture the evolution of micro cracks. In contrast, DFOS offers a superior solution in that a small optical fiber or cable can conveniently attached to the beam, either bonded to rebar, concrete surface or buried inside concrete matrix to obtain precise distributed strain profile, which can not only capture densely distributed strain but also monitor crack quantitively. For instance, when cracks occur and propagate, the optical fibers traversing the small crack gap tend to bring about a change in strain, typically with the appearance of local strain spikes along the fiber strain profile as demonstrated in Fig. 7.

Berrocal et al. [10] conducts a three-point bending test on scaled concrete beams (shown in Fig. 8), and the detailed strain profiles yielded by the optical fiber facilitates the successful identification of early-stage crack development. The findings confirm that the attachment of an optical fiber to the lower part of reinforcement inside the beam can yield measurements as precise as those obtained from traditional foil strain gauges, all while leaving the reinforcement unaltered.

Monsberger and Lienhart [39] discusses an approach for shape sensing in concrete structures using DFOS and FBGs sensors for strain monitoring. By integrating curvature values from distributed strain data across two sensor layers (namely the top layer and bottom layer, as shown in Fig. 9), the performance of various sensor types under different installation conditions in concrete beams and tunnel linings is evaluated, affirming the feasibility and accuracy of this method in practical applications. In the research by Glisic and Inaudi [20], a long fiber optic cable is designed as extensometers (anchored at several discrete points) to quantify cracks in concrete, demonstrating its capability to identify cracks exceeding 0.35 mm across a span of 10 centimeters in laboratory tests.

In the study by Jayawickrema et al. [29], strain patterns in short-span reinforced concrete beams under flexural loading are

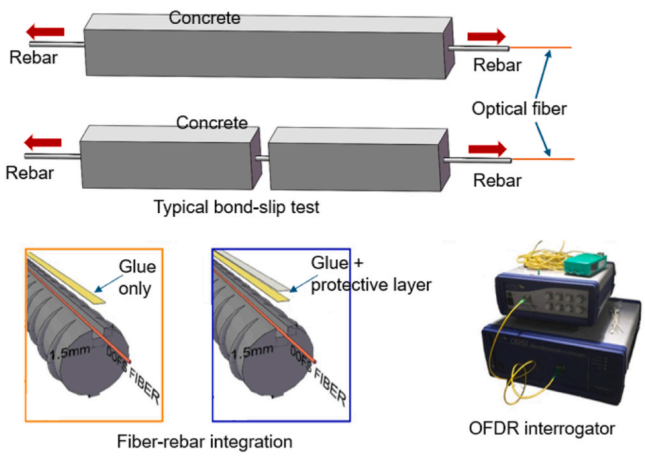

Fig. 6. Rebar-concrete bond test using high-resolution DFOS monitoring (based on [2]).

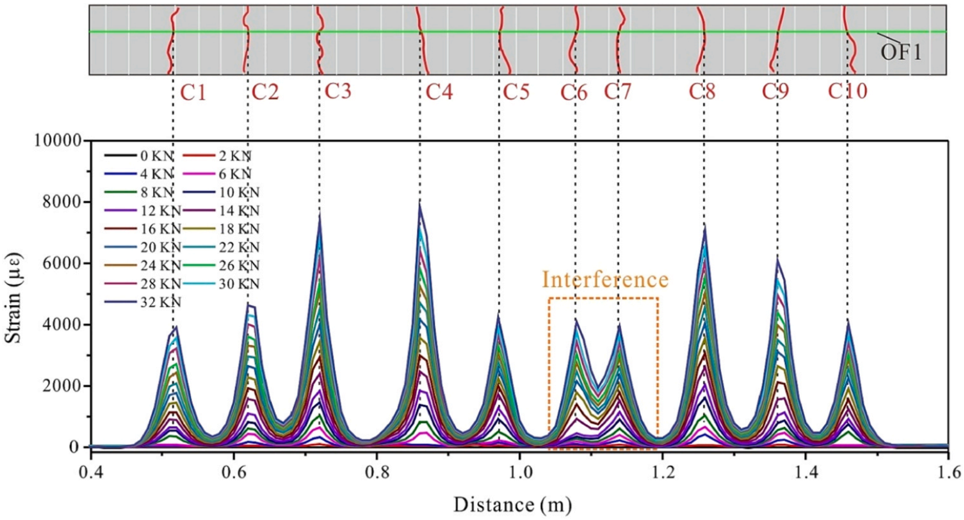

Fig. 7. A typical strain distribution along the concrete beam under loading instrumented with DFOS on the bottom [70].

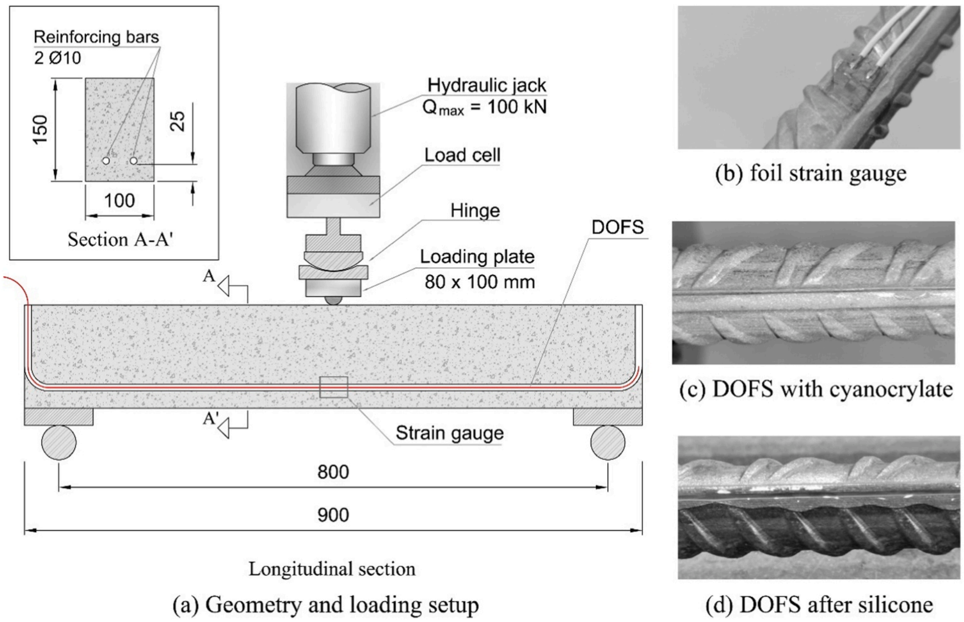

Fig. 8. Schematic of crack detection tests: (a) geometry and loading setup; (b) foil strain gauge installation; (c) DOFS bonded with cyancrylate and (d) silicone protection [10].

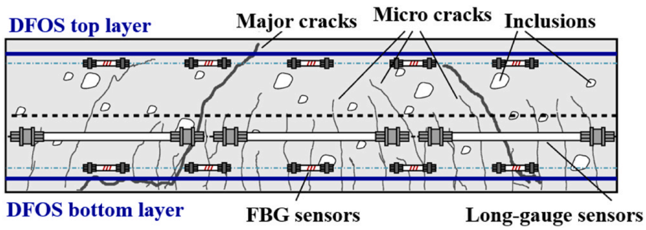

Fig. 9. Schematic Representation of Crack Detection Using Various Sensor Technologies [39].

analyzed using DFOS and compared with concrete damaged plasticity based finite element analysis models. In the experiment by Li et al. [33], the fiber is installed on the surface of the beam on front and back sides, where on one side the fiber is buried into a slot, while on the other side the fiber is fixed at several discrete points with clamps, serving as an extensometer chain. The study shows that continuous bonding method is more effective than point fixing installation.

Howiacki et al. [24] explores the performance of different optical fiber types in crack monitoring using OFDR, and examines the properties of fibers for crack monitoring, including its stiffness, physical structure, and bonding methods. Fernandez et al. [16] investigates the influence of different fiber installation methods on crack detection and width calculations, based on four-point bending tests, and results indicate that although all methods effectively detected cracks, they still show varying sensing efficiencies. Zdanowicz et al. [66] and Jayawickrema et al. [29] analyze the advantages of optical fiber strain monitoring in both small and large concrete specimens. For quantitative crack sensing, Zhang et al. [70] analyzes the impact of varying crack spacing on crack width calculations and proposes a method accounting for overlapping effects based on an indoor four-point bending beam tests. Tan et al. [58] conducts post-tensioned scaled T-shaped beam tests using carbon fiber-reinforced polymer (CFRP) in a four-point bending setup. Sawicki et al. [51] conducts scaled T-shaped beam tests using ultra-high-performance fiber-reinforced concrete, where the sensing fibers are embedded in surface grooves of the concrete to analyze their crack detection performance. In these studies, an OFDR interrogator is employed for precise strain sampling, and the findings confirm the high performance of DFOS in detecting even very narrowly spaced cracks, a capability unmatched by conventional instruments.

For the post-processing of distributed optical fiber data, Berrocal et al. [11] develops a digital twin model for data visualization and processing. For extensive monitoring data, initial strain values at cracks often lead to anomalies, necessitating some data post-processing to ensure reliability. For instance, Barrias et al. [4] proposes a Spectral Shift Quality (SSQ) threshold to assess the reliability of raw strain data, suggesting the removal of data points with SSQ below 0.20 and interpolation of remaining values to enhance data accuracy and interpretation.

Additionally, some researchers combine DFOS with other sensing methods to yield significantly improved results. Bassil et al. [8] combines strain sensing with DFOS and ultrasonic Coda Wave Interferometry (CWI) techniques for damage monitoring in concrete beam loading tests, and the results demonstrate a more accurate damage localization performance. Imai et al. [28] performs scaled T-shaped fiber-reinforced beams tests, with optical fibers bonded to the bottom surface of the concrete. They analyze the crack detection performance using a Brillouin Optical Correlation Domain Analysis (BOCDA) system, which has a spatial resolution of 29 mm and a measurable range of 15.7 m. Glisic and Inaudi [20] attempt to use BOTDA for crack detection. However, due to its limited spatial resolution, BOTDA is often only capable of detecting the occurrence of cracks, making it challenging to accurately estimate crack widths.

In addition to laboratory beam load tests, the performance of distributed optical fibers in monitoring of full-scale beams in the field has also been demonstrated. For instance, Howiacki et al. [25] applies fiber optic cables for crack detection in several in-service bridges, confirming their effectiveness in real-world conditions (see Fig. 10). In the study by Sieńko et al. [56], distributed optical fibers embedded in the ceiling beams of an actual factory demonstrate their capability for health monitoring from the concrete hardening stage through to normal load-bearing conditions, since the buried optical fibers can monitor the thermal temperature during the hydration process of mass structure and possible shrinkage cracks.

3.1.4. Concrete slabs and walls

Grunicke et al. [21] employs a DFOS system with OFDR to detect localized strain variations within tunnel linings, and their experience shows that the DFOS system can attain a strain measurement accuracy of 1 μm/m and was capable of detecting crack width changes at the scale of 0.01 mm. Buda-Ożóg et al. [13] explores the DFOS for monitoring reinforcement yielding strains and detecting cracks in slab structures during simulated column failure, and the setup enabled continuous monitoring throughout the progressive

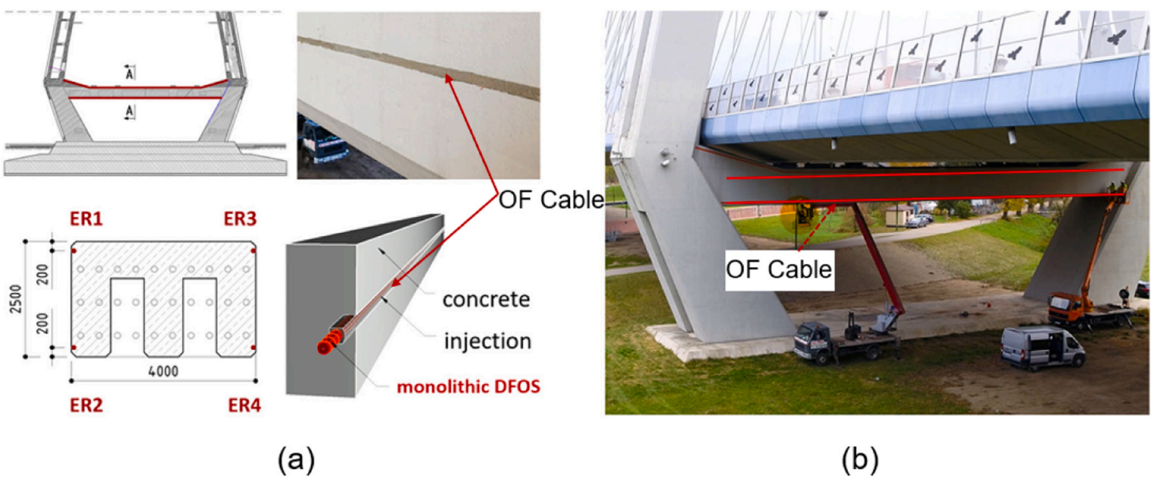

Fig. 10. Field installation of DFOS for beam crack detection: (a) Cable-beam integration methos; (b) field implementation [25].

collapse simulation. In the experimental study by Zdanowicz et al. [66], DFOS fiber sensors are installed on the surface of the concrete and within CFRP materials to enable continuous monitoring of strain and crack propagation in the slabs. Through four-point bending tests, the researchers analyze the strain distribution in concrete slabs under different loading conditions and validate the accuracy of DFOS measurements (using OFDR) with digital image correlation (DIC) technology.

Fernandez et al. [17] employs OFDR sensing technology in a multi-layer configuration within a reinforced concrete wall specimen, as illustrated in Fig. 11. The experimental setup involves embedding the DFOS in three directions, namely horizontal, vertical, and diagonal, across the mid-section of the wall to facilitate detailed strain measuring and crack detection during three-point bending tests. The findings indicate that DFOS effectively captures strain distributions, identifies crack locations, and detects secondary strut-and-tie mechanisms within the slab D-region. Wang et al. [61] employs BOFDA for internal strain monitoring of concrete slabs throughout their full life cycle, including stages such as preparation, casting, curing, corrosion, and loading. The results demonstrate that the system effectively captures strain evolution, detects cracks, and identifies strain patterns consistent with finite element simulations, even under harsh conditions.

3.1.5. *Structural joint*

The structural joint in concrete structures usually exhibits very complex mechanical behaviour, combining shear and bending effects when subjected to external loadings, and understanding its strain characteristics and cracking patterns is a prerequisite for its design and safety evaluation. However, for concrete structure the joint area is usually designed with dense reinforcement layouts, which impose difficulties to add sensor as well, particularly when large number of sensors are preferred. A thin fiber optic cable can be conveniently attached to the reinforcement cage or bonded on surface and can thus obtain dense strain data without occupying too much space. For instance, Zhang et al. [68] carries out a laboratory loading experiment on a reinforced concrete joint and uses an OFDR for strain sensing, as shown in Fig. 12. The detection of local maxima within the tensile strain profile facilitates identifying both the onset and precise locations of cracks. Moreover, placing fibers across various planes helps infer the direction and depth of the cracks. A similar experimental study on column-beam joint is conducted in Liu et al. [35], and both studies have validated the advantages of DFOS to point sensors when utilized to instrument critical concrete structural part that is strongly reinforced.

3.1.6. *Shear cracking sensing*

Although optical fibers were mainly installed perpendicular to the most possible crack direction, so as to reach a high sensitivity in the preceding studies, some experiments have also explored using optical fibers for detecting shear cracks (that do not extend perpendicular to the fiber axis). For instance, in the test by Rodriguez et al. [48], the optical fiber is installed as a web on the surface of the shear zone of a beam (near the end support, see Fig. 13), while the two-dimension strain information is obtained using fiber optic cable with OFDR interrogator. The results confirmed the effectiveness of DFOS for monitoring diagonal cracks of beams. Nowak et al. [42] presents a specimen testing that demonstrates the ability of the fiber optic cable to detect strain variations when extended across

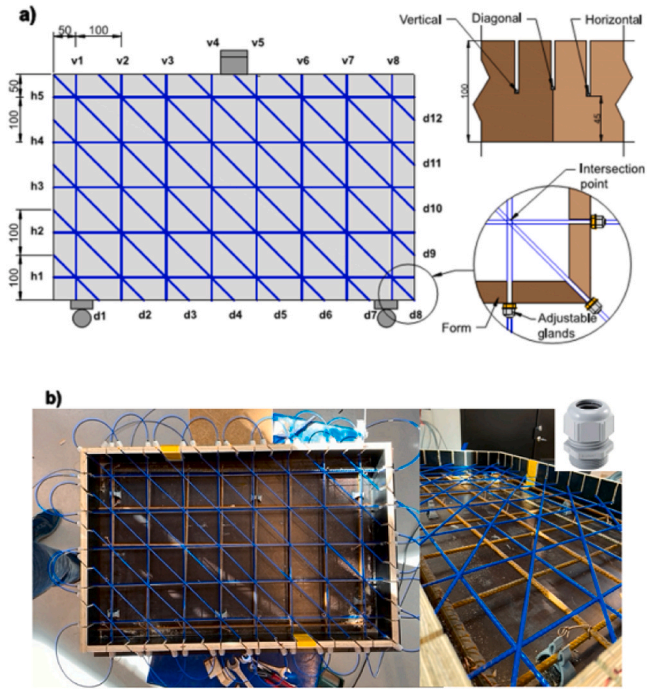

Fig. 11. Multiple-layers installation of fibre cables for strain sensing within slab specimen: (a) optic fibers layout and (b) its placements in a wooden framework (All units are in millimeters) [17].

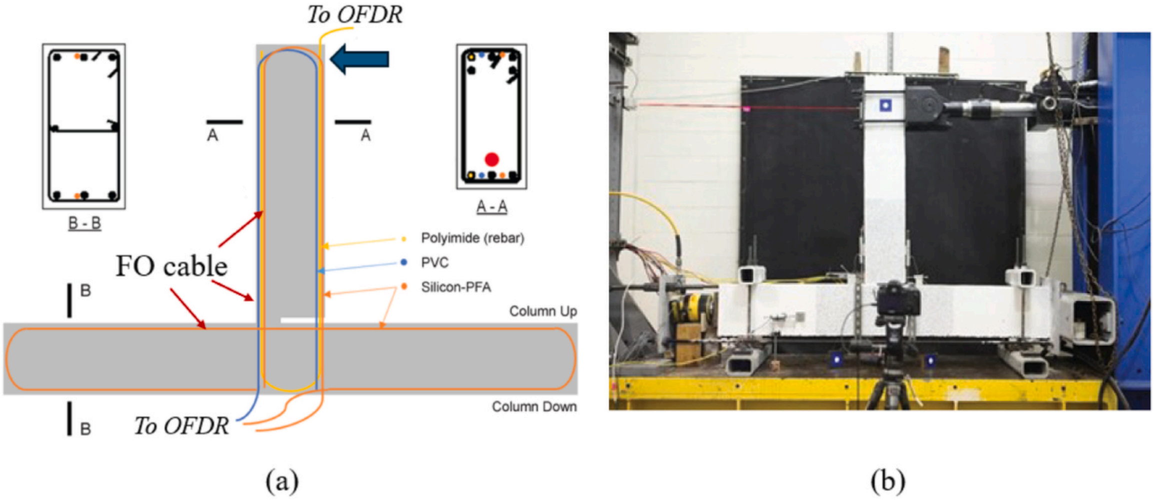

Fig. 12. Joint test with instrumented DFOS: (a) FO cable instrumentation; (b) laboratory load test [68].

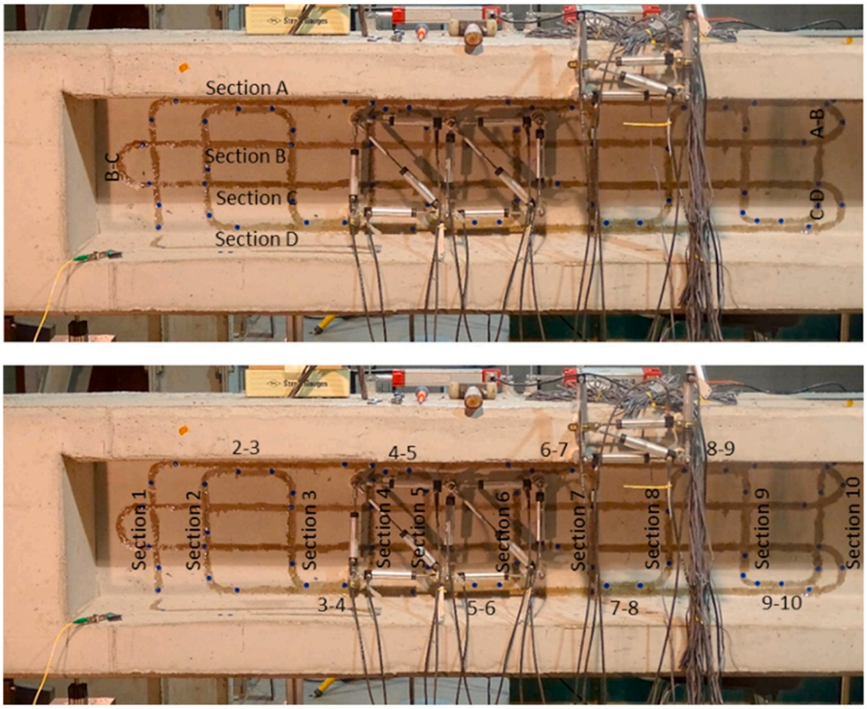

Fig. 13. DFOS 2D strain sensing mesh on the web of the beam [48].

highly localized zones subjected to both tension and shear deformation, and they propose further linear relationships for estimating the displacement magnitude from strain results sampled by a BOTDA interrogator.

3.2. Micro-bend sensitized cracking sensing using DFOS

Different from strain-sensing based crack monitoring, a second type of crack sensing principle operates by recognizing the attenuation of light resulting from the micro-bend of the fiber as it traverses a crack (see Fig. 14), where Rayleigh scattering based OTDR is mostly employed to monitor the signal attenuation along the fiber. For instance, the laboratory tests by Leung et al. [31] have demonstrated the fiber's capacity to detect and differentiate cracks with a minimum width of approximately 0.2 mm, and the accuracy of such a setup increases with the presence of broader cracks. In a laboratory test by Wu et al. [64], a micro-bend sensitized fiber is placed to cross a crack with a skew angle of 60 degrees, and the quantitative correlation between optical loss and the width of cracks is

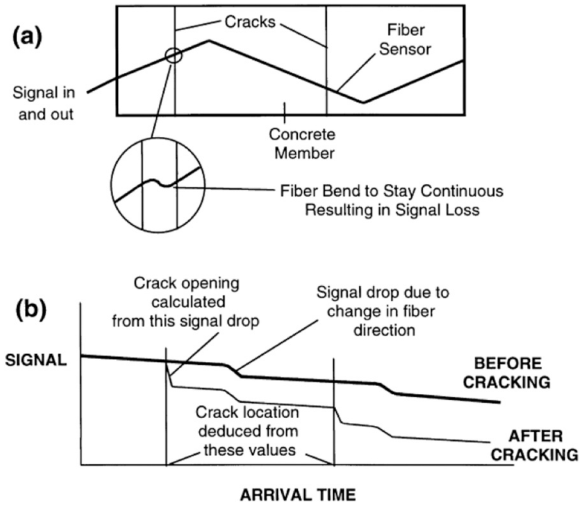

Fig. 14. The principle of micro-bend sensitized fiber for crack detection [31].

established. The study confirms a crack detection precision of 0.05 mm with an OTDR assessing the optical power loss.

Notably, almost all the fibers used in the previous listed applications are silica fibers, which are brittle (with a maximum elongation only around 1 %) and easy to break, which limits their applications in monitoring large cracks. Zhao et al. [78] explores polymer optical fibers (POFs) (rather than conventional silica fibers) for crack detection, given its higher adaptability to elongation and resistance to impacts, focusing on the influences of the intersection angle (between the fiber and crack) on the POFs' signal loss that can be detected by power meter, with a further validation in a three-point bending test (seen in Fig. 15). In the experimental study by Yuen et al. [65], the light intensity loss of POFs is correlated to the shear deformation imposed, and a photon-counting Optical Time Domain Reflectometer (ν-OTDR) is used for signal intensity measuring. The performance of this setup to detect both crack formation locations as well as the magnitude of crack width has been determined for several scenarios. A similar macro-bending based crack sensing study is conducted by Cheng et al. [15].

To further boost the sensitivity of POF to external strain and bends, the optical fiber may be further tapered to the exposed core in crack monitoring. Luo et al. [37] investigates the application of tapered polymer fiber sensors (TPFS) for crack detection, where the TPFSs are made by manually removing the external cladding layer to enhance its sensitivity to strain or cracking. The TPFSs are embedded within and adhesively attached to the surface of the beams in a four-point bending test. The study demonstrates that TPFS can qualitatively detect both the initiation and progression of cracks through changes in light transmission. However, the delicate manual fiber tapering required, and the exposed fragile core may limit its extended application.

Bremer et al. [12] innovates a fiber optic crack sensor with a textile reinforcement mesh (see Fig. 16), through the integration of functionalized textile net structures (TNSs) crafted from alkali-resistant glass within a concrete beam. To evaluate the efficacy of the sensor, signal loss of the optical fiber crossing cracks is monitored using an OTDR while simultaneously quantifying the crack sizes. The results of the experiment reveal that the sensor offers an efficient approach for identifying crack-induced failures in concrete structures, with a sensitivity to cracks as small as 1.4 mm. However, the study also pointed out that the developed fiber optic crack sensor works well for crack detection but not so effective for quantitative measuring, because of the difficulty to determine the correlation

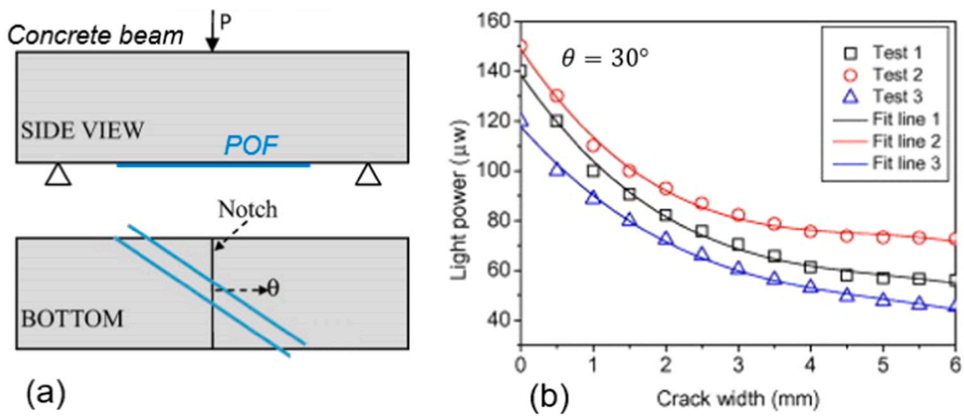

Fig. 15. The relation between signal loss and crack opening [78].

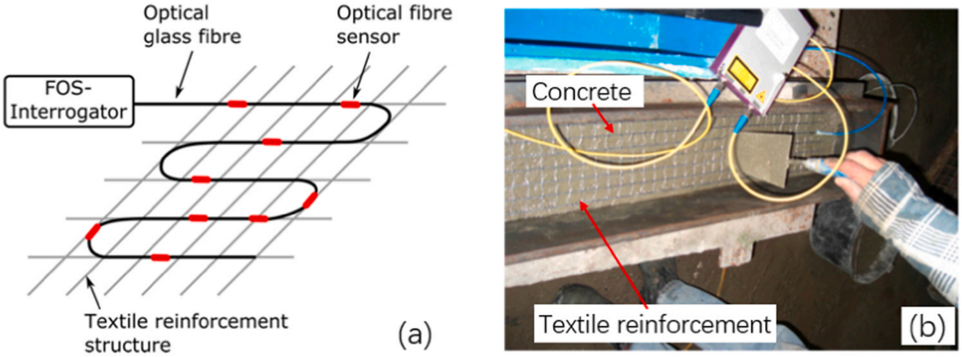

Fig. 16. Schematical illustration of a (a) textile reinforcement structure integrated with optical fibers and (b) its further embedding into a concrete beam [12].

between the crack size and light attenuation. The concept of self-sensing is further implemented to develop a carbon fiber reinforcement polymer (CFRP) with embedded optical fiber cable for long-term strain sensing.

3.3. Temperature variation based cracking sensing

In addition to strain or bend sensitized signal intensity, temperature variation may also serve as an indicator for potential cracking, especially for early-age concrete in hydration process. Shi et al. [54] proposes a methodology to forecast the risk of crack formation in early-age concrete using a distributed temperature sensing (DTS) system based on Raman backscattering. The data acquisition is via an OTDR with meter-level spatial resolution and a temperature resolution of 0.01°C and an accuracy of 0.1°C. The sensing principle is firstly meticulously calibrated by emplacing the fiber optic cable within and around the concrete structures. Furthermore, FEM simulations are employed to replicate temperature distributions and thermal stress fields within the early-age concrete, particularly in the context of dam construction. The DTS data serves a pivotal role in calibrating the thermal parameters of the concrete, thereby refining the predictive model's accuracy for crack development. The subsequent validation process demonstrates a high degree of concordance between the FEM predictions and the actual empirical data obtained via the DTS system, thus indicating the efficacy of the proposed method in the crack warning within dam infrastructure. However, currently there is not much literature concerning the precise crack detection based on temperature sensing via Raman scattering.

4. Discussion and future perspectives

4.1. Applicability of different cracking sensing principles

Based on the literature review, among the three primary sensing principles of DFOS for crack monitoring, namely strain measuring, optical signal loss measuring, and temperature measuring, strain measuring emerges as the most reliable and practical technique for crack monitoring. This method predominantly employs OFDR, BOTDA, BOFDA as strain acquisition instruments. Those studies that provide details on the measurement technique used and its accuracy have been summarized in Table 1.

The OFDR, due to its high spatial resolution (on the millimeter scale), is capable of capturing more precise strain distribution profile and exhibits greater sensitivity to strain variations in optical fibers traversing minor crack zones. Consequently, OFDR achieves higher crack detection precision and sensitivity, particularly for closely spaced cracks, thereby demonstrating a superior recognition ability [58,72]. In contrast, Brillouin scattering-based demodulators such as BOTDA and BOFDA typically possess spatial resolutions on the order of 20–50 centimeters. As a result, their effectiveness in crack sensing is less pronounced compared to OFDR, especially regarding the accuracy of quantitative crack parameter monitoring and the identification of closely spaced cracks (see Table 1). Nevertheless, BOTDA and BOFDA offer significantly extended sensing ranges, reaching several tens of kilometers, which makes them well-suited for monitoring large-scale linear infrastructure [76]. Consequently, strain sensing based cracking monitoring techniques exhibit higher applicability for field monitoring and have been successfully implemented in the monitoring of actual structural components [9,25].

Monitoring cracks by detecting light signal loss induced by optical fiber bending has, to date, been predominantly investigated through laboratory model experiments and rarely applied to actual field concrete structures (see Table 1). This limitation arises because the signal loss resulting from fiber bending due to cracks is influenced by numerous factors, particularly the angle between the fiber axis and the crack orientations, the width of the crack, the integration of fiber, and the type of fiber used, all of which introduce significant uncertainties. Consequently, the quantitative relationships derived from laboratory experiments often fail to correspond accurately to actual structural conditions, rendering quantitative crack monitoring exceedingly challenging. Furthermore, Rayleigh scattering based OTDR instruments, which are commonly employed for monitoring fiber signal loss, possess limited precision and spatial resolution, potentially hindering the identification of closely spaced crack events. Nonetheless, OTDR's detection range, which can extend to several tens of kilometers, holds potential for qualitative crack monitoring in large-scale structures, facilitating the detection of crack occurrences. However, achieving quantitative crack detection remains difficult.

Table 1
Summary of key DOFS information from previous studies.

Source	Sensing principle	Application type	Interrogator type	Installation method	Spatial resolution	Crack sensing performance
Berrocal et al. [10]	Strain change	Laboratory beam test (three-point bend)	OFDR (ODiSI 6000)	Glued on rebar surface, embedded into concrete	0.625 mm	Quantitative sensing ± 3 cm for crack location; ± 20 µm for crack width
Li et al. [33]	Strain change	Laboratory beam test (three-point bend)	BOFDA (ftb2505)	Glued on surface groove; Point-fixed on surface by clamps;	20 cm	Qualitative sensing
Liu et al. [35]	Strain change	Laboratory beam test	OFDR	embedded in a reinforced concretestructure	up to 1 mm	measurement accuracy (± 1 micro strain)
Alj et al. [1]	Strain change	Laboratory beam test	OFDR	sealed in grooves at the concrete surface	Not available	Not available
Barrias et al. [4]	Strain change	Laboratory beam test (three-point bend)	OFDR (ODiSI 6000)	Glued on concrete surface; Glued on rebar surface, embedded into concrete;	1 cm	Qualitative sensing; Crack initiation detection;
Richter et al. [47]	Strain change	Laboratory beam test (four-point bend)	OFDR (ODiSI 6100)	One fiber glued on rebar groove; and one directly embedded into concrete;	0.65 mm	Quantitative sensing ± 3 cm for crack location; ± 50 µm for crack width
Bado et al. [2]	Strain change	Laboratory beam test	OFDR	Bonded to rebars with adhesive and silicone	5 mm to 7.5 mm	Not available
Tan et al. [58]	Strain change	Laboratory beam test	OFDR	Glued continuously on concrete surface; Point-fixing on concrete surface; embedded into concrete;	0.65 mm, 1.3 mm, 2.6 mm	Not available
Rodriguez et al. [48]	Strain change	Laboratory beam test	OFDR (OBR 4600)	Bonded to concrete surface	1 cm	Quantitative sensing: Around ± 20 µm for crack width
Imai et al. [28]	Strain change	Laboratory beam test	BOCDA	Glued on concrete surface;	38 mm	Quantitative sensing: ± 20 µm for crack width
Sieńko et al. [56]	Strain change	Field beam monitoring	OFDR (OBR 4600)	Point-fixing and embedded in concrete	10 mm	Not available
Grunicke et al. [21]	Strain change	Field tunnel monitoring	OFDR (OBR 4600)	Glued on concrete surface;	10 mm	Quantitative sensing: ± 150 µm for crack width
Leung et al. [31]	Signal intensity loss	Laboratory beam test	OTDR	Embedded in concrete structures	Not available	Not available
Bremer et al. [12]	Signal intensity loss	Laboratory beam test	OTDR	Stitched onto a textile net, then placed in a concrete block	Not available	Not available
Cheng et al. [15]	Signal intensity loss	Laboratory sample test	OTDR	Attached to plexiglass plates	Not available	Crack resolution 0.03 mm; crack width relative error less than 6 %
Glisic and Inaudi. [20]	distributed sensor	Laboratory beam test	Not available	Glued to metallic supports, exposed to translation.	1 m	Strain accuracy ± 21 µε
Wu et al. [64]	Signal intensity loss	Laboratory beam test	OTDR	Embedded in concrete	0.05 mm	Not available
Zhao, et al. [78]	Signal intensity loss		OTDR	Glued to the bottom surfaces of concrete beams	Not available	Not available
Luo et al. [37]	Signal intensity loss		OTDR	Embedded and surface glued in concrete beams	Not available	Not available
Shi et al. [54]	Temperature variation		DTS	Embedded in concrete	1 m	error range within ± 0.5°C

Detecting the initiation of concrete crack based on spatial temperature variations using DFOS, has been relatively limited in the existing literature (see Table 1). Considering that concrete is a composite material composed of cementitious substances and both coarse and fine aggregates, it exhibits anisotropic and heterogeneous characteristics at meso scale. Local temperature fluctuations during the hydration process can be influenced by factors such as boundary conditions, internal porosity, and the non-uniform distribution of aggregates. Consequently, relying solely on temperature changes makes it challenging to distinguish the presence of cracks and renders the quantitative crack characteristics monitoring unfeasible.

In summary, crack monitoring based on strain measurement has been extensively validated through numerous laboratory model experiments and a number of field cases of bridge girders and beams, enabling the quantitative assessment of cracks. In contrast, crack detection through signal loss induced by fiber bend offers a potential detection range extending to several tens of kilometers, but presents significant challenges for the quantitative monitoring of crack widths. Crack detection in ordinary concrete structures based on temperature variation measurements, both in laboratory experiments and field monitoring, is still subject to considerable technical uncertainties.

4.2. Proper fiber (cable) integration with concrete structure

The specific method used for integrating optical fibers within concrete differs and influences its crack sensing performance. In literature, there are typically three methods employed:

(1) Attaching the fiber to rebar and then casting it into concrete. The optical fiber (OF) is longitudinally bonded to the rebar using continuous adhesive and then cast within the concrete to function as a strain sensor. The very thin fiber can be either be directly attached to the rebar surface or placed in a pre-cut notch as illustrated in Fig. 17(a) and (b). In this configuration, the fiber primarily measures the strain of the rebar itself, resulting in less pronounced strain levels during cracking compared to fibers directly embedded in the concrete (see Fig. 18).
(2) Embedding directly within the concrete. The OF cables are first secured to existing reinforcement, typically stirrup rebar, at spaced intervals as shown in Fig. 17(c). Subsequently cast concrete protects the sensors from mechanical damage and sunlight while fully encapsulating them, to ensure optimal bonding and strain transfer. Notably, this approach allows for analysis from a true zero strain–stress state throughout construction. However, it is limited to new structures, as sensors must be embedded prior to concreting and are not applicable to existing infrastructure [44,55].
(3) Bonding on the concrete surface or near surface. For existing structures, OF sensors can be directly adhered to the cleaned, smooth, concrete surface after curing, as shown in Fig. 17(d). While suitable for short-term laboratory testing, this method is unsuitable for long-term monitoring due to sensor exposure to solar radiation, which hinders thermal compensation and may degrade adhesives. Another alternative is to embed the fiber in a pre-cut near-surface groove along the structure's length (seen in Fig. 17(d)) and subsequently filling the grooves with adhesive materials like mortar. This technique provides benefits similar to direct concrete embedding [44].

It is important to note that the sensitivity of optical fibers to concrete cracking varies with the installation method. Specifically, fibers directly embedded in the concrete matrix and isolated from the reinforcement rebar exhibit significantly higher strain peaks at crack locations compared to those bonded to the reinforcement rebar, as demonstrated in Fig. 18 from Herbers et al. [23]. The strain curve of the OF cable directly embedded within the concrete matrix (Cable-concrete) differs significantly to that when bonded to the rebar (Cable-rebar). While the former displays pronounced strain peaks at cracked sections, the baseline strain levels of cable-rebar are predominantly influenced by the applied bending moment, resulting in substantially lower strain amplitudes. Additionally, from the strain curve of cable-concrete, it is easier to determine crack locations and, consequently, crack spacing for subsequent crack width calculation.

The physical design of a cable, particularly the type of sheath or jacket used, influences its sensitivity to strain and susceptibility to cracking. In a standard fiber optic cable, the central fiber core and its cladding constitute the primary light transmission pathway and serve as the sensing element (see Fig. 2). To enhance the cable's resilience against external forces and improve its durability, additional protective layers are typically added, such as basic coatings, plastic jackets, and reinforcing sheaths (shown in Fig. 2). However, while these reinforcement components, like jacket armor and internal reinforcement wires, are intended to increase the fiber's toughness, they also make the fiber stiffer, which consequently reduces its sensitivity. For example, Bassil [5] found that the strain pattern of an optical fiber equipped with high-strength armor differs from that of an unarmored optical fiber. Consequently, using a simplified strain transfer model based on the latter may not be entirely accurate and could lead to significant errors in estimating crack width. Therefore, choosing the appropriate fiber type should involve careful consideration of its strain sensitivity, impact resistance, and ease of installation.

In cases of fiber installation using adhesives, typical adopted adhesives include cyanoacrylate, epoxy resin, silicone, and injection mortar. The analysis of the impact of adhesive stiffness on the accuracy of crack detection by optical fibers reveals that the softer the

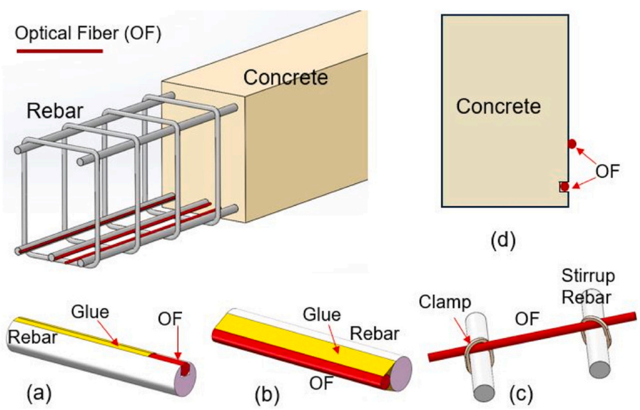

Fig. 17. Optical fiber (or cable) integration with structure: (a) embedding into a precut slot on rebar; (b) surface continuous bonding on rebar; (c) point fixing with glue and clamps to stirrup; (d) glued on concrete surface or embedded into a shallow groove.

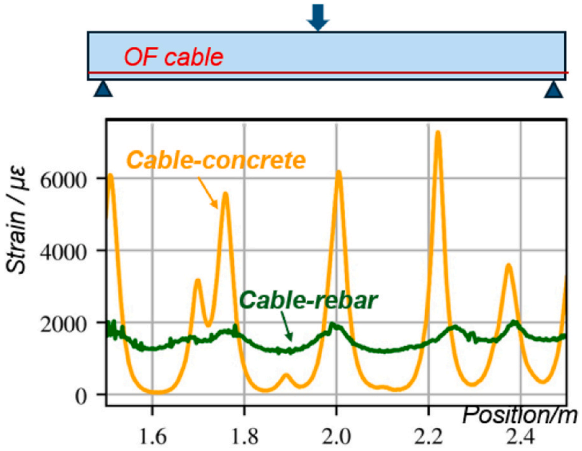

Fig. 18. Typical strain curves of FO cable in a beam bending test with two different installation methods (revised from [23]).

adhesive, the lower the strain transferred to the OF glass core due to a redistribution over a greater length of the sensor [1,23]. The use of softer adhesives can reduce the strain sensitivity of the optical fibers, potentially enhancing their lifespan by preventing brittle fractures. However, this approach necessitates a balance, as excessively soft adhesives may diminish the sensitivity of bonded DFOS instrumentation in the concrete structure. In addition to stiffness, other properties of the adhesive need to be considered, such as curing time, viscosity, resistance to chemicals and weathering, and shrinkage. Generally, the shorter the curing time, the more convenient for cable installation. Low-viscosity fluid glue may not easily settle on the fiber-host material interface. For concrete structures in highly corrosive environments, as well as the surface directly exposed to sunshine, the glue should preferably have a higher durability and weathering resistance, because the aging of the glue may affect the strain transfer at the fiber-host material interface [23,5]. In summary, a pre-check on the properties of the glues and beforehand tests helps decide suitable adhesive solutions.

4.3. Quantitative crack width monitoring

4.3.1. Strain integral method

Quantitative crack width measurement is a crucial component in the deployment of DFOS for monitoring concrete cracks. Although

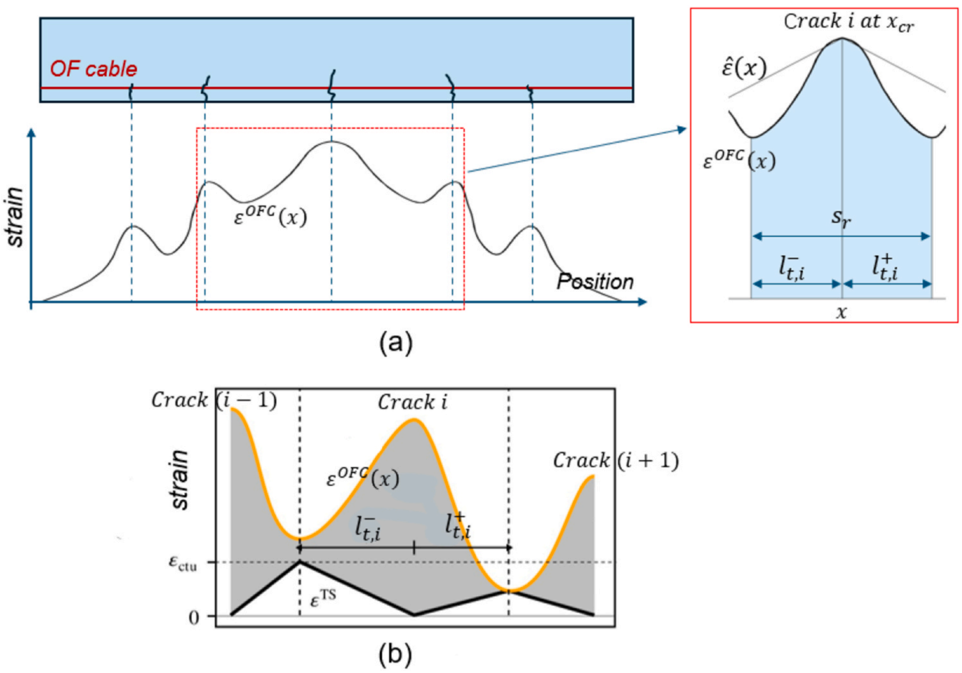

Fig. 19. Schematical illustration of the parameters for transferring strain data into crack width for OF cable (a) integrated to rebar and (b) directly embedded into concrete (revised based on Berrocal et al. [10] and Herbers et al. [23]).

the analysis of strain transfer mechanisms in the influenced concrete near a crack is inherently complex, simplifications are necessary to establish a practical relationship that facilitates crack width calculations. According to Berrocal et al., [10] the current structural design standards, such as Eurocode 2 [14] determine crack width within reinforced concrete members based on mechanical models derived from the analysis of slender members under direct tensile forces. These models assert that the characteristic crack width, w_{cr}, is quantified using:

$$w_{cr} = s_{r,\max}(\varepsilon_{sm} - \varepsilon_{cm}) \tag{1}$$

Here $s_{r,\max}$ denotes the maximum crack spacing, while ε_{sm} and ε_{cm} represent respectively the average strain of the steel and concrete. In these models, the parameters in Eq.(1) are acquired considering the tensile forces equilibrium between the crack section and the section located at 0.5 *$s_{r,\max}$from the preceding crack when the concrete stress reaches its ultimate tensile capacity.

For scenarios where the optical fiber was bonded to the reinforcement rebars, it can be deduced that the non-linear distribution of strain between cracks sensed by the DOFS must account for the effect of the stress transfer between the rebar and the concrete due to bond action. Berrocal et al. [10] proposed the following expression Eq.(2) to calculate the crack width:

$$w_{cr,i} = \int_{-l_{t,i}^{-}}^{l_{t,i}^{+}} \varepsilon^{FOC}(x)dx - \rho\alpha\left[\int_{-l_{t,i}^{-}}^{l_{t,i}^{+}} (\widehat{\varepsilon}(x) - \varepsilon^{FOC}(x))dx\right] \tag{2}$$

where $\varepsilon^{FOC}(x)$ is the strain of the reinforcement monitored by the DOFS, $\widehat{\varepsilon}(x)$ indicates the assumed linear strain profile between cracks but neglecting the steel-concrete interaction, $\rho = A_s/A_{c.ef}$ and $\alpha = E_s/E_c$ represent the reinforcement ratio and the modular ratio, respectively and $l_{t,i}^{+}$ and $-l_{t,i}^{-}$ are the transmission length to the left and right sides of the *ith* crack, as illustrated in Fig. 19(a). Notably, the actual boundary length of the integral in Eq.(2) is not clearly determined and must be based on specific loading conditions.

For scenarios when the OF cable is directly embedded into the concrete (isolated form the rebar), [23] assumed the width $w_{cr,i}$ of the *ith* crack is equal to the integral of the DFOS strain $\varepsilon^{OFC}(x)$along the assumed transfer length of cable-concrete interface as in Eq.(3):

$$w_{cr,i} = \int_{-l_{t,i}^{-}}^{l_{t,i}^{+}} \left(\varepsilon^{OFC}(x) - \varepsilon^{TS}(x)\right)dx \tag{3}$$

where $\varepsilon^{OFC}(x)$ is the strain measured by the OF cable, $l_{t,i}^{-}$ and $l_{t,i}^{+}$ are the transfer length of the *ith* crack, and $\varepsilon^{TS}(x)$ indicates the part of strains resulting from rebar-concrete bond transfer (referred to as tension stiffening, TS). The location of the crack is generally determined by searching for the strain peaks, while the transfer length is usually assumed to be equal to half of the crack spacing as shown in Fig. 19(b).

Although the OF cables in this context are independent of the reinforcement rebars, it is important to note that tensile forces are reintroduced into the concrete away from the crack openings through bond interactions with the reinforcement, a phenomenon attributed to tension stiffening effects. Various methodologies addressing the tension stiffening influence are documented in the literature. For simplification, tension stiffening is mostly assumed to increase linearly from zero at the crack position to concrete's maximum tensile strain ε_{ctu}:

$$\varepsilon^{TS}(x) = \min(\delta_\varepsilon * \varepsilon_{ctu}, \varepsilon^{OFC}) \tag{4}$$

where

$$\delta_\varepsilon = \begin{cases} \dfrac{s_r - x}{l_t}-, ifx \le s_r \\ \dfrac{x - s_r}{l_t}+, ifx > s_r \end{cases} \tag{5}$$

The maximum (ultimate) tensile strain in Eq.(4) at the onset of cracking ε_{ctu} can be calculated from the material properties, which is mostly around 100 microstrains ($\mu\varepsilon$) [18].

To further simplify the above crack width quantification procedure, the concrete strain between the two adjoining cracks can be ignored, and as a result Tan et al. [58] proposes a more concise formula for crack width calculation:

$$w_{cr,i} = \int_{-l_{t,i}^{-}}^{l_{t,i}^{+}} \varepsilon^{OFC}(x)dx \tag{6}$$

Since the strain profile generated by DFOS systems typically comprises a densely sampled sequence of discrete points (ε_i) with interval spacings (d_s) on the order of millimetres or centimetres, the integral process in Eq.(6) can be effectively transformed into a summarization step, as proposed by Howiacki et al. [24]:

$$w_c = \sum\nolimits_{-l_{t,i}^{-}}^{l_{t,i}^{+}} \varepsilon_i d_s \tag{7}$$

In summary, the aforementioned methods for calculating crack width using DFOS exhibit varying performances. The optimal approach is influenced by factors such as the optical fiber installation (e.g., bonding to rebar, embedding within concrete, or surface adhesion), reinforcement ratio, and other related parameters. For practical engineering applications, it is advisable to conduct calibration laboratory tests tailored to the specific monitoring conditions anticipated in the field.

4.3.2. Exponential fitting method

Through a theoretical examination of the strain transfer mechanism from the host material to the core of an optical fiber, a new method for calculating crack width has been proposed. This method is based on an exponential fitting model of the strain profile at the crack. It assumes that the total fiber strain, denoted as $\varepsilon_{cr}(x)$, comprises two components: one component $\varepsilon^{FOC}(x)$ results from the elongation of the fiber spanning the crack, while the other component $\varepsilon_c(x)$ arises from the deformation of the host material. Bassil et al. [6] introduced an equation that characterizes the strain transfer relationship between a multilayer fiber optic cable and concrete, taking into account scenarios of imperfect bonding:

$$\varepsilon^{FOC}(x) = \varepsilon_{cr}(x) + \varepsilon_c(x) = \lambda \frac{w_{cr}}{2} e^{-\lambda|x|} + \varepsilon_c(x) \tag{8}$$

where λ is defined as shear lag parameter, is highly associated with the geometrical and material properties of the optical fiber and the adhesive layer; w_{cr} indicates the crack width.

Since the strain component from host material is insignificant compared to that from the fiber elongation at crack, $\varepsilon_c(x)$ can be neglected. At the crack central position ($x = 0$) the strain peak value is:

$$\varepsilon^{FOC}(0) = \varepsilon_{cr}(0) = \lambda \frac{w_{cr}}{2}(x) \tag{9}$$

Accordingly the crack width can be calculated as:

$$w_{cr} = \frac{2\varepsilon_{cr}(0)}{\lambda}(x) \tag{10}$$

where $\varepsilon_{cr}(0)$stands for the strain peak value at the crack centre, which can be directly recorded by DFOS.

It is meaningful to compare the two methods for quantifying crack width: the strain integral method and the exponential fitting method, particularly in terms of their implementation and accuracy. According to the crack width quantification in Eq. (6) and Eq. (10), the strain integral method relies on accurately sampling the strain profile around the crack, without the need for additional parameters. However, the accuracy of the crack width estimation is heavily dependent on precise strain sensing, which necessitates the deployment of an appropriate fiber type. For example, some layered and stiff cables may have lower sensitivity to crack strain compared to monolithic soft cables, leading to a reduced crack width estimate [9]. In contrast, the exponential fitting method only necessitates the precise determination of strain profile induced by cracks, and the shear lag parameter and the crack width are simultaneously obtained by fitting the strain profile. In summary, both methods are validated practically for quantifying crack widths, provided that a suitable sensing cable and integrator are used.

Another crucial aspect to consider is the precision of crack width estimation using the two methods. Both methods have been validated in previous laboratory studies, demonstrating sufficient precision for cases with single and with multiple cracks, but the error in crack width quantification depends on the width range being estimated and the types of sensing cables used. For example, in some laboratory tests, the exponential fitting model shows a relative error of below 10 % for crack widths ranging from 0.05 mm up to a limit that is highly dependent on the fiber type. However, the error can become unacceptably high if the crack width is below 0.05 mm (Zhang et al., 2023; [7] & 2020). In contrast, the strain integral method has reported errors for crack width ranging from 0 % to as high as 50 % ([58]; Berrocal et al., 2021; [9]). Therefore, it is recommended that laboratory calibration tests be conducted in advance for both methods when monitoring crack width in actual concrete structures.

4.4. Optimal DFOS leverage with combined sensing technology

For effective crack monitoring, the three most critical aspects are the initiation of cracks, their corresponding locations, and the development trends of crack width. Based on the monitoring of strain variations, DFOS has been demonstrated in several studies to possess the capability for quantitative crack monitoring, including measurements such as crack locations and width. However, it is important to note that most existing literature focuses on laboratory experiments, with only a limited numbers of cases applied to actual field monitoring of concrete structures [9,25]. Additionally, even in field monitoring scenarios, optical fibers have primarily showcased their ability to effectively capture structural strain rather than experience the significant cracking phenomenon such as in failure period. Nevertheless, since the monitored structures have not yet reached an ultimate cracking state, the long-term efficacy of crack monitoring remains to be further verified. This necessitates that monitoring practitioners carefully consider how to better leverage the advantages of DFOS to enhance crack detection efficiency in spatial dimensions while also achieving the necessary precision in crack width measurements (approximately 0.1 mm).

Considering the current DFOS interrogator technology, Rayleigh scattering based OFDR offers high millimeter-order spatial resolution, making it more suitable for precise crack detection. However, its detection range is limited, to approximately 100 m. A more balanced approach is achieved through Brillouin-based techniques such as BOTDA and BOFDA. Although these methods have lower spatial resolution, they can facilitate longer detection distances (exceeding ten kilometers), rendering them more appropriate for monitoring extensive linear concrete structures, such as bridges, tunnels and pipelines [72,73,76]. Nonetheless, given that the interrogators used on Brillouin scattering typically have spatial resolutions in the order of several tens of centimeters, they have significantly lower sensitivity to cracks compared to OFDR. This limitation implies that the precision in monitoring crack width may not be high, although their capability to detect the approximate location of crack initiation may satisfy engineering requirements.

Therefore, a rational strategy involves combining distributed optical fibers or cables with traditional high-precision strain or displacement sensors. Initially, the optical fibers are employed primarily to detect the occurrence and location of cracks. Subsequently, manual visual inspections or other visual monitoring technologies, such as unmanned aerial vehicles (drones) or robots (as illustrated in Fig. 20) [38,49], can be utilized to further confirm and facilitate the installation of higher-precision strain or displacement sensors, such as Linear Variable Differential Transformers (LVDTs), for detailed monitoring [79,63]. Given that depth of major surface crack may serve as an important indicator to assess concrete structure safety, other techniques such as ultrasonic horizontal shear waves can be additionally applied to detect the crack depth [34,53,62]. This combined approach can achieve enhanced overall effectiveness in crack monitoring.

5. Conclusion

Crack monitoring has become a vital aspect of structural health monitoring systems for concrete infrastructure. This study presents a comprehensive review of crack sensing in concrete using distributed fiber optic sensor (DFOS) technology. DFOS offers distributed data sampling capabilities through dedicated optical fibers, effectively addressing the spatial limitations of conventional discrete sensors such as foil strain gauges and transducers. The main conclusions are summarized as below:

(1) Smart concrete crack sensing typically involves quantitative monitoring that addresses three key objectives: detecting crack initiation, identifying crack location, and determining crack width along with its evolution.
(2) When using DFOS for crack monitoring, the three primary sensing principles include: measuring localized strain spikes in optical fibers or cables spanning cracks, using Rayleigh-scattering OFDR and Brillouin-scattering technologies, such as BOTDA and BOFDA; detecting signal intensity loss due to micro-bend deformation in optical fibers intersecting cracks, using Rayleigh-scattering OTDR; and monitoring precise local temperature variations in the crack area, using Raman-scattering OTDR.
(3) In terms of sensing performance and application versatility, strain-based crack sensing has emerged as the dominant method, with extensive validation in laboratory experiments and some field monitoring of concrete structures. Micro-bend sensitized crack sensing has been experimentally validated but faces limitations in ensuring a reliable correlation between crack formation and signal loss, making it less suitable for practical applications in concrete structures. Monitoring temperature variations continues to face challenges and has yet to achieve effective quantitative crack sensing.
(4) The sensitivity of optical fibers to concrete cracks varies with the installation method. Specifically, fibers directly embedded in the concrete matrix (isolated from the reinforcement rebar) exhibit significantly higher sensitivity compared to those bonded to the reinforcement rebar.
(5) Quantitative crack width measurement requires the precise determination of crack locations from fiber strain profiles, and the width can typically be calculated through an integral or exponential fitting of strain along the transmission length to both sides of the crack. Considering the rebar-concrete bond action when doing this offers partial error correction.

DFOS has been shown to possess the capability for quantitative crack sensing, including detecting crack initiation, identifying crack locations, and measuring crack width. However, it is important to note that most existing studies primarily focus on laboratory experiments, with only a limited number of cases of actual field monitoring. This suggests that the long-term effectiveness of crack monitoring across the full life cycle of structures has yet to be fully verified. To enhance its sensing performance, a rational strategy may involve integrating DFOS with manual visual inspections or other visual monitoring technologies, such as unmanned aerial vehicles (drones) or robots, for detailed follow-up assessments in structural health monitoring.

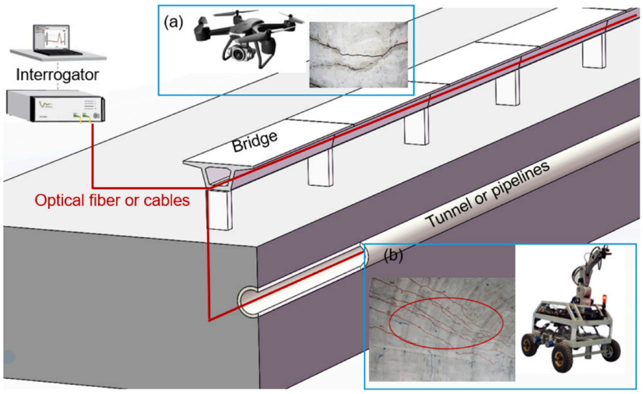

Fig. 20. Combining DFOS cracking sensing with computer visions technologies based on (a) drone and (b) robot vehicle.

Funding information

This research received no financial fundings.

CRediT authorship contribution statement

Broere Wout: Writing – review & editing, Supervision, Project administration, Methodology, Investigation. **Long Luyuan:** Investigation, Conceptualization. **Zhang Xuehui:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Bao Xiaohua:** Writing – review & editing, Supervision, Resources, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data supporting the findings of this study are available within the article.

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