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Crack Localization and Detection in Small-Scale Reinforced Concrete Beams With Smart Technology

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Abstract: Reinforced concrete structures form the backbone of modern civil engineering, yet the emergence of cracks poses a significant challenge to their long-term integrity. The integration of smart sensors and data analytics further augments precision by enabling real-time data collection and analysis, allowing for early intervention. Continuous monitoring, facilitated by remote sensing and wireless communication, ensures a dynamic understanding of crack propagation. To validate the proposed approach, an experimental campaign was conducted using reinforced concrete beams. Three point bending tests were conducted on two small-scale reinforced concrete beams. Different configurations of SEC arrays were used on the two specimens to assess the capacity and limitation of the proposed approach. Results show that the sensing skin was capable of detecting and localizing cracks that formed in both specimens.

Keywords: Reinforced, Cracks, Concrete, Strain, Curve

I. INTRODUCTION

The enduring utility of reinforced concrete structures in modern civil engineering cannot be overstated. From towering skyscrapers to vital infrastructural elements like bridges and dams, reinforced concrete forms the backbone of our built environment. However, the long-term integrity of these structures is constantly challenged by various factors, with the emergence of cracks being a critical concern. Cracks in reinforced concrete not only compromise the structural stability but also expose the embedded steel to corrosive elements, leading to further deterioration. As such, the timely and accurate detection and monitoring of cracks have become imperative for ensuring the longevity and safety of these essential structures.

The presence of cracks in reinforced concrete is a natural consequence of its material properties and the dynamic loads it endures throughout its lifespan. Factors such as shrinkage, thermal expansion, and external forces from traffic or environmental conditions contribute to the initiation and propagation of cracks. Left unchecked, these seemingly innocuous fissures can evolve into more significant structural issues, posing threats to both human safety and economic investments. Therefore, it becomes crucial to develop robust methods for the early identification and continuous monitoring of cracks in reinforced concrete.

One of the primary challenges in crack detection lies in its inherently hidden nature. Unlike surface defects, which are readily visible, cracks may remain concealed within the structural elements, escaping casual observation. Traditional inspection methods often rely on manual visual assessments or rudimentary techniques that are not only time-consuming but also prone to human error. Furthermore, the limitations of these conventional approaches become even more pronounced in large-scale or hard-to-reach structures, where accessing critical areas for inspection becomes a logistical challenge.

Advancements in non-destructive testing (NDT) techniques have revolutionized the field of crack detection and monitoring in reinforced concrete structures. These methods employ a range of sophisticated technologies, including ultrasonic testing, radiographic imaging, electromagnetic techniques, and ground-penetrating radar, to name a few. By leveraging the principles of wave propagation, electromagnetic interference, and material properties, NDT techniques enable the penetration of concrete surfaces to reveal hidden cracks, providing invaluable insights into the structural health of the elements.

Moreover, the integration of modern sensor technologies and data analytics has significantly enhanced the precision and efficiency of crack detection and monitoring processes. Smart sensors embedded within concrete elements can continuously collect real-time data on parameters such as strain, displacement, temperature, and humidity, allowing for the early detection of structural anomalies and potential crack formation. This wealth of data can then be analyzed using advanced algorithms and machine learning techniques to predict the evolution of cracks and assess their criticality.

In addition to early detection, continuous monitoring of cracks plays a pivotal role in ensuring the structural integrity of reinforced concrete elements over time. Static visual inspections, performed at infrequent intervals, may fail to capture the dynamic nature of crack propagation and the evolving structural conditions. Real-time monitoring, on the other hand, provides a comprehensive understanding of how cracks progress, enabling engineers to implement timely interventions and mitigate potential hazards before they escalate.

Furthermore, the integration of remote sensing technologies and wireless communication systems has extended the capabilities of crack monitoring beyond the confines of physical proximity. This allows for the establishment of comprehensive structural health monitoring networks, facilitating real-time data transmission and analysis, even in geographically dispersed or hard-to-access locations. As a result, engineers and stakeholders can make informed decisions based on accurate, up-to-date information about the condition of reinforced concrete structures.

II. REVIEW OF LITRATURE

Ahcene, Arbaoui (2021) In this study, we provide a novel approach to fracture monitoring and identification in preexisting concrete buildings. This method relies on analyzing a concrete sample or specimen that has been exposed to many forms of stress at multiple resolutions. Internal fractures and crack start can be detected by doing multi-scale analysis on the picture generated from an ultrasonic inspection and processed with a specialized wavelet. The overarching goal of this study is to provide a method for automated crack type recognition using convolutional neural networks (CNN). With this method, fractures may be detected before they become evident on the concrete's surface, and their progression can be tracked remotely Wavelets and deep learning two powerful methods for analyzing data, work together to accomplish this. An accuracy of over 90% is demonstrated for this novel method. We also employed an open-access database (SDNET2018) for the automated identification of exterior fractures to evaluate the performance of the suggested CNN architectures.

Zaki, Ahmad et al., (2021) It has been widely documented how big an issue cracking in reinforced concrete (RC) constructions is across the world. Damage and destruction to RC structures may result from cracking. The cracks are the damage to RC buildings that necessitates fixing or replacing them. Cracks in a reinforced concrete (RC) building might have a bigger impact and repair costs if not assessed as soon as feasible. Therefore, it is necessary to use a non-destructive testing (NDT) approach on the RC structure, namely the visual inspection method. After a visual inspection, a picture is captured of the area of interest and processed using image analysis software. The quality (compressive strength) of the cracked concrete structure is then evaluated utilizing a rebound hammer technique using a rebound index. The damage from the cracks that developed may be determined from the results of the image processing and rebound index, making repairs more efficient and effective.

Berrocal, Carlos G. et al., (2020) In order to monitor the health of civil engineering structures, this research delves into the possibility of using distributed optical fiber sensors (DOFS) based on Optical Frequency Domain Reflectometry of Rayleigh backscattering. To be more precise, the outcomes of a series of laboratory tests are given, all of which were designed to evaluate the applicability and precision of DOFS for crack monitoring in reinforced concrete members subjected to external loading. In these tests, a polyamide-coated optical fiber sensor was glued to the surface of an unmodified reinforcement bar and covered by a layer of silicone before the beams were subjected to three-point bending. The DOFS system yielded strain readings with an accuracy comparable to that of conventional electrical foil gauges. In addition, DOFS's high spatial resolution strain profiles allowed for accurate identification of fracture development via analysis. The digital image correlation system measurements were compared to the reinforcement strain profiles, and both the crack location and the crack width evolution could be determined with errors of less than ±3 centimeters and ±20 millimeters, respectively.

Liu, Tingjin et al., (2020) In order to keep reinforced concrete (RC) buildings in good condition, crack identification at an early stage is essential. In this work, a distributed optical fiber (DOF) sensing system was applied to an RC structural part under a monotonic lateral load in a large-scale laboratory experiment using the Rayleigh Optical Frequency Domain Reflectometry (OFDR) approach. Continuous strain measurements inside the RC member are carefully implemented using an interrogator (OSI-S by Semicon) with high spatial resolution (up to 1 mm) and measurement accuracy (1 micro strain). The visible fracture mapping performed during the test and the outcome of the crack detection analysis using the observed tensile strain profiles agree quite well. This substantiates the efficacy of the optical fiber embedded inside the RC members for detecting surface fractures in concrete. Furthermore, fracture orientation and depth detection is achieved by comparing strain measurements of optical fibers at various installation points.

Deif, Amre et al., (2020) Crack detection in a simply supported reinforced concrete beam under four-point stress utilizing distributed Brillouin fiber sensors is shown in this article. In order to improve the spatial and strain resolutions of the data, a Brillouin multiple-peak fitting technique was applied. The fiber's 15 cm spatial resolution was compared to a 5 cm read-out resolution to calculate the beam's dispersed strain profile. In contrast to traditional strain reading, which only considers the peak of the Brillouin frequency spectrum, the location of the cracks was determined by pinpointing the points in the strain profile where the strain suddenly changes. Standard peak or area fitting methods would have missed the Brillouin peak for the suddenly changed strain (crack) because its amplitude is less than half of the amplitude of the maximum Brillouin peak at the maximum strain location corresponding to the average strain of the material. This is especially true for fine cracks or the initial crack build-up period.

Chakraborty, Joyraj et al., (2019) Reinforced concrete (RC) buildings are susceptible to damage from both dynamic and static loads. Slowly progressing, locally confined damage is notoriously difficult to detect with current inspection tools, especially in inaccessible parts of the superstructure. The quality and sensitivity of the embedded sensors were evaluated using a four-point bending test on the reference RC structure. This enabled evaluation of the detectability of cracking and its subsequent propagation using the integrated sensors. The ultrasonic waves are analyzed using a wide variety of techniques. Features are extracted from ultrasonic signals in order to assess global structural changes. Multiple non-destructive testing techniques were used to evaluate the RC benchmark structure's structural deterioration and get a final conclusion regarding its status. It is demonstrated that ultrasonic sensors have a detection probability of 100% for cracks, even if the damage is not in the direct path of the ultrasonic wave, and even before it is detectable by the naked eye and other approaches. The acquired findings validated the established approach for early fracture identification employing embedded and external sensors and sophisticated signal processing.

Zhang, Qinghua (2018) As a vital feature of any building or structure, reinforced concrete must be inspected for crack identification as part of ongoing structural health monitoring. As it stands, most existing crack detection technologies rely on a single technology and can only identify fractures on the surface or within a structure. In order to detect internal and surface cracks and their development in reinforced concrete structures, as well as to attempt to estimate the width of surface cracks, the authors of this paper propose a new sensing system that combines BOFDA (Brillouin optical frequency-domain analysis) and FBG (fiber Bragg grating) technology. For these tests, the author developed a novel reinforced concrete beam construction for detecting cracks under stress. Within the reinforced concrete beam, a steel skeleton is fastened to four continuously dispersed optical fibers. The beam has three FBG sensors mounted on its underside, rather close to its center. Data analysis shows that the BOFDA-distributed fiber can be used to detect internal cracking before surface cracking, and that the difference between scans can be used to judge the time of onset of internal cracking, but with a relative error in position of about 5%. In contrast, the FBG sensor can detect the cracking time of micro cracks on the lower surface in near real-time and be used to calculate the crack width. It is found experimentally that the strain data obtained by multiple groups of BOFDA monitoring can be used to predict the general location of the internal cracks, that the exact location of the surface cracks can be monitored by FBG in the medium term, and that the width of the final expansion of the cracks can be estimated using this combined technology.

Taghavipour, Saber et al., (2017) Smart Aggregate (SA) transducers have already been shown to be a viable option for monitoring RC constructions, as shown by previous research. Although they discussed the use of embedded SAs in new structural members, they gave little attention to the monitoring of preexisting RC members through the use of externally mounted SAs. For the purpose of continuous health monitoring of existing RC beams, this research proposes a mounted SA-based method. To test the effectiveness of the proposed method, SA transducers are installed as actuators and sensors on RC beams and monitored as they bend under flexural loads. In terms of the peak of power spectral density and damage indices acquired from several sensor sites, the experimental findings demonstrate that the proposed SA-based technique efficiently analyses the cracking condition of RC beams. It is also demonstrated that the suggested sensor system can record a warning signal for significant breaking.

III. RESEARCH METHODOLOGY

An experimental campaign was carried out on miniature reinforced concrete (RC) beams to examine the practicability of the suggested method. The detectability of bending fractures using an SEC array was investigated by subjecting two separate specimens to a three-point bending test. The identical loading procedure was applied to both samples. The impact of spatial distribution on damage detection and locating capabilities was investigated using two alternative configurations of SEC arrays.

Experimental Setup

Two RC beams, each measuring 60.96 cm 15.24 cm 15.24 cm (24 in 6 in 6 in), were subjected to three-point bending tests. A thin coating of commercially available epoxy (JB Kwik) was used to attach the SECs. Beam I (Figure 1(b)) was the first specimen to have an SEC A, B, and C sensor array. In Figure 1(b), SEC B can be seen installed at the midspan's base, while the other two are positioned symmetrically above it. Additional crack evaluation capacity was investigated by installing a second SEC (SEC C) on the second specimen (Beam II) at midspan but higher than SEC B with respect to the surface (Figure 1(c)).

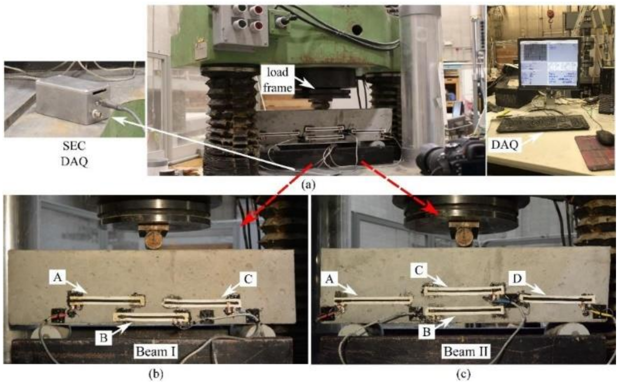

Figure 1: (a) RC beams three-points bending test setup; (b) sensor schematic of Beam I; (c) sensor schematic of Beam II

Both samples were bent at three different points using quasi-static testing equipment. Beam supports were installed at a 45.72 cm (18 in) radial distance from the centerline. Figure 1(a) shows that a roller support was put between the concrete and the load frame, where the load was applied to the top of the beams at midspan. Midspan displacement was increased from 0 to 2 mm (0.079 in to 0.078 in) using a displacement controlled method with 0.25 mm (0.0098 in) increments. A visual assessment of the beams was performed after each iteration to detect and emphasize the appearance of any new cracks or the progression of preexisting ones. Data on load, displacement, capacitance, and fracture position and size was gathered during the experiment. Measurements of force and motion were taken using the quasi-static testing machine's built-in data acquisition (DAQ) system. LabVIEW code controlled a specialized data acquisition device to get the capacitance data. Finally, a 6000 x 4000 pixel Nikon D7100 digital camera was used to keep an eye on the cracks' positions and diameters. At a distance of 1.0 m (39.37 in.), the camera was positioned perpendicular to the surface of the beam being seen. Two free programs, FFmpeg and Fiji, were used for post-processing the movies in order to measure the crack opening using the known width of the reference points.

IV. RESULTS AND DISCUSSION

Figure 2 displays the location results; whereas Figure 4 displays the fracture creation results from Beam I. Figure 4's gray dashed lines represent machine stops and starts throughout the production of incremental loads. These hiccups occurred because the testing machine's load fluctuated while it was halted. At first, there was just one fracture down the center of the beam when the displacement was small. The fracture width amplitude, normalized by averaging the crack width at the top and bottom of SEC, and the study of the load-displacement curve of the specimen all corroborated this. When the cracks open, the load-displacement curve suddenly drops, and the fracture opens up in the middle of the span. After the fracture opened, the displacement in the beam was stable up to 2 mm (Figure 3), at which point the slope decreased relative to the elastic one before crack opening. When the stiffness decreased even further, a second shear-type crack sprang up (yellow dots in Figure 3).

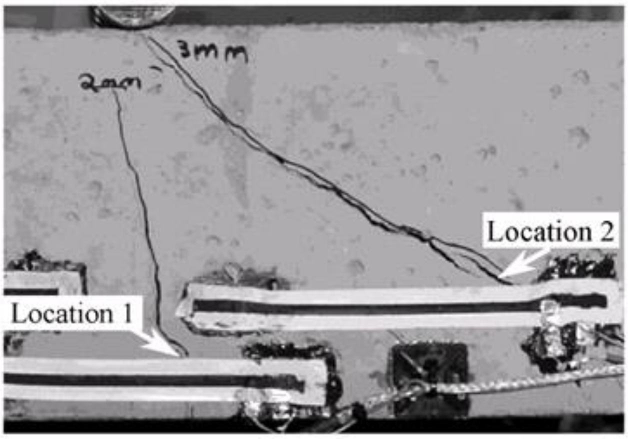

Figure 2: Crack locations of Beam I

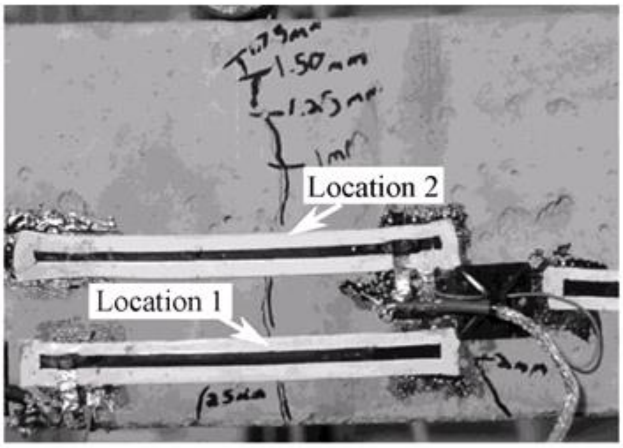

Figure 3: Crack locations of Beam II

A decrease in the size of the flexural fracture was seen with the expansion of the shear crack during this phase. As the specimen fractured along the shear crack, the lower half of the beam slid downhill, sealing the break at the beam's midpoint. The SEC network that was set up on the specimen was able to catch every nuance of this activity. Before can be seen in Figure 5, the slope of SEC A decreases just before the first flexural fracture appears. The considerable decrease in capacitance (second blue line in Figure 5) recorded by SEC B during the closure phase of the mid-span fracture corresponded to the rise in compressive strain. Because sensor C's signal seems to come from the creation of the crack via the epoxy glue (Figure 5) that connects the sensor to the beam, its results were found to be inconclusive for crack

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monitoring. Altering the direction and amount of SEC overlaps in the design of an SEC array can help overcome this difficulty.

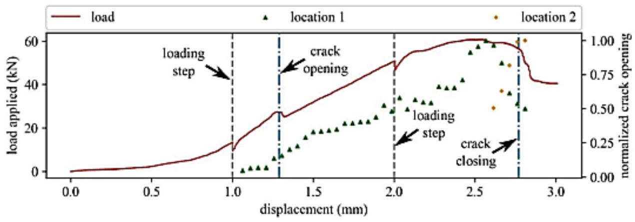

Figure 4: Load-displacement curve and normalized crack opening widths history of Beam I

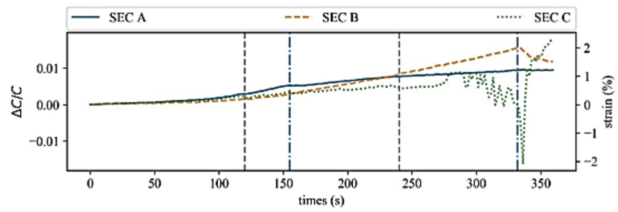

Figure 5: Capacitance change and computed strain history Beam I

Beam II data showed that fractures formed in the center of the specimen's base (Figure 4). The opening of the crack at the mid-span (termed Location 1, illustrated as green dots, and Location 2 on top of Location 1 illustrated as orange triangles in Figure 6), and the slight drop in the load-displacement curve (between the third and fourth gray dashed line from the left in Figure 5) all pointed to the formation of a single crack. Up to a 2 mm displacement, the flexural fracture spread to the compression zone, causing a loss of stiffness. Due to a shear fracture opening on the reverse side of the concrete specimen, there is a drop in stiffness of around 1.9 mm. The force is constant from that point up to 3.6 mm. The SEC network that had been set up on the specimen caught practically all of this action. Figure 7 depicts how the slope of SECs A, C, and D decline at the same time that the first flexural crack forms. The stress redistribution that accompanied the opening of the new shear fracture was captured by SEC C as a dip in its capacitance, followed by an unstable capacitance rise (Figure 7). It is important to remember that the strain value/capacitance change should be greatest in the SEC B positioned at the base of the tension zone. However, SEC B has the least capacitance variation in the launch phase. Possible explanation: installation-related strain transfer at the interface, which is difficult to quantify. When the observed capacitance changes from the other SECs are reduced, the slope of the change in SEC B for beams I and II does not vary noticeably.

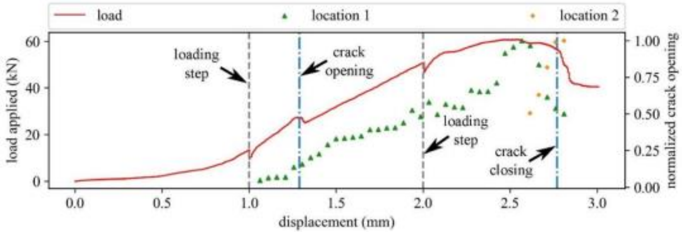

Figure 6: Load-displacement curve and normalized crack opening widths history of Beam II

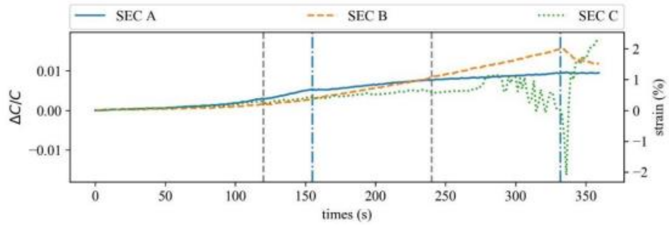

Figure 7: Capacitance change and computed strain history of Beam II

V. CONCLUSION

In conclusion, the detection and monitoring of cracks in reinforced concrete structures represent a critical area of study and application in modern civil engineering. The traditional methods, while valuable, are often limited in their scope and efficiency. The advent of non-destructive testing (NDT) techniques has revolutionized this field, offering more accurate and reliable means of identifying hidden cracks. Through the utilization of technologies like ultrasonic testing, radiographic imaging, and ground-penetrating radar, we can now penetrate concrete surfaces to reveal structural vulnerabilities that may otherwise remain concealed. Furthermore, the integration of smart sensors and advanced data analytics has ushered in a new era of precision and timeliness in crack detection and monitoring. These technologies provide real-time data on critical parameters, enabling engineers to make informed decisions and implement necessary interventions promptly. The predictive capabilities afforded by machine learning algorithms offer a valuable tool in assessing the evolution of cracks and prioritizing necessary repairs. Continuous monitoring is equally pivotal in maintaining the long-term integrity of reinforced concrete structures. By leveraging remote sensing and wireless communication, we can establish comprehensive structural health monitoring networks, transcending geographical barriers and ensuring that even hard-to-reach locations are under constant surveillance. This dynamic approach allows for a nuanced understanding of crack propagation, facilitating timely interventions before issues escalate.

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