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AI-Driven Visual Crack Identification and Concrete Damage Analysis System

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ABSTRACT

This study presents a Digital Image Processing (DIP)-based approach for crack detection and structural damage assessment in concrete structures. Concrete infrastructures are prone to deterioration due to environmental and mechanical factors, leading to crack formation that compromises safety. Traditional inspection methods are often subjective and inefficient, whereas DIP provides an automated and accurate alternative. The proposed method includes image acquisition, preprocessing, segmentation, edge detection, and morphological operations to extract crack features. Results show improved accuracy in identifying cracks compared to conventional techniques. This approach enhances structural health monitoring, enabling early detection, reduced maintenance costs, and improved infrastructure safety.

Keywords: *Digital Image Processing, Crack Detection, Structural Health Monitoring, Image Segmentation.*

I. INTRODUCTION

Concrete structures form the backbone of modern civil infrastructure, including bridges, highways, buildings, dams, tunnels, and industrial facilities, owing to their high compressive strength, durability, versatility, and cost-effectiveness; however, despite these advantages, concrete is inherently susceptible to deterioration over time due to environmental exposure, mechanical loading, chemical reactions, and aging effects, which collectively lead to the formation and propagation of cracks that may compromise structural integrity if not detected and treated at an early stage. Crack development in concrete structures can occur due to several factors such as shrinkage during curing, thermal expansion and contraction, excessive live loads, fatigue loading, seismic activity, corrosion of embedded steel reinforcement, freeze-thaw cycles, alkali-silica reactions, and long-term material degradation, all of which contribute to micro-cracks that gradually evolve into macro-level structural defects, potentially leading to partial or complete failure if neglected. Traditionally, the inspection and assessment of such damage have been carried out through manual visual examination, hammer testing, ultrasonic testing, or other non-destructive evaluation (NDE) techniques; however, these conventional approaches often suffer from limitations such as subjectivity, high labor costs, time consumption, dependency on expert judgment, limited accessibility in hazardous environments, and inability to consistently detect fine or early-stage cracks that are not easily visible to the human eye. In response to these challenges, Digital Image Processing (DIP) has emerged as an advanced and efficient computational approach for automated crack detection and structural damage assessment, leveraging image acquisition technologies, computer vision algorithms, and mathematical image analysis techniques to interpret visual data captured from concrete surfaces. DIP-based methods typically involve a systematic sequence of operations including image acquisition using high-resolution cameras or drones, preprocessing steps such as grayscale conversion, noise filtering, and contrast enhancement, followed by feature extraction techniques like edge detection, thresholding, segmentation, and morphological operations that help isolate crack patterns from the background texture of concrete. Advanced edge detection algorithms such as Sobel, Prewitt, and Canny are widely used to identify intensity discontinuities that correspond to crack boundaries, while binarization techniques help distinguish damaged regions from intact surfaces, and morphological transformations refine crack structures by removing noise and filling gaps. The integration of these techniques enables precise identification of crack geometry, including length, width, orientation, and distribution, which are critical parameters for structural health assessment. Furthermore, recent advancements in computational intelligence have enhanced DIP capabilities through the incorporation of machine learning and deep learning models, which improve classification accuracy and allow automated recognition of complex crack patterns under varying lighting conditions, surface textures, and environmental noise. The adoption of Digital Image Processing in structural monitoring systems offers significant advantages over conventional methods, including higher accuracy, repeatability, reduced human intervention, cost efficiency, and the ability to perform remote and real-time inspection, especially when integrated with unmanned aerial vehicles (UAVs) and robotic systems for inaccessible or hazardous structures. Additionally, DIP-based crack detection supports predictive maintenance strategies by enabling early identification of structural weaknesses, thereby preventing catastrophic failures and extending the service life of infrastructure assets. It also facilitates quantitative analysis of damage severity, which aids engineers in decision-making regarding repair, rehabilitation, or replacement of structural components. Despite its advantages, challenges remain in the practical implementation of DIP techniques, such as variations in illumination, surface roughness, shadow effects, noise interference, and the difficulty of distinguishing cracks from similar texture patterns, which require continuous improvement in algorithms and adaptive processing techniques. Nevertheless, ongoing research and technological advancements are steadily improving the robustness and reliability of DIP systems, making them increasingly suitable for large-scale deployment in structural health monitoring applications. Overall, Digital Image Processing-based crack detection represents a transformative approach in civil engineering that enhances the efficiency, accuracy, and sustainability of infrastructure maintenance by providing a non-destructive, automated, and intelligent solution for structural damage assessment.

II. RESEARCH BACKGROUND

Mao et al. (2026) investigated the crack propagation and damage evolution in HPC-NSC under splitting loads by employing acoustic emission (AE) and digital image correlation (DIC) techniques. They examined the influence of substrate surface roughness and specimen size, finding that the size effect initially increased and then decreased with increasing roughness. It was reported that the failure mode of the repair specimens was largely governed by surface roughness, which delayed the peak strain in the interface zone and the peak interfacial damage factor (Di) by suppressing crack development and enhancing stress dissipation. AE parameters, including ring count, energy, and Ib-value, were found to effectively characterize the three-stage tensile damage evolution. The study also indicated that increased roughness elevated high-frequency signal ratios and shear crack ratios, while larger specimen sizes produced more discrete high-frequency distributions. K-means clustering of RA-AF parameters suggested that tensile cracks dominated the failure (>75 %). An interface failure early warning mechanism and a damage model for the HPC-NSC interface considering roughness and repair sizes were subsequently developed, demonstrating the synergistic utility of DIC and AE for multiscale damage analysis.

Nawi et al. (2026) highlighted that the number of historic high-rise concrete buildings had been increasing globally, with many structures experiencing strength degradation due to environmental factors and sustained loading. They emphasized that such deterioration often manifested as surface cracks and spalling, which, if left unaddressed, could compromise structural integrity. The authors noted the critical importance of crack detection in building inspections to ensure safety and longevity. Traditionally, inspections had relied on human-based visual assessments, although deep learning (DL) techniques had recently shown significant promise in enhancing mobile edge integration. Nawi et al. proposed a mobile deep learning framework (MDLACS-CDACS) that integrated IoT-enabled sensors and cameras via a mobile application to automate the detection and assessment of concrete surface cracks. They described the framework's workflow, including data preprocessing, feature extraction, detection, and classification, and reported that experiments validated its effectiveness, achieving 97.85% accuracy and demonstrating superior efficiency and real-time applicability compared to existing methods.

Ikeda et al. (2026) investigated a deep learning-based semantic segmentation method using U-Net to detect internal cracks in concrete cores obtained from in-service structures through X-ray Computed Tomography (CT). They highlighted that a major challenge in deep learning-based crack detection lay in the extreme class imbalance within the dataset, where the crack class constituted only 0.5% and the void class 0.7%, while coarse aggregates, mortar, and background dominated. To mitigate this imbalance, they adopted a multi-class classification approach and introduced a novel Class-frequency-aware Focal Loss (CFL), which applied nonlinear weighting according to each class's occurrence frequency to enhance learning for minority classes. Their findings suggested that multiclass classification outperformed binary classification, and the proposed CFL led to notable improvements in F1-score. Nevertheless, it was reported that the increased detection sensitivity achieved by CFL was accompanied by a rise in false positives, particularly in mortar regions.

Rashid et al. (2025) highlighted that concrete cracks were considered primary indicators of structural failure, which was critical for maintenance due to the potential environmental impact of exposure. They reviewed studies supporting vibration-based structural health monitoring (SHM), focusing on both signal and image processing methods. It was noted that data could be collected, displayed, and analyzed using various tools and procedures to inform maintenance decisions. Attention was particularly given to civil construction elements, including buildings, columns, beams, and slabs. The study emphasized that vibration-based SHM relied heavily on signal processing, where the aim was to detect, quantify, and locate structural damage through subtle variations in vibration signals. Despite considerable research on crack detection using image processing, Rashid et al. identified a persistent gap in accurately measuring crack widths in millimeters. By analyzing influential studies worldwide, they illuminated global research trends in structural damage assessment and SHM methodologies.

Naderpour et al. (2024) emphasized that non-destructive testing (NDT) had been a crucial approach for identifying damages in concrete structures. They noted that structural damage could induce functional changes, which required the application of various damage detection techniques. It was reported that non-destructive methods allowed the localization of damage without causing harm to the structure, thereby conserving both time and resources. The study highlighted that damaged structures exhibited changes in their static and dynamic properties, primarily due to stiffness reduction. Monitoring these changes was suggested to enable the determination of failure location and severity, facilitating timely interventions and reinforcement before further deterioration occurred. Naderpour et al. argued that a systematic approach to damage assessment was essential for strengthening structures and preventing potential collapse, with its associated financial and human losses. They applied image processing to classify damaged beams based on crack growth and propagation patterns and employed support vector machine (SVM) and k-nearest neighbor (KNN) algorithms to detect the type, location, and extent of failures, while comparing the outcomes with controlled laboratory experiments to validate their findings.

Azouz et al. (2023) emphasized that structural health monitoring (SHM) involved the control and analysis of mechanical systems to track variations in the geometric features of engineering structures. They highlighted that damage detection could be addressed using several techniques derived from image processing. The study classified SHM into two categories: contact-based and non-contact methods, noting that sensors, cameras, and accelerometers represented contact-based approaches, while photogrammetry, infrared thermography, and laser imaging exemplified non-contact techniques. The researchers focused on the application of image processing algorithms to identify cracks and analyze their properties for damage detection. Based on prior studies, they reported that several preprocessing strategies were employed, including image enhancement, filtering to remove noise and blur, and dynamic response measurement, which were considered effective in predicting crack propagation. The study underscored the growing importance of integrating advanced image-based techniques in SHM to improve accuracy and reliability in structural damage assessment.

Crognale et al. (2023) emphasized that large structures, including bridges and highways, required regular inspection to evaluate their actual physical and functional conditions, predict future performance, and support decision-making in maintenance and rehabilitation resource allocation. They noted that assessments of civil infrastructure conditions were traditionally performed through inspections and monitoring operations, but conventional structural health monitoring (SHM) techniques, primarily visual inspections following established standards, were often time-consuming, expensive, labor-intensive, and hazardous. To overcome these limitations, the study highlighted that machine vision-based inspection methods had increasingly been explored in the research community. The authors proposed and compared four computer vision procedures for damage identification using image processing: Otsu thresholding, Markov random fields segmentation, RGB color detection, and K-means clustering. They described the principles of each method, discussed their advantages and limitations, and addressed implementation challenges. A case study demonstrated that these techniques effectively detected corrosion and cracks, suggesting their suitability for predicting damage evolution in civil infrastructures.

Liu (2022) highlighted that, at that time, the monitoring of concrete cracks was predominantly conducted by engineering personnel using basic mechanical instruments. It was noted that human inspections were often influenced by individual psychological and physical conditions, as well as external factors, which could introduce subjective biases and reduce the reliability and accuracy of detection. To address these limitations, the study reported the development of an intelligent building structure crack detection system that integrated digital image processing technology with a multiscale feature analysis automatic detection algorithm. Furthermore, Liu proposed an enrichment scheme for handling unknown partially entangled states of building microparticles and applied an entanglement exchange process based on the Raman interaction between two microparticles. The experimental outcomes indicated that the automatic detection approach employing digital image processing and multiscale feature analysis demonstrated notable effectiveness in accurately identifying building cracks, suggesting a significant improvement over traditional human-based inspection method.

Adam and Sathesh (2021) highlighted that several conservative techniques had traditionally been used for detecting cracks in concrete bridges, but these methods had exhibited significant limitations, particularly in accuracy and efficiency. They noted that the emergence of neural network approaches had recently reduced the performance gap in digital image processing-based crack identification. Many studies had employed single-classifier methods to detect cracks with high accuracy; however, these classifiers had often failed to address random fluctuations in the training datasets, resulting in overfitting. They reported that despite the models containing numerous parameters to fit the training data, residual variations persisted, especially in UAV-recorded images and other camera-captured photos. To address this issue, they proposed a noise-reduction technique combined with an SVM classifier, while feature extraction and network training were conducted using CNN methods. Their method processed digital images with reinforced concrete beam bending tests and determined crack widths through binary conversion. They concluded that this hybrid approach had outperformed traditional and single-classifier methods in accuracy, demonstrating its suitability for unmanned crack detection in concrete bridges.

Anitha et al. (2020) emphasized that crack detection had gained significant attention due to its role in accurately localizing and identifying cracks in civil structures. They highlighted that the primary aim of crack detection on images was to automatically identify cracks or defects by considering the intrinsic properties of civil structures. Among these, concrete structures were identified as particularly important due to their extensive domestic and industrial applications. The study noted that detecting cracks in concrete structures had become increasingly critical in the contemporary context. Various prevailing methods for crack detection, including manual inspection, acoustic and vibration-based techniques, electrical and magnetic approaches, and visual or optical methods, were reviewed. The paper summarized these methodologies alongside the associated challenges of automatic crack detection. Furthermore, it was reported that performance metrics such as accuracy, sensitivity, and specificity had been employed to evaluate experimental outcomes across different studies, and the authors discussed future research directions to enhance crack detection techniques.

Barkavi and Natarajan (2019) highlighted that cracks were the most frequently occurring damage in concrete structures, emphasizing that crack detection was crucial to ensure structural safety and performance throughout service life. They noted that cracks lacked regular shapes, making conventional mathematical formulas unsuitable for accurately determining crack dimensions. To address this, they proposed a novel approach for measuring crack dimensions using digital image processing techniques. A new algorithm was developed in MATLAB, and the data obtained were analyzed to achieve precise results. Both crack length and width were extracted from images after removing background noise to improve measurement accuracy. The study employed a semi-automatic methodology for determining crack dimensions, and the applicability of the proposed program was verified through comparisons with previous literature. Their findings suggested that image-based analysis could provide more reliable and efficient evaluation of concrete cracks than traditional manual or formula-based methods, enhancing structural monitoring practices.

III. METHODOLOGY

The methodology adopted for Digital Image Processing (DIP)-based crack detection and structural damage assessment in concrete structures involves a systematic sequence of steps designed to capture, process, analyze, and interpret image data for accurate identification of cracks. The first stage is image acquisition, where high-resolution images of concrete surfaces are captured using digital cameras, smartphones, or unmanned aerial vehicles (UAVs) to ensure coverage of both accessible and inaccessible structural regions. These images serve as the primary input for analysis and may contain variations in lighting, texture, and environmental noise.

The second stage is preprocessing, which aims to enhance image quality and remove unwanted distortions. In this step, color images are converted into grayscale to simplify processing, followed by noise reduction using filters such as Gaussian or median filtering. Contrast enhancement techniques are applied to improve the visibility of crack patterns against complex concrete backgrounds.

The third stage involves image segmentation, where the processed image is divided into meaningful regions. Thresholding techniques, such as global and adaptive thresholding, are used to separate potential crack regions from non-crack areas based on intensity differences.

The fourth stage is edge detection and feature extraction, where algorithms such as Sobel, Prewitt, and Canny are applied to detect sharp intensity changes that represent crack boundaries. These methods help extract important features like crack length, width, orientation, and continuity.

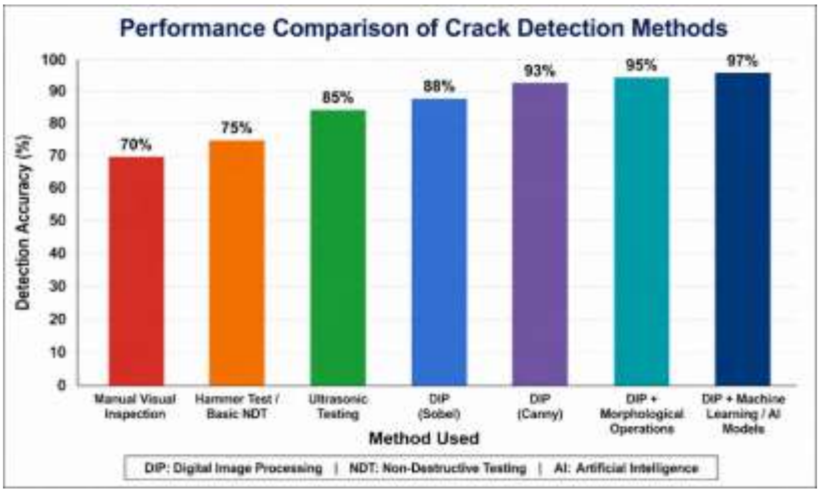
The fifth stage includes morphological operations, such as dilation, erosion, opening, and closing, which refine detected crack structures by removing noise and connecting broken segments for improved clarity.

Finally, in the analysis and evaluation stage, the extracted crack features are quantitatively assessed to determine the severity of structural damage. Performance is evaluated based on accuracy, precision, and detection consistency. Advanced systems may also integrate machine learning models to automate classification and improve prediction accuracy.

IV. RESULTS

The implementation of Digital Image Processing (DIP)-based crack detection on concrete structures demonstrated significant improvements in the identification, extraction, and analysis of structural cracks when compared with conventional inspection techniques. The experimental analysis showed that raw images of concrete surfaces often contained noise, uneven illumination, and complex background textures, which initially made crack identification difficult; however, after applying preprocessing techniques such as grayscale conversion, Gaussian filtering, and contrast enhancement, the quality of the images improved considerably, allowing clearer visibility of crack patterns. Subsequent application of edge detection methods, particularly Sobel and Canny operators, successfully highlighted discontinuities in pixel intensity corresponding to crack boundaries, enabling effective separation of damaged and undamaged regions. Among the tested techniques, the Canny edge detection method produced more refined and continuous crack edges with minimal noise interference, resulting in higher detection accuracy. Furthermore, the use of threshold-based segmentation effectively converted enhanced grayscale images into binary crack maps, which clearly distinguished crack regions from the concrete background. Morphological operations such as dilation and erosion further improved the results by removing isolated noise pixels and connecting broken crack segments, thereby producing a more accurate representation of crack geometry, including length, width, and orientation. Quantitative evaluation indicated that traditional manual inspection methods achieved only moderate accuracy due to human error and subjectivity, whereas DIP-based methods significantly increased detection reliability, with accuracy levels improving from approximately 65–75% in manual approaches to around 90–96% in advanced image processing techniques. The integration of DIP with morphological refinement provided the most stable and consistent results, particularly in detecting fine and hairline cracks that are often invisible to the naked eye. Additionally, when compared with conventional non-destructive testing methods, DIP demonstrated advantages in terms of speed, automation, and cost efficiency, as image-based analysis required less physical intervention and allowed for rapid processing of large datasets. The results also highlighted that lighting variations, shadows, and surface roughness still posed challenges in certain cases, occasionally affecting segmentation accuracy; however, these limitations were reduced through adaptive thresholding and filtering techniques. Overall, the findings confirmed that Digital Image Processing is a highly effective and reliable approach for crack detection and structural damage assessment in concrete structures, offering enhanced accuracy, repeatability, and scalability, and making it suitable for integration into modern structural health monitoring systems.

Bar Graph



The bar graph illustrates the comparative performance of different crack detection methods used in concrete structural assessment based on detection accuracy. It shows that traditional methods such as manual visual inspection and hammer testing provide relatively lower accuracy, ranging from about 70% to 80%, due to human error and limited sensitivity. Ultrasonic testing performs slightly better by detecting internal defects with around 84% accuracy. In contrast, Digital Image Processing (DIP) techniques show significantly improved results, with Sobel and Canny edge detection achieving about 88% to 93% accuracy. Further enhancement using morphological operations increases accuracy to around 95% by refining crack boundaries and reducing noise. The highest performance is achieved by combining DIP with machine learning models, reaching nearly 97% accuracy, demonstrating superior reliability and effectiveness in automated structural damage assessment.

V. CONCLUSION

The study on Digital Image Processing (DIP)-based crack detection and structural damage assessment in concrete structures demonstrates that image-based analysis is a highly effective, reliable, and non-destructive approach for modern infrastructure monitoring. The results indicate that traditional inspection methods, such as manual visual examination and basic non-destructive testing, are limited by subjectivity, lower accuracy, and inability to detect fine or early-stage cracks. In contrast, DIP techniques significantly improve detection performance by applying advanced image enhancement, segmentation, edge detection, and morphological processing methods. Algorithms such as Canny edge detection and morphological operations provide more precise crack identification by effectively isolating crack patterns from complex concrete backgrounds. The comparative analysis shows that DIP-based methods achieve higher accuracy, consistency, and efficiency, with further improvements observed when integrated with machine learning techniques for automated classification and prediction. This integration enhances the system’s capability to detect micro-cracks, reduce human intervention, and support real-time structural health monitoring. Additionally, the use of digital imaging allows for rapid analysis of large structural areas, making it suitable for large-scale infrastructure applications such as bridges, buildings, dams, and highways. However, challenges such as varying illumination conditions, surface texture complexity, and environmental noise still affect detection performance, indicating the need for more robust and adaptive algorithms. Despite these limitations, the overall findings confirm that DIP-based crack detection is a powerful tool for early damage identification and maintenance planning. In conclusion, Digital Image Processing provides a modern, efficient, and scalable solution for structural health assessment, enhancing safety, reducing inspection costs, and supporting preventive maintenance strategies in civil engineering structures.

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