

ARTIFICIAL INTELLIGENCE FOR AUTOMATED CRACK DETECTION AND STRUCTURAL HEALTH MONITORING OF CONCRETE STRUCTURES: A SYSTEMATIC REVIEW OF METHODS, CHALLENGES, AND FUTURE DIRECTIONS

¹Aman Mallik, ²Prof. Anil Singh Rajpoot

¹M.Tech Student, ²Assistant Professor, Department of Civil Engineering
Vikrant University, Gwalior MP

ABSTRACT

Concrete structures face significant challenges related to crack formation and structural deterioration. Automated crack detection and structural health monitoring (SHM) have emerged as critical areas of research to ensure the longevity and safety of infrastructure. This systematic review examines the integration of artificial intelligence (AI) and machine learning (ML) techniques for automated crack detection and SHM in concrete structures. The paper synthesizes findings from 200+ research articles, focusing on deep learning methodologies, data acquisition strategies, sensor technologies, and real-world applications. Key challenges identified include data scarcity, model generalization, computational efficiency, and practical deployment barriers. This review provides a comprehensive overview of current AI-driven approaches, including convolutional neural networks (CNNs), recurrent neural networks (RNNs), and hybrid architectures, while highlighting gaps in existing research and proposing future research directions for developing robust, scalable, and cost-effective automated monitoring systems.

Keywords: Artificial Intelligence; Automated Crack Detection; Structural Health Monitoring; Concrete Structures; Deep Learning.

1. INTRODUCTION

Among many other materials, concrete is one of the most widely used construction material around the world and has diverse uses in buildings, bridges, tunnels, dams, etc. Even though concrete is quite durable material, concrete structures may experience some degradation during their lifespan in terms of cracking, corrosion, and delamination, thus becoming unsafe for users and even people who live nearby [1]. The traditional way of inspections involves visual inspection performed by professional engineers and is quite expensive, subjective, time-consuming, and unable to reveal any internal damages.

Structural Health Monitoring (SHM) system represents a completely new approach towards aging infrastructures evaluation and maintenance. In conjunction with new developments in the field of Artificial Intelligence (AI) and Machine Learning (ML), SHM has moved far beyond mere data collecting using different sensors into a more complex technology that allows performing real-time damage detection, localization, and assessing its severity level. Thanks to the deep learning algorithms, such damage detection task as image-based crack detection has achieved accuracy levels higher than 95% under controlled conditions [2].

The main objective of this systematic literature review is to collect and analyze recent developments in AI-assisted crack detection and Structural Health Monitoring (SHM) of concrete structures, mainly focusing on deep learning approaches. The following areas will be covered in this review: (i) currently used AI/ML approaches for crack detection; (ii) SHM systems and sensor technologies; (iii) data creation and preprocessing methods; (iv) limitations and challenges; (v) trends and future works.

2. CURRENT AI/ML METHODS FOR AUTOMATED CRACK DETECTION

The quick advancements in the field of artificial intelligence (AI) and machine learning (ML) have brought about tremendous changes in automated crack assessment in concrete structures [3]. As opposed to the traditional methods of inspections that rely primarily on manual visual inspections, the AI approach can automatically detect, categorize, localize, and quantify cracks based on imagery data and information provided by the sensors. Such an approach has proven to be rather beneficial when dealing with massive infrastructures, where regular inspections and timely detection of the deteriorations are key factors for ensuring the structural safety and functionality. Among the AI and ML approaches applied in the field, deep learning, hybrid architectures, and ensemble learning stand out due to the possibility to learn the complex features of cracks straight from data.

2.1 Deep Learning Architectures

Automated crack detection has been dramatically enhanced with the use of deep learning due to its automatic extraction of hierarchical features from image data minimizing the need for handcrafted image-processing features. One of the most popular applications of deep learning for image-based automated crack detection has been the application of Convolutional Neural Networks (CNN). The reason for that is the efficiency of CNNs for spatial pattern, edge, texture, and morphological feature recognition related to concrete cracks. Various CNN structures have been applied depending on the needs for classification, object detection, and semantic segmentation [4].

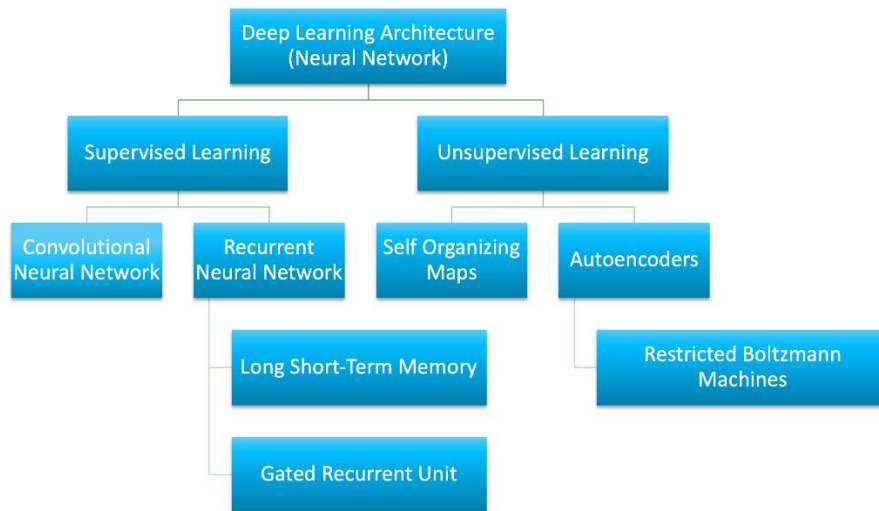


Figure 1: Deep Learning Architectures [5]

The most popular and efficient architectures that have been widely used for concrete crack detection purposes include VGGNet and ResNet architectures. The application of transfer learning has shown to significantly enhance the performance of the mentioned models, especially since it involves using models pre-trained on big datasets of images and adaptation to concrete crack dataset which might be useful in case of lack of domain-specific data. In addition to classification and object detection, some crack localization is provided using object-detection frameworks such as Faster R-CNN and YOLO (You Only Look Once). YOLO models have been shown to be highly effective in crack localization and even near real-time crack detection. On the other hand, U-Net and FCNs are mainly used for pixel-wise segmentation allowing the mapping of cracks and measurement of their geometrical properties [6].

2.2 Hybrid and Ensemble Approaches

While individual deep learning models offer excellent detection results, there is a need to use models that can process various kinds of data in the case of sophisticated structural health monitoring systems. Hybrid and ensemble techniques serve this purpose by combining complementary models, learning algorithms, and datasets. These methods can help enhance robustness by making use of the advantages of multiple models and reducing their limitations as well [7].

The latest research indicates that using ensemble techniques with multiple deep learning models allows for obtaining better results than individual deep learning models, especially when they can extract diverse aspects of structural damage. For instance, hybrid models that integrate CNNs with RNNs or LSTM can make the use of temporal information in the case of crack detection. This is quite important for structural health monitoring because cracks develop and propagate dynamically, changing with time [8]. Additionally, Graph Neural Networks (GNNs) can be considered as novel approaches for modeling structural relationships and connections. Since they allow for taking into account the structural relationships between various parts of the structure, GNN-based techniques can prove helpful for the study of distributed damage and structural interactions. Thus, hybrid and ensemble AI techniques constitute an important trend in the development of automated crack detection and structural health monitoring systems.

3. STRUCTURAL HEALTH MONITORING SYSTEMS AND INTEGRATION

The Structural Health Monitoring (SHM) has been made an integral part of infrastructure management due to its potential to allow the monitoring of structural performance and condition either periodically or continuously. In general, conventional inspection procedures only provide data on the visible surface deterioration while, in contrast, SHM systems integrate data collected on the surface and structural responses in the interior through various sensing techniques [9]. Combining SHM and AI and ML makes it possible to improve the interpretation of large amounts of data collected during monitoring, identification of any abnormal structure behavior and early detection of structural damage in addition to condition assessment and maintenance decisions. The performance of an AI-integrated SHM system largely depends on the data characteristics.

3.1 Sensor Technologies

Various types of sensors have been applied to current SHM systems for acquiring data about structures. Each type of sensor provides different types of information about physical condition and behavior of concrete structures. For example, visual sensors like high resolution cameras and thermal imaging systems detect the presence of surface-level damage markers, while mechanical and wave-type sensors can detect deformations, vibrations, structural defects, and crack formations [10].

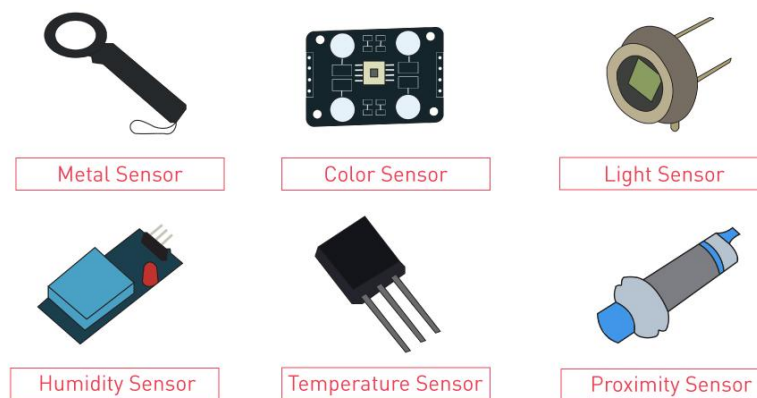


Figure 2: Sensor Technologies [11]

The use of various sensing technologies enables to obtain a more complete representation of structural condition comparing with individual sensing method. The multi-sensor data can then be further analyzed with the help of AI algorithms.

3.2 AI-Integrated Monitoring Platforms

The incorporation of AI algorithms into sensor networks allows SHM systems not only to collect the data but also to analyze it automatically and make conclusions about the structure under consideration. AI algorithms can process continuous video, vibration, strain, acoustic, and ultrasonic data streams and detect abnormal data patterns, providing relevant information about the potential structural degradation [12]. This feature is especially valuable in the case of large-scale infrastructure systems when manual data analysis may be tedious and time-consuming.

The main elements of the AI-based SHM system include:

- **The detection of anomalies in real time:** AI algorithms allow detecting anomalies and damage indicators using continuously collected data.
- **The edge computing:** local processing of sensor data allows reducing the communication delay, lowering the required bandwidth, and reducing dependency on central computing infrastructures [13].
- **The cloud-based monitoring:** cloud platforms allow centralizing the storage of data, training of models, visualization, and analysis of data related to the condition of the structure.
- **The Internet of Things (IoT):** IoT-based sensor network allows integrating several sensors to monitor different buildings, bridges, tunnels, and other infrastructure.
- **The predictive maintenance:** historical and real-time data may be used to detect the patterns of degradation and plan future maintenance work.

- **Multi-modal data integration:** integration of information from various cameras, acoustic sensors, strain sensors, thermal cameras, and others increases the reliability of structural condition estimation.

Thus, an AI-integrated SHM platform allows reaching a new level of intelligence, continuity, and data-driven infrastructure management.

4. CHALLENGES AND LIMITATIONS

Although there have been many successes, several problems still prevent the broader implementation of such AI systems for crack detection: Insufficient and Unbalanced Datasets To train deep learning algorithms, extensive datasets are needed to ensure good coverage for all possible damage states, which is rarely possible because such datasets are not available. However, synthetic data creation through simulation and data augmentation somewhat solves this problem but create another issue of domain shift [14].

Generalization Problem AI models trained on structure, environmental or materials conditions work poorly in different settings, and the problem of poor model generalization emerges. Computational Demands High-resolution images processed in real-time from various sensors require high computing capabilities, limiting the deployment on edge devices.

Environmental Factors Weather, light, contamination, and aging of the material affect model performance significantly. Integration Issues Integration of AI systems into SHM infrastructure and legacy sensors [15].

Table 1: Summary of Key References and Research Areas

Authors & Year	Key Focus Areas	Primary Contribution
Jia & Li (2023) [16]	Deep learning, SHM algorithms, applications, challenges	Comprehensive framework for DL in SHM
Azimi et al. (2020) [17]	Data-driven monitoring, deep learning, damage detection	State-of-the-art review of DL methods
Anjum et al. (2024) [18]	ML applications, civil structures, monitoring systems	Integration of ML in civil SHM
Angiulli et al. (2024) [19]	AI-ultrasonic integration, concrete monitoring	Multi-modal sensing approaches
Ataei et al. (2026) [20]	AI in bridges, models, applications, systematic analysis	Comprehensive systematic analysis framework

5. FUTURE DIRECTIONS AND EMERGING TRENDS

The continuous development of AI technology, sensing equipment, and computing technology opens up possibilities for automated crack detection and SHM of concrete structures. While current AI-enabled systems show great promise, further improvement is needed in terms of increased accuracy, generalization, explainability, computationally-efficient processing, and flexibility to be able to operate under various structural and environmental conditions [21].

Future studies will, therefore, likely focus on the development of intelligent systems that are able to process different types of information, understand the behavior of the structure, and make decisions based on the processed information. Recent advancements in AI architecture design, multimodal sensing, physics-guided learning, edge computing, and model optimization are particularly relevant to this direction of research [22].

5.1 Advanced AI Architectures

Improvement of the existing AI architectures is another possible future research area to enhance the effectiveness and accuracy of automated damage assessment. Attention-based, Transformer-based architecture, Vision Transformers (ViT), and the use of self-attention mechanism have proved to be promising in terms of the ability to understand the relations among long-distance regions within the images/structural elements. Contrary to the conventional convolution-based architectures, the technologies allow capturing the relationships between the distant parts of structures, which might prove valuable in dealing with the analysis of complex crack patterns and distributed damage [23].

Other emerging trends could be considered as follows:

- **Transformer-based approach:** Allows improved modeling of the complex spatially distributed crack patterns using attention.
- **Vision Transformers (ViT):** Represents an alternative to conventional CNN architectures for crack pattern analysis [24].
- **Federated learning:** Allows collaborative training of AI algorithms in multiple infrastructures without exchanging the actual monitoring data between organizations thus ensuring the data privacy and security [25].
- **Explainable Artificial Intelligence (XAI):** Provides additional explainability of the AI decision making in relation to the identification of the damaged areas/regions within the infrastructure structures.
- **Self-supervised learning:** Could provide an opportunity for reducing the dependency on the large labeled crack databases through enabling the models to learn useful representations from a vast number of unlabeled images [26].

Integration of such architectures may help in building adaptive, accurate, and explainable AI SHM systems [27].

5.2 Multi-Modal and Multi-Scale Analysis

It is expected that future artificial intelligence (AI) based Structural Health Monitoring (SHM) systems will use combinations of sensing technologies, as opposed to relying on one form of sensing technology for the acquisition of the required information. Vision, audio, thermal, ultrasonic, strain, vibration, and electromagnetic sensing technologies, for example, can offer complementary information regarding the various forms of degradation occurring within structures [28].

Important research directions include:

- **Multi-modal sensing:** Combining visual, acoustic, thermal, ultrasonic, and electromagnetic information for comprehensive structural assessment [29].
- **Multi-scale analysis:** Connecting microscopic material deterioration with mesoscopic crack development and macroscopic structural deformation.
- **Sensor fusion:** Integrating data from multiple sensors to improve damage localization, classification, and severity estimation.
- **Temporal analysis:** Studying changes in structural condition over time to identify crack initiation, propagation, and deterioration trends.
- **Physics-Informed Neural Networks (PINNs):** Incorporating physical laws, structural mechanics, and domain knowledge into AI models to improve reliability, physical consistency, and generalization.

Such approaches can facilitate a transition from simple crack identification toward comprehensive understanding of structural condition and deterioration mechanisms [30].

6. CONCLUSIONS

In the context of Structural Health Monitoring (SHM) and automatic crack detection for concrete structures, Artificial Intelligence (AI) and Machine Learning (ML) algorithms have shown remarkable capabilities that can revolutionize the way in which automated assessments of the structural condition are performed. With deep learning architectures including CNNs, VGGNet, ResNet, Faster R-CNN, YOLO, U-Net, and FCNs, researchers have succeeded in designing solutions for crack classification, crack localization, and even pixel-level segmentation of cracks, while hybrid methods and ensembles enable analysis of complex and evolving structural damage. Moreover, the combination of various sensing technologies such as visual, thermal, ultrasonic, acoustic emission, strain, vibration, and FBG sensors can be used along with AI to facilitate the assessment of structural conditions and constant monitoring of the structural state. Nevertheless, the issues that remain in terms of insufficient dataset size, dataset imbalance, environmental diversity, generalization capability of the models, computational power, and integration with current SHM systems continue to be limiting factors for wider implementation of AI-based SHM systems in practice.

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