Vibrational-based damage localization of bending frames using CNNs

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KEYWORDS

Structural Damage Detection, Machine Learning, Deep Learning, Structural Health Monitoring, Convolutional Neural Networks

Introduction

Structural damages in civil engineering structures are inevitable due to environmental, operational, and human factors. Given the progressive nature of damage, regular inspections are essential to enhance serviceability, prevent reduced lifespan, and ensure safety. Structural damage detection methods are broadly categorized into global and local approaches. Among global methods, vibration-based techniques have gained significant attention due to their ability to identify, quantify, and localize damages using acceleration signals [1-3]. Traditional machine learning methods require manual extraction of damage-sensitive features from time-series data, making them challenging and time-consuming [4]. In recent years, the advent of deep learning has revolutionized the field by enabling automatic feature extraction and classification [5, 6]. However, deep architectures demand high computational resources and extensive data, making them unsuitable for real-time applications [7, 8].

To address these challenges, this study proposes a novel approach based on two-dimensional Convolutional Neural Networks (2-D CNNs) that integrates feature extraction and classification into a single framework. Unlike deep networks, our method uses shallow CNNs, optimized for individual structural elements, to achieve high accuracy with reduced computational costs. The elimination of preprocessing steps, combined with the use of raw acceleration signals for damage detection, ensures the method's suitability for real-time structural health monitoring.

Proposed Method

Building on the need for efficient damage detection, the proposed framework employs a decentralized architecture where a separate CNN is assigned to monitor the health of each structural element. This approach not only reduces computational complexity but also facilitates simultaneous damage detection across multiple elements. Each CNN comprises two convolutional layers for feature extraction and a fully connected layer for classification. These layers are carefully optimized to strike a balance between accuracy and processing speed.

A distinctive aspect of this methodology is the use of three accelerometers for each structural element. By incorporating data from multiple sensors, the method reduces the volume of training data required while maintaining high accuracy [9, 10]. Furthermore, raw acceleration signals from a large-scale laboratory structure are directly fed into the CNNs, bypassing traditional preprocessing steps. During the training phase, balanced datasets are created by equalizing the number of healthy and damaged samples for each element. This ensures the robustness and reliability of the CNNs in diverse conditions.

Validation and Results

To evaluate the efficacy of the proposed method, validation was conducted using data from the Qatar University Grandstand Simulator (QUGS), a large-scale experimental steel structure [11]. Damage scenarios were simulated by loosening bolts at joint connections, and dynamic responses were recorded using 30 accelerometers. The study encompassed 13 scenarios, including single and multiple damages, providing a comprehensive testbed for the framework.

The results revealed an impressive average accuracy of 99.8% on training data and 99.6% on validation data. The CNNs successfully localized damages in all scenarios, achieving probabilities greater than 98.4% for damaged joints while maintaining probabilities below 3.1% for healthy joints. Additionally, the method's superior performance in scenarios with proximal sensor placement underscored the importance of strategic sensor positioning.

Further analysis was conducted to investigate the impact of sensor placement on detection accuracy. Two scenarios were evaluated using data from sensors positioned far from the damaged locations. For Joint 1, data from sensors near Joint 10 were used, and for Joint 10, data from distant sensors near Joint 1 were employed. The results showed a decrease in detection accuracy compared to scenarios where sensors were proximal to the damage. Specifically, validation accuracy dropped to 94.8% and 93.9% for Joints 1 and 10, respectively. Despite this decline, the method still demonstrated acceptable performance, confirming its robustness even under less favorable conditions. These findings emphasize the advantage of selecting sensors closer to the damage for optimal results.

In terms of computational efficiency, the method processed each second of input signals in approximately 2 milliseconds, meeting the stringent requirements for real-time processing [10]. The shallow architecture allowed the system to operate efficiently on standard computing hardware, thereby enhancing its accessibility and scalability for practical applications.

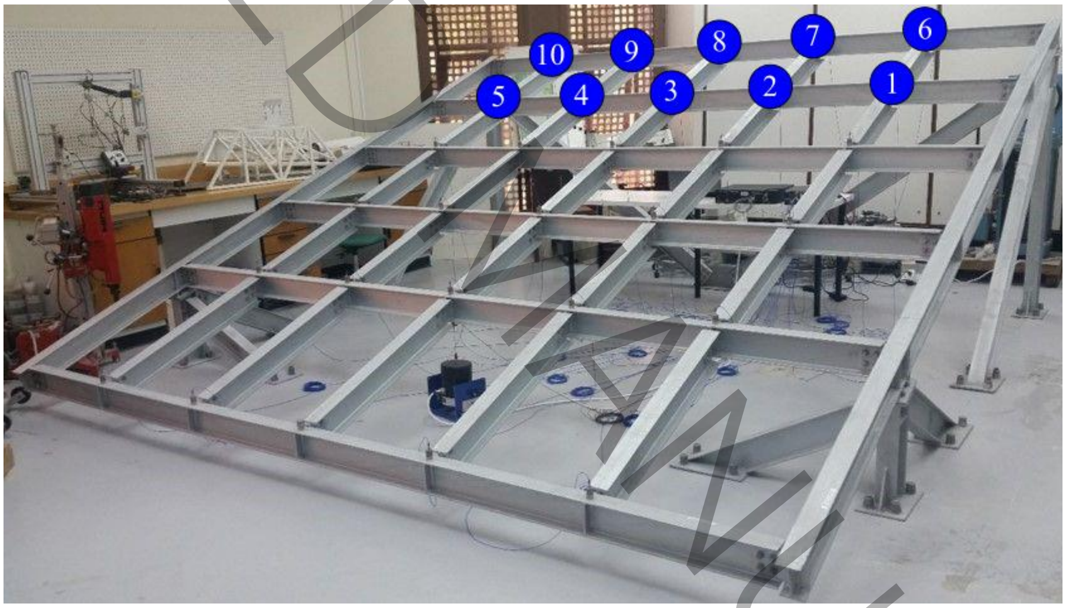

Fig 1. Arrangement of accelerometers at joints (locations of damage scenarios)

Conclusion

This study presents a fast, accurate, and efficient framework for structural damage detection using 2-D CNNs. The decentralized approach not only ensures high accuracy by optimizing each CNN for specific elements but also maintains computational efficiency. By utilizing raw acceleration signals without preprocessing, the method addresses the critical limitations of traditional approaches, making it highly suitable for real-time applications. Validation on a large-scale experimental structure demonstrated the method’s robustness and effectiveness in detecting and localizing damages under various scenarios. These results highlight the practical applicability of the proposed framework in structural health monitoring systems, contributing to enhanced safety and serviceability in civil engineering structures.

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