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Editorial

Editorial for the Special Issue on Civil Structural Health Monitoring: Techniques, Systems and Applications

Fei Kang [1,*] and Yonglong Li [2,*]

[1] School of Infrastructure Engineering, Dalian University of Technology, Dalian 116024, China
[2] Sichuan Energy Internet Research Institute, Tsinghua University, Chengdu 610213, China
* Correspondence: kangfei@dlut.edu.cn (F.K.); liyonglong@hotmail.com (Y.L.)

1. Introduction

Civil structures and infrastructure, including bridges, high-rise buildings, towers, dams, and tunnels, form the backbone of modern economies. Their long-term operational safety is vital to socioeconomic stability and the protection of public life and property [1–3]. As engineering projects grow in scale and complexity, structural deterioration due to material aging, environmental corrosion and extreme load conditions has emerged as a major threat to infrastructure safety and functionality [4–6]. In the era of smart technology, enabling intelligent diagnosis and prognosis of structural health throughout the entire lifecycle has become an urgent priority.

Recent advances in monitoring systems, sensor technologies, and artificial intelligence have promoted the integration of multi-source data and the adoption of intelligent algorithms, positioning structural health monitoring (SHM) at the forefront of addressing these challenges [7–9]. By synthesizing advanced sensing, numerical simulation, and machine learning, SHM systems establish an intelligent feedback loop of sensing–diagnosis–prediction, substantially improving monitoring efficacy and proactive maintenance.

This Special Issue is dedicated to presenting the latest research progress in civil structural health monitoring, encompassing areas such as damage detection, data processing algorithms, modeling and simulation, sensor development, and experimental validation.

2. Summary of the Special Issue Contents

The evolving discipline of civil structural health monitoring (SHM) lies at the intersection of sensor technology, data science, and civil engineering, aiming to ensure the safety, durability, and intelligent management of infrastructure. This Special Issue, entitled "Civil Structural Health Monitoring: Techniques, Systems and Applications," presents a curated collection of nine innovative studies that showcase the breadth and depth of contemporary SHM research. The contributions highlight sophisticated methodologies—ranging from signal processing and unmanned systems to artificial intelligence and physics-informed inverse analysis—applied to a diverse set of critical structures, including bridges, dams, and tunnels. Nine papers were ultimately included in this issue.

2.1. Bridge Infrastructure Monitoring: From Load Separation to Model Updating

The Special Issue begins with two advanced studies focused on bridges. In the first study, the complex challenge of monitoring long-span railway cable-stayed bridges is addressed. These bridges are subject to significant and overlapping load effects from trains and environmental temperature. A novel framework is proposed by employing an adaptive filtering method to meticulously separate these two response components

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from continuous health monitoring data. Subsequently, the authors introduce dedicated analysis methods: a train load effect assessment based on influence lines and a temperature effect evaluation using correlation analysis. The application of this method to the Chongqing Nanjimen Railway Track Bridge demonstrates its effectiveness in providing an objective, real-time operational assessment, proving its utility for managing high-demand transport infrastructure.

Complementing this, the work by Hekič et al. explores the critical task of finite element model updating for an existing concrete roadway bridge. Utilizing long-term data from a Bridge Weigh-in-Motion system, the authors derive strain influence lines (ILs) induced by calibration vehicles. They then apply the Error-Domain Model Falsification methodology to update the bridge's numerical model based on these ILs, a method they compare against traditional frequency-based updating approaches. Their results are compelling: the IL-updated model shows excellent agreement (within 5%) with independently measured displacements, significantly outperforming conventional methods. This research underscores the high fidelity of traffic-load-response-based model updating for accurate digital twinning and long-term structural assessment.

2.2. Thermal Behavior and Inversion Analysis in Concrete Structures

Understanding thermal effects is paramount for concrete structures. The third study delves into the intricacies of the three-dimensional temperature field within box girders. Their study develops a comprehensive computational method that integrates key boundary conditions, including solar radiation, shading, and convective heat transfer. By analyzing the influence of parameters like atmospheric transparency and concrete's short-wave absorptivity, the research provides valuable guidelines for thermal design and material selection, ultimately aiming to mitigate detrimental thermal stresses.

Expanding on parameter identification, the fourth study tackles the inverse analysis of thermal parameters for mass concrete in arch dams. Recognizing the gap between laboratory-tested parameters and actual field conditions, the authors employ the novel Walrus Optimization Algorithm to inversely determine key parameters from measured temperature data. The algorithm's robustness is first validated against classical test functions and then successfully applied to a real arch dam case on the Jinsha River. This approach enhances the accuracy of thermal stress simulations during construction, offering a powerful tool for lifecycle management of massive concrete structures.

2.3. Dam Safety: From Surface Inspection to Foundation Degradation

Monitoring dam safety leverages both surface inspection and internal condition assessment. The next paper presents an integrated UAV-based system for small reservoir dams. The methodology combines Structure from Motion (SfM) for accurate georeferencing without ground control points, an improved YOLOv8 network for detecting small targets like pedestrians, and thermal imaging for seepage identification. This routine surveillance strategy exemplifies how automated, non-contact measurement can enhance operational safety and maintenance efficiency for distributed water-retaining structures.

Beneath the surface, the long-term behavior of dam foundations is critical. The sixth paper introduces a dynamic inversion method for concrete gravity dams on soft-rock foundations. Moving beyond static analysis, their improved Particle Swarm Optimization algorithm incorporates time-series monitoring data to inversely identify the deteriorating elastic modulus of the foundation rock. The study reveals a clear exponential decay trend in foundation stiffness over time, a factor crucial for accurate displacement prediction and long-term safety evaluation, thus informing proactive maintenance strategies.

2.4. Tunnel and Underwater Structural Assessment

The Special Issue also covers the inspection of enclosed and submerged structures. Cracking mechanisms in diversion tunnel linings are investigated by using robotic 3D laser scanning. By analyzing defect distribution patterns and employing finite element analysis to simulate crack propagation under water pressure, the study identifies high-risk zones (e.g., the vault area) and quantifies stress increases due to cracking. These findings provide a scientific basis for targeted inspection and reinforcement in underground hydraulic tunnels.

Inspecting structures underwater presents unique challenges. The eighth paper proposes the Edge-Enhanced Underwater CrackNet (E2UCN), a dual-stage deep learning framework for crack detection on submerged dam surfaces. The method first employs a specially tailored Cycle-GAN to enhance underwater images with a focus on preserving crack edges and textures, overcoming the issues of low contrast and distortion. A subsequent YOLOv11 detector then achieves remarkably high precision in crack identification. This research offers a practical technological solution for intelligent inspection in deep-water environments.

Supporting such underwater vision tasks, the next study addresses the fundamental problem of image quality with "MambaUSR," a novel super-resolution network. By integrating a Vision State-Space Model (Mamba) with frequency-domain processing via a Fast Fourier Transform-based module, the method effectively restores global structure and recovers fine details in degraded underwater images, thereby providing higher-quality input data for any subsequent visual inspection or detection algorithm.

3. Conclusions

The papers in this Special Issue reflect a paradigm shift towards intelligent, integrated, and data-centric SHM systems. They demonstrate successful synergies between advanced sensing platforms (UAVs, ROVs, laser scanners, and dense sensor networks) and cutting-edge computational techniques (adaptive filtering, computer vision, metaheuristic optimization, and state-space models). Each contribution not only presents a methodological innovation but also validates it through rigorous application to real-world structures, bridging the gap between research and practice. We believe this collection will serve as a valuable resource for researchers, engineers, and asset managers, offering both innovative tools and profound insights for the next generation of civil structural health monitoring.

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