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A Review on Guided Wave-Based Damage Detection of Concrete-Filled Steel Tubular Structures

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Abstract

Concrete-filled steel tubular (CFST) structures are widely applied in bridges, buildings, and seismic engineering owing to their excellent load-bearing capacity, ductility, and construction efficiency. However, during service, CFST structures are prone to multiple types of damage, such as crack propagation, interfacial debonding, and steel tube corrosion, which severely threaten their safety and durability. In recent years, guided wave technology has gradually become an important approach for structural health monitoring of CFST structures, owing to its long-range propagation capability, high sensitivity to minor damage, and feasibility for online monitoring. This paper systematically reviews the research progress on guided wave applications in CFST structures, including propagation mechanisms, typical damage detection methods, signal processing, and intelligent recognition techniques. Particular attention is given to monitoring strategies for cracks, debonding, and corrosion. Furthermore, challenges and development trends of guided wave-based damage detection in CFST applications are summarized, highlighting the urgent need for breakthroughs in multi-mode guided wave mechanisms, integration with artificial intelligence methods, adaptability to complex environments, and engineering implementation. This review aims to provide valuable references for nondestructive evaluation and health monitoring of CFST structures.

Keywords

CFST; Guided Wave Technology; Damage Detection; Interfacial Debonding; Artificial Intelligence.

1. Introduction

Concrete-filled steel tubular (CFST) structures are a type of composite structural system in which the steel tube is filled with core concrete[1-4]. This configuration combines the high strength of steel with the compressive resistance of concrete, and thus has been extensively employed in high-rise buildings, bridges, and seismic-resistant structures. However, under long-term service conditions and complex environments such as earthquakes, freeze-thaw cycles, and corrosion, CFST structures may suffer from cracks, interfacial debonding, and steel corrosion. If not identified in time, these damages can lead to a reduction in load-bearing capacity and potential structural failure, thereby endangering engineering safety.

Conventional damage detection methods, such as rebound hammer tests, ultrasonic echo techniques, and static load tests, exhibit significant limitations: their detection range is restricted, they are not sensitive to incipient damage, and they cannot readily support long-term online monitoring[5-8]. Therefore, an efficient and reliable nondestructive testing method is urgently needed. Guided wave technology has attracted increasing attention due to its long propagation distance, high damage sensitivity, and suitability for complex structural monitoring. In recent years, guided wave detection methods integrated with piezoelectric sensors, smart aggregates, and artificial intelligence algorithms have shown tremendous potential in damage detection of CFST structures[9-10].

2. Fundamental Principles of Guided Waves

Guided waves are a class of elastic waves whose propagation is constrained by the geometric and material boundaries of structures, enabling them to travel over long distances with relatively low energy attenuation in finite media. Compared with bulk waves, guided waves possess multiple propagation modes (e.g., symmetric, antisymmetric, longitudinal, torsional), each with distinct displacement fields and frequency-dependent behavior. They also exhibit dispersion, where wave velocity and mode shape vary with the frequency-thickness product. Although this dispersive nature increases analytical complexity, it provides multiple information channels for structural interrogation. Owing to their multimodality, dispersion, and high sensitivity to defects, guided waves have been extensively applied in structural health monitoring.

In concrete-filled steel tube (CFST) structures, guided waves can propagate along the steel tube wall or be coupled into the core concrete through piezoelectric excitation, thereby realizing cross-medium and multi-channel sensing. This coupling effect allows the interrogation not only of the steel tube but also of the steel-concrete interface and the inner concrete core. The heterogeneous and anisotropic nature of CFSTs further induces wave scattering and mode conversion, which can serve as additional indicators of internal damage. Typical damage scenarios, such as cracks, debonding, voids, and corrosion, alter guided wave responses in characteristic ways, including amplitude attenuation, phase delay, mode conversion, and spectral distortion. These changes provide rich diagnostic information for both surface and subsurface defects. Combined with advanced signal processing methods-such as wavelet packet decomposition, time-frequency analysis, and dispersion curve matching-guided wave monitoring establishes a powerful approach for accurate defect detection, localization, and long-term health monitoring of CFST structures.

3. Applications of Guided Waves in CFST Structures

Guided wave technology has been increasingly applied to address typical damage scenarios in CFST structures, demonstrating strong potential for long-term health monitoring.

First, crack detection. Guided waves are particularly effective in identifying early-stage cracks owing to their high sensitivity to geometric discontinuities. Both amplitude attenuation and spectral distortion have been shown to correlate with crack initiation and propagation. Specific guided wave modes, such as longitudinal L(0,2) and certain flexural modes, are capable of penetrating the concrete core and thus detecting internal cracks that are invisible on the surface. Quantitative methods based on energy loss, transmission coefficients, and frequency-wavenumber domain analysis have further enabled the estimation of crack depth, length, and growth rate, supporting the prognosis of structural degradation.

Second, interfacial debonding detection. The steel-concrete interface plays a critical role in the composite action of CFST members, and its deterioration can significantly compromise structural integrity. Guided waves are highly sensitive to debonding because of the impedance mismatch at the interface. Studies have shown that changes in energy ratios, phase delays, and mode conversion patterns can serve as robust indicators of interfacial damage. Multi-channel sensing and advanced signal separation techniques have been employed to decouple overlapping modes, allowing for more accurate localization and quantification of debonding regions.

Third, corrosion monitoring. Corrosion of the steel tube remains a major threat to the durability of CFST structures. Long-range guided waves, especially when combined with magnetostrictive or electromagnetic acoustic transducers (EMATs), provide effective tools for corrosion detection over large structural spans. Variations in signal amplitude, time-of-flight, and wave dispersion can be correlated with wall-thickness reduction and corrosion extent. Moreover, hybrid monitoring systems integrating piezoelectric arrays with guided waves enable both localization and quantitative assessment of corrosion-induced defects.

Overall, these applications confirm the feasibility and promising prospects of guided waves in detecting cracks, debonding, and corrosion in CFST structures. By leveraging multimodal sensing, advanced signal processing, and intelligent recognition algorithms, guided wave technology is expected to evolve toward comprehensive, real-time, and predictive health monitoring frameworks that ensure the safety and serviceability of CFST infrastructure.

4. Guided Wave Signal Processing and Intelligent Recognition

The inherent complexity of CFST structures leads guided wave signals to exhibit multimodal, dispersive, and cross-medium coupling characteristics, which makes effective signal processing an indispensable step for accurate damage identification. Raw signals are often contaminated by boundary reflections, environmental noise, and multimode interference, necessitating advanced analysis methods. Time-frequency domain approaches such as wavelet packet decomposition, short-time Fourier transform, and Hilbert-Huang transform are widely applied to capture transient, non-stationary features associated with incipient cracks. Beyond these, empirical mode decomposition, synchrosqueezing transform, and sparse representation methods have been developed to enhance time-frequency resolution and suppress noise, further improving feature extraction in complex environments.

To quantify structural damage, multiple feature parameters have been proposed, including amplitude attenuation rate, wave velocity variation, and spectral distortion. In addition, mode-conversion ratios, energy leakage, and phase-shift indicators have shown high sensitivity to interfacial debonding and internal cracking. By constructing damage indices from these parameters, it is possible to characterize both the initiation and progression of damage in CFST members.

Intelligent recognition methods further elevate the capability of guided wave monitoring systems. Classical machine learning algorithms, such as support vector machines (SVM) and random forests, have demonstrated good performance when combined with wavelet-based features for debonding and crack classification. Deep learning techniques-including deep neural networks (DNN) and convolutional neural networks (CNN)-enable automatic, end-to-end feature extraction and pattern recognition, reducing reliance on handcrafted features. Recent advances extend to recurrent neural networks (RNN) and long short-term memory (LSTM) models for capturing temporal dependencies, and graph neural networks (GNN) for learning the spatial relationships of multi-sensor guided wave data. Furthermore, digital twin technology integrates experimental monitoring data with high-fidelity numerical simulations, enabling prediction of structural service life, early-warning of damage evolution, and adaptive maintenance decision-making. The synergy between advanced signal processing and intelligent algorithms therefore provides a powerful and scalable framework for the long-term health monitoring of CFST structures.

5. Challenges

Although guided wave technology has shown significant potential for health monitoring of CFST structures, several critical challenges remain to be addressed before large-scale engineering applications can be realized.

First, wave propagation in heterogeneous media. CFST structures feature a complex composite system where guided waves must propagate across steel tubes, concrete cores, and their interfaces. The strong acoustic impedance mismatch and heterogeneous material properties induce mode conversion, scattering, and energy leakage, making guided wave patterns difficult to predict and interpret. Accurate modeling of wave propagation in such multi-material domains is still a major research bottleneck.

Second, high attenuation and limited penetration in concrete. Unlike wave propagation in homogeneous steel pipelines, guided waves entering the concrete core suffer severe attenuation and dispersion due to the heterogeneous and viscoelastic nature of concrete. This restricts detection range and sensitivity, especially for deeply embedded cracks or interfacial debonding, and requires innovative excitation and sensing strategies to enhance penetration depth.

Third, environmental and operational variability. CFST members in service are subjected to temperature fluctuations, stress changes, and moisture ingress, all of which significantly affect guided wave velocity, phase, and amplitude. These variations can mask or mimic damage signatures, thus reducing reliability in long-term monitoring. Robust environmental compensation models and adaptive algorithms are urgently needed to improve detection accuracy under realistic service conditions.

Fourth, sensor durability and deployment challenges. Embedding piezoelectric sensors inside concrete raises concerns of long-term durability, debonding, and degradation under harsh environments. On the steel tube surface, sensor arrays face challenges of sufficient coverage, installation cost, and stable coupling. For large-scale CFST applications, optimizing sensor density, placement strategies, and energy-efficient excitation methods remains a critical issue.

Fifth, gaps between laboratory studies and field applications. Most existing research on guided waves in CFST structures is conducted at the laboratory scale, focusing on small specimens under controlled conditions. In contrast, real-world CFST members (e.g., bridge piers, high-rise columns) are large, heavily reinforced, and exposed to complex boundary conditions. Field demonstrations are scarce, and standardized procedures for guided wave-based CFST monitoring have yet to be established.

Finally, lack of standardized damage evaluation and intelligent integration. At present, there is no consensus on unified damage indices, threshold values, or evaluation protocols for CFST guided wave monitoring. Although machine learning and deep learning have enhanced recognition performance, their “black-box” nature reduces interpretability and limits acceptance in safety-critical engineering practice. Integrating guided wave data with digital twins and multi-source monitoring remains at a conceptual stage, requiring further research to achieve reliable, transparent, and field-ready systems.

In conclusion, while guided wave techniques provide unique advantages for crack, debonding, and corrosion monitoring in CFST structures, addressing the above challenges is essential for transitioning from laboratory feasibility to robust, standardized, and scalable field applications.

6. Future Trends

Future development of guided wave-based damage detection for CFST structures is expected to focus on: (1) advancing multi-modal and nonlinear guided wave mechanism research to enhance sensitivity to early-stage micro-damage; (2) developing novel distributed sensing technologies, such as piezoelectric smart aggregates and optical fiber sensors, to achieve embedded long-term monitoring; (3) integrating artificial intelligence and big data techniques, leveraging deep learning and digital twins to enable intelligent prediction of damage and service life; (4) improving adaptability in complex environments, with applications extended to extreme conditions such as earthquakes, fire, and underwater service; and (5) accelerating standardization and engineering implementation to enable large-scale applications in bridges, tunnels, and high-rise buildings.

7. Conclusion

In summary, guided wave-based damage detection has demonstrated unique advantages in CFST structures, enabling early identification of multiple types of damage including cracks, interfacial debonding, and corrosion. Combined with artificial intelligence, guided wave technology has made remarkable progress in signal recognition, damage localization, and evolution prediction. However, challenges remain in terms of adaptability to complex environments, application in large-scale structures, and engineering implementation. Future research should emphasize guided wave mechanism studies, development of novel sensing techniques, and promotion of intelligent detection methods in practice, in order to achieve full-life-cycle health monitoring and safety assurance of CFST structures.

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