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Review Paper on Assessment of Deterioration in Concrete Filled with Steel Tubular Section via Guided Waves

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ABSTRACT

This study focuses on a non-destructive technique for monitoring the degradation of concrete filled steel tubular (CFST) sections. CFST structures are widely used in engineering due to their strength and ease of construction. However, their susceptibility to environmental attack, particularly corrosion of the steel components, can significantly reduce their strength and lifespan. The inner surface of the steel tube, in contact with the concrete, acts as an electrolyte, accelerating the corrosion process. If left undetected, this degradation can lead to catastrophic consequences. To address this issue, the researchers propose a method using guided ultrasonic waves to detect and monitor corrosion-induced damage in CFST sections. Corrosion leads to debonding and pitting in the steel, which can be detected through the analysis of guided waves. The researchers conducted experiments involving simulated pitting and delamination defects in CFST sections, and pulse transmission was employed to monitor the specimens in both healthy and damaged states. A successful methodology was developed and implemented for the monitoring of CFST sections undergoing accelerated chloride corrosion. The ultrasonic signals effectively provide insights into the corrosion state of the steel tubes.

1. INTRODUCTION

CFST structures, comprising of concrete-filled steel tubes, have gained significant popularity in the construction industry, particularly in high-rise buildings, bridges, and industrial structures. These structures offer remarkable seismic performance, characterized by high strength, ductility, and energy absorption capacity. The combination of steel and concrete in composite frames results in excellent mechanical behavior and convenient construction processes. CFST structures also exhibit favorable hysteresis behavior when subjected to cyclic loading, making them desirable for various applications. The adoption of CFST concepts can lead to substantial steel savings compared to conventional steel structures. Composite members with CFST elements leverage the structural strength provided by both steel and concrete, creating an ideal complement between the two materials.

In current practice, CFST structures typically employ steel supports combined with profiled steel sheeting or pre-cast partial thickness composite sections. Vertical members designed for lateral load-resisting systems can be categorized into four main types:

- encased composite columns,
- concrete-filled steel tubular (CFST) columns,
- reinforced concrete filled tubular steel (RCFT), and
- double-skinned concrete-filled steel tubular (CFST) columns (as illustrated in Figure 1).

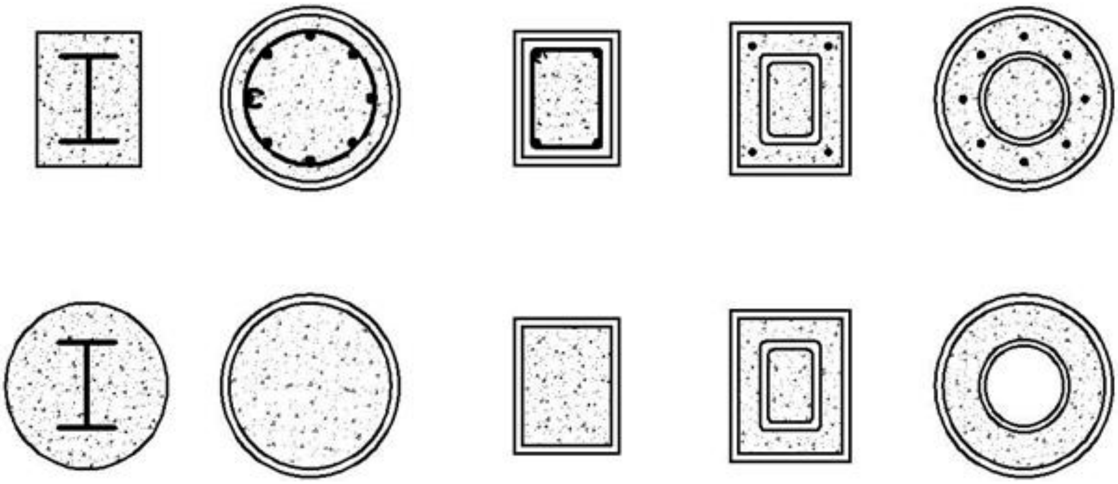

Figure 1: Composite Steel and Concrete columns

2. DAMAGE/CORROSION MONITORING METHODOLOGIES

Effective and continuous health monitoring of components such as concrete filled steel tubes is crucial to ensure the structural integrity and prevent any compromise. Various non-destructive techniques are available to assess damages and corrosion in these structures while they are in service. Some of these techniques include visual inspection, magnetic particle inspection, magnetic flux leakage, eddy current testing, pressure testing, magnetic resonance imaging, laser interferometry, acoustic emission, penetrating gamma and X-rays, thermographic imaging, holographic interferometry, and the use of sensors like galvanic thin film, electrochemical sensors, and chemical sensors.

However, there is a need to develop a comprehensive non-destructive damage monitoring technique specifically for corrosion-induced damages in concrete filled steel tubes. This technique should either replace or complement existing methods. The present study aims to address this need by developing a complete damage monitoring methodology for concrete filled steel tube structures using ultrasonic guided waves. This approach will enable in-situ and real-time monitoring of the specimens, allowing for early detection of corrosion-induced damages such as cracks, dents, and corrosion, thereby ensuring the structural integrity of these components.

3. ULTRASONIC WAVES- A IMPENDING SOLUTION

The current methods used for non-destructive testing and damage evaluation of concrete filled steel tube assemblies, as discussed earlier, provide indirect indicators of potential damage or corrosion. However, these methods face practical limitations, such as scale-up issues and high costs associated with implementation and maintenance. While techniques like corrosion monitoring can be utilized to diagnose the cause and extent of corrosion in structures, they also have their own limitations.

Therefore, there is a critical need to develop a non-intrusive and non-contact technique for monitoring the health of concrete filled steel tube structures in civil infrastructures. In the past, ultrasonic bulk waves have been employed as an effective method for assessing the health of various structures. These waves propagate within the material's interior, away from boundaries, and exhibit a finite number of wave modes with small wavelengths compared to the object's dimensions. Parameters such as transmission amplitudes, traveling time, and signal attenuation are used to evaluate the structure's health. Time of flight can also be utilized to locate and quantify the severity of damage based on the amplitude of the reflected signal. However, bulk waves have limited scanning capabilities due to energy loss caused by material attenuation.

Guided waves have emerged as a promising option for efficient and reliable monitoring of larger structural domains. They possess characteristics such as solid entrance, rapid propagation, omnidirectional dispersion, adaptability for actuation and sensing, good performance, and high sensitivity to structural damage and material inhomogeneities, even when they are small in size or located beneath the surface. These unique propagation characteristics make guided waves suitable for damage detection in various geometries, including plates, pipes, and rods. In most applications, the structure being monitored is placed in air, and transducers need direct contact with the structure.

4. REVIEW OF LITERATURE

The use of concrete filled steel tubular (CFST) columns is a beneficial approach for enhancing the structural characteristics of concrete elements. Extensive research and investigations have been conducted on CFST, focusing on four main aspects: the study of major structural behavior, dynamic properties, interface bonding theory, and damage analysis of concrete filled square steel tubes. It is widely acknowledged that the concrete filling within the steel tube provides confinement and protection, creating a tri-axial compression state. This compression state significantly enhances the compressive strength and torsional capacity of the concrete. Additionally, the presence of the concrete filling helps prevent local buckling of the steel tube, further improving the overall stability and performance of the CFST column.

Hanagud et al. (2009) focused on developing an analytical expression for a damage measure that correlates strain energy with the location and magnitude of damage. The researchers calculated the strain energy by analyzing the modes and natural frequencies of beams that had incurred damage. To validate the derived analytical expression, the authors conducted various experiments specifically targeting non-spreading cracks resembling notches, while considering subjective boundary conditions.

Chen et al. (2010) focused on the early detection of corrosion in order to prevent extensive degradation of metallic structures exposed to corrosive environments. The authors presented a corrosion detection technique that involved pulse echo measurements in submerged structures, utilizing the A0 mode. This mode was preferred over the S0 mode due to factors such as ease of excitation, lower wavelengths, and larger signal amplitude. However, the presence of the coupled fluid medium significantly affected the propagation characteristics of the A0 mode, leading to incorrect identification of damages. To address this issue, the authors conducted investigations and calibrated the influence of varying degrees of fluid coupling on the A0 mode. The proposed technique was validated both analytically and numerically by assessing through-thickness holes and chemical corrosion in submerged aluminum plates. The authors employed a probability-based diagnostic imaging approach to evaluate the effectiveness of the technique.

Poddar et al. (2011) conducted experimental research on the application of time reversibility of Lamb waves for detecting damage in aluminum plates. The researchers focused on reconstructing the original signal at the receiver and observing any changes in the reconstructed signal to determine the presence of damage along the signal path. PZT wafer transducers were utilized to investigate the impact of various factors such as frequency, pulse frequency bandwidth, transducer size, and tuning parameters on the quality of the reconstructed input signals, aiming to enhance the sensitivity to damage. The authors also employed the time reversal process (TRP) to detect different types of defects, including block mass, notches, and surface corrosion, in aluminum plates. Through the quantification of reconstructed signals, these defects could be effectively identified. The study demonstrated the potential of using time reversibility of Lamb waves as a reliable technique for standard free damage detection, offering improved damage sensitivity in aluminum structures.

Leleux et al. (2013) utilized a low-frequency, multi-element matrix probe based on phased array principles to generate and capture pure Lamb wave modes in large plates. They selectively launched and detected modes that propagated in specific directions where the phase and group velocities were collinear. The researchers experimentally examined the directivity of the guided beams and investigated the feasibility of detecting, locating, and sizing acoustic sources placed at different positions around the receiving probes. Various defects, including 3D-shaped delaminations, impact damages in composite plates, and corrosion-like defects in metallic plates, were successfully detected using the developed prototype setup. When it comes to concrete filled steel tubular (CFST) structures, in-situ damage monitoring presents a unique and challenging task. Previous works have explored the application of guided waves for monitoring such structures, but there is still a need to identify the specific Lamb wave modes that are sensitive to different types of damage and corrosion. Additionally, the technology must be validated in structures undergoing progressive corrosion, and the ultrasonic readings need to be calibrated with actual degradations to accurately predict the residual strength of the structure. The objective of the present work is to investigate the propagation of ultrasonic guided waves through CFST structures and develop a non-invasive, in-situ damage monitoring methodology.

Sharma and Mukherjee (2013) conducted non-destructive evaluation of corroding reinforcing bars in the presence and absence of chlorides using ultrasonic guided waves. They employed specific center and surface scanning modes to identify the type, rate, and mechanism of corrosion in reinforcing bars embedded in concrete under various exposure conditions. The experimental investigation included monitoring of reinforced concrete bars undergoing accelerated impressed current corrosion. The results revealed significant signal attenuation and non-uniform area loss in the presence of chloride-induced corrosion, which were effectively detected using the center scanning mode. The corrosion process was observed to initiate with delamination, followed by an increase in signal amplitude detected by the surface scanning mode. This study provides insights into the use of ultrasonic guided waves for non-destructive evaluation of corroding reinforcing bars, allowing for early detection and characterization of corrosion-induced damage in concrete structures.

Xie et al.(2018) In this research, a comprehensive study was conducted involving 14 circular and square concrete-filled steel tubular members with different types of concrete (general and recycled) and varying corrosion rates (0%, 10%, 20%, and 30%). Four-point bending tests were performed on these members to analyze their flexural behavior. The focus was on studying failure modes, moment versus deformation curves, and ultimate strength of the corroded and uncorroded concrete-filled steel tubular beams. The results revealed that corrosion had a significant impact on the structural performance of the members. It led to a notable decrease in yield strength, elastic modulus, and tensile strain capacity of the steel plates, as well as a deterioration in the ultimate strength of the concrete-filled steel tubular structures. Interestingly, the replacement of general concrete aggregate with recycled concrete aggregate had minimal influence on the flexural performance of both corroded and uncorroded concrete-filled steel tubular beams. Furthermore, a comparison was made between the experimental results and predicted ultimate strengths from four existing codes: GB 50936-2014, DB36/J001-2007, AIJ, and EN 1994-1-1:2004. This analysis provided insights into the accuracy and reliability of these codes in predicting the ultimate strength of corroded concrete-filled steel tubular members.

Overall, this study highlights the detrimental effects of corrosion on the flexural performance of concrete-filled steel tubular structures and emphasizes the limited influence of recycled concrete aggregate. The findings contribute to improving the understanding of corrosion-induced degradation and provide valuable information for the development of design codes and guidelines for such structures.

Vasugi et al.(2019) CFST columns have gained popularity in recent decades due to their unique advantages. Circular CFST columns typically exhibit local outward buckling, while elephant foot buckling is observed near the top end of the column. On the other hand, square columns mainly experience outward buckling. The predicted failure behavior of circular columns using FEM software aligns well with experimental results. The confinement provided by the steel section extends the failure in the concrete, enhancing the overall performance of CFST columns compared to reinforced structural systems in terms of strength, stiffness, and stability. As a result, CFST columns can be considered as a viable alternative to steel or reinforced structures. In high-rise buildings, the combination of CFST and reinforced concrete (RC) systems, known as hybrid systems, offers excellent performance. Additionally, the rectangular or square shapes of CFST columns provide advantages during connection processes.

Cui et al.(2020) This study aimed to evaluate the response and damage of two different cross-sectional concrete-filled steel tubular (CFST) columns under near-field blast loading conditions. The experimental analysis was combined with numerical simulation to assess the columns' behavior. The results indicated that plastic bending deformation occurred on the surfaces facing the explosive for both columns, with the normal solid-section (NSS) CFST column exhibiting better anti-explosion performance compared to the concrete-filled double-skin steel tubular (CFDST) column. The peak pressure distributions showed that the middle points of the columns experienced the highest peak pressures, while the bottom had higher pressures than the top. Damage analysis revealed that the middle section of the columns sustained the most severe damage. Pressure-impulse damage evaluation curves were established for both NSS and CFDST columns using pressure-impulse damage theory and validated numerical simulations. Damage criteria were defined based on deflection, and mathematical formulas were developed to generate pressure-impulse diagrams for the two column types. These formulas can be used to evaluate the damage of CFST columns with similar cross sections under near-field blast loading, providing a method for assessing the damage of CFST columns with different cross section types.

Yang and Ligui (2021) This study focuses on investigating the static behaviors of concrete-filled corrugated steel tubular (CFCST) members. Various aspects of CFCST behavior were examined, including axial and eccentric compression, stability, slender column behavior, and torsional behavior. The goal was to understand the confinement mechanism and composite work mechanism of CFCST. The experimental program consisted of testing 21 axially compressed short columns, including 12 CFCST specimens. Factors such as confinement, load carrying mode, and specimen types were varied. The analysis involved studying failure modes, load carrying capacity, and stress distribution in the corrugated steel tube (CST). A uniaxial stress-strain constitutive model was developed for finite element models in ABAQUS. Solid-shell nonlinear finite element models were created to predict the axial behavior of CFCST sections. The study also revealed non-uniform confinement along the longitudinal direction of CFCST members and derived theoretical formulas to determine the distribution of local confining stress. Parametric analysis was conducted on the geometry and material strength to quantify the equivalent confining stress of the CST.

Tokgoz et al.(2021) This paper presents experimental and theoretical investigations on eccentrically loaded concrete-filled stainless steel tubular composite columns. The column specimens were fabricated using a high-strength outer stainless steel tube, concrete infill, and inner carbon structural steel. Two types of concrete were used: plain concrete and steel fiber reinforced concrete. The specimens underwent testing, and the experimental load-deflection curves were documented. The study also included a theoretical method to predict the strength and load-deflection behavior of the tested plain and steel fiber concrete-filled stainless steel tubular composite columns. The results showed that the tested tubular columns exhibited ductile behavior, and there was good agreement between the experimental and theoretical load-deflection curves. Furthermore, a parametric study was conducted to investigate the effects of loading eccentricity, slenderness, plate slenderness, and concrete compressive strength on the behavior of the concrete-filled stainless steel tubular composite columns. The study concluded that increasing the stainless steel wall thickness and concrete compressive strength resulted in increased column strength.

Mohanraj et al.(2022) The findings of this study provide several important conclusions regarding composite columns. Firstly, the predicted axial strengths using EC4 part 1-1 are lower than the experimental results, with variations ranging from 5% to 35%. The ACI/AS equation also underestimates the strengths, with variations of 30% to 78%. However, it is noted that the ACI/AS equation performs better for long columns with a slenderness ratio (L/D) greater than 10. To address the shortcomings for L/D ratios below 12, a modified equation is proposed, introducing a multiplying factor 'k' based on different L/D ratios. Verification experiments support the accuracy of the proposed equation in predicting the strength of concrete-filled tubular columns. Additionally, it is observed that the strength of steel tubular columns filled with concrete is approximately 58% to 112% of that of hollow columns, depending on the compressive strength of the infilled materials. Lastly, the strength of CFSTs with partial replacement of fine and coarse aggregate by waste materials is comparable to that of plain concrete.

Abraham et al.(2022) This study focuses on the seismic analysis of beam-column junctions between H steel beams and CFST columns under cyclic loading. H steel beams consist of an H-steel core within a precast concrete beam and offer high bearing capacity compared to RC columns. CFST structures, on the other hand, consist of hollow steel tubes filled with plain or reinforced concrete and are lighter and more reliable in seismic regions. The objective of the study is to evaluate the behavior of the joints between H steel beams and CFST columns, comparing the performance of CFST tubes with normal beam sections and Reduced Beam Section (RBS) beams. The results highlight the significant seismic behavior observed in the RBS section, as evidenced by the load-displacement hysteresis curve.

Kumar et al.(2023) In their recent study, Kumar et al. (2023) investigated the utilization of manufactured sand in concrete and highlighted the beneficial effects it offers on concrete performance. When compared to traditional sand concrete, the use of manufactured sand in both M40 and M50 grade concretes showed a noticeable reduction in water absorption. This reduction was achieved by employing a lower water-binder ratio, resulting in concrete that is impermeable and more resistant to water penetration. In addition to reduced water absorption, the inclusion of manufactured sand also led to a decrease in chloride ion penetrability. This indicates an improvement in durability and lower permeability of the concrete, making it more resistant to the ingress of harmful chloride ions. Another advantage of using manufactured sand is its enhanced resistance to acid and alkaline attacks, which resulted in reduced weight loss compared to concrete made with traditional sand. Furthermore, concrete mixes incorporating synthetic sand demonstrated improved resistance to impact and abrasion, making them more resilient in challenging conditions. These positive effects contribute to enhanced overall concrete performance when manufactured sand is utilized. Overall, the study highlights the various beneficial effects of incorporating manufactured sand in concrete, including reduced water absorption, improved durability, lower chloride ion penetrability, enhanced resistance to acid and alkaline attacks, and improved impact and abrasion resistance.

Fujinaga et al.(2023) This study proposes an evaluation method to determine the accurate ultimate flexural strength of a rectangular CFST (Concrete Filled Steel Tubular) beam-column.

The method is applicable to materials with a wide range of strengths and steel tubes with large width-to-thickness ratios. The proposed approach considers the strain at the extreme concrete compression fiber and the stress reduction of the steel tube on the compression side to estimate the ultimate flexural strength. The comparison with experimental data led to the following conclusions: Firstly, the proposed method can effectively and safely evaluate the ultimate flexural strength, even for cases involving large width-to-thickness ratios and high-strength materials, when the strain at the extreme concrete compression fiber is set to cεu = 0.004. Secondly, when the strain at the extreme concrete compression fiber is cεu = 0.005, the calculated ultimate strength accurately predicts the average maximum strength.

5. SUMMARY

The review paper focuses on the assessment of deterioration in concrete filled with steel tubular (CFST) sections using guided waves. Guided waves offer a promising non-destructive testing technique for detecting and evaluating various types of deterioration in CFST structures. The paper provides a comprehensive summary of the existing research in this field. The review begins by discussing the fundamental principles of guided wave-based damage assessment and its application to CFST structures. It highlights the advantages of guided wave testing, such as its ability to cover large areas and detect hidden defects, making it suitable for inspecting CFST structures. The paper then delves into specific types of deterioration that can occur in CFST, including corrosion, cracking, and delamination. It explores the effects of these deteriorations on the guided wave propagation characteristics and discusses various signal processing techniques used for damage identification and quantification. Furthermore, the review paper discusses the experimental setups and test procedures employed in previous studies. It emphasizes the importance of selecting appropriate excitation sources, transducers, and signal analysis techniques to achieve accurate and reliable results. The review also highlights the challenges and limitations associated with guided wave testing in CFST structures, such as the influence of structural complexities and the interpretation of acquired signals. It suggests potential avenues for future research, including the development of advanced signal processing algorithms and the integration of guided wave testing with other inspection methods. Overall, the review paper provides a comprehensive summary of the current state of knowledge in the assessment of deterioration in CFST structures using guided waves. It serves as a valuable resource for researchers and practitioners involved in the inspection and maintenance of CFST infrastructure, offering insights into the potential of guided wave testing for detecting and quantifying various types of deterioration in these structures.

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