Unmanned Aerial Vehicle-Assisted Assessment of Cable-Stayed Bridge Slant Cables and Piers: Methods and Applications

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2024 International Conference on Green Energy, Computing and Sustainable Technology (GECOST) | 979-8-3503-5790-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/GECOST60902.2024.10474697

***Abstract*—This study focuses on the structural integrity assessment of the slant cables and piers of the Damen Bridge in Wenzhou City using unmanned aerial vehicle (UAV) technology. By integrating rotary-wing UAVs, high-resolution cameras, and other advanced inspection equipment, we achieved a comprehensive inspection of critical structural components of the bridge. During the inspection process, each slant cable was subdivided to ensure complete image capture. Additionally, high-definition videos of the piers were recorded from various angles using UAVs. Through the analysis of these high-quality imaging data, a total of 141 structural defects were identified, including 117 in the slant cables and 24 in the piers. Furthermore, advanced image processing and data analysis techniques were applied to analyze the captured data in detail, accurately pinpointing the specific locations and nature of the defects. The results of this study not only demonstrate the effectiveness of UAVs and digital imaging technology in bridge inspection and maintenance but also provide crucial technical support for the long-term stability and safe operation of the bridge. Additionally, our methodology holds significant reference value for similar large-scale bridge health monitoring, offering new perspectives for future bridge maintenance strategies.**

Keywords— Structural Integrity Asesssment, Structural Defects, UAV, RGB camera

I. INTRODUCTION

Recent advancements in Bridge Health Monitoring (BHM) have increasingly focused on innovative methodologies for assessing and enhancing the safety and durability of cable-stayed bridges. The pioneering research in indirect BHM for cable damage identification in cable-stayed bridges significantly extended the Vehicle-Bridge Interaction (VBI) framework to accommodate large-scale cable-stayed bridges. This marked a substantial advancement in the field, highlighting the potential of integrating indirect BHM techniques into complex bridge structures [1]. This approach marked a significant step in understanding the complex interactions influencing bridge health.

Parallel to these developments, the utilization of UAVs has emerged as a transformative tool in bridge maintenance. A groundbreaking study was conducted on image-based crack assessment of bridge piers, utilizing UAVs in conjunction with three-dimensional scene reconstruction. This innovative approach represents a significant advancement in the methodology for evaluating structural integrity of bridge piers, integrating modern imaging technology and spatial analysis [2]. This methodology not only mitigates the risks associated with manual inspections but also provides a comprehensive approach to maintaining transportation infrastructures.

In addressing seismic challenges, Recent studies have explored the assessment and mitigation of near-fault earthquake wave effects on seismic responses in soil-pile-bridge models. This research delves into understanding the impact of seismic activities, particularly near fault lines, on the structural integrity of bridge foundations and offers insights into effective mitigation strategies [3]. Their study utilized a 1/70-scale model of an extremely long-span cable-stayed bridge, demonstrating how elastic cables and supporting piers can effectively control seismic responses, thereby reducing potential damage.

Further contributing to the field, A novel seismic vulnerability assessment method for cable-stayed bridge systems has been introduced, utilizing the Pair Copula iterative model. This innovative approach provides a comprehensive framework for evaluating the seismic resilience of cable-stayed bridges, enhancing the understanding of their behavior under seismic stress[4]. This method provides a holistic approach to evaluating seismic vulnerabilities, enhancing the overall understanding of bridge resilience.

Recent research has focused on the performance evaluation of long-span cable-stayed bridges, employing non-destructive field loading tests. This approach emphasizes the importance of assessing structural integrity and durability of such bridges under various load conditions, contributing significantly to the field of bridge engineering and safety analysis [5]. Their research on the Pingnan Xiangsizhou Bridge, the cable-stayed bridge with the largest span in Guangxi, underscored the importance of structural responses in bridge operation, particularly concerning the transfer of loads from the main girder to the piers and tower through the stay cables. The integration of computer vision technology in bridge inspections, particularly in UAV-assisted scenarios, has been another area of significant progress. Recent advancements have verified the effectiveness of Convolutional Neural Network (CNN) models in automating structural recognition tasks. This development showcases the significant potential of technology in simplifying complex inspection processes, marking a substantial step forward in the application of machine learning in structural engineering [6] [7].

Recent studies have conducted seismic fragility analyses to evaluate the vulnerability of cable-stayed bridges, with a particular focus on the effects of fault ruptures. This research provides critical insights into the seismic resilience of such structures, enhancing understanding of their behavior and response in seismic events [8]. Their findings revealed that pylons and bearings exhibit increased vulnerability in the transverse direction for bridges crossing faults, compared to those near faults, while the vulnerability of cables remains consistent. The dynamic characteristics of cable-stayed bridges have been comprehensively analyzed, with a specific focus on their behavior during the maximum cantilever stage and after completion. This research offers critical insights into the response and stability of cable-stayed bridges throughout different phases of their construction and operational lifespan, enhancing the understanding of their structural dynamics [9]. Their study highlighted how factors such as structure rigidity, cable dip angles, and auxiliary pier positions critically influence the dynamic behavior of cable-stayed bridges. This burgeoning body of research, encompassing various influential studies, underlines the evolving landscape of cable-stayed bridge assessment.

The continuous advancements in this field reflect a growing understanding and innovative approaches to evaluating the structural integrity and performance of cable-stayed bridges [10]. Collectively, these studies provide valuable insights and methodologies, paving the way for more efficient, safe, and resilient bridge design and maintenance strategies in the face of modern infrastructural challenges.

Our work lies in the assessment of cable-stayed bridge slant cables and peirs, in particularly, with case studies on Damen Bridge in Whenzhou City. As depicted in Figure 1, the Phase I project of the Damen Bridge serves as a crucial infrastructure connecting Yongqiang Town of Yueqing City with the Daomen Islands of Dongtou District. This bridge plays a vital role in both transportation and the economy. The project's main line begins south of the second middle school in Yongqiang Town, Yueqing, and ends at the petrochemical industry base in Wenzhou City, adjacent to the Wenzhou Port, one of the three major hub ports in the region. The total length of the project's main line is 7,487 meters, with the bridge section spanning 6,155 meters and the remainder comprising roads and related facilities.

The key main bridge structure is located in the second contract section of the project, with pile numbers ranging from K3+867.0 to K4+453.0. The main bridge is designed as a double-tower, double-cable-plane prestressed concrete (PC) cable-stayed bridge with a span combination of (135+316+135) meters. The cable-stays are arranged in a fan-shaped configuration, with each tower equipped with 22 pairs of cable-stays, totaling 176 cables. Additionally, the main beam is designed as a prestressed concrete ribbed slab structure, featuring a main rib height of 2.8 meters and a width of 2 meters. The bridge deck consists of 0.3-meter-thick unidirectional load-bearing slabs, with transverse beams set every 6.6 meters, each 0.4 meters thick. The main tower features a unique vase-shaped design, with a total height from the base to the top of the tower of 136 meters, including segments of various heights in straight and curved lines. The tower's top has a lateral width of 13 meters, while the bottom width is 43 meters. The overall design of the bridge not only addresses the structural and engineering requirements but also focuses on aesthetic appeal and harmonious integration with the environment.

Fig. 1. The Damen Bridge in Wenzhou City

II. RESEARCH METHODOLOGY

A. Overview

The aim of the inspection is to conduct a comprehensive examination of the outer sides of the bridge's cable-stays and the surfaces of its piers. By doing so, the objective is to ascertain the current condition of these surfaces, extract details of any damage, and determine their exact locations. This information will provide a basis for ensuring the safety of the bridge's subsequent operation and maintenance [11].

In this study, we adhered to a series of stringent standards and guidelines to ensure the safe and effective application of UAV technology in the structural integrity assessment of the bridge's cable-stays and piers. These standards and guidelines not only encompass the safety and technical requirements of UAV operations but also include specific operational procedures for low-altitude digital aerial photogrammetry. As detailed in Table 1, the adoption of these standards and guidelines not only enhanced the scientific rigor and systematic approach of our research but also ensured the safety of the experimental operations and the validity of the data. They provided solid theoretical and technical support for the UAV aerial photography operations in this study, ensuring efficient and accurate assessment of the structural integrity of the bridge's cable-stays and piers. Aimed at efficient and accurate inspection of the cable-stays of the large bridge, we adopted a series of advanced instruments and equipment. These tools not only enhanced the accuracy of the inspections but also significantly increased work efficiency. The selection of these devices was based on their performance in specific application scenarios, ensuring both reliable and comprehensive inspection processes. As shown in Table 2, the instruments and equipment, including their models and specific uses, are listed. Each item plays a crucial role in the integrity assessment of the cable-stays.

TABLE 1. Standards and Guidelines for Inspection Basis

S/N	Standard Code	Standard Name
1	CH/Z3001 —2010	Basic Requirements for UAV Aerial Photography Operations
2	CH/Z3002 —2010	Technical Requirements for UAV Aerial Photography Systems
3	CH/Z3004 —2010	Field Operation Guidelines for Low-Altitude Digital Aerial Photogrammetry

The rotary-wing UAVs used in our study, including the Falcon 8 and DJI Phantom 4 Pro models, provided us with clear, high-resolution image data. These UAVs were specifically designed for stability and operational flexibility, enabling safe flight in complex bridge environments while capturing critical structural details. Additionally, the use of the Sony a7r2 camera complemented the UAV imagery, with its high dynamic range and sensitive sensors ensuring the capture of high-quality images even in low-light conditions. To accurately measure the dimensions of the cable-stays, we employed a 10-meter steel measuring tape. This simple yet reliable tool played a key role in the physical dimension measurements, especially in assessing the tension and potential deformation of the cable-stays. Finally, Lenovo laptops served as the center for data processing and analysis, supporting advanced image processing and data analysis software. Not only did this accelerate the data processing, but it also enhanced the ability to extract accurate information from complex datasets. The combined use of these devices provided a comprehensive and precise technological platform for our study, significantly improving the quality of the cable-stay inspection and providing reliable data support for our structural health monitoring. In this way, we ensured the safety and long-term stability of the bridge, which is crucial for the maintenance of infrastructure and public safety.

TABLE 2. Standards and Guidelines for Inspection Basis

S/N	Equipment Name	Model	Purpose
1	Rotary-wing Unmanned Aerial Vehicle	Falcon 8	Image Acquisition
2	Rotary-wing Unmanned Aerial Vehicle	DJI Phantom 4 Pro	Image Acquisition
3	Camera	Sony a7r2	Image Acquisition
4	Steel Measuring Tape	10m	Dimension Measurement
5	Laptop Computer	Lenovo	Data Processing

B. Inspection Methods

This study employed a meticulous method of subdividing cable-stays, ensuring that every part of each cable-stay was thoroughly covered during the image acquisition process. This strategy was based on the structural characteristics of the cable-stays and the types of potential damages that might be present. By subdividing each cable-stay, we were able to more accurately locate potential structural issues. Before conducting UAV inspections, a detailed on-site survey was carried out. This step was crucial as it determined the flight path and strategy for the UAV, taking into consideration various environmental factors such as wind speed and obstacle distribution to devise the most effective flight route, ensuring comprehensive and efficient data collection.

The UAVs were flown at a uniform speed over the surface of the cable-stays to record videos. During this process, we precisely controlled the UAV's flight distance and speed to ensure the clarity and coverage of the imagery. For the inspection of the piers, the UAVs slowly ascended from the base to the top of the piers, recording high-definition videos of each side to ensure that every part of the piers was thoroughly inspected. In the acquired videos and images, advanced image processing techniques were used to extract and annotate damages on the cable-stays and piers, such as marking the locations of cracks in the cable-stays as shown in Fig 2. This included the identification and documentation of potential issues such as cracks and corrosion. With this method, we were able to effectively assess the overall health of the bridge and provide accurate data support for subsequent maintenance work.

In the comprehensive inspection of the bridge piers, the project's main tower, designed in a vase-like shape and standing 136 meters tall, showcased a unique structural design aimed at maximizing stability and durability. Detailed descriptions of each part of the tower were recorded, including segments of varying heights and the dimensions of both the tower top and base. This detailed structural information proved crucial for the planning and execution of UAV flight paths and subsequent data analysis. Prior to the UAV flights, meticulous pre-flight preparations were undertaken. This involved the careful selection of takeoff and landing sites and thorough checks of the necessary vehicles. Moreover, an exhaustive inspection of the UAVs was conducted to ascertain their performance and reliability for the mission, a critical step to ensure smooth data collection. During the flight data acquisition phase, the Independent Camera Control (ICC) system was utilized for the pier inspection, capturing images with a high degree of overlap. This method guaranteed sufficient overlap between images, facilitating high-precision image stitching and detailed analysis in the later stages of data processing. The comprehensive approach to data acquisition was instrumental in capturing the necessary details for a thorough evaluation of the piers' condition.

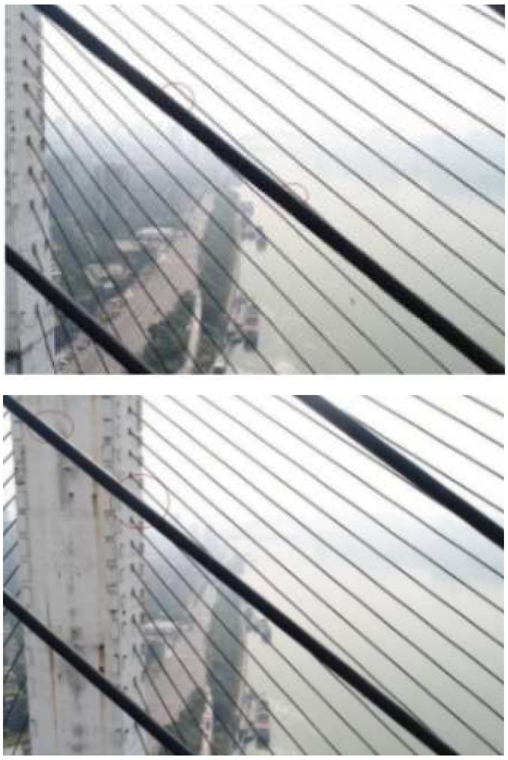


Fig. 2. Image-Annotated Diagram of the Cable-Stay Crack Locations (Cable NX-16 crack)

C. Integration of Advanced Formulas and Algorithms in Structural Integrity Assessment

In conducting a comprehensive structural integrity assessment of the Damen Bridge's cable-stays and piers, this study incorporated a variety of critical engineering mechanics formulas and advanced data analysis algorithms. The implementation of these mathematical and computational tools was instrumental in enhancing the accuracy and depth of our analysis. The fundamental stress-strain relationship, expressed as

$$\sigma = E\varepsilon$$

where σ signifies stress, E represents the material's modulus of elasticity, and ε denotes strain, played a key role in evaluating the tension and potential fatigue within the cable-stays. For the quantification of crack widths, we applied

$$W = \frac{P}{N}$$

with W representing the crack width, P the pixel count of the crack image, and N the conversion factor from pixels to actual length measurements.

In addressing the load-bearing analysis of the piers, the moment of inertia was calculated

$$I = \frac{1}{12} bh^3$$

where b is the base width and h is the height. This calculation was pivotal in determining stress and strain distribution under various load conditions. To detect and analyze structural damages more precisely, the study employed Fourier Transform to vibration data. This transformation from the time domain to the frequency domain allowed for the identification of abnormal vibration patterns, indicative of structural anomalies or damages. Moreover, Machine Learning algorithms, particularly Supervised Learning techniques, were deployed to analyze and classify the structural integrity data obtained. The use of algorithms such as Support Vector Machines (SVM) and Random Forests enabled the categorization of data points into healthy or damaged states based on their feature sets, thus enhancing the predictive accuracy of potential structural failures.

These advanced formulas and algorithms were essential in the data processing and analysis phase, particularly in the high-resolution defect detection and evaluation conducted through UAV imagery. The amalgamation of these sophisticated mathematical models and computational techniques facilitated precise calculations and predictions of the bridge's structural behaviors, thereby providing a robust scientific basis for maintenance and reinforcement strategies.

III. RESULTS AND DISCUSSION

In this study, through the use of advanced detection equipment and comprehensive data analysis methods, we conducted a thorough structural integrity assessment of the Damen Bridge's cable-stays and piers. As shown in Table 3, the inspection results revealed a total of 117 defects in the cable-stays and 24 defects in the piers, amounting to a combined total of 141 defects. This detailed tabulation provides a comprehensive breakdown of the defects, categorized by their specific types and locations, underscoring the thoroughness and precision of the UAV-based structural assessment. The calculated detection accuracy based on these sample of 141 identified defect was at a satisfactory level of 98.6%.

This finding is crucial for understanding the current structural health of the bridge and provides important data support for future maintenance and repair work. Detailed information about each defect are presented in Figure 4. This figure not only lists the specific locations and types of defects but also provides a preliminary assessment of their severity. These data, based on high-resolution imagery and precise measurements obtained from UAVs, ensure the accuracy and reliability of the assessment. Through this systematic analysis, we were able to identify the most critical weaknesses in the structure, providing guidance for subsequent repair work.

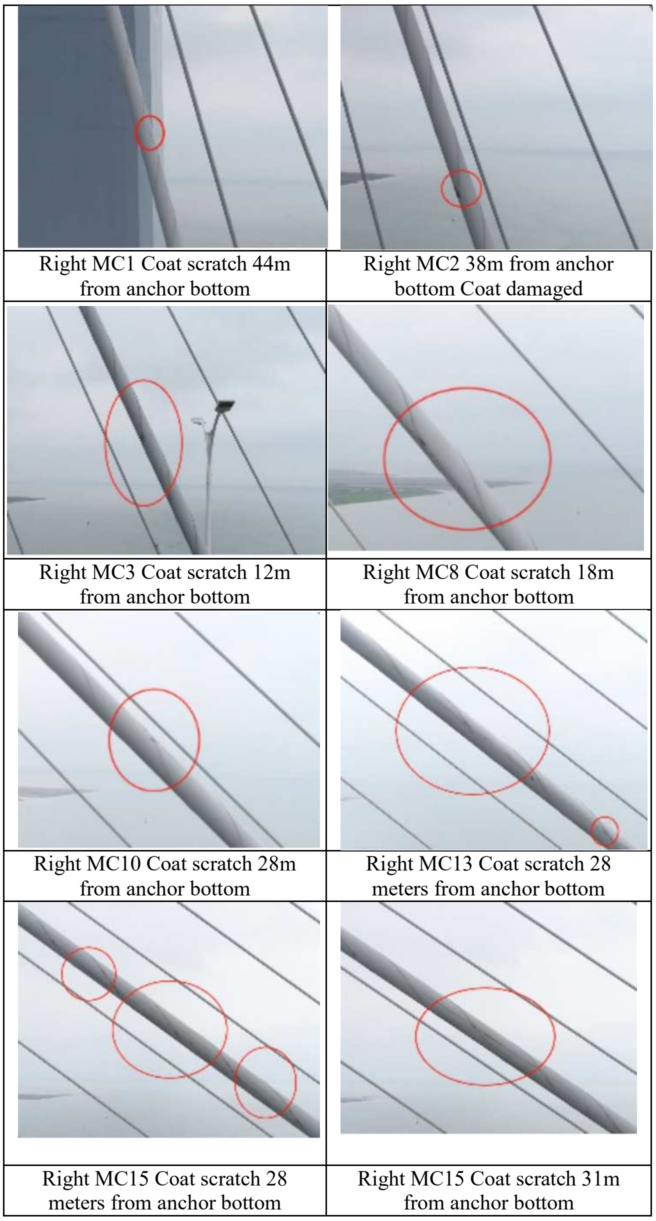
Table 3. Detailed Summary of UAV Inspection Results for Damen Bridge

Type of Defect	Identified by UAV	Correct Identification	False Positives
Crack	20	19	1
Corrosion	15	15	0
Wear and Tear	30	30	0
Displacement	52	52	0
Structural Crack	10	9	1
Erosion	14	14	0

IV. CONCLUSIONS

This study employed a range of advanced techniques and methodologies to conduct a comprehensive structural integrity assessment of the cable-stays and piers of the Damen Bridge in Wenzhou City. Utilizing rotary-wing UAVsand high-resolution cameras, among other sophisticated equipment, we successfully obtained detailed imagery of the bridge structure and accurately identified a total of 141 structural defects, including 117 in the cable-stays and 24 in the piers. These results not only demonstrate the effectiveness of UAVs and digital imaging technology in the field of bridge maintenance but also provide crucial data support for subsequent maintenance and repair activities. Detailed analysis of these defects allowed for a deeper understanding of the current health status of the bridge, thereby more effectively guiding maintenance efforts. Furthermore, the methodology of this study offers an efficient, safe, and cost-effective approach, providing significant reference value for health monitoring of similar large-scale bridges.

Future work will focus on further enhancing the accuracy and automation level of data analysis, as well as exploring the potential applications of UAV technology in a broader range of infrastructure inspection fields. Additionally, the integration of artificial intelligence and machine learning technologies for in-depth analysis of captured data will further improve the efficiency and accuracy of bridge health monitoring. The findings of this study demonstrate the tremendous potential of combining UAV technology with advanced data processing methods in bridge inspection and maintenance, offering new perspectives and solutions for future bridge health monitoring and maintenance strategies.



Right MC1 Coat scratch 44m from anchor bottom

Right MC2 38m from anchor bottom Coat damaged

Right MC3 Coat scratch 12m from anchor bottom

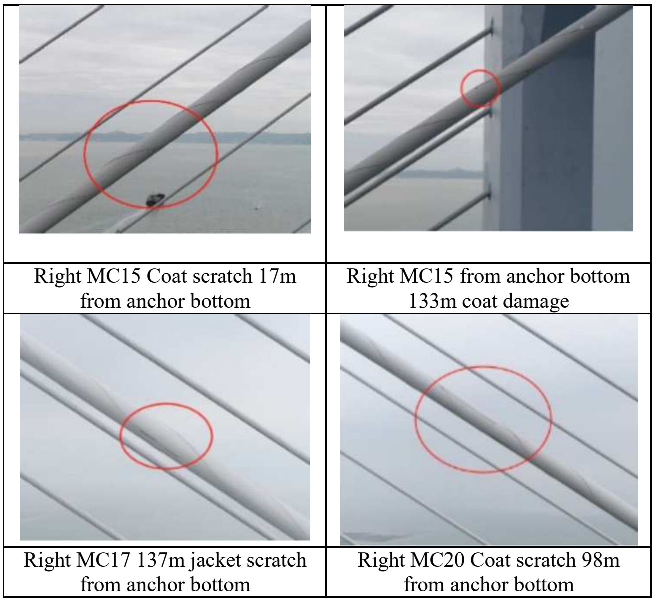
Right MC8 Coat scratch 18m from anchor bottom

Right MC10 Coat scratch 28m from anchor bottom

Right MC13 Coat scratch 28 meters from anchor bottom

Right MC15 Coat scratch 28 meters from anchor bottom

Right MC15 Coat scratch 31m from anchor bottom



Right MC15 Coat scratch 17m from anchor bottom

Right MC15 from anchor bottom 133m coat damage

Right MC17 137m jacket scratch from anchor bottom

Right MC20 Coat scratch 98m from anchor bottom

Fig. 4. Standards and guidelines for inspection basis

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