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Health Monitoring and Evaluation for the Cables or Suspenders in Cable-Strut System Bridges

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Abstract: *Since the late 1980s, cable-strut system bridges, including suspender bridges, cable-stayed bridges, and arch bridges, have been extensively constructed due to advancements in cable material technology. These structures are favored for their lightweight design, large spans, high navigational clearance and economic benefits. The stay cables or suspenders serve as critical components for force transmission in these bridges, and their safety and durability are paramount for the proper functioning of the structure. Unfortuantely, operational and environmental factors can lead to corrosion and fatigue damage in the cable systems, occasionally necessitating premature repairs or replacements of multiple cables or suspenders. To monitor and detect changes in the cable-strut system and mitigate potential damage, various protective measures and damage monitoring technologies have been proposed to ensure the safety of cable-strut system bridges. This paper first presents the types of cable damage and analyzes the mechanisms behind their formation, followed by a summary of the available detection technologies that have been implemented in practice.*

Keywords: *Stable-strut System Bridge; Cable or Suspender Damage; Operational and Environmental Factors; Damage Monitoring and Detection*

1. Introduction

Civil infrastructure systems, including bridges, buildings, pipelines and offshore structures, represent significant national assets that require ongoing maintenance to ensure both economic prosperity and public safety. In many developed nations, numerous bridge structures have reached the end of their intended design life and will necessitate either replacement or retrofitting to continue functioning effectively. For instance, in the United States, of the 611,845 public road bridges, 58,791 (9.6%) were classified as structurally deficient in 2015, while an additional 84,124 (13.7%) were deemed functionally obsolete [1]. A comparable scenario is anticipated in several European countries, where many existing bridges have now surpassed 50 years of age [2]. Consequently, there has been a significant focus among researchers on the assessment of structural conditions and the potential extension of service life for these critical infrastructures [3].

Since the late 1980s, the construction of stable-strut system bridges, including suspender bridges, cable-stayed bridges and arch bridges, has proliferated, largely due to advancements in cable material production techniques. These structures capitalize on several advantages, such as lightweight design, extensive spans, high navigational clearance, and cost efficiency. In these systems, cables (or suspenders) function as the primary load-bearing elements, and their safety and durability are crucial for the proper functioning of the overall structure.

Various factors can compromise the integrity of these bridges, including damage to the sheath during manufacturing, transportation, and construction; erosion of galvanized steel wires; aging of the sheath under operational environmental conditions; and the occurrence of wire cracks or fractures due to stress corrosion and corrosion fatigue resulting from combined corrosive and mechanical stresses. Collectively, these issues have led to significant damage in a considerable number of cable-strut system bridges, often necessitating premature repair or replacement of cables, as shown in Figure 1 and Table

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1. Regular maintenance and timely inspections are vital to avert catastrophic failures and to ensure that bridges can endure environmental stresses and increased traffic loads [4]. In extreme instances, such damage has resulted in deck collapses, breakages or structural failures.

For example, the Yibin South Gate Bridge in Sichuan Province, China, experienced short cable breaks and partial deck collapses on November 7, 2001. Investigations revealed severe corrosion at the edges of the main cables, with the area of the largest broken wire exceeding two-thirds of the cable's total cross-section. Significant corrosion was also noted in the adjacent cables. Currently, cable defects represent the predominant issues identified in arch bridges, with many of these defects leading to a degradation of mechanical properties, diminished durability and a reduced service life. Inspections of existing arch bridges indicate that a majority of cables are either already damaged or approaching failure. Although the designed service life of cables is typically 100 years, their actual lifespan often ranges from merely 3 to 20 years. While the introduction of prefabricated cables has slightly extended cable lifespans in recent years, multiple replacements remain necessary throughout a bridge's operational phase. Consequently, understanding cable behavior, investigating damage and degradation mechanisms, identifying key influencing factors, evaluating and predicting load-bearing capacity and residual lifespan, and establishing a scientific basis for refining design standards, failure criteria and applicable specifications for cables, have emerged as critical priorities in cable-related research.

(a) (b) (c) (d)

Fig.1 Typical case of damage for cable or suspender of the cable-strut system bridges

1) On September 13, 2002, at approximately 8:00 a.m., a wire rope on the Haiyin Bridge in Guangzhou Province, China, experienced a sudden failure. One end of the rope remained suspended from the bridge cable, while the other end extended over the deck, measuring over 20 meters in length. The fractured rope was entangled around the main cable, and the wires at the lower section of the cable had separated into four or five branches, which likely compromised its ability to endure the adverse effects of strong winds and rainfall.

2) The deck of the Peacock River Bridge, situated approximately 457 kilometers from National Highway No. 314 in the Bayingolin Mongolian Autonomous Prefecture of the Xinjiang Uygur Autonomous Region, China, collapsed at around 5:30 a.m. on April 12, 2011. The width of the collapsed section was approximately 25 meters. Fortunately, there were no reported injuries or vehicles that fell during the incident. At the time, the Peacock River Bridge, which featured a span of 150 meters and a width of 24.5 meters, was recognized as the largest steel arch bridge in northwestern

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China.

3) A structural failure occurred at approximately 8:50 a.m. on July 14, 2011, at the northern section of the Wuyi Mountain Mansion Bridge, China. This incident resulted in a tourist bus plunging into the river, leading to one fatality and 22 injuries. The Wuyi Mountain Mansion Bridge, which was completed on November 20, 1999, is characterized as a half-through steel arch bridge with a span of 301 meters and a width of 18 meters.

4) On October 3, 2006, a steel cable on the Xinlong Bridge, China, was abruptly severed. This particular cable was the fifth to fail on the eastern side of the bridge's cable frame. The fracture occurred at the junction between the cable and the frame, leaving the severed cable suspended in mid-air.

Table 1 The cable-strut system bridge damage accident all over the world

	Name of the Bridge	Location	Damage date	Damage condition/ Solution
1	Lake Maracaibo Bridge	Venezuela	1959-1962	Style cable breakage/ Changed cables
2	Köhlbrand Bridge	Germany	1969-1974	Style cable was corroded seriously/ Changed cables
3	Saint-Nazaire Bridge	French	1998/2002	Stay cable was corroded seriously
4	Aquitaine Bridge	French	1999	Main cable was corroded
5	Brotton Bridge	French	1984	Corrosive pits on the sheath/
6	Pont de Tancarville Bridge	French	1959	Main cable was corroded seriously/ Changed main cables
7	Williamsburg Bridge	USA	1921/1924/1963	Wires of the main cable corrode
8	Portsmouth General Grant	USA	1940	Anchor shoe was cracked
9	Pasco-Kennewick Bridge	USA	1925-1927	Cable load-capability failure/ Changed the cable
10	Mississippi river Bridge	USA	2007	Half of the bridge collapse
11	Seongsu Bridge	South Korea	1994	Cable fatigue break
12	Leshan Shawan Bridge	China	2011	Suspender and tied bar damage seriously/ Changed the spspender
13	Hangzhou Yeqingdou Bridge	China	2004	Ponding in the sheath, wire bare/ Changed the spspender
14	Yibin Xiao Nanmen Bridge	China	2001	Partly collapse, spspender breakage/ Changed the spspender

2. Cable-strut system damage

The characteristics of the cable or suspender, including its appearance, material composition, mechanical properties and other attributes, are subject to alteration due to various influences such as manufacturing processes, transportation, installation, construction, corrosion, fatigue, fire and additional factors. These changes may result in a loss of operational functionality or potential damage. The assessment of suspender defects has been categorized into three distinct types: sheath disease, anchor disease, and wire disease. Empirical tests conducted on actual bridges, along with relevant research, have identified sheath breakage, wire corrosion and the presence of cracks as the primary contributors to damage and degradation of the suspender, while the effects of other defects are considered negligible.

2.1 Sheath disease

Investigations into the deterioration of various bridge suspenders have revealed that the polyethylene (PE) protective sheaths of the majority of bridges exhibit both lateral and vertical cracking. The duration of crack development varies, with the shortest cracks identified as having formed over a period of one year, while the longest have been observed to exceed ten years. The types of damage include cracks, scratches, and both longitudinal and transverse fissures, with longitudinal cracks representing the predominant category of defects observed in the sheaths.

The reasons contributing to sheath damage can be categorized as follows: (1) The cable-strut structure experiences inappropriate force distributions, resulting in the high-density polyethylene (HDPE) sheath being subjected to sustained high-stress conditions. This scenario diminishes the sheath's ability to resist environmentally induced cracking, thereby facilitating the early onset of cracks. (2) The sheath's inadequate resistance to environmental stress-induced cracking, coupled with discrepancies in the thermal expansion coefficients of the filling materials, exacerbates the occurrence of sheath cracking. (3) Environmental factors such as light exposure, oxygen, temperature fluctuations, microbial activity, moisture and harmful gases contribute to the accelerated degradation and cracking of the sheath. (4) Initial damage may occur during the manufacturing, maintenance, or installation processes, such as when small drum diameters are utilized during reeling, potentially leading to cracking. Furthermore, operational incidents or impacts from suspender damping limit blocks may also compromise the integrity of the sheath. (5) The cooling contraction of HDPE material following repairs, particularly when the sheath is patched under tension at the repair site, can reactivate pre-existing damage. (6) Additionally, the extrusion of inspection robot vehicles during the diagnosis of cable-related issues may inadvertently inflict damage on the suspender sheath.

2.2 Anchor disease

Anchor head defects are primarily characterized by corrosion, cracking, deformation and seepage. Corrosion of the anchor head is predominantly observed on the threads of the outer surface of the anchor cup, where the accumulation of seepage and dust is more likely to occur. There is a scarcity of documented instances of anchor cracking, with only one case noted in the test report for the Maracaibo Bridge. Deformation of the anchor head typically occurs during the inspection process of post-tension cables at the factory, with the most common manifestation being the retraction of the anchor plate.

The infiltration of water into the anchor head can be attributed to various sources, including rainwater on the bridge deck and cable surfaces, condensate water from embedded pipes, and grouting water within the protective sheath. The factors contributing to seepage include: damage or cracking of the suspender protective sheath; gaps between tubes and cables within the beam structure; failure of the sealing mechanism; and cracking at the junctions between cables and lower anchor heads.

2.3 Suspender wires disease

Wire defects in suspenders predominantly manifest as corrosion, cracking, relaxation and breakage, with corrosion representing the most significant concern in defect assessments. The failure of protective measures, such as coatings or sleeves, facilitates direct exposure of the wires to corrosive environments, instigating electrochemical reactions that primarily contribute to wire corrosion. Environmental factors, including rainwater, humid air, and microorganisms present in the suspender's surroundings, can exacerbate this corrosion process.

Wire breakage is infrequently identified during standard inspections, however, corrosion-induced reductions in cross-sectional area or alterations in geometry can lead to localized stress concentrations, thereby diminishing the mechanical integrity of the wires. Over time, these conditions may culminate in inter-wire cracking. Additionally, slackness in suspender wires, which may arise from issues such as bundle offset (misalignment of the wire bundle), disrupts the load distribution among individual wires, resulting in significantly unbalanced stress and hastening wire failure.

Wire breakage is typically observed in main cables, stay cables and suspenders, and can be categorized into four primary types: (1) A-type broken wire, characterized by an initial crack that is perpendicular to the wire, which then skews at a 45-degree angle upon reaching 50% of the wire's cross-sectional area, ultimately forming a through crack [5]; (2) B-type broken wire, where the crack begins perpendicularly and then abruptly breaks when it extends to 50% of the cross-sectional area, resulting in a jagged fracture [5]; (3) C-type broken wire, which starts with a perpendicular crack that extends along the wire's direction, then reverts to the initial direction before fracturing suddenly [6]; and (4) D-type broken wire, which exhibits a sharp conical shape with no visible cracks nearby. Fracture analysis indicates that D-type breakage is primarily attributed to corrosion alone, while A-type and B-type breakages are mainly due to corrosion-fatigue. In contrast, C-type breakage results from a combination of stress-corrosion and corrosion-fatigue. Figure 2 illustrates each type of wire breakage [7].

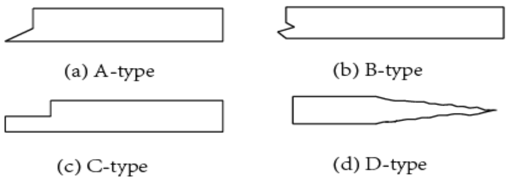

Fig.2 Four types of broken wire

In the context of suspender defects, the occurrence of sheath breakage does not diminish the bearing capacity of the structure. However, it significantly accelerates the corrosion of the zinc coating and the wires, thereby influencing the timing of corrosion onset in galvanized steel wire. The corrosion of the wire is a critical precursor to wire corrosion-fatigue or stress-corrosion cracking, necessitating comprehensive monitoring to ascertain its progression. This corrosion is a pivotal factor that contributes to the deterioration of the suspender system. In contrast, other defect types exert a comparatively minor influence on suspender damage and may be considered negligible.

Various factors can contribute to the degradation of cable-strut system bridges, which can be categorized into two main groups: natural disasters and long-term cumulative damage. Natural disasters encompass damage resulting from severe weather events such as high winds, flooding, earthquakes, and impacts from floating debris; such damage can often be mitigated through appropriate protective strategies. Long-term cumulative damage includes phenomena such as corrosive pitting, reduction in cross-sectional area, and wire fractures, which stem from the combined effects of fatigue and corrosion on bridge suspenders and cables subjected to prolonged, variable loads.

3. Loading behavior of the suspender

The interplay of various factors, including dead load, live load, concrete shrinkage and creep, temperature fluctuations, vibrations, construction inaccuracies and others, results in differential longitudinal deformation between the arch ribs and the deck of long-span arch bridges. This deformation generates bending and shear stresses within the tie rods. Due to their comparatively low stiffness, tie rods demonstrate a high degree of adaptability to deformation and typically do not experience substantial stress. In contrast, short tie rods, which possess greater stiffness and reduced adaptability to structural deformation, encounter more detrimental stress conditions. Particularly, the shortest tie rods are at heightened risk; the complex and adverse forces acting on their internal wires or steel strands can easily compromise the protective layer, thereby diminishing corrosion resistance and fatigue strength.

Field studies and investigations of actual bridges reveal that temperature variations and the vertical/longitudinal dynamic responses of the bridge deck under live load are the most significant factors contributing to tie rod damage. While other elements—such as construction or installation errors, concrete shrinkage and creep, and free vibrations of the deck—do induce longitudinal relative displacement between the upper and lower ends of the tie rods, the extent of this displacement is relatively minor and does not substantially impact the uniformity of internal force distribution within the tie rods.

Temperature effects encompass both overall structural temperature variations and localized temperature discrepancies along the tie rod sections. Overall structural temperature variations lead to considerable longitudinal relative deformation, whereas localized temperature differences create internal temperature stresses within the tie rods, further contributing to uneven internal force distribution. The dynamic responses of the bridge deck under live load conditions result in periodic fluctuations in the axial force of the tie rods, which significantly disrupt the uniformity of stress distribution and exacerbate fatigue issues. Consequently, the damage mechanism of tie rods must consider the degradation evolution of steel wires under the combined influences of static (dead load) and dynamic (live load) effects, as well as temperature-induced impacts.

4. Detection and monitoring of the bridge cable-strut system

The maintenance of safety and structural integrity in bridge cable-tie rod systems, which serve as essential load-bearing elements, is of paramount importance. The anchorage zone, characterized by its intricate force dynamics within the overall cable-tie rod framework, is particularly susceptible to vulnerabilities. External vibrations caused by environmental factors such as wind or rain can be transmitted to the anchorage zone, heightening safety risks as the service life of the structure extends. Numerous bridge failures worldwide, including collapses and the need for cable replacements, have been linked to corrosion or fractures within the anchorage zone, resulting in both direct and indirect economic repercussions. Conversely, investigations conducted by research institutions in various countries have revealed that many replaced suspenders or cables were found to be undamaged, leading to significant resource inefficiencies. A pertinent example is the Haixin Bridge in Guangzhou, which experienced a failure in Stay Cable No. 9 on May 25, 1995, with Stay Cable No. 15 subsequently identified as loose after its completion in late 1988. Consequently, relevant authorities undertook the replacement of all cables and suspenders within a six-month period, incurring costs estimated at approximately USD 3 million.

In light of these considerations, the implementation of regular inspections for bridge cables is essential. Such inspections facilitate the identification and subsequent repair or replacement of severely damaged cables or tie rods, thereby mitigating the risk of catastrophic failures. Additionally, the re-evaluation of cables or tie rods exhibiting surface cracks provides critical data to ascertain their continued viability for service, thus preventing unnecessary resource expenditure associated with indiscriminate cable replacements. Furthermore, routine inspections contribute to the assessment of the structural health of the bridge, allowing for timely intervention to address latent defects arising from construction. This proactive approach not only diminishes the likelihood of cable replacements but also ensures the safe operation of the bridge and aids in the development of a comprehensive bridge profile. These profiles are indispensable for the ongoing maintenance, repair, safe operation and technical guidance of bridge infrastructure.

4.1 Damage detection of the cable or suspender

(1) Manual detection

For an extended duration, manual inspection has served as the predominant approach for evaluating the cable-tie rod systems of long-span bridges. As showin in Figure 3(a), this process encompasses the examination of corrosion within the system, the inclination of tie rods, and the tightness of fasteners, among other visual assessments. Additionally, it necessitates the routine application of anti-corrosive paint to all components of the cable-tie rod system, timely removal of rust from corroded areas, quantification of the steel wires present in cables or tie rods, and an evaluation of the corrosion extent.

Nevertheless, manual inspection is constrained to the assessment of the external condition of the cable-tie rod system. It is incapable of detecting or evaluating the state of corroded wires without compromising the protective sheath, leading to several significant limitations: (1) It does not fulfill the requirements for the early detection and warning of corrosion or wire failures. (2) It may inflict considerable damage to the protective system during the inspection process. (3) It encounters difficulties in assessing the overall health of entire cables or tie rods. (4) It is characterized by being time-consuming, labor-intensive and costly.

(2) Climbing rope robot inspection

The robotic system comprises two principal components: the robot body and the robot car, as shown in Figure 3(b). The robot body is designed to ascend cables at various angles and autonomously execute a series of maintenance tasks, including inspection, polishing, cleaning, antistatic treatment, primer application, and topcoat application. It is equipped with a charge-coupled device (CCD) camera to facilitate real-time monitoring of operational conditions. Conversely, the robot car is intended to transport the robot body, supply water and paint, and concurrently monitor the operational status of the robot body at elevated positions.

The robot is capable of climbing up to 160 meters along cables at any inclination angle, achieving a climbing speed of up to 8 meters per second. When utilized in conjunction with other non-destructive testing methodologies, it can detect and identify instances of wire breakage along the cable. Furthermore, it is equipped to ascertain whether it has reached the top of the cable, monitor wind force and other environmental conditions, and execute appropriate responses.

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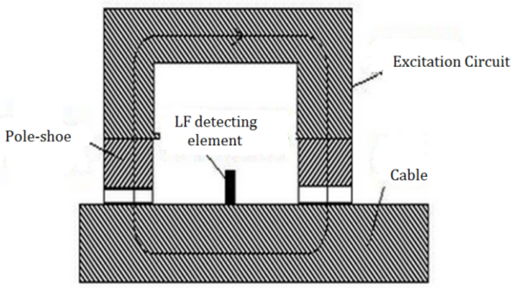
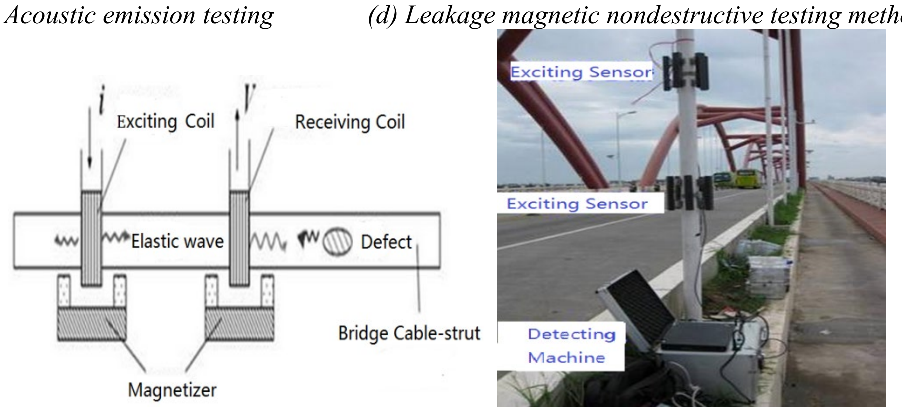
(a) Manual detection *(b) Detection by climbing rope robot*



(c) Acoustic emission testing *(d) Leakage magnetic nondestructive testing method*



(e) Magnetostrictive effect guided waves based detection

Fig.3 The common methods for suspender inspection

(3) Acoustic emission inspection[8]

Acoustic emission (AE) represents a non-destructive testing technique that does not necessitate any external energy input into the material. As shonw in Figure 3(c), this method relies on the detection of ultrasonic signals that are spontaneously emitted by materials under stress, which result from irreversible phenomena such as damage, microcracking, degradation, and corrosion. As a dynamic and passive detection technique, AE analyzes the ultrasonic pulses generated during the formation of cracks.

(4) Magnetic flux leakage detection technique [9-11]

The magnetic flux leakage (MFL) detection method utilizes the magnetic characteristics of parallel strands or wires within bridge cables. The operational principle involves magnetizing the cable through a permanent magnet excitation circuit, while a detector traverses along the cable, which simultaneously functions as a component of the excitation circuit, as shown in Figure 3(d).

In instances where a fracture occurs—resulting in a broken wire—a magnetic leakage field is produced. Consequently, any alteration in the total cross-sectional area of the wires within the cable leads to corresponding changes in the primary magnetic flux of the excitation circuit. Therefore, information regarding the defect status of the bridge cable can be derived by measuring fluctuations in the magnetic field. To improve measurement precision, a prevalent strategy involves the incorporation of a magnetic core during the leakage detection process, which facilitates the identification of leakage magnetic fields at varying levels.

(5) Magnetostrictive effect guided waves based detection[12-14]

The magnetostrictive effect is characterized by the phenomenon in which the dimensions (length and volume) of ferromagnetic materials experience minor alterations when subjected to an external alternating magnetic field. By modulating the magnetic field variations, this effect can produce a range of mechanical waves, including longitudinal waves (P-waves), torsional waves, flexural waves, and surface waves. These waves propagate along the confined boundaries of a structure and are guided by the geometry of the boundary, as shown in Figure 3(e). Additionally, when defects or fractures are present along the path of wave propagation, a portion of the wave signal is reflected, resulting in modifications to the wave signal characteristics. Ultimately, the extent of damage can be evaluated by capturing and analyzing the altered signals using sensors.

Magnetostrictive guided wave technology is predominantly utilized for the efficient assessment of extensive cable structures, particularly in the evaluation of cables, anchorages, stay cables, and tie rods within cable-stayed bridges and tie rod systems. The advantages of this technology in comparison to other nondestructive testing methods are as follows:

1) Internal damage within the entire cable system can be identified by simply installing the sensor and actuator on the cable in proximity to the bridge deck, thereby eliminating the necessity for comprehensive climbing rope inspections.

2) The method does not require any damage to the cable's polyethylene protective sheath or anchorage protection, and it circumvents the need for climbing rope inspections, thus preserving the integrity of the polyethylene protective system.

3) The detection range for cables extends beyond 50 meters, with capabilities reaching up to 200 meters or more. The detection distance in the anchorage area exceeds 7 meters.

4) This technology is capable of identifying damage across the entire cable length once the degree of damage at a given section surpasses a specified threshold; it achieves a detection rate exceeding 95% for steel cross-sections exhibiting a 5% loss. Under optimal conditions, it can detect damage corresponding to a 2% loss in the steel cross-section.

4.2 Force and load detection for the cable

As essential load-bearing elements of arch bridges, the service life and operational condition of tie rods significantly influence the overall safety of the structure. Consequently, it is imperative to monitor the stress states of tie rods. A critical concern is the accurate measurement of internal stress states, as this accuracy is pivotal for effective construction control of arch bridges and for ensuring the successful completion of the structure.

However, discrepancies in tie rod stress measurements frequently arise due to various factors, including the measurement devices employed, calculation models utilized, methods of tie rod anchorage, tie rod lengths, slope angles of twin suspenders, and other variables. Furthermore, measurement outcomes often demonstrate considerable variability across different projects. Therefore, the selection of appropriate measurement methodologies and data processing techniques is crucial, as it directly influences the efficacy of monitoring during arch bridge construction.

Common methods for inspecting cable force include load sensor measurement, pressure measurement via hydraulic methods, magnetic flux techniques, frequency methods, resistance strain methods, and fiber Bragg grating (FBG) sensor measurements for cable force assessment.

(1) Load sensor-based measurement method and pressure measurement type hydraulic measurement method[15]

The pressure sensor technique entails the installation of a sensor between the tool anchor cup and the hydraulic jack, enabling direct measurement of the tensile force exerted by the jack. This method is characterized by its high precision and ease of operation. However, the weight of the sensor presents practical challenges, and the measurement process is often time-consuming and labor-intensive.

An alternative pressure-based approach operates on the principle that the hydraulic pressure within the jack is directly proportional to the tensile force applied. Given a fixed effective area of the hydraulic cylinder, the tensile force can be derived by converting the measured oil pressure. This method is straightforward and does not necessitate additional equipment. Furthermore, it provides high accuracy in cable force measurement, particularly when the system has been pre-calibrated.

(2) Magnetic flux method[16]

The Magnetic Flux Method utilizes electromagnetic sensors embedded within the cable to detect fluctuations in magnetic flux. The force exerted on the cable is subsequently determined by examining the correlation among cable force, temperature, and variations in magnetic flux. A significant benefit of this approach is that it does not alter the mechanical or physical characteristics of the cable, aside from inducing magnetization within the cable itself. Nonetheless, this method necessitates calibration in the field and is vulnerable to disturbances caused by temperature variations and electromagnetic fields. Furthermore, it is associated with high costs and is predominantly suited for newly constructed cable-stayed bridges.

(3) Frequency method[17, 18]

To assess the dead load internal forces within bridge cables, a systematic methodology is generally employed. Initially, external excitation is introduced to induce vibrations in the cables, following the removal of any interference caused by live loads on the deck. The vibration signals from each cable are subsequently collected and analyzed using computational tools to determine their respective vibration frequencies. Utilizing principles from structural vibration theory, the dead load internal force for each cable is computed based on its vibration frequency and mass characteristics. For the purpose of signal acquisition, the excitation signal is captured by a servo acceleration sensor, which transmits the data to a data acquisition system where it is amplified and converted into digital format. The natural frequency of each cable is then analyzed through Fourier transform techniques. By incorporating various parameters, such as mass and stiffness, the internal force of the cable is ultimately calculated.

(4) Measurement of cable force using FBG sensors [19-23]

The central wavelength of a Fiber Bragg Grating (FBG) sensor experiences a shift in response to external strain and temperature variations. By demodulating the changes in this central wavelength, it is possible to effectively acquire data related to strain and temperature. The FBG sensor is particularly advantageous due to its compact size, high accuracy, resistance to electromagnetic interference, capability for distributed monitoring, and durability, making it an ideal choice for sensing applications.

4.3 Suspender Monitoring

Intelligent self-monitoring fiber grating technology has been developed for the assessment of the safety of suspenders and cables by continuously monitoring their strain. This technology is applicable to both new and existing suspenders and cables.

Health monitoring technology utilizing fiber grating for in-service suspenders involves the integration of fiber Bragg grating (FBG) sensors at critical locations, thereby facilitating the protection and maintenance of multiple in-service suspenders.

Additionally, the health monitoring of in-service suspenders and anchor heads can be achieved through acoustic emission technology. This method employs linear localization to detect damage locations and analyzes variations in waveform characteristics and frequency ranges to identify the types of damage. It effectively monitors common issues such as wire slippage, broken wires, and wear of anchor heads, allowing for the assessment of damage severity and localization of defects with high accuracy, all without necessitating bridge closures or traffic disruptions.

Flux magnetic technology serves as a diagnostic tool for suspender health, utilizing flux sensors to measure internal forces within suspenders, achieving measurement errors of less than 7%. Notably, the accuracy of these measurements improves as the internal forces increase, making this technology highly suitable for monitoring internal forces in suspenders.

Furthermore, corrosion monitoring technology is focused on predicting the corrosion fatigue life of tie rods and anchor heads, with the objective of evaluating their service life and safety performance within bridge structures.

Lastly, a method for evaluating the ultimate bearing capacity and reliability of suspenders has been developed. This involves an algorithm that calculates the reliability of tie rod arch bridges, assessing suspender safety based on the bearing capacity factor and incorporating a probabilistic reliability approach.

5. Conclusion

In comparison to conventional bridge systems, cable-stayed bridges present several notable advantages, including a lightweight design, substantial span capacity, elevated navigational clearance, and cost efficiency, which have contributed to their extensive construction worldwide. As the principal load-bearing element of the bridge, the integrity and longevity of the cable-stayed system are crucial for the proper functioning of the structure throughout its intended lifespan. Nonetheless, various components, including the sheath, internal steel wires, and anchorage systems, are susceptible to damage due to environmental and operational factors, such as high winds, precipitation, and heavy traffic. Common defects observed in bridges include corrosion, cracking, relaxation, and wire failure. Consequently, regular maintenance and real-time monitoring are imperative to avert potential accidents and structural failures.

This paper is organized as follows: Initially, it examines global bridge incidents attributable to damage in cable-stayed systems. Subsequently, it elucidates the load-bearing characteristics and damage mechanisms associated with tie rod internal wires, sheaths, and anchorage components. Finally, it emphasizes damage detection technologies and load-force measurement techniques that are prevalent in practical applications.

It is important to acknowledge that the detection technologies addressed in this study possess certain limitations, including operational challenges, low accuracy, time inefficiency, and high costs. Therefore, the development of innovative detection technologies to mitigate these shortcomings and improve practical applicability is both necessary and critical.

Acknowledgments

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