Correlation Characteristics of Multi-Source Monitoring Data of a Cable-Stayed Bridge under Multiple Loading Conditions

Weifeng Li[1,2], *Hongyin* Lam[1,*]

[1] Universiti Tun Hussein Onn Malaysia, Parit Raja, Johor, Malaysia
[2] Nanjing Vocational Institute of Transport Technology, Nanjing, Jiangsu, China

Abstract. Cable-stayed bridges are widely applied in long-span bridge systems, and their long-term operational safety remains a key concern. Structural Health Monitoring (SHM) systems provide continuous multi-source data; however, environmental actions, operational loads, and structural damage may produce complex correlations that complicate condition assessment. This study investigates correlation characteristics of SHM data from a concrete cable-stayed bridge under temperature loading, vehicle loading, and cable damage scenarios. Correlation relationships among girder deflection, stay cable force, and pylon displacement were evaluated using the Pearson correlation coefficient based on processed monitoring data. Results show that temperature effects dominate long-term structural responses and generate strong global correlations, whereas vehicle loading mainly induces transient responses. Complete cable fracture significantly alters correlation structures, while partial wire breakage has limited influence. The proposed framework supports reliable structural condition assessment and damage identification.

1 Introduction

Cable-stayed bridges are widely used in long-span bridge systems, and their long-term operational safety has become a critical concern.[1] During service, environmental and operational effects such as temperature variation and vehicle loading may alter structural responses and internal force distributions, while conventional inspections cannot provide real-time condition evaluation. Structural Health Monitoring (SHM) systems therefore enable continuous acquisition of multi-source data, including temperature, displacement, deflection, and cable force; however, data heterogeneity and environmental interference make direct assessment challenging.[2] Monitoring parameters often exhibit strong correlations, with temperature variations governing long-term structural trends and vehicle loading inducing transient high-frequency responses that complicate data interpretation. This study analyzes multi-source SHM data from a concrete cable-stayed bridge using time- and

*Corresponding author: uthmfrank@gmail.com

frequency-domain analyses, outlier detection, and data normalization to investigate correlations among girder deflection, cable force, and pylon displacement under different conditions. The results establish a multi-parameter correlation analysis framework that improves SHM data interpretation and supports more reliable damage identification for cable-stayed bridges.[3]

2 Characteristics and Processing of Structural Health Monitoring Data for Cable-Stayed Bridges

2.1 Fundamental Characteristics of SHM Data for Cable-Stayed Bridges

Structural Health Monitoring (SHM) systems for cable-stayed bridges employ multiple sensors at key structural locations to continuously collect data related to environmental conditions, load effects, and structural responses during long-term service.[4] Monitoring data typically include environmental parameters, such as temperature and wind speed, as well as structural responses, including girder deflection, displacement, pylon movement, and stay cable force. Although these data differ in time scale, variation characteristics, and physical meaning, their evolution is often interrelated due to the coupled behavior of the bridge structure. Based on physical attributes and sampling characteristics, SHM data can generally be classified into static and dynamic types: static data describe long-term structural variations, such as temperature-induced deformation, while dynamic data capture transient responses under vehicle loading and are characterized by randomness and high-frequency features. [5] Understanding these characteristics provides the basis for subsequent data processing and correlation analysis.

2.2 Time-Domain and Frequency-Domain Characteristics of SHM Data

2.2.1 Time-Domain Characteristics of Monitoring Data

Time-domain analysis is employed to investigate the temporal variation characteristics of monitoring data by describing the average level, fluctuation intensity, and effective response amplitude through representative indicators such as mean value, standard deviation, and root mean square (RMS), as summarized in Table 1. These indicators quantitatively characterize statistical properties of structural responses and provide a basis for comparative evaluation among different monitoring parameters.[6] Analysis of cable-stayed bridge SHM data indicates that temperature-induced responses generally exhibit long-term trend or periodic characteristics, whereas vehicle loading produces transient and stochastic fluctuations. Consequently, interpretation based solely on a single monitoring parameter is insufficient to reveal structural behavior mechanisms, and integrated multi-parameter analysis is required.

2.2.2 Frequency-Domain Characteristics of Monitoring Data

Frequency-domain analysis converts time-domain signals into the frequency domain to identify frequency components and their energy distributions. Common approaches include Fast Fourier Transform (FFT), Power Spectral Density (PSD) analysis, and dominant frequency identification, which are used to characterize the frequency components and energy distribution of monitoring signals, as summarized in Table 1. In cable-stayed bridge structural health monitoring, frequency-domain analysis helps distinguish responses caused by different external effects: temperature-induced responses mainly appear in low-frequency ranges due to gradual long-term variations, whereas vehicle loading generates medium- to high-frequency components associated with transient dynamic actions. Analysis of these frequency characteristics enables separation of response sources and provides a basis for subsequent correlation analysis and data decoupling.[3]

Table 1. Representative Signal Features Used in This Study

Type	Category	Formula / Method	Function
Time -domain	Mean value	$\bar{x}=\frac{1}{N}\sum_{i=1}^{N}x_i$	Describes the average response level
	Standard deviation	$x_{\mathrm{std}}=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i-\bar{x})^2}$	Reflects signal fluctuation
	Root mean square	$x_{\mathrm{rms}}=\sqrt{\frac{1}{N}\sum_{i=1}^{N}x_i^2}$	Indicates effective response amplitude
Frequency -domain	FFT	$X(k)=\sum_{n=0}^{N-1}x(n)e^{-j2\pi kn/N}$	Identifies frequency components
	PSD	$PSD(f)=\frac{1}{Nf_s}$	Describes the frequency-domain energy distribution
	Dominant frequency	$f_d=arg\ maxPSD(f)$	Identifies the main vibration frequency

2.3 Preprocessing Methods for Structural Health Monitoring Data

In practical engineering applications, structural health monitoring (SHM) data of cable-stayed bridges are inevitably affected by sensor malfunctions, communication interruptions, and environmental disturbances. As a result, the collected monitoring data may contain outliers, missing values, and noise contamination. If such issues are not properly addressed, the reliability of subsequent data analysis and correlation evaluation may be significantly compromised.

Therefore, prior to conducting correlation analysis of monitoring data, it is essential to perform systematic preprocessing of the raw data. Typical preprocessing procedures include outlier detection, missing data reconstruction, noise filtering, and data normalization, as summarized in Table 2. These preprocessing steps aim to enhance data quality, improve consistency among different monitoring parameters, and ensure the validity of subsequent statistical and correlation analyses.

Table 2. Abnormalities in Bridge Monitoring Data and Processing Methods

Data issue	Processing method	Purpose
Outliers	3σ criterion	Remove abnormal data caused by sensor or transmission errors
Missing data	Spline interpolation	Reconstruct short-term missing monitoring data
Noise disturbance	Smoothing or filtering	Reduce random fluctuation in monitoring signals
Different scales	Normalization	Improve comparability among different monitoring variables

2.3.1 Outlier Identification and Removal

Outliers in monitoring data usually appear as isolated data points or abrupt segments that deviate significantly from the general variation trend. These abnormal values are often caused by sensor malfunction, signal transmission errors, or temporary external disturbances. In this study, the statistical 3σ criterion was adopted to identify and remove outliers. According to this criterion, a monitoring value y_k is regarded as abnormal when $|y_k - \bar{y}| \geq 3\sigma$ where $\bar{y}$and σ denote the mean value and standard deviation of the monitoring series, respectively. The abnormal values identified by this criterion were removed or replaced using adjacent normal data to maintain the continuity of the monitoring sequence. Fig.1 compares the deflection monitoring data before and after outlier removal. The results indicate that the 3σ criterion can effectively remove unrealistic data points while preserving the overall variation trend of the structural response. Therefore, the quality of the monitoring data is improved without significantly distorting the inherent response characteristics.[7]

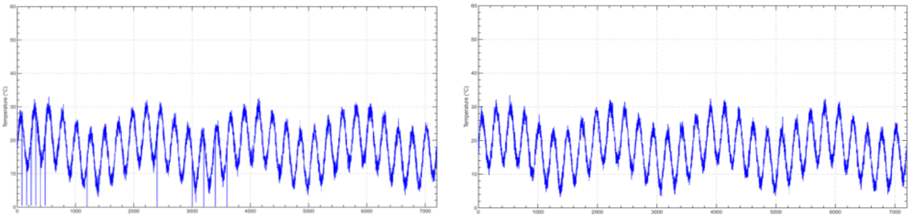


Fig. 1. Comparison of Deflection Signals Before and After Outlier Removal

2.3.2 Missing Data Processing and Data Smoothing

Missing monitoring data are typically caused by temporary sensor malfunction or communication interruptions. For short-duration data gaps, interpolation techniques can be employed to reconstruct the missing values. In addition, for monitoring signals affected by significant noise, smoothing methods are applied to reduce random fluctuations and improve signal stability.

Proper data reconstruction and smoothing procedures help maintain the continuity and consistency of monitoring data, thereby enhancing data reliability for subsequent analysis. Fig. 2 presents a comparison of the monitoring signals before and after missing data reconstruction.

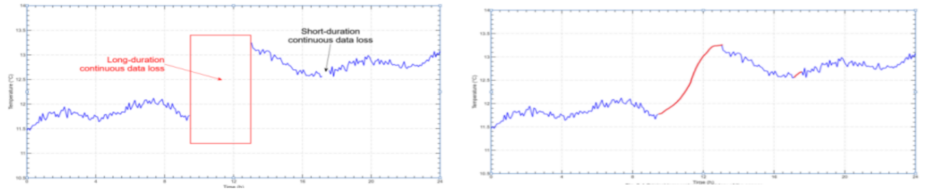


Fig. 2. Comparison Before and After Spline Interpolation of Missing Data

2.3.3 Data Normalization

Due to significant differences in units and numerical ranges among various types of monitoring data, direct comparison and correlation analysis may lead to biased results. Therefore, prior to conducting multi-parameter correlation analysis, data normalization is required to transform different monitoring variables onto a unified numerical scale.Normalization reduces the influence of magnitude disparities among variables and enhances the comparability and reliability of subsequent analytical results. By ensuring consistency in data scale, the effectiveness and stability of correlation analysis can be significantly improved.

2.4 Pearson Correlation Analysis of Monitoring Data

Prior to correlation analysis, monitoring data preprocessing is required to ensure reliability and comparability. Outliers caused by sensor malfunction, transmission errors, or external disturbances are identified using the statistical 3σ criterion. Data normalization is subsequently applied to eliminate the influence of different physical units and numerical scales among monitoring variables.[7] Through preprocessing, monitoring datasets are transformed into a consistent analytical form, improving the stability and effectiveness of subsequent correlation analysis. The preprocessing procedures are presented concisely here because they serve primarily as preparatory steps for the proposed correlation evaluation framework rather than as the main research contribution.

In this study, correlation analysis specifically refers to the Pearson correlation coefficient. For two synchronized and normalized monitoring series X and Y, the coefficient is calculated as

$$r_{XY} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (1)$$

where r_{XY} ranges from −1 to 1 and is used to quantify the linear relationship among temperature, girder deflection, stay cable force, and pylon displacement.

3 Correlation Analysis of Monitoring Data under Temperature and Vehicle Loading

3.1 Engineering Background and Overview of the SHM System

In this study, a cable-stayed bridge was selected as the research object. After its completion, a comprehensive Structural Health Monitoring (SHM) system was installed to continuously monitor environmental conditions, structural responses, and the operational status of key components during long-term service.[8] The layout of the SHM system is illustrated in Fig.

3.The monitoring system includes measurements of air temperature and structural temperature, main girder deflection, longitudinal displacement at the girder ends, pylon top displacement, and stay cable forces. These monitoring parameters provide a comprehensive representation of the structural behavior of the cable-stayed bridge under various working conditions, enabling systematic analysis of its response characteristics.

3.2 Correlation Analysis of Structural Responses under Temperature Effects

3.2.1 Correlation Characteristics between Temperature Variation and Main Girder Responses

Temperature variation is a dominant environmental factor affecting the structural response of cable-stayed bridges. Finite element analysis shows that unit temperature changes cause noticeable variations in stress and midspan deflection of the main girder, exhibiting a stable linear relationship with temperature, as illustrated in Fig. 4. Deflection responses at different girder locations follow

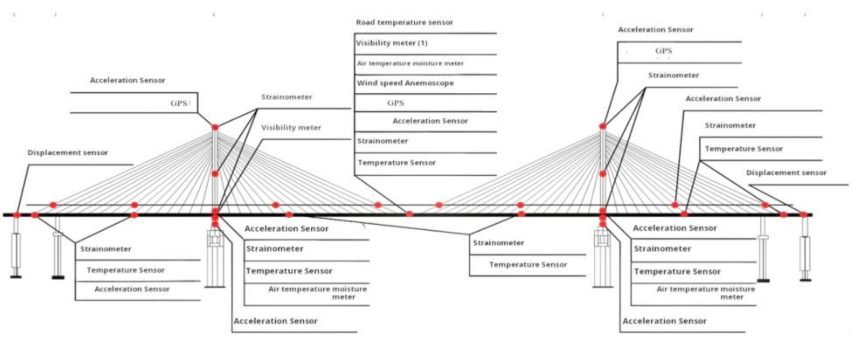


Fig. 3. Full-Bridge Sensor Layout of the Cable-Stayed Bridge Structural Health Monitoring System

consistent trends under temperature variation, indicating a relatively uniform spatial influence of thermal effects. This consistency highlights the strong sensitivity of girder deflection to temperature and provides a basis for correlation analysis among deflection monitoring data.

Temperature effects on stay cable forces vary with cable location, as shown in Fig. 5, where BK and ZK denote the side span and main span, respectively. Under temperature increase, long cables near the side span experience reduced forces, while cables near the pylon on the side-span side show increased forces, and short cables near the main-span pylon exhibit decreased forces; opposite trends occur during temperature decrease. Larger force variations are observed in long side-span cables and short cables adjacent to pylons, whereas mid-region cables show smaller transitional responses. Additionally, temperature increase reduces cable forces near the main-span midspan, while temperature decrease produces the opposite effect. [9][10]

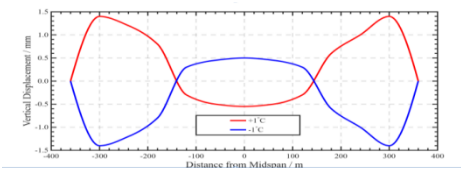


Fig. 4. Variation of Main Girder Deflection under a Unit Temperature Change

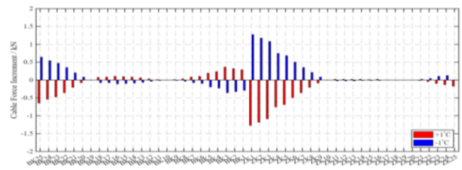


Fig. 5. Variation of Cable Force under a Unit Temperature Increase

3.2.2 Correlation Characteristics between Temperature Effects and Stay Cable Force Variation

Stay cables are critical load-bearing components in cable-stayed bridges, and their force variations are highly sensitive to temperature effects. Finite element analysis shows that temperature changes cause significant force variations in long cables located in both the side span and main span, as well as noticeable changes in short cables near the pylons. Although responses differ among cable locations, their overall variation trends exhibit clear correlation, reflecting internal force redistribution within the structural system under thermal effects.

These findings indicate that long-cable force variations should receive particular attention in structural health monitoring systems. Monitoring these parameters provides valuable indicators for evaluating structural performance and supports reliable assessment of operational safety under temperature-induced conditions.

3.3 Correlation Analysis of Monitoring Data under Vehicle Loading

3.3.1 Influence of Vehicle Loading on Main Girder Structural Responses

Vehicle loading represents one of the primary operational effects acting on cable-stayed bridges during service. It induces noticeable transient disturbances in structural responses.[11] Finite element analysis results indicate that under vehicle loading alone, significant variations occur in the midspan deflection of the main girder as well as in the forces of side-span cables, as illustrated in Fig. 6 and Fig. 7. The magnitude of these variations is closely related to both the intensity and the position of the applied vehicle load.Compared with temperature effects, vehicle-induced structural responses are characterized by short duration and strong fluctuations. This transient nature results in monitoring data with distinct time-scale characteristics compared to temperature-induced responses. Consequently, the structural behavior under vehicle loading exhibits pronounced temporal variability, which should be carefully distinguished from long-term environmental effects during monitoring data analysis.[12]

3.3.2 Correlation Characteristics of Monitoring Data under Vehicle Loading

Analysis under vehicle loading conditions shows that main girder deflection, stay cable forces, and pylon displacement exhibit synchronous responses during vehicle passage, indicating correlated behavior among structural components. However, due to the randomness of vehicle loading, these correlations are transient and unstable over long time scales, typically appearing as short-term high-frequency fluctuations distinct from long-term environmental effects. Therefore, SHM data analysis should account for time-scale characteristics and properly identify and process vehicle-induced high-frequency responses to prevent short-term operational disturbances from affecting long-term structural performance evaluation.

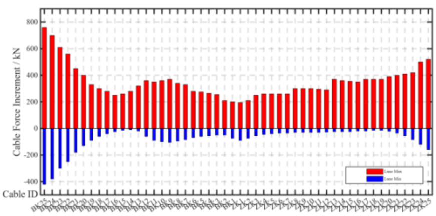


Fig. 6. Variation of Stay Cable Forces under Vehicle Loading

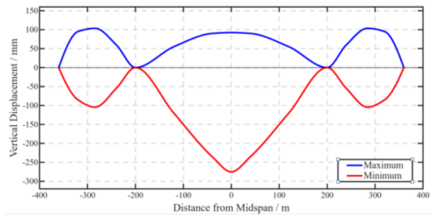


Fig. 7. Variation of Main Girder Deflection under Vehicle Loading

3.4 Comparative Analysis of Correlation Characteristics under Different Loading Conditions

A comprehensive comparison of temperature and vehicle loading effects reveals significant differences in their influence mechanisms on structural responses of cable-stayed bridges. Temperature variation primarily affects the global deformation of the structure and the redistribution of cable forces, with monitoring data exhibiting sustained and often periodic trends. In contrast, vehicle loading mainly induces localized and transient responses characterized by short duration and randomness.Therefore, when conducting correlation analysis of SHM data for cable-stayed bridges, it is essential to distinguish between different loading types and their corresponding time-scale characteristics. Proper separation of environmental and operational effects enhances the accuracy and reliability of monitoring data interpretation and structural condition assessment.[13]

4 Correlation Characteristics of Monitoring Data under Cable Damage Conditions

4.1 Cable Damage Scenarios and Analytical Method

Stay cables are primary load-bearing components of cable-stayed bridges, and their force

state directly affects the global structural safety of the bridge.[14] To investigate the influence of cable damage on structural responses and monitoring data characteristics, numerical simulations were conducted using a validated finite element model of the bridge.Two representative cable damage scenarios were considered: partial wire breakage and complete cable fracture. By comparing the structural response variations of key components—including the main girder, stay cables, and pylons—under different damage conditions, the correlation characteristics among monitoring parameters and their sensitivity to damage severity were analyzed. The objective is to provide a basis for cable damage identification and determination of key monitoring indicators.

4.2 Correlation Characteristics under Partial Wire Breakage

When partial wire breakage occurs in a stay cable, finite element results indicate that the overall structural force system remains relatively stable. The variations in global structural responses, such as main girder deflection and pylon displacement, are limited in magnitude. Moreover, the overall variation trends among different monitoring parameters remain generally consistent, without pronounced abnormal features.[15]

Four representative damage scenarios were analyzed for comparison:

(1) 10% cross-sectional area reduction of a side-span long cable;

(2) 10% cross-sectional area reduction of a main-span long cable;

(3) 10% cross-sectional area reduction of a side-span short cable;

(4) 10% cross-sectional area reduction of a main-span short cable.

From the perspective of monitoring data correlation, partial wire breakage primarily induces localized changes in the force of the damaged cable itself, while its influence on adjacent cables and global structural responses is relatively limited. As a result, most monitoring parameters maintain their original correlation relationships under partial damage conditions, indicating relatively low sensitivity of multi-parameter monitoring data to this type of localized damage. The corresponding results are illustrated in Fig. 8 and Fig. 9.

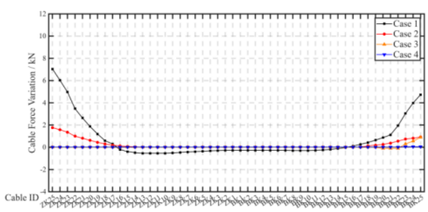


Fig. 8. Stay Cable Force Variation under Cable Damage Condition

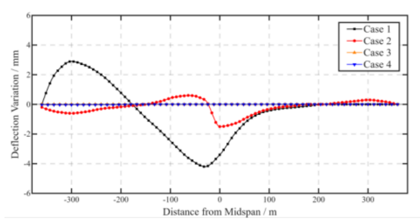
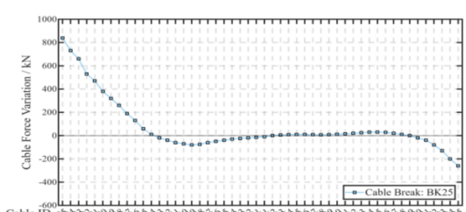


Fig. 9. Variation of Main Girder Deflection under Partial Wire Breakage

4.3 Correlation Characteristics under Complete Cable Fracture

Under side-span long-cable fracture conditions, correlation characteristics among monitoring parameters change markedly. Cable forces near the damaged-cable pylon differ significantly from those at the opposite side, as illustrated in Fig. 10 and Fig. 11, while correlations among global structural responses, such as girder deflection, become notably stronger with consistent variation trends (Fig. 12). These modifications reflect internal force redistribution after severe damage and demonstrate the effectiveness of multi-parameter correlation analysis for identifying and characterizing critical structural failures.



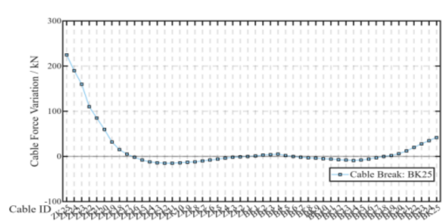


Fig. 10. Variation of Cable Forces on the Pylon Side under Cable Breakage

Fig. 11. Variation of Cable Forces on the Opposite Pylon Side

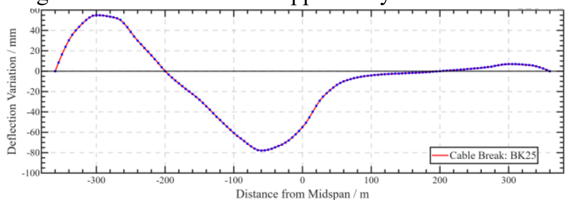


Fig. 12. Variation of Main Girder Deflection

4.4 Comparative Analysis of Correlation Characteristics under Different Cable Damage Types

A comparative analysis between partial wire breakage and complete cable fracture reveals significant differences in their influence on the correlation characteristics of monitoring data. Partial wire breakage represents a localized and relatively controllable damage scenario, exerting limited influence on the global structural response and on the correlation relationships among multiple monitoring parameters. In contrast, complete cable fracture substantially alters the structural load-bearing system, resulting in abrupt changes in the correlation structure among monitoring variables.

Furthermore, the results indicate that fracture of long cables in the main span has a more pronounced impact on overall structural safety compared with short cables. Therefore, within the SHM system of cable-stayed bridges, long cables should be prioritized as critical monitoring targets. Integrating multi-parameter correlation analysis can significantly enhance the reliability and robustness of cable damage identification.

5 Conclusions

This study examined correlation characteristics of multi-sensor structural health monitoring (SHM) data for a cable-stayed bridge using Pearson correlation analysis. Results show that temperature variation dominates long-term structural correlations, producing stable and consistent relationships among monitoring parameters, whereas vehicle loading mainly induces short-term transient correlations with limited persistence. Structural damage affects correlation structures according to severity, with complete cable fracture causing significant reconstruction of inter-parameter relationships. The application of Pearson correlation analysis enables quantitative evaluation of linear dependency among monitoring parameters, thereby improving the reliability of sensor anomaly detection and structural condition assessment. The proposed framework provides an effective basis for interpreting multi-source SHM data and supporting bridge safety monitoring.

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