Smart Structures and Systems, *Vol. 26, No. 1 (2020) 11-21*
DOI: https://doi.org/10.12989/sss.2020.26.1.011

Cloud monitoring system for assembled beam bridge based on index of dynamic strain correlation coefficient

Yiming Zhao [1,3a], Danhui Dan*[1,2], Xingfei Yan [4b] and Kailong Zhang [4c]

[1] *School of Civil Engineering, Tongji University, 1239 Siping Road, Shanghai, 200092, China*
[2] *Key Laboratory of Performance Evolution and Control for Engineering Structures of Ministry of Education, Tongji University, 1239 Siping Road, Shanghai, 200092, China*
[3] *Shanghai Construction Group, Engineering General Institute, Shanghai, 201114, China*
[4] *Shanghai Urban Construction Design Research Institute, Shanghai, 200125, China*

(*Received August 31, 2019, Revised April 9, 2020, Accepted April 20, 2020*)

Abstract. The hinge joint is the key to the overall cooperative working performance of the assembled beam bridge, and it is also the weakest part during the service period. This paper proposes a method for monitoring and evaluating the lateral cooperative working performance of fabricated beam bridges based on dynamic strain correlation coefficient indicator. This method is suitable for monitoring and evaluation of hinge joints status between prefabricated girders and overall cooperative working performance of bridge, without interruption of traffic and easy implementation. The remote cloud monitoring and diagnosis system was designed and implemented on a real assembled beam bridge. The algorithms of data preprocessing, online indicator extraction and status diagnosis were given, and the corresponding software platform and scientific computing environment for cloud operation were developed. Through the analysis of real bridge monitoring data, the effectiveness and accuracy of the method are proved and it can be used in the health monitoring system of such bridges.

Keywords: cloud monitoring and diagnosis system; assembled beam bridge; dynamic strain; correlation coefficient; lateral collaborative working performance

1. Introduction

In recent years, China has built 823,000 highway bridges, ranking first in the world. Despite this, it is still unable to meet the rapidly growing transportation needs, and there is still an urgent need for bridge construction throughout the country. In some busy central and eastern regions or western cities, it is not only necessary to continue to build a large number of bridges, but also requires simultaneous development of transportation network operations, which imposes restrictive requirements on the construction period and construction speed of bridges. Rapid bridge construction technology can speed up the construction of bridges, reduce the total cost of the project, and minimize the adverse impact on existing traffic. Therefore, it has been rapidly developed around the world in recent years (Mashal *et al*. 2017, Culmo 2011, Aktan and Attanayake 2015, Chung *et al*. 2008). In China, the rapid bridge construction technology with assembled beam bridges as the main bridge type has been developed for nearly 30 years, which is the bridge type with the highest proportion at present. In recent years, with the requirements for construction efficiency and environmental protection, this trend has been translated into the policy needs of national governments (General Office of the State Council 2016).

The assembled beam bridges are characterized by high industrialization, low cost, rapid and efficient construction, and therefore becomes one of the common bridge types when the highway and other infrastructures cross obstacles such as mountains and rivers. The assembled beam bridge has simple structure and small span. The main beam section is mainly hollow slab, T-shaped beam and small box girder that the mechanical characteristics are clear and the design theory is sound. Benefiting from the advantages of easy control of factory processing quality, the mechanical properties of prefabricated girders can generally be fully guaranteed (Jahromi *et al*. 2018a, b, Shah *et al*. 2007). However, the overall performance of fabricated bridges does not depend solely on the mechanical properties of the single prefabricated girder, but rather depends to a large extent on the combined force capacity of the individual girders after assembly as a whole (Bakht and Jaeger 1992, Abendroth *et al*. 1995). That is, the external load is distributed to all single-girder through the lateral connection system. This lateral connection system is mainly composed of longitudinal joints and lateral beams between the prefabricated girders, and its strength will directly affect the force distribution of the prefabricated girders.

In the course of service, the main problems of this kind of bridge structure lie in the degeneration of lateral

*Corresponding author, Professor,
E-mail: dandanhui@tongji.edu.cn
[a] Ph.D. Student, E-mail: chabansheng588@163.com
[b] Ph.D., E-mail: yanxingfei@163.com
[c] Ph.D., E-mail: zhangkailong@sucdri.com

http://www.techno-press.org/?journal=sss&subpage=7 ISSN: 1738-1584 (Print), 1738-1991 (Online)

connection capacity and the destruction of weak parts of joints. The joint failure is the weakening of the lateral connection of the assembled beam bridges, which will make the force distribution between the girders uneven, and the internal force of the single-girder will become larger. It can not only cause its own safety problems, but also cause other various diseases. A timely understanding of the lateral cooperative working ability of the assembled beam bridge and the working status of the joint between the prefabricated girders will help to form a correct and timely management decision for the service period, thereby ensuring the safety and durability of the bridge (Wen *et al*. 2017, Dan *et al*. 2018). It is very necessary to use monitoring and evaluation methods to achieve the above objectives during the operation period of assembled beam bridges without interruption of traffic.

Over the past two decades, bridge structural health monitoring systems have been mostly applied to long-span bridges. Through the construction of a complete monitoring system, the monitoring of bridge technical parameters, status, and even damage can be achieved (Ding *et al*. 2018, Ye *et al*. 2017, He *et al*. 2018). Some small and medium-sized bridges have also begun to install simplified monitoring equipment for specific purposes such as load monitoring, response monitoring and disease monitoring (Seo *et al*. 2015, Miyamoto *et al*. 2018, Ma and Solís 2018). Because of the cost, these small and medium-sized bridges are often monitored by means of remote monitoring technology. Only data acquisition system is installed on site. Monitoring data are transmitted to the remote end through Ethernet and 3G/4G wireless communication network. Therefore, Internet of Things technology, cloud computing technology and cyber physical system become the best choice for the construction of such bridge monitoring system (Ozer and Feng 2019, Miyamoto and Motoshita 2017, Loubet *et al*. 2019, Fu *et al*. 2019).

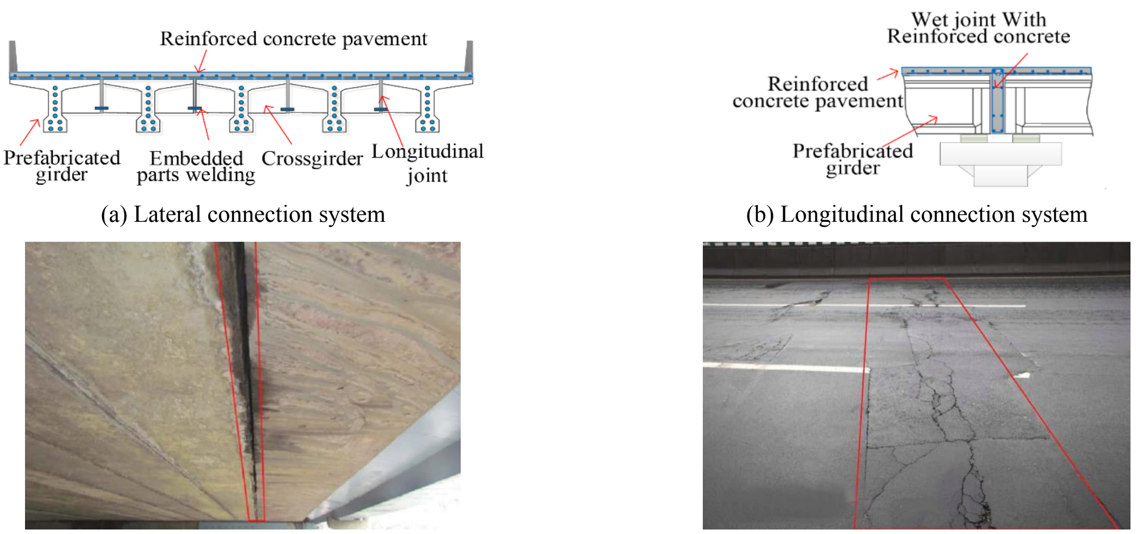
In view of this, aiming at the basic laws of mechanical properties and diseases of assembled beam bridges during service period, this paper puts forward a monitoring index of transverse cooperative working ability of assembled beam Bridges Based on strain monitoring information, and constructs a remote cloud monitoring and diagnosis system for assembled beam bridges around the online monitoring and identification of the index. With this system, the online remote monitoring and evaluation of the viaduct on Tongji Road is realized.

2. Key monitoring mode and cloud system

Most of assembled beam bridges are small-size and medium-size, with simple structures. Therefore, the related monitoring method should be different from large-span or complex bridges. The cost of monitoring systems should also be an important constraint. In order to maximize the utilization of limited monitoring resources, we should identify the key mode firstly, and then design the related cloud system.

2.1 Key monitoring mode

Assembled beam bridge is constructed by placing the prefabricated girders in place and then installing the lateral and longitudinal connection system. Among them, the lateral connection system mainly includes cross girder, reinforced concrete pavement, longitudinal joint and embedded parts welding, as shown in Fig. 1(a), and the longitudinal connection system, which is aimed at simply supported and then continuous structure system, mainly includes wet joint with reinforced concrete and reinforced concrete pavement, as shown in Fig. 1(b). With regard to the hollow slab girder, T-shape girder, or griders of other cross-section, the most important diseases during long-term use are longitudinal joints failure and lateral cracking of reinforced concrete pavement over the piers, which respectively means the occurrence of two most unfavorable mechanical stress states, includes the loss of lateral cooperative capacity and the degeneration of the bridge



(a) Lateral connection system

(b) Longitudinal connection system

(c) Longitudinal joints failure

(d) Lateral cracking of pavement over the piers

Fig. 1 Two connection systems of the assembled beam bridge force mode that is delegating from continuous beam bridge to simply supported beam bridge. The two states are not allowed to occur during the service period, and must be prevented as early as possible.

Structural health monitoring technology can measure the response of bridge by sensors, and recognize the working status of the bridge on line. It aims at detecting structural disease in advance to ensure bridge safety. In response to the above requirements for assembled beam bridges, we will propose a method to monitor the key mechanical parameters of the bridges, identify two unfavorable stress states, and finally achieve early detection of the two main diseases.

Due to the time-varying characteristics and randomness of vehicle loads, the mechanical response of structure also changes over time and presents significant randomness. The response related to structural diseases are commonly overwhelmed by the vehicle load effect, can not be directly obtained from monitoring information. Certain data analysis algorithms must be adopted to find the disease information from the monitored response of structure. In the previous study (Wen *et al*. 2017, Dan *et al*. 2018), we have proposed an evaluation indicator for assembled beam bridges based on dynamic strain. It is defined as the correlation coefficient of the longitudinal strain at the mid-point of the bottom of each girder. Let ε_i and ε_j represent the longitudinal strain time series of the i-th and j-th prefabricated girders respectively, the indicator ρ_{ij} can be demonstrated as

$$\rho_{ij} = \frac{Cov(\varepsilon_i, \varepsilon_j)}{\sqrt{D(\varepsilon_i) \cdot D(\varepsilon_j)}} \tag{1}$$

where i and j rank from 1 to n, and n represents the total number of the girders, Cov represents covariance, D represents variance. Through theoretical analysis, numerical simulation and real bridge monitoring data analysis, we have proved that the indicator is not affected by vehicle loads, can effectively recognize the lateral cooperative working capacity among the girders, and can evaluate the status of the longitudinal joints.

Thus, in the basis of the indicator ρ_{ij}, a key monitoring mode of the assembled beam bridge can be given, which aims to evaluate the lateral cooperative working capacity among the girders. The Structural health monitoring system should be designed to measure strain, and to recognize the performance of every hinge joint. The steps can be clarified as follows.

(a) Install longitudinal strain sensors at the mid-point of the bottom of every girder.
(b) Measure the strain response under the live loads synchronously in real time.
(c) Process the data continuously to calculate the indicator ρ_{ij} among the girders.
(d) Evaluate the stiffness changes of the hinge joints.

2.2 Remote cloud monitoring system

Taking an assembled continuous beam bridge in Shanghai as an example, which has three spans and each span is composed of 17 hollow slab girders with a length of 20 meters. To investigate the lateral cooperative working capacity of the bridge, we have installed one Fiber Bragg Grating (FBG) strain sensors on the surface of each girder, and the installation position is unified at the center of the girder bottom. The total number of sensors is 51. The strain data is collected by the on-site FBG demodulator continuously and synchronously at a sampling rate of 50 Hz, and transmitted to the cloud server in real time by the remote gateway. Data analysis work is completed in the cloud. The topology diagram of the entire remote cloud monitoring system is shown in Fig. 2.

As the relative stiffness of short span bridge is generally large, and the strain effect under the vehicle load, which is the key parameter to calculate the indicator, is always small. In order to acquire the part of strain under the vehicle load, the sensors should be selected concerning the accuracy and resolution, up to one micro-strain level. This high accuracy strain sensor must be securely connected to the concrete at the bottom of the girder by means of expansion screws and be protected by an integral stainless-steel shield, as shown

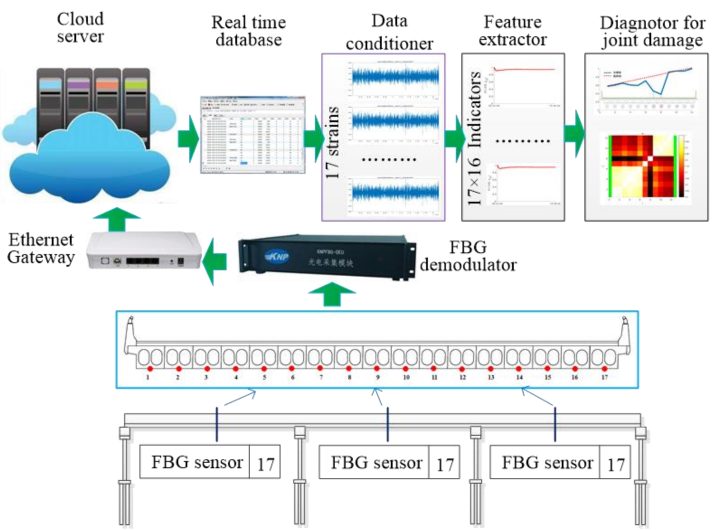


Fig. 2 Topology diagram of the remote cloud monitoring system

(a) Lateral connection system (b) Sensor protection cover slot

Fig. 3 On-site installation and protection measures of FBG strain sensors

in Fig. 3. All the sensors at the same cross section connect in series, finally link to the on-site FBG demodulator through main optical cables. When the data collection is started, the optical signal is converted to digital form by the FBG demodulator and transmitted to the cloud server by the remote gateway.

2.3 Software technology of data analysis in the cloud server

As mentioned above, the strain data directly monitored cannot give the mechanical status of the assembled beam bridge. It is necessary to deploy software in the cloud server and establish an online processing algorithm to realize real-time indicator calculation, status identification and disease diagnosis. Deploying software in a cloud server requires both data storage and interface display as well as scientific computing engine.

This paper uses MySQL to build a real-time database for storing raw real-time data and indicator results, Java EE platform to build an online monitoring system, and MATLAB to form a scientific computing engine. Due to the large amount of calculation and high real-time requirements, InfluxDB is used as a supplement to the MySQL database. The time-series storage and HTTP API are used to complete the initial processing of the database to meet the real-time tasks of multi-channel strain data processing. The entire software environment can be illustrated by Fig. 4.

It is worth noting that the indicator defined by Eq. (1) is a statistical value, and it needs to meet the dual requirements of statistical convergence and real-time calculation, to obtain the timely characterization of bridge's status. Therefore, it is necessary to study an online algorithm different from the index definition formula to efficiently process strain data blocks with enough length. Prior to this, it is necessary to study the corresponding online and real-time pre-processing schemes, as well as the indicator-based analysis and judgment algorithm. The technical support for these issues is the focus of this paper and will be given as below.

3. Online processing algorithm

In the service period, timely understanding of the degradation of the bridge, early detection of various diseases that may occur, can make bridge maintenance decisions in the first time, improve the management quality, and ensure structural health and safety. The installation of a health monitoring system can provide a basis for this. However, the real realization of this purpose must also rely on the timely analysis and processing of monitoring data through means of scientific calculation, and early identification of performance degradation and disease through a given discriminating method. Of course, if this calculation is realized in an automated and real-time manner, it will not only greatly reduce the workload of

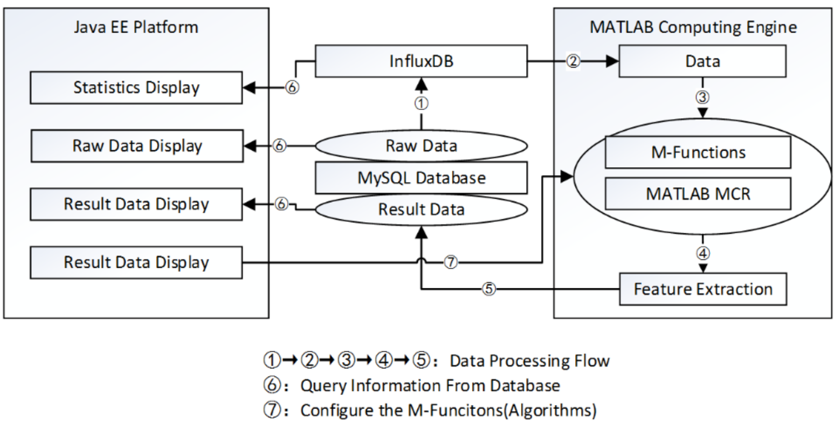


Fig. 4 Software environment for cloud monitoring system

manual analysis, but also shorten the reaction time, truly take advantage of the monitoring technology, and form an intelligent monitoring and diagnosis platform for the bridge.

In this paper, the monitoring and diagnosis of assembled beam bridges is realized by the correlation coefficient indicator based on strains of each girder bottom. Therefore, the key of the system lies in realizing the real-time online processing algorithm of the indicator, which is defined by the strain effect of each girder under traffic flow load. However, the strain actually monitored includes various noise and temperature effects, thus the algorithm should also include preprocessing operations to get rid of those effects that is inevitable.

A simple real-time calculation method for indicator extraction is to apply repeated overlap of batch processing algorithms. The scheme can enhance the real-time performance of monitoring indicators by increasing the overlap length of data calculation frames. However, due to numerous redundant calculations with the longer length, the waste of computing resources and energy supply will be presented. On the contrary, with the longer data series, the interval between two calculations are getting longer and the indicator changes can not be realized timely as expected, so the real-time performance of the algorithm is not really improved but reversed. A better algorithm should be proposed.

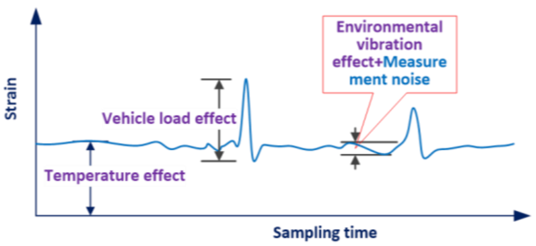


Fig. 5 Composition of the girder strain signals

The indicator calculation process based on the recursive algorithm does not have the above disadvantages, and thus becomes one of the preferences in the monitoring system with high timeliness requirements. In this section, firstly, a set of simple and efficient treatment schemes is given depends on the characteristics of monitoring strain data. Then, the recursive recognition algorithm of the indicators is proposed. Finally, a whole set of real-time diagnosis schemes will be given.

3.1 Real time removal of noise and temperature effect from strain data

The Saint Venant's Principle determines that the response of the girder is localized under traffic flow loads. Only when the vehicle passes near the section of the sensor, the strain can exhibit a higher pulse oscillation. After the vehicle is far away, the recorded strain signal is rapidly reduced to a random from with limited energy, which is mainly composed of temperature effect, noise and structural constant vibration, as shown in Fig. 5.

For a quality-assured measurement system, the random noise mixed in the strain signal recorded has stability in the time domain, and its energy does not change substantially with time. The strain of the structure under environmental vibration effect is generally also a zero-mean random signal, and the energy is less than the noise. The signal spectrum analysis indicates that, in most cases, the peak of the spectrum at the modal frequency of the structure is submerged in the noise. Temperature effect in the signal is mainly caused by the difference between temperatures at the period of installation and service, but the temperature

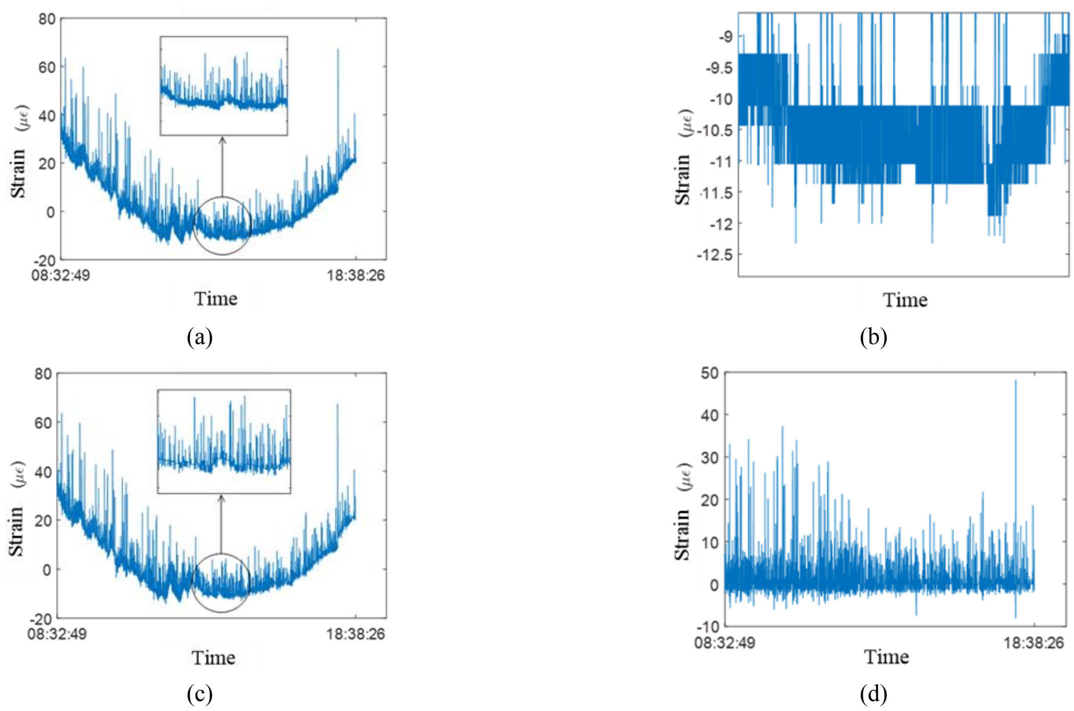


Fig. 6 Removal of noise and temperature effect in real time

drift can be compensated by the sensor design, and may be disregarded.

Since the health status indicator of the assembled beam bridge is based on the strain under traffic load, other components of the signal, which affect the accuracy of the calculation results of the indicator, must be removed. Considering the above characteristics of the actual signal, and the requirement that the treatment process must adapt to real-time performance, the related algorithm for removing noise and temperature effects is given as below:

(1) A continuous strain data series is used to form a data frame for a given length of time T.
(2) In current data frame, judge whether the maximum data difference R is less than r. The variable r is defined as the peak value of specified noise.
(3) If $R < r$, calculate the mean value of the data frame, and record the value as the current strain value induced by temperature, and replace the values in the current data frame with the mean value to eliminate most of the noise effects.
(4) Continue to set the frame to zero, and the temperature effect of the frame will be eliminated.
(5) If $R \geq r$, it indicated that some vehicles have passed the strain measurement section in the sampling period. Let the data in the frame be subtracted from the current temperature effect value.
(6) Enter next sampling frame.

Taking the real measured strain of Tongji Road viaduct in Shanghai as an example. The treatment process is carried out through the above method, and the results are shown in Fig. 6.

Fig. 6(a) is the original strain data, including data frames with traffic load and without traffic load. Fig. 6(b) shows the noise signal which is obtained by subtracting the temperature strain from the original data frame. In the figure, we can define the peak value of the noise signal as r while the noise signal is in a lower level, based on the the signal change caused by noise is less than by vehicle pass. Next, the strain data after removal of noise according to steps (1)~(3) for data frames can be illustrated in Fig. 6(c), and the strain data after removal of noise and temperature effects by steps (1)~(6) can be illustrated in Fig. 6(d), respectively. As shown in Fig. 6(d), after performing data analysis according to the above steps, the strain signal is distributed at the zero stress baseline, and the temperature effect trend line is well removed. Moreover, the value of strain peaks caused by the vehicle load is not affected.

3.2 Recursive algorithm for strain correlation coefficient indicator

In the previous work (Wen *et al*. 2017, Dan *et al*. 2018), we proposed a method to extract the information reflecting the change of structural status from strain data. That is, define correlation coefficient of dynamic strain between adjacent girders as the performance indicator for lateral connection system, and use the indicator to reflect the strength of the hinge joints. The indicator is defined as the correlation coefficient of the longitudinal strain at the midpoint of each prefabricated girder on the same cross section, as below

$$\rho_{ij} = \frac{Cov(\varepsilon_i, \varepsilon_j)}{\sqrt{D(\varepsilon_i) \cdot D(\varepsilon_j)}} = \frac{E(\varepsilon_i \varepsilon_j^T) - E(\varepsilon_i)E(\varepsilon_j)}{\sqrt{\{E(\varepsilon_i^2) - E^2(\varepsilon_i)\}\{E(\varepsilon_j^2) - E^2(\varepsilon_j)\}}} \tag{2}$$

Where ε_i, ε_j represents the longitudinal strain time series of the i-th and j-th prefabricated girders respectively, i, j = 1, 2, … n. n represents the number of girders, and Cov is covariance, D is variance.

We have already proved in the paper (Dan *et al*. 2018) that the longer the frame length is, the more statistically stable indicator ρ_{ij} tends to be, and less affected by the short-term variation of traffic load. To achieve the best results of identifying the structural characteristics, we expect to calculate the indicator by the longest data frame online. Ideally, if we use all the strain data in the past monitoring history to calculate the indicator, it will converge to a fixed value statistically and accurately finally. For this purpose, the following recursive algorithm is designed as follows.

With continuous dynamic strain monitoring, the data series of longitudinal strain ε_i at the bottom of the i-th girder can be frame-blocked as $\varepsilon_{i,k}$. k is used to represent the sequence number of the sampling data frame, k = 1,2, …, K. Where, $\varepsilon_{i,k} = \{\varepsilon_{im}\}$, I = 1, 2, …, n, m = 1, 2, …, n_k and n_k is the length of the sampling frame. A data unit consisting of all sampled frames in chronological order, referred to as the K-th computational frame, called $\varepsilon_{i,K}$, and the length of $\varepsilon_{i,K}$ is denoted by N_K. Thus

$$N_K = \sum_{k=1}^{K} n_k \tag{3}$$

The length of $(k+1)$-th sampling frame $\varepsilon_{i,k+1}$ is n_{k+1}, and the length of computational frame $\varepsilon_{i,K+1}$ can be denoted as

$$N_{K+1} = N_K + n_{k+1} = \sum_{k=1}^{K} n_k + n_{k+1} \tag{4}$$

Let $\mu_{ij}(K) = E(\varepsilon_{i,K}\varepsilon_{j,K}^T)$, $\mu_i(K) = E(\varepsilon_{i,K})$, $\mu_j(K) = E(\varepsilon_{j,K})$, $\mu_{ii}(K) = E(\varepsilon_{i,K}^2)$, $\mu_{jj}(K) = E(\varepsilon_{j,K}^2)$, then Eq. (2) can be calculated with the K-th computational frame, as

$$\rho_{ij}(K) = \frac{\mu_{ij}(K) - \mu_i(K)\mu_j(K)}{\sqrt{\{\mu_{ii}(K) - \mu_i^2(K)\}\{\mu_{jj}(K) - \mu_j^2(K)\}}} \tag{5}$$

All items on the right side of the Eq. (5) can be given in recursive manners, that is

$$\begin{cases} \mu_i(K) = \frac{N_{K-1}}{N_K}\mu_i(K-1) + \frac{n_k}{N_K}E(\varepsilon_{i,k}) \\ \mu_j(K) = \frac{N_{K-1}}{N_K}\mu_j(K-1) + \frac{n_k}{N_K}E(\varepsilon_{j,k}) \\ \mu_{ij}(K) = \frac{N_{K-1}}{N_K}\mu_{ij}(K-1) + \frac{n_k}{N_K}E(\varepsilon_{i,k}\varepsilon_{j,k}^T) \\ \mu_{ii}(K) = \frac{N_{K-1}}{N_K}\mu_{ii}(K-1) + \frac{n_k}{N_K}E(\varepsilon_{i,k}^2) \\ \mu_{jj}(K) = \frac{N_{K-1}}{N_K}\mu_{jj}(K-1) + \frac{n_k}{N_K}E(\varepsilon_{j,k}^2) \end{cases} \quad (6)$$

By Eqs. (5) and (6), the online and timely calculation of the longitudinal strain correlation coefficient can be realized. We can only do simple arithmetic average calculation of the finite length sampling frame each time, and then update the result with the previous calculation. Thus, direct calculation of whole computational frames with large data capacity is avoided. It not only promotes the real-time performance of calculation, but also ensures the statistical stability with the premise that length of computational frames is long enough.

3.3 Online real-time diagnosis of assembled beam bridge

After the indicator is identified, it can be used to determine the state of the hinge joints of the assembled beam bridge in real time. The indicator ρ_{ij} defined by the Eq. (1) can be further divided into two categories. One is the strain correlation coefficient between adjacent girders which are i-th and $(i+1)$-th, recorded as $\rho_{i,\ i+1}$, corresponding to the joints between the two girders. The other is the strain correlation coefficient among the girders which is separated by at least one girder, that is still recorded as ρ_{ij}.

It has been proved in the paper (Dan *et al.* 2018) that when the data length is long enough, as the time range is more than 48 hours, two indicators based on simulation data and real bridge monitoring data can all achieve statistical convergence, and the discreteness of the identified indicators approaches zero. Thus, it can be judged whether the calculated indicator is normal by a simple comparison of the indicator ρ_{ij} and its threshold $[\rho_{ij}]$. Two different real-time judgment criteria are formed as follows,

Discriminant Rule I:

(1) When $\rho_{i,\ i+1} \le [\rho_{i,\ i+1}]$, the hinge joint between the i-th and $(i+1)$-th girders is degraded.

(2) The degradation of hinge joint can be measured by the relative change of the indicator.

$$\delta_{i,i+1} = \frac{\rho_{i,i+1} - [\rho_{i,i+1}]}{[\rho_{i,i+1}]} \quad (7)$$

(3) A tolerance value $\alpha_{i,\ i+1}$ can be preset. If $\delta_{i,\ i+1} \le \alpha_{i,\ i+1}$, it can be recognized as a joint failure.

(4) In the series $\{\delta_{i,\ i+1}\}$, the hinge joint corresponding to the maximum value is the most serious and should be taken measures.

Discriminant Rule II:

(1) When $\rho_{ij} \le [\rho_{ij}]$, j-i > 1, the lateral cooperative working capacity between the i-th and j-th girders is degraded.

(2) The degradation of the lateral cooperative working capacity between the i-th and j-th girders can be measured by the relative change of the indicator.

$$\delta_{ij} = \frac{\rho_{ij} - [\rho_{ij}]}{[\rho_{ij}]} \quad (8)$$

(3) A tolerance value α_{ij} can be preset. If $\delta_{ij} \le \alpha_{ij}$, it can be recognized as the lateral cooperative working capacity failure.

(4) In the series $\{\delta_{ij}\}$, the degradation of cooperative working capacity of the girders corresponding to the maximum value is the most serious and should be taken measures.

Between the above discriminant rules, the indicator threshold $[\rho_{ij}]$ and tolerance value α_{ij} can be obtained through numerical simulation. When calculating the indicator threshold $[\rho_{ij}]$, it is necessary to simplify the mechanical model of the assembled beam bridge and set the shear stiffness of each hinge joint to the initial design state value k_0, that is defined as the shear force when a unit displacement is occurred between adjacent girders. The shear force is related to the reinforced pavement and wet joint, called shear transfer zone shown in Fig. 7, and can be estimated based on the bridge design. For hollow slab beam bridge, the wet joint region can be ignored, only the contribution of the reinforced pavement layer should be considered. In the simulation process, the statistical model of traffic flow load can be given according to the actual on-site measurement, or refers to the same road, as illustrated in the paper (Wen *et al.* 2017, Dan *et al.* 2018). To calculate the tolerance value α_{ij}, k_0 should be reduced to an extent

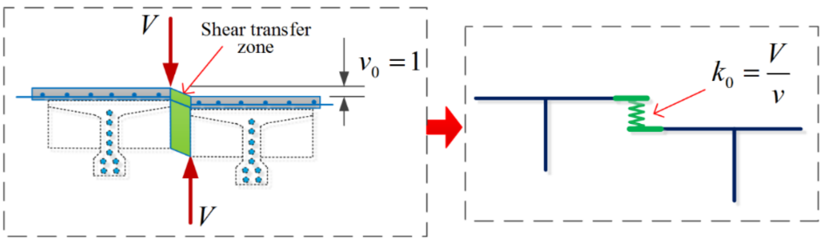
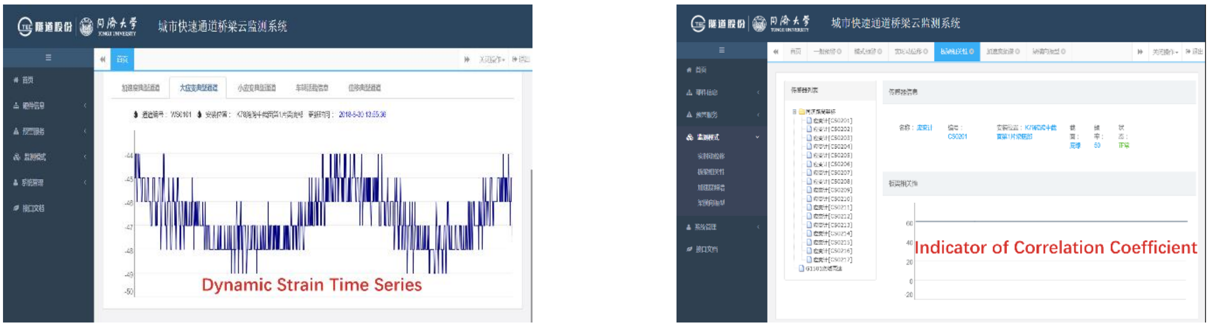


Fig. 7 Estimation of stiffness of the hinge joints



(a) (b)

Fig. 8 Screenshots of the cloud monitoring system of urban expressway viaduct

that the maximum of single-girder strain reaches any desired limit state under the simulated traffic flow load.

4. System implementation

Taking Shanghai Urban Expressway Viaduct as the application bridge and Tongji Road Bridge referred above as the first pilot project, a cloud monitoring system for Urban Expressway Viaduct is designed and implemented. The system was completed in March 2017, and after 6 months debugging and optimization, it was officially opened in September 2017. The system is an important subsystem of Shanghai Smart City Monitoring Platform and supplies bridge monitoring information for the whole platform. It will provide a pilot sample for the monitoring of urban municipal bridges in Shanghai. In order to facilitate the later system expansion, it is built in the integrated software style, and adopting the mode of separation of data, page and algorithm. Among them, the page increases customizable menu item and the Geographic Information System (GIS) map, which can easily append new bridge. Data storage and management adopts principle of separation by bridge to facilitate to store new data. Considering that bridges are highly personalized, the algorithm realization is separated in the form of software modules, and then integrated into the cloud platform. The screenshots of the system are shown in Fig. 8.

Tongji Road Bridge is a three-span continuous beam bridge. Each span has 17 prefabricated hollow slab girders and adjacent girders are connected by wet concrete joints. According to the algorithm mentioned above, we implemented the online treatment of all dynamic strain signals and online calculation of correlation coefficient between any two girders, includes the two types of indicators. And we selected 16 indicators, which is first class, to do the real-time and online calculation. Using the above indicators, online early warning, and evaluation can be further realized.

To verify the statistical stability and real-time performance of the indicator, we choose the one day's data on March 1,2017 to analyze. Fig. 9 shows the real-time curves of the seven first-class indicators, corresponding to the 1st, 2nd, 5th, 8th, 12th, 14th and 16th hinge joints. It can be seen from the figure that in the initial stage of calculation, each indicator has a large oscillation. With the

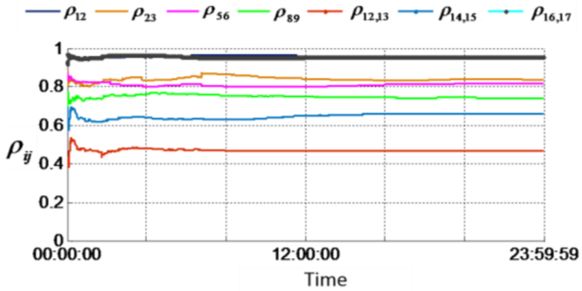


Fig. 9 Strain correlation coefficient between adjacent girders

increase of time, all indicators are quickly (within 12 hours) steadily near a fixed value, and reaching statistical convergence. Among them, the stability value of indicators corresponding to the hinge joints near the middle of the bridge is lower than the joints near the edge of the bridge. It indicates that the statistical stability value of the strain correlation coefficient is not only related to the structural characteristics, but also to the traffic load distribution mode at each bridge lane.

The ultimate goal of identify the indicator is to judge the state of the structure. Specifically, it is to judge the safety state of the hinge joint between the adjacent girders and to assess the lateral cooperative working capacity among all the girders. Fig. 10 shows a cloud map of the statistical stability values of the strain correlation coefficients between each two girders during the above period. As can be seen, in general, the closer to the main diagonal, which is from upper left corner to lower right corner, the smaller the indicator is; and the closer to the secondary diagonal, which is from lower left corner to upper right corner, the bigger the indicator is. For example, the indicator value between 1st and 17th beams in the main diagonal is less than 0.1, and the indicator value between 10th and 11th beams is close to 1.0. This means that for any two girders of the bridge, the farther the distance is, the weaker the connection is and the weaker the ability to work together; the closer the distance is, the stronger the connection is and the stronger the ability to work together. It can also be seen that the value in some local areas are smaller than the surrounding, which is contrary to the general law, indicates the lateral connection system corresponding to the area may be weakened.

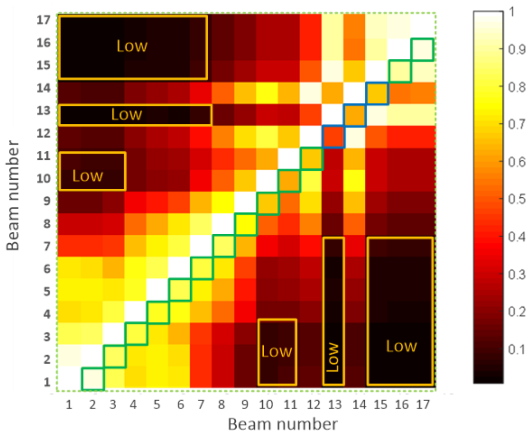


Fig. 10 Cloud map of strain correlation coefficient between any two girders

The indicators in the green frame in Fig. 10 are first-class and directly corresponding to the hinge joints. Extract the values, and plot in curve with serial number of the hinge joints, and compare the values with the thresholds obtained by simulation, as shown in Fig. 11. The figure also gives the relative difference between the two curves.

What needs to be explained here is that the bridge is a dual way 4-lane bridge. Two lanes on the right side are in the direction of entering the urban area, and the left side is the direction out of the urban area. According to the statistics of the traffic volume in the field, most of the vehicles entering the urban area are in the state of heavy vehicles, and the idling of vehicles leaving the urban area is more common. Therefore, the traffic load is on the right side larger than the left side. When the threshold is calculated by simulation, the probability of the vehicle upper bridge event in the right two lanes is 1.5 times on the left side, and the weight of the right two lanes is also greater than the left side 50%. When the threshold is calculated by simulation, the probability of the vehicle passed in the right two lanes is 1.5 times on the left side, and the vehicle weight in the right is also 1.5 times on the left side. Although the same shear stiffness of hinge joints k_0 is used, the calculated threshold $[\rho_{ij}]$ is significantly smaller on the right side than on the left side. Compared with the measured joint indicator ρ_{ij}, the correlation coefficients between the 12th and 13th girders, the 13th and 14th girders, and the 14th and 15th girders are obviously deviated from the threshold, and the relative differences are 33.6%, 16.7% and 19.8%, respectively. According to this, it can be concluded that the lateral connections of the three joints are seriously degraded.

The above conclusions of the hinge joint damage reflected by the indicators can be confirmed by the site survey photos. As shown in Fig. 12, the three hinge joints among the 12th, 13th, 14th and 15th girders have significantly more water leakage than other hinge joints. The reason why water leakage occurs in the hinge joint is that the pavement layer on it is cracked. As mentioned above, the pavement layer is an important structural measure for the lateral connection system. Therefore, the more serious the leakage of the joint is, the more serious the joint damage is, and the weaker the joint strength is. It is reasonable to believe that the photograph in Fig. 12 shows that the three hinges are more severe than other hinges. This is consistent with the above conclusions from the monitoring indicators. This also shows that the monitoring indicators and systems of assembled beam bridge established in this paper can effectively monitor and diagnose the lateral cooperative working performance between the prefabricated girders.

Moreover, we can see in Fig. 12 that there are obvious concrete damages between the 16th and 17th girders but no obvious water stain, also we can see in Fig. 11 the indicator almost reaches 100%. Thus, we can conclude that the joint between 16th and 17th girders has no diseases that need to

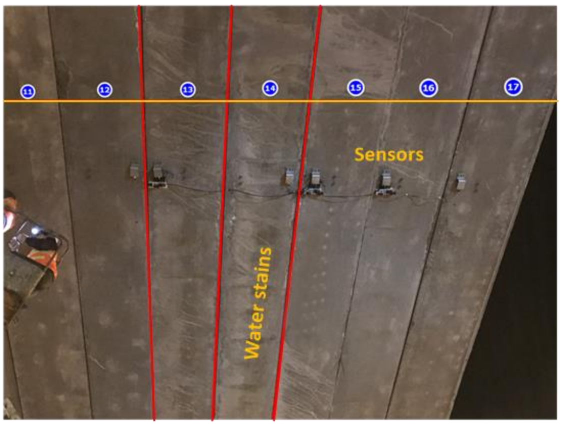


Fig. 12 Photo of disease of Tongji Road Bridge

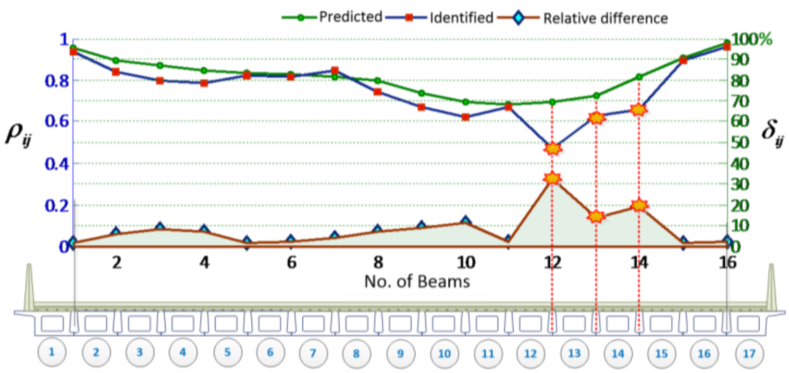


Fig. 11 Strain correlation coefficient of adjacent girders

be treated, and that is different from visual inspection results, for the reason that the indicator can identify the internal performance degradation of joints while the visual inspection can only realize the surface damage.

5. Conclusions

Assembled beam bridge is commonly used due to its advantages of accelerated and industrial construction. Aiming at the frequent hinge joint failure during the use period of the bridge, this paper has done the following work.

- A systematic monitoring and diagnosis technical scheme are proposed. The technology revolves strain correlation coefficient, which can be used to characterize the lateral cooperative working capacity between prefabricated girders.
- Successfully design and implement a monitoring hardware and software system for Shanghai Tongji Road Bridge. The system has firstly realized strain data collection in real time, data transmission with the cloud server remotely, scalable data storage and management, and then built a scientific computing environment suitable for assembled beam bridge.
- On the basis of the system, online treatment of monitored data and recursive algorithm of indicators, as well as the early warning and diagnosis method are given and implemented.

Through the application of Tongji Road Bridge, the effectiveness of the monitoring system established in this paper is verified. The online treatment of the monitored data shows that the proposed algorithm can effectively remove the noise and temperature effects in the signal. The online indicator calculation shows that the strain correlation coefficient between each prefabricated girder can be statistically stable within 12 hours, thus, based on data collected for more than 12 hours, the indicator can be calculated steadily. Further, through the comparison between the indicator and the corresponding threshold, the diagnosis of the lateral cooperative working capacity of the assembled beam bridge can be realized.

Acknowledgments

This study is funded by the Opening Project of National Key Laboratory for Bridge Structural Health and Safety (BHSKL18-05-GF), National Natural Science Foundation of China (51878490); the National Key R&D Program of China (2017YFF0205605); Shanghai Urban Construction Design Research Institute Project 'Bridge Safe Operation Big Data Acquisition Technology and Structure Monitoring System Research.

References

Abendroth, R.E., Klaiber, F.W. and Shafer, M.W. (1995), "Diaphragm effectiveness in prestressed-concrete girder bridges", *J. Struct. Eng.*, **121**(9), 1362-1369. https://doi.org/10.1061/(ASCE)0733-9445(1995)121:9(1362)

Aktan, H. and Attanayake, U. (2015), "Research On Evaluation and Standardization of Accelerated Bridge ConstructionTechniques", USA.

Bakht, B. and Jaeger, L.G. (1992), "Ultimate load test of slab-on-girder bridge", *J. Struct. Eng.*, **118**(6), 1608-1624. https://doi.org/10.1061/(ASCE)0733-9445(1992)118:6(1608)

Chung, P., Wolfe, R., Ostrom, T. and Hida, S. (2008), "Accelerated Bridge Construction Applications in California a 'Lessons Learned' Report", USA.

Culmo, M.P. (2011), "Accelerated Bridge Construction - Experience in Design, Fabrication and Erection of Prefabricated Bridge Elements and Systems", United States.

Dan, D., Zhao, Y., Wen, X. and Pengfei, J. (2018), "Evaluation of lateral cooperative working performance of assembled beam bridge based on the index of strain correlation coefficient", *Adv. Struct. Eng.*, **22**(5), 1062-1072. https://doi.org/10.1177/1369433218804924

Ding, Y.L., Ren, P., Zhao, H.W. and Miao, C.Q. (2018), "Structural health monitoring of a high-speed railway bridge: five years review and lessons learned", *Smart Struct. Syst., Int. J.*, **21**(5), 695-703. https://doi.org/10.12989/sss.2018.21.5.695

Fu, H., Sharif Khodaei, Z. and Aliabadi, M.H. (2019), "An energy-efficient cyber-physical system for wireless on-board aircraft structural health monitoring", *Mech. Syst. Signal Process.*, **128**, 352-368. https://doi.org/10.1016/j.ymssp.2019.03.050

Guiding Opinions of the General Office of the State Council on Vigorously Developing Prefabricated Buildings-General Office of the State Council of the People's Republic of China (2016), http://www.gov.cn/zhengce/content/2016-09/30/content-5114118.htm

He, X., Shi, K. and Wu, T. (2018), "An integrated structural health monitoring system for the xijiang high-speed railway arch bridge", *Smart Struct. Syst., Int. J.*, **21**(5), 611-621. https://doi.org/10.12989/sss.2018.21.5.611

Jahromi, A.J., Dickinson, M., Valikhani, A. and Azizinamini, A. (2018a), "Assessing structural integrity of closure pours in ABC projects", *Transportation Research Board 97th Annual Meeting*, Washington DC, USA

Jahromi, A.J., Valikhani, A. and Azizinamini, A. (2018b), "Toward development of best practices for closure joints in ABC projects", *Transportation Research Board 97th Annual Meeting*, Washington DC, USA.

Loubet, G., Takacs, A. and Dragomirescu, D. (2019), "Implementation of a battery-free wireless sensor for cyber-physical systems dedicated to structural health monitoring applications", *IEEE Access*, **7**, 24679-24690. https://doi.org/10.1109/ACCESS.2019.2900161

Ma, Q. and Solís, M. (2018), "Damage localization and quantification in beams from slope discontinuities in static deflections", *Smart Struct. Syst., Int. J.*, **22**(3), 291-302. https://doi.org/10.12989/sss.2018.22.3.291

Mashal, M., Aguilar, I., Ebrahimpour, A. and Ruminski, L. (2017), "Accelerated bridge construction (ABC) in Idaho: the state-of-the-art bridge technologies, current practice and future research", *IABSE Symposium Report*, **109**(20), 2642-2650.

Miyamoto, A. and Motoshita, M. (2017), "An intelligent bridge with an advanced monitoring system and smart control techniques", *Smart Struct. Syst., Int. J.*, **19**(6), 587-599. https://doi.org/10.12989/sss.2017.19.6.587

Miyamoto, A., Kiviluoma, R. and Yabe, A. (2018), "Frontier of continuous structural health monitoring system for short & medium span bridges and condition assessment", *Front. Struct. Civil Eng.*, **13**(3), 569-604. https://doi.org/10.1007/s11709-018-0498-y

Ozer, E. and Feng, M. (2019), "Structural reliability estimation with participatory sensing and mobile cyber-physical structural health monitoring systems", *Appl. Sci.*, **9**(14), 2840. https://doi.org/10.3390/app9142840

Seo, J., Czaplewski, T., Kimn, J. and Hatfield, G. (2015), "Integrated structural health monitoring system and multi-regression models for determining load ratings for complex steel bridges", *Measurement*, **75**, 308-319. https://doi.org/10.1016/j.measurement.2015.07.043

Shah, B.N., Sennah, K., Kianoush, M.R., Tu, S. and Lam, C. (2007), "Experimental study on prefabricated concrete bridge girder-to-girder intermittent bolted connections system", *J. Bridge Eng.*, **12**(5), 570-584. https://doi.org/10.1061/(ASCE)1084-0702(2007)12:5(570)

Wen, X., Wei, L., Dan, D. and Liu, G. (2017), "Study on a measurement index of transverse collaborative working performance of prefabricated girder bridges", *Adv. Struct. Eng.*, **20**(12), 1879-1890. https://doi.org/10.1177/1369433217700422

Ye, X.W., Yi, T.H., Su, Y.H., Liu, T. and Chen, B. (2017), "Strain-based structural condition assessment of an instrumented arch bridge using FBG monitoring data", *Smart Struct. Syst.*, *Int. J.*, **20**(2), 139-150. https://doi.org/10.12989/sss.2017.20.2.139

HJ