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Design and implementation of a SHM system for a heritage timber building

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Abstract. Heritage timber structures represent the history and culture of a nation. These structures have been inherited from previous generations; however, they inevitably exhibit deterioration over time, potentially leading to structural deficiencies. Structural Health Monitoring (SHM) offers the potential to assess operational anomalies, deterioration, and damage through processing and analysis of data collected from transducers and sensors mounted on the structure. This paper reports on the design and implementation of a long-term SHM system on the Feiyun Wooden Pavilion in China, a three-story timber building built more than 500 years ago. The principles and features of the design and implementation of SHM systems for heritage timber buildings are systematically discussed. In total, 104 sensors of 6 different types are deployed on the structure to monitor the environmental effects and structural responses, including air temperature and humidity, wind speed and direction, structural temperatures, strain, inclination, and acceleration. In addition, integrated data acquisition and transmission subsystem using a newly developed software platform are implemented. Selected preliminary statistical and correlation analysis using one year of monitoring data are presented to demonstrate the condition assessment capability of the system based on the monitoring data.

Keywords: heritage timber structure; heritage timber structure; monitoring system integration; structural health monitoring; structural response monitoring

1. Introduction

As an important part of the cultural heritage of human civilization, ancient buildings have significant values in terms of history, culture, art, and scientific research. However, these ancient heritage buildings inherently deteriorate with the passing of time and due to natural and manufactured hazards (Glisic *et al*. 2007). The suddenly occurred natural disasters can cause the collapse of such heritage structures. Thus, accurate assessment of the current structural performance is crucial to ensuring the safety, performance, and cost-effective maintenance of heritage buildings.

Heritage buildings have complex characteristics regarding their unique material properties and structural systems, while structural design drawings are rarely available. Accordingly, visual inspections or manual assessments for heritage buildings are challenging, costly, laborious and subject to significant uncertainty. Structural Health Monitoring (SHM) enables obtaining information about the structure and relevant environmental factors using sensors and data acquisition systems; structural conditions can then be assessed through appropriate data analyses (Housner *et al*. 1997, Spencer *et al*. 2004). SHM is a very active field of research in structural engineering and has rapidly developed in recent years. The application of SHM to heritage buildings can record the long-term behavior of the structure, analyze the influence of environmental factors. It can provide timely early warning of abnormal conditions of the structure, laying a scientific foundation for structural maintenance and management decision-making. Maintenance and preservation of heritage buildings require a balance between ensuring structural safety and respect for their heritage value; SHM provides essential information that can be used to assess strengthening needs while avoiding unnecessary interventions.

Over the last few decades, long-term SHM systems have been successfully implemented on many important engineering structures, such as large-span bridges (Koo *et al*. 2013, Tennyson *et al*. 2001), high rise buildings (Ni *et al*. 2012, Cristina *et al*. 2016), spatial structures (Diord *et al*. 2017), dams (Gamse and Oberguggenberger 2017), underground structures (Xu *et al*. 2015) and so on. Some application cases of SHM technology have been reported for heritage masonry buildings, mainly focusing on the monitoring of cracks, deformation, and structural dynamic characteristics (Masciotta *et al*. 2017, Duvnjak *et al*. 2016, Rossi and Rossi 2019, Ceravolo *et al*. 2017). Twentieth-century cultural heritages, like the Flaminio Stadium in Rome, one of the iconic reinforced concrete sport facilities,

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(a) Front view (b) Southwest side view (c) Inside view

Fig. 1 The Feiyun Wooden Pavilion

applied structural analysis and health monitoring technics for a proactive structural conservation strategy (Re *et al.* 2021). SHM systems also have been implemented for the monitoring of heritage timber buildings. Full-scale wind effects and modal parameter identification were carried out on the Yingxian wooden tower (Chen *et al.* 2013). SHM framework was proposed for an ancient Tibetan timber building to evaluate the structural response of crowd loads. The measured strain was shown to be strongly related to the number of visitors (Dai *et al.* 2016). The dynamic characteristics of a heritage Korean timber structure using ambient vibration tests have been investigated, and a novel method for estimating story stiffness was proposed for vibration-based SHM (Min *et al.* 2013). Fiber Bragg Grating (FBG) sensing devices are also widely used for SHM of heritage timber buildings because electric power is not run through cables, thus minimizing fire risk (Falciai *et al.* 2003, Marsili *et al.* 2018). It should be noted that timber structure generally has discreteness of material properties, and it is easily affected by ambient temperature and humidity (Casciati and Domaneschi 2007). The joint of the structure is usually semi-rigid, and its performance is important to the whole structure (Casciati 2007). While existing studies are instructive, comprehensive SHM systems for heritage timber structures are still limited, particularly compared to other types of civil infrastructure.

This paper reports on the design and deployment of an innovative SHM system for the Feiyun Wooden Pavilion, a three-story heritage timber building in Shanxi Province, China. The hardware was carefully designed and implemented to accommodate the structure's unique features. Following a brief overview of the Feiyun Wooden Pavilion, the application requirements and associated design for the SHM system are presented. Then, the implementations of the SHM system on the Feiyun Wooden Pavilion are detailed, including the sensor subsystem, data acquisition and transmission subsystem, and data management and processing subsystem. The online-based SHM software platform is newly developed that enables intelligent perception, data integration, remote system control, and real-time data analysis. The performance of the developed SHM system is investigated using one year of monitoring data. The preliminary statistical and correlation analysis of the monitoring data validates the efficacy of the SHM system.

2. The Feiyun Wooden Pavilion and design of the SHM system

2.1 Introduction of the Feiyun Wooden Pavilion

The Feiyun Wooden Pavilion, located in the Dongyue Temple of Wanrong County, Shanxi Province, China, is one of the more preserved heritage timber buildings, as shown in Fig. 1. It was built in the Zhengde period of the Ming Dynasty (1506-1521) and had a history of more than 500 years. It has an open tetragonal symmetrical structure in three levels and a total height of approximately 23 meters. The four main columns, which have a diameter of 0.7 m and run straight from the foundation to the roof, are the primary support system for the structure. The internal beams and columns are connected by mortise-and-tenon joints and dou-gong brackets. All the columns are standing on stone bases directly without any connections. The structure is stabilized by self-weight and friction. Rocking of the structure would occur under seismic loads; the input seismic energy would be dissipated by rocking and joint deformation. This flexible structural system can self-reset to its initial conditions after the dynamic loading (Wang *et al.* 2018).

On-site condition assessment shows that the structure has been suffered from weaknesses in its initial design. The cross-section dimensions of the timber members were intentionally designed to be small to achieve a slim and light visual effect, resulting in insufficient bearing capacity and large vertical deformation of the structure. A series of retrofit measures have been carried out by adding auxiliary components, as shown in Fig. 2. Despite the restoration in 2015, some structural deficiencies are still reported, e.g.,

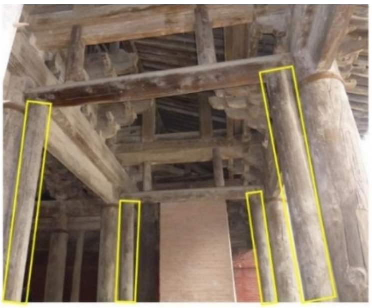
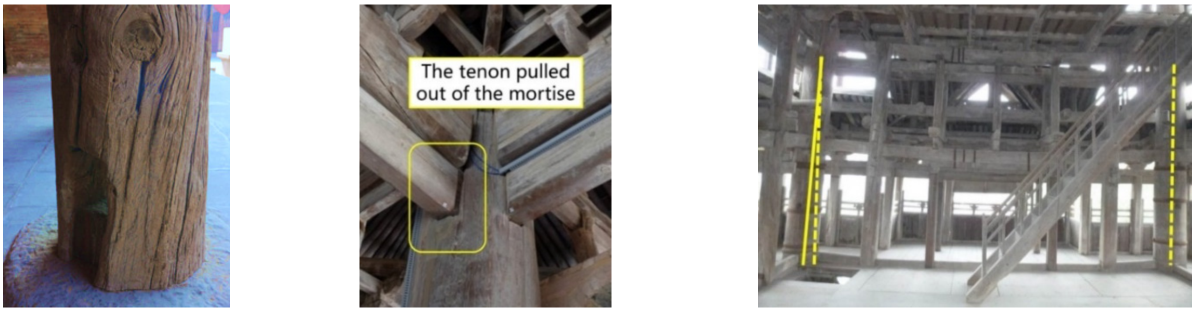


Fig. 2 Retrofit measure by adding auxiliary columns



(a) Material aging (b) Joint damage (c) Inclination of column

Fig. 3 Structural problems for the Feiyun Wooden Pavilion

material aging, joint damage, and structural tilt deformation (Fig. 3). Visitors have been forbidden from entering the upstairs portion of the building since 2016. Therefore, the main environmental effects of concern for the structure are thought to be temperature, humidity, wind, and ambient vibration.

2.2 Unique features impacting the design and implementation of a SHM system for heritage timber buildings

There are more challenges in designing and implementing SHM systems for a heritage timber building than other modern engineering structures. These challenges are mainly due to the Pavilion's structural configuration and its importance as a cultural heritage. The following issues should be carefully considered in the design and implementation of the SHM system of such heritage timber buildings.

- The detailed design information and the initial state of the structure are unknown, while the current structure is subjected to multiple damage sites and deterioration in materials, members, and joints. These features introduce significant complexity and uncertainty in structures.
- Heritage timber structures usually have large deformations due to the flexibility of the joints, which are mortise-and-tenon joints combined with dou-gong brackets; the associated mechanical properties are very difficult to identify accurately.
- Unlike many modern building structures, the static deformation of heritage timber buildings dominates in normal operational conditions. These static deformations change due to long-term slow deterioration.

Moreover, the SHM system must be implemented based on the premise of not damaging the cultural heritage value, which leads to more constraints to the design and implementation. Accordingly, the following principles are required for cultural heritage protection (UNESCO 2014): (i) the minimum intervention principle: the shape and characteristics of heritage buildings, structural construction, murals, interior decoration, and other cultural heritages elements should not be changed; non-destructive or non-contact monitoring equipment is preferred; monitoring equipment and lines arranged on heritage buildings should be coordinated with the visual features of the building; (ii) principle of reversibility: monitoring equipment installed in heritage buildings can be removed; (iii) reliability principle: monitoring equipment must be able to provide long-term reliable performance with minimum maintenance.

Based on the characteristics of the Feiyun Wooden Pavilion and the requirements of cultural heritage management, the architecture of the SHM system was designed, as shown in Fig. 4. The proposed SHM system is multi-functional and integrated, focusing on monitoring environmental effects and structural responses. The main purpose of the SHM system is as follow:

- Real-time warning for abnormal environmental loads and structural responses
- Capturing time-varying environmental loads
- Monitoring long-term deterioration trends for the structure
- Identifying the relationship between the environmental inputs and structural responses
- Data-driven structural condition assessment

3. Implementation of the integrated real-time SHM system on the Feiyun Wooden Pavilion

This section presents the implementation details and functional description of each SHM subsystem. The monitoring parameters and corresponding monitoring procedures are outlined in detail. From the point of view of system construction and implementation, the SHM system consists of the following three subsystems: (i) sensor subsystem; (ii) data acquisition and transmission subsystem; (iii) data management and processing subsystem. The sensor subsystem comprises different types of sensors that can measure the environment loads and structural responses. The data acquisition and transmission subsystem collects the signals from the various sensors and transmits them to the data management and processing subsystem through different types of demodulators and data transmission networks. The data management and processing subsystem is mainly composed of a database, data management, and web servers, a condition assessment module, and online software, which is used to control the data acquisition system and manage the monitoring data,

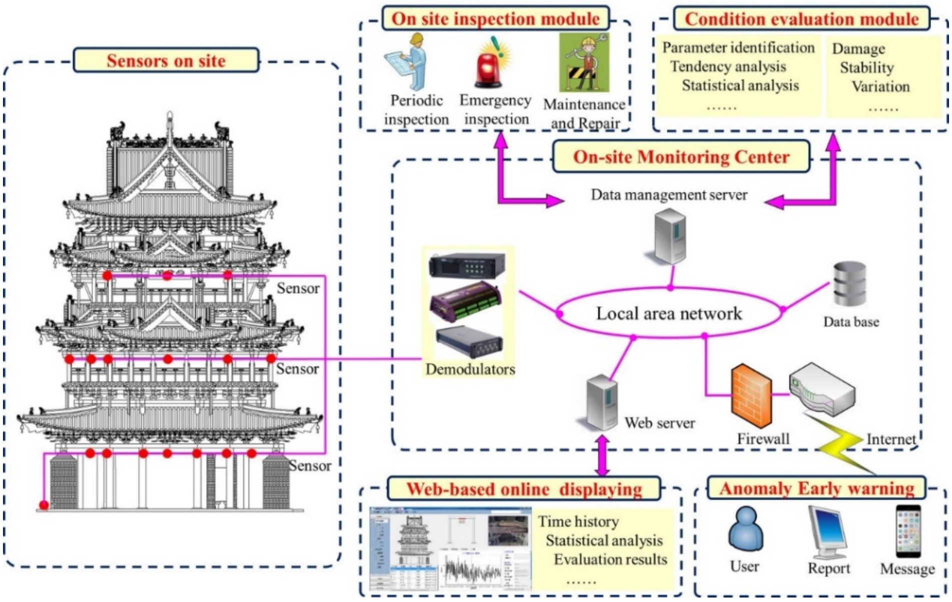


Fig. 4 Architecture of the SHM system

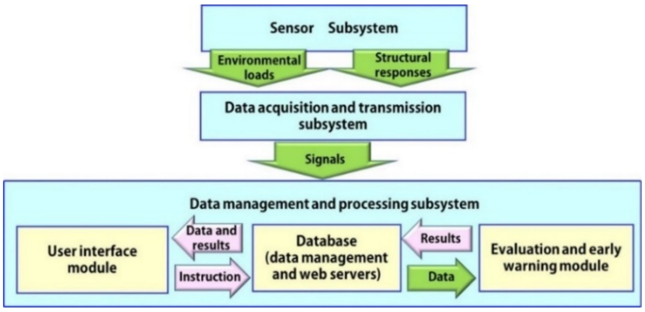


Fig. 5 Subsystems of the SHM system

Table 1 Sensors deployed on the Feiyun Wooden Pavilion

Sensing subsystem	Parameter	Sensor type	Number	Model and manufacture
Environmental loads	Wind speed and direction	Propeller anemometer	1	05103V R.M. Young Company, US
	Temperature and humidity	Temperature and humidity meter	1	41382VC R.M. Young Company, US
Dynamic response	Vibration	Accelerometer	6	941B Institute of Engineering Mechanics, CEA, China
Static response	Strain	FBG strain sensor	36	BGK-FBG-4000T China Geokon Instruments CO., LTD.
	Structural temperature	FBG temperature sensor (packaged together with stain sensor)	36	
	Inclination angle	FBG inclinometer	24	BGK-FGB-6160 China Geokon Instruments CO., LTD.
Total			104	

including data storage, reading, processing, analysis, display, inquiry, and early warning. The relationships between the subsystems are systematically shown in Fig. 5.

3.1 Sensor subsystem

The sensor subsystem consists of 104 sensors of 6 types, as listed in Table 1. The sensors are generally classified into two categories: (i) for monitoring of environmental loads: wind speed and direction, environmental temperature and humidity; and (ii) for monitoring of structure responses: dynamic accelerations, structural temperature, strain, and inclination. The sensor layout on the Feiyun Wooden Pavilion is shown in Fig. 6. The sensor locations for

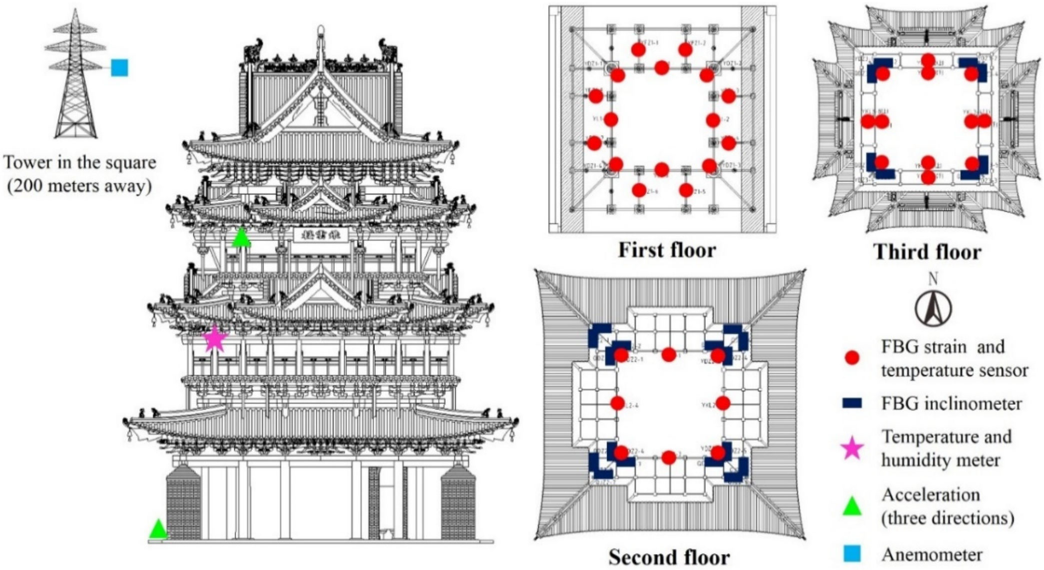


Fig. 6 Sensor layout on the Feiyun Wooden Pavilion

measuring environmental loads were selected to be the most sensitive to changes. Based on the previous research results (Qiao *et al*. 2016), the locations for monitoring structural responses were determined to measure both the global and local deformation and to monitor severely damaged components.

3.1.1 Environmental monitoring

A propeller anemometer was installed on the communication tower at Houtu square, which is about 200 m away from the Feiyun Wooden Pavilion, as shown in Fig. 7. As there are few obstacles to disturb the flow field between the tower and the Feiyun Wooden Pavilion, the measured wind data can adequately characterize the wind environment around the structure. The anemometer was mounted on the tower at the height of 51 m with the customized stainless steel bracket, with an extender of length 5 m to prevent interference by the tower structure itself. The bracket was fabricated to have sufficient rigidity and strength, meeting the requirements for wind resistance design. The range of wind speeds and directions that can be measured are 0~100 m/s and 0~360°, respectively, while the accuracies are ±0.3 m/s and ±3°, respectively. The anemometer can operate at temperatures of -50~50°C. Fig. 8 shows the wireless configuration, consisting of a solar saver module, a rechargeable battery, and a wireless module contained inside a plastic protection box. A battery is powered by a solar panel installed next to the anemometer. The collected data is transmitted to the monitoring center by a wireless module with GFSK modulation mode, 433 MHz frequency, and RS485 Serial port.

The performance of wood, as a biological material, is easily affected by environmental temperature and humidity. Because the building is an open structure, the integrated temperature-humidity sensor shown in Fig. 9 was installed in the southwest corner on the second floor. The high-precision capacitive humidity sensor and platinum resistance temperature detector are combined and packaged in a single probe. The probe provides 0~1 VDC or 4~20 mA current output for temperature and humidity, respectively. The measurement ranges for temperature and humidity are -50~50°C and 0~100% relative humidity (RH), respectively, while the measurement accuracies are 0.3°C at 0°C and 2% RH at 20°C, respectively.

Fig. 7 Installation of anemometer

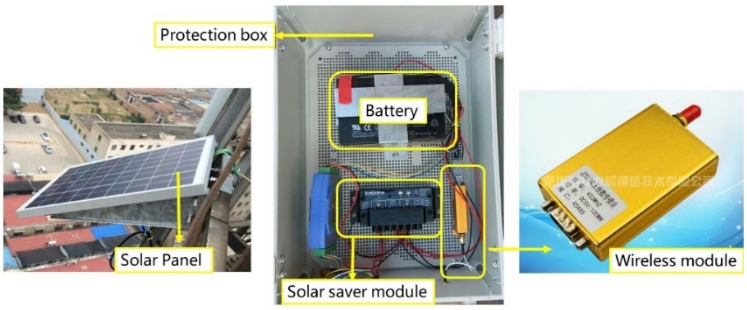


Fig. 8 Solar cells and Wireless module

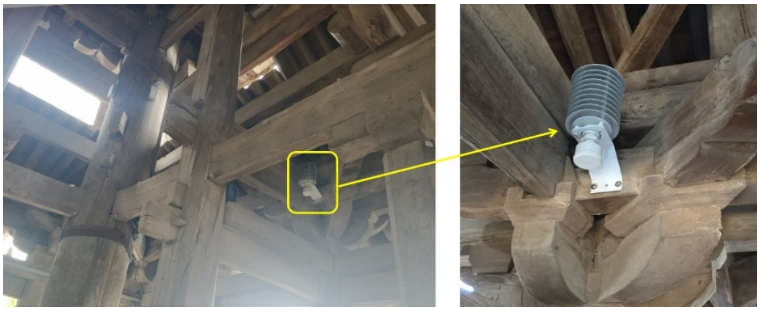


Fig. 9 Installation of the integrated temperature-humidity sensor

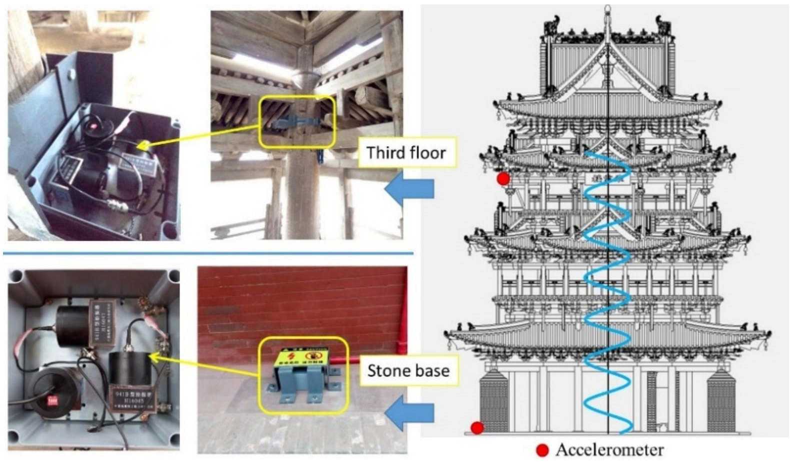


Fig. 10 Installation of the accelerometers

Fig. 11 Route and traffic around the Feiyun Wooden Pavilion

Table 2 Technical specifications of accelerometers

Parameters	Accelerometer
Sensitivity (V·s^2/m)	0.3
Maximum range (m/s^2, 0-p)	20
Passband (Hz)	0.25~80
Resolution (m/s^2)	5×10^{-6}

3.1.2 Dynamic response moitoring

The Feiyun Wooden Pavilion is located in an active seismic belt in eastern China. According to the Chinese ground motion parameter zoning map (GB 18306 2015), the peak ground acceleration in this area is 0.15 g, and the characteristic period of the ground acceleration response spectrum is 0.45 s. In addition to ground motion, the east-west local trunk road near the south entrance potentially generates traffic-induced vibration during the daytime (see Fig. 11). Considering severe damages that may be caused by ground motion as well as vibrational serviceability, relevant dynamic monitoring stations have been set up, as shown in Fig. 10. Because the timber structure is standing on the platform foundation, a low-frequency monitoring station consisting of three single-axis accelerometers was installed on the platform foundation in the southwest corner of the building. To investigate the vibration transmission pattern of the structure, the same monitoring station was installed using a steel hoop bracket at the top of the southwest main column of the third story as well. The technical specifications of accelerometers are listed in Table 2.

3.1.3 Static response monitoring

To assess the condition of the key structural members, 36 crucial points have been selected based on the previous structural analysis and on-site investigation results (Qiao *et al*. 2016). A total of 20 main beams and 16 main columns were equipped with the integrated strain-temperature sensors. The FBG strain and temperature sensor are protected and packaged in a stainless-steel tube, as shown in Fig. 10. The technical specifications are listed in Table 3. Here, the tensile and compressive strain is represented as a positive and negative sign, respectively. The temperature sensors also allow for temperature compensation in the measured strains. The sensors were mounted on the wooden structure using the specially fabricated bases with screws (Fig. 12(c)), which reduce destructions caused by sensor installation.

Table 3 Technical specifications of FBG strain and temperature sensor

Type	BGK-FBG-4000T	
	Strain	Temperature
Measuring range	±1500 με	-30 ~ +80℃
Accuracy	≤ 1.0%FS	≤ 1.0%FS
Sensitivity	0.1%FS	0.1℃
Gauge distance	150 mm	
Working temperature	-30~+80℃	
Size	162 × φ18 (Excluding mounting block size)	

Table 4 Technical specifications of FBG inclination sensor

Type	BGK-FBG-6160
Measuring range	±15°
Accuracy	0.5%FS
Resolving power	0.05%FS
Working temperature	-30 ~ +80℃
Size	150 mm × 80 mm × 36 mm

Inclined deformation is one of the common structural deficiencies of structural members, which influences much on the stability of the structure for heritage timber buildings. In total, 24 FBG inclination sensors have been deployed using fastening screws on the top of the main columns and the cantilever corner columns to measure the inclination angle of the columns (Fig. 13). The technical specifications of FBG inclination sensor are shown in Table 4.

(a) FBG inclination sensor on the top of the column

(b) FBG inclination sensor on the cantilever column

Fig. 13 Installation of FBG inclination sensors

(a) FBG strain sensor on the top of the column

(b) FBG strain sensor on the mid-span of the beam

(c) Installation base of the FBG sensor

Fig. 12 Installation of FBG strain sensors

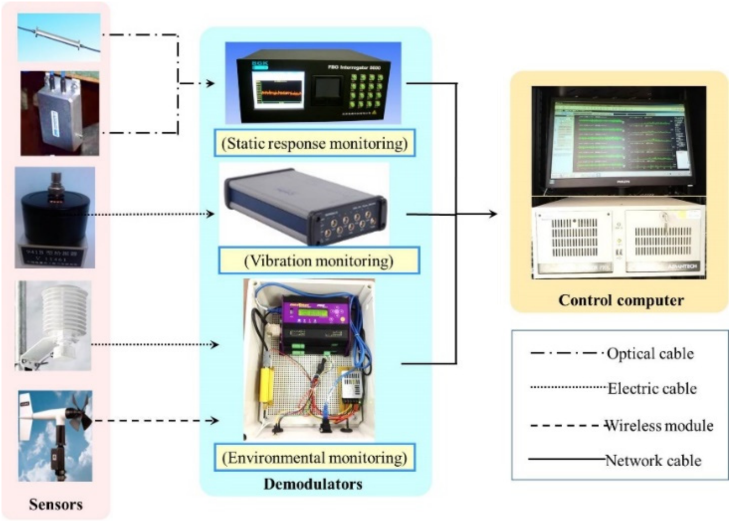


Fig. 14 Framework of data acquisition and transmission subsystem

Fig. 15 Cabinet in the monitoring center

3.2 Data acquisition and transmission subsystem

As shown in Fig. 14, the data collected via wired/ wireless sensor networks on the monitoring center are transmitted to the control computer through the local area network. All the acquisition instruments are located in the monitoring center (Fig. 15). On-site inspection reports, including periodic and emergency inspections, maintenance, and repair information, are also stored in the database.

Fig. 16 shows the network topology diagram for the transmission path planning for optical sensors according to the sensor locations. As can be seen, 4 or 6 sensors are connected in series with a single-core optical cable running along the beams and columns. The optical signals collected from the FBG strain, temperature, and inclination sensors are transmitted through a fiber optical cable. Cables from multiple channels in each layer are gathered into the junction box to form a multi-core optical cable. An optical fiber terminal box in the monitoring center connected to the different channels of the demodulator acquires the data. All the cables are protected by PVC tubing and configured, as shown in Fig. 17, to minimize the impact on the external aesthetics of the building. The acceleration and temperature-humidity sensors are all at the southwest corner of the building. Thus, as shown in Fig. 18, the electric cables in the PVC tubing converge to the southwest side of the first floor to transmit the signals from the Feiyun Wooden Pavilion to the corresponding demodulators in the monitoring center. The wind speed and direction signal are

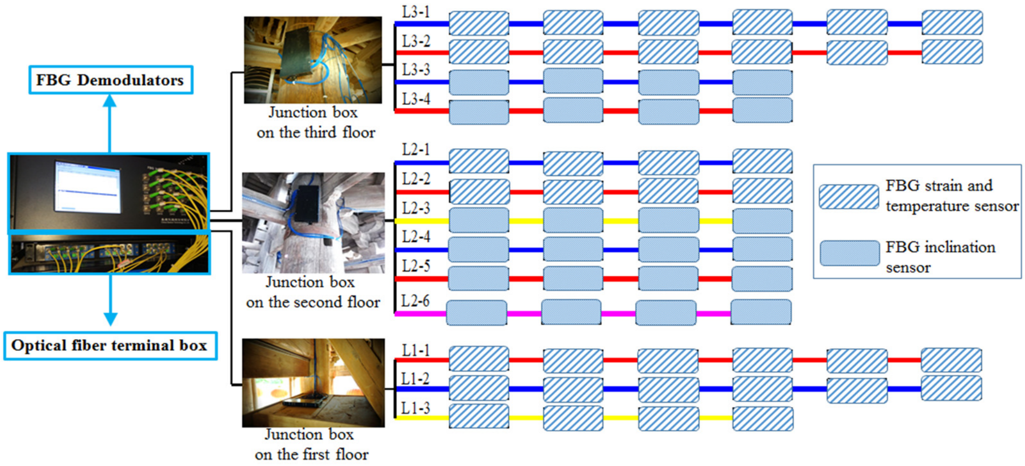


Fig. 16 Network topology diagram for optical signals

(a) On the first floor (b) On the third floor

Fig. 17 Transmission optical cables after implementation

Fig. 18 Electric cable transmission

Fig. 19 Wireless transmission

transmitted to the demodulator wirelessly, as shown in Fig. 19.

The FBG interrogator provides continuous monitoring with a predefined sampling frequency ranging from 1 Hz to 100 Hz. In this study, the sampling frequency of 1 Hz has been chosen for the FBG interrogator to acquire the static data for the Feiyun Wooden Pavilion. The sampling frequency for the wind speed, direction, temperature, and humidity was also set to 1 Hz for storage management during continuous and long-term monitoring. The dynamic acceleration was collected with the sampling frequency of 80 Hz for precise frequency domain analysis and modal analysis. By considering the capacity of the database for this high sampling frequency, threshold triggering was employed to acquire only important events rather than continuous monitoring. According to the peak acceleration of ground motion, the acceleration threshold was set to 0.5 m/s^2. Dynamic acceleration was measured over 1-minute, taking into account a short duration of ground motion.

3.3 Data management and processing subsystem

The data management and processing subsystem mainly consists of the data management and network transmission servers, the database, the condition assessment module, and the corresponding software for information display and user interaction. Fig. 20 shows the data flow path for the system.

The data management is divided into two levels: the original data at the bottom level and the processed data at the upper level. The original data indicates the signals obtained by the SHM system, while the processed data represents the data analyzed by the condition evaluation module. Here, as the highest security level was applied to the original data, modification is not allowed. The SQL Server database, an extensible, high-performance database designed for distributed server computing, is adopted. This database combines with Windows NT and has the advantages of openness, scalability, security, high performance, simple operation, etc.

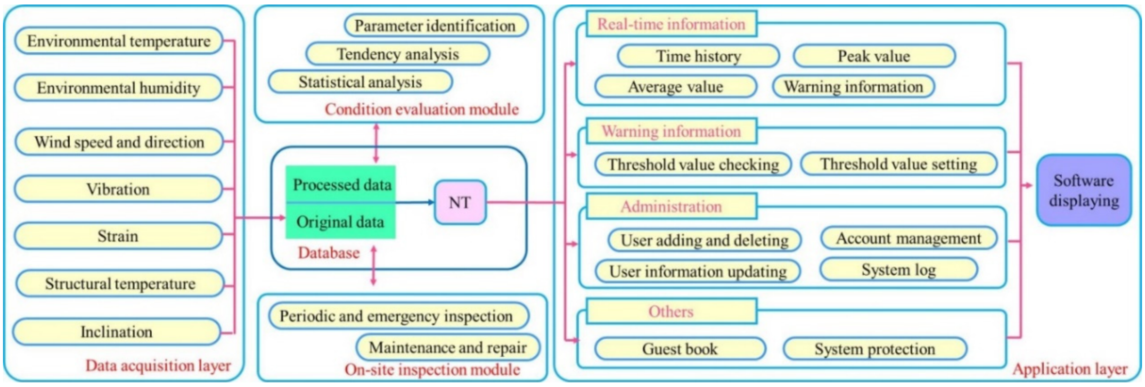
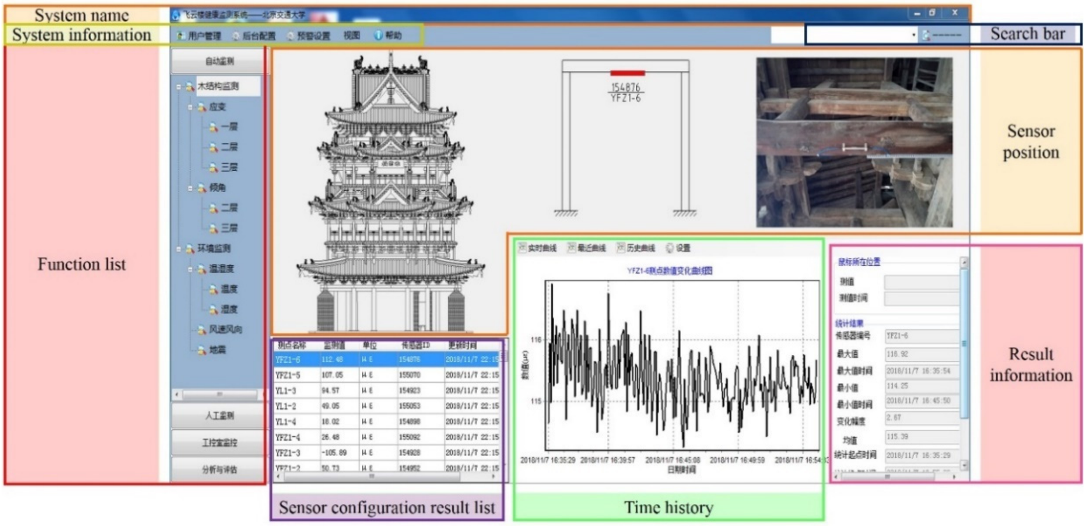


Fig. 20 Data flow path in the data management and processing subsystem

A client/server software has been developed based on C# .net and VB.net. The software can display the original and processed data in real-time as graphs and tables and provide the function of data sharing and download at the same time. The remote user can communicate with the monitoring center servers through the online software. It allows users to control and manage the SHM system remotely and access the monitoring data with different permissions for different users. The operation interface is shown in Fig. 21.

The condition assessment module performs both online and offline evaluations. The online evaluation process includes fundamental statistical analysis of the real-time data and abnormal data alarms. The fundamental statistical analysis evaluates the mean, maximum, and minimum values of the measured data, mainly used for daily, monthly,

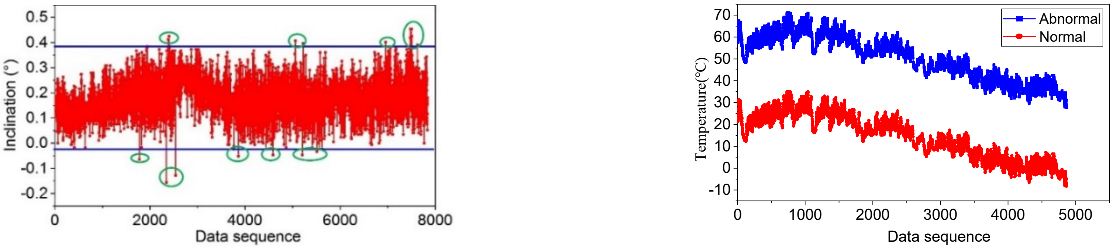


测点名称	监测值	单位	传感器ID	更新时间
YFZ1-6	112.48	με	154876	2018/11/7 22:15
YFZ1-5	107.05	με	155070	2018/11/7 22:15
YL1-3	94.57	με	154923	2018/11/7 22:15
YL1-2	49.05	με	155053	2018/11/7 22:15
YL1-4	18.02	με	154898	2018/11/7 22:15
YFZ1-4	26.48	με	155092	2018/11/7 22:15
YFZ1-3	-105.89	με	154928	2018/11/7 22:15
YFZ1-2	50.73	με	154952	2018/11/7 22:15

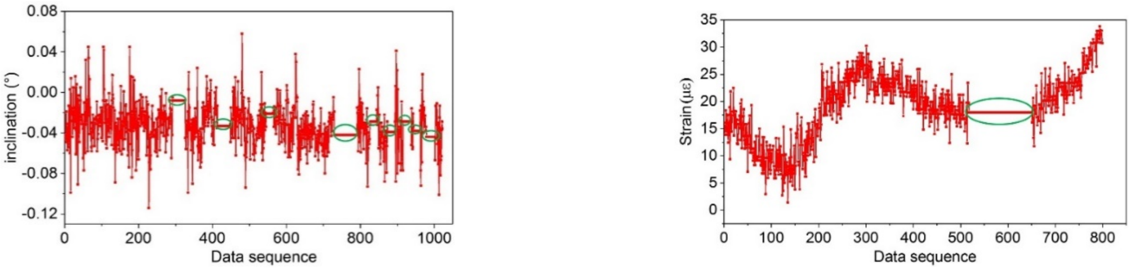
鼠标所在位置
测值
测值时间

统计结果
传感器编号 YFZ1-6
最大值 116.92
最大值时间 2018/11/7 16:35:54
最小值 114.25
最小值时间 2018/11/7 16:45:50
变化幅度 2.67
均值 115.39
统计起点时间 2018/11/7 16:35:29

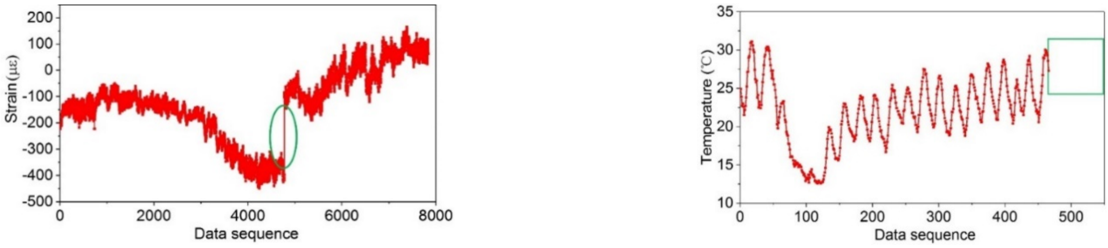
Fig. 21 The operating interface of the online software



(a) Spikes (b) Drift



(c) Temporal stuck-in (d) Constant stuck-in



(e) Bias (f) Loss of signal

Fig. 22 Abnormal data conditions

and annual online reports. The web-based online software can display the statistical analysis and condition evaluation results. Early warning is then carried out based on predefined thresholds and abnormal changes in the data, such as spikes, drift, stuck-at, bias, and loss of signal (Silva *et al*. 2013, Dragos and Smarsly 2016, Jan *et al*. 2017), as shown in Fig. 22. The redundancies in the monitoring data govern the early warning system to send an alarm to the owner via an email report or a message to a remote authorized terminal. The methods for dealing with abnormal or missing data can be divided into two main categories, which are the removal method and data imputation methods (Patidar and Tiwari 2013). Data imputation methods are sub-divided into statistical methods and machine learning methods. Most statistical methods like expectation-maximization filling algorithm (Dempster *et al*. 1977), regression analysis method (Bashir and Wei 2018), multiple interpolations (Quartagno and Carpenter 2019), etc. make assumptions based on the data set itself, and then use the original data set to fill the missing data accordingly. The machine learning methods classify or cluster the missing data sets and then fill them. Representative methods include K-Means Imputation (Shi *et al*. 2020) and the Bayesian network method (Ye *et al*. 2020).

As the aforementioned changes in the system are mainly due to several causes (i.e., structural damages, hardware faults, environmental/operational variations), the source of anomalies should be distinguished through precise procedures (Kullaa 2011). The offline evaluation with in-depth professional analysis is subsequently carried out for evaluating the local and overall performance s in the structure and associated changes. The following data-driven structural condition assessments can be carried out based on the acquired long-term monitoring data: (i) the long-term time-varying regularity of environmental actions can be obtained by using the monitoring data, and the environmental action models can be constructed (Moropoulou *et al*. 2019); (ii) the environmental load effects can be separated by principal component analysis or singular spectrum analysis (Bai *et al*. 2018); (iii) the deterioration law and evolution process of the structural performance can be tracked based on the structural responses excluding environmental effects. Also, model-based structural condition assessment can be employed based on the updated structural model derived from the monitored data. In the finite element model, the mortise-and-tenon connection is usually simulated as a spatial spring element, which is the critical factor affecting the overall stiffness of the structure. These stiffness parameters for the joints can be identified by applying the temperature response sensitivity method to the monitored temperature and strain of the connected structural components (Lyu *et al*. 2017). Then, the ultimate bearing capacity analysis and overall safety assessment of the structure can be carried out based on the updated finite element model, reflecting the current state of the structure. The condition assessment results are released regularly in reports providing decision support for management and maintenance.

4. Preliminary monitoring results

The continuous monitoring of the Feiyun Wood Pavilion started in May 2017 with the developed SHM system. This section shows a subset of the selected monitoring results, including environmental temperature and humidity, wind speed and direction, the inclination of the main column, structural temperature, and strain of the main column. The results of preliminary correlation analysis are presented as well.

4.1 Environmental variations

The environmental variations during one year of collected data (from 12/01/2017 to 11/31/2018) are shown

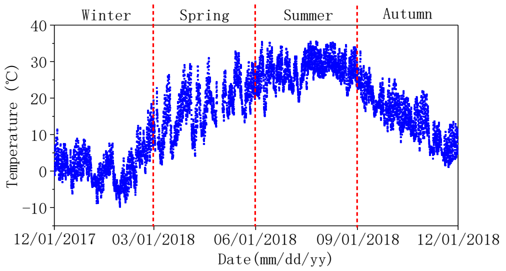


Fig. 23 The time history of environmental temperature

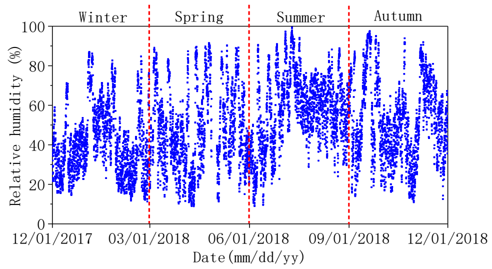


Fig. 24 The time history of relative humidity

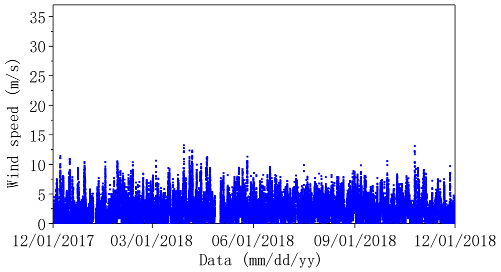


Fig. 25 The time history of wind speed

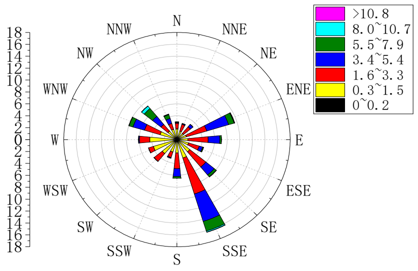


Fig. 26 Wind rose diagram

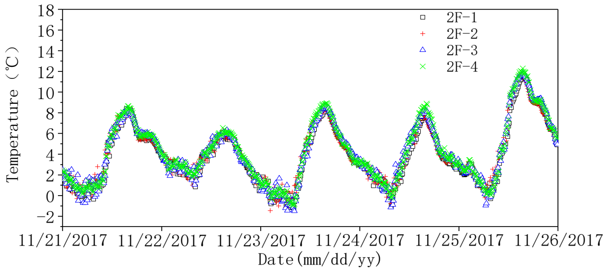


Fig. 27 The time history of structural temperature

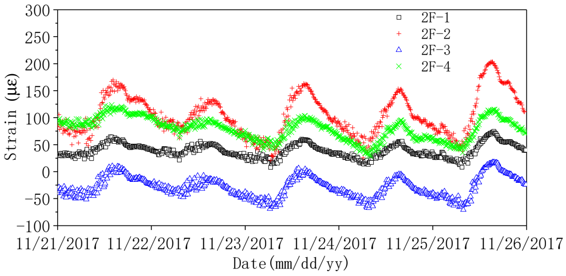


Fig. 28 The time history of strain

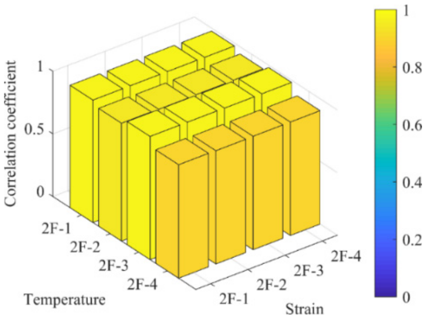


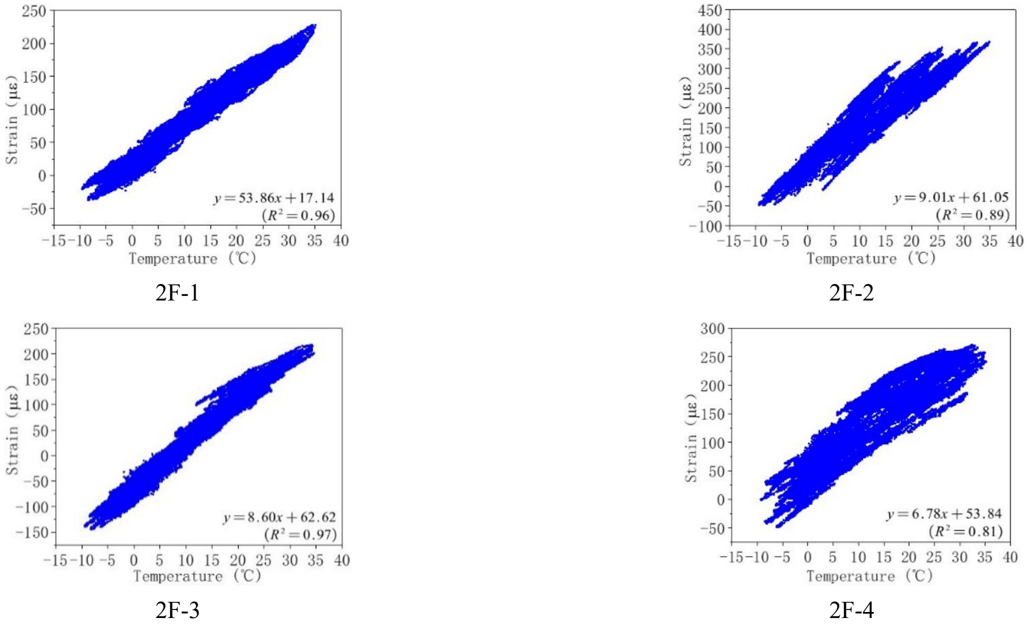
Fig. 29 Histogram of correlation analysis: column strain and temperature

in Figs. 23-26. Each data point for temperature and humidity represents a one-hour average, while velocity represents a 10-minutes average value, respectively. As can be seen, the environmental temperature has obvious seasonal trends: high temperature in summer and low temperature in winter. The regularity of relative environmental humidity in one year is not apparent, but the annual average relative humidity is about 50%. The average relative humidity was high in summer and low in winter. The wind speed near the Feiyun Wood Pavilion was shown to be generally low, mostly below 10.8 m/s, while the main wind direction was along the south-southeast.

4.2 Correlation analysis in structural responses

The 10-minute average temperatures for the Feiyun Wood Pavilion are shown in Fig. 27. Here, the notations 2F-1 to 2F-4 represent the sensor location of the second floor located on the four main columns in the northwest, northeast, southeast, and southwest, respectively. For the detailed analysis of the daily temperature, only the data from 11/21/2017 to 11/25/2017 was selected. The temperatures at the four locations present similar characteristics. The fluctuating temperatures form a daily cycle whose shape resembles a sine curve. The lowest temperature appears before dawn, and the highest temperature occurs in the afternoon. Although the four sensors are at different locations, there is almost no temperature difference between them. Fig. 28 illustrates the 10-minute average values of strain in the same position as the temperatures. The daily signature for each strain gauge agrees well with the corresponding temperature.

Fig. 29 shows the result of correlation analysis between the stain and temperature measured on the second floor. All the column strains were highly correlated with temperatures. Fig. 30 shows the relationship between temperature and strain at the four main columns on the



2F-1
2F-2
2F-3
2F-4

Fig. 30 Relationship between temperature and strain second floor for one year (from 06/01/2017 to 05/31/2018). Almost linear correlation between temperature and strain is observed as well.

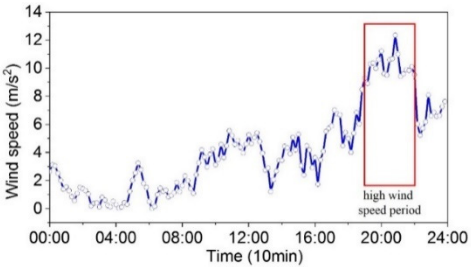
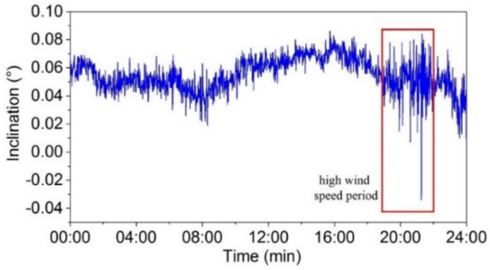
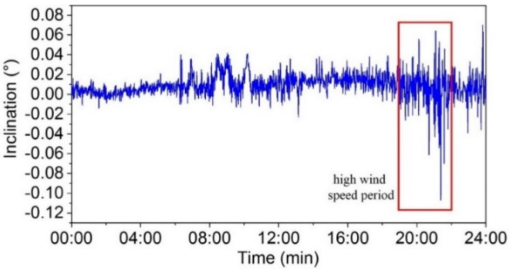


Fig. 31 10-minute mean wind speed on April 3rd, 2018



(a) East-west direction



(b) North-South direction

Fig. 32 Inclination on April 3rd, 2018

4.3 Inclination deformation under strong winds

The inclination deformation of the main columns on April 3rd, 2018, when strong winds blew, was analyzed. Fig. 31 shows the 10-min mean wind speed. Relatively high wind speeds were found during the period of 19:00-22:00. The 1-minute averaged inclination angles of the southeast column on the third floor during that day are plotted in Fig. 32. The inclinations vary significantly during the high wind period. The time-varying effect of the column inclination angle may have been caused by wind load.

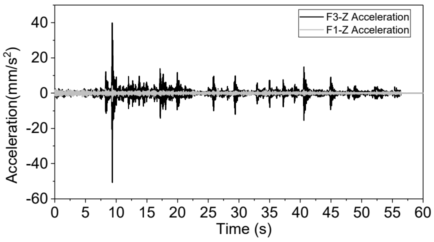
4.4 Acceleration responses under environment vibration

The time histories of dynamic response on the stone base and third floor on October 3rd, 2018, are illustrated in Fig. 33. During this period, relatively high ambient vibration was found around the Feiyun Wooden Pavilion. The time histories reveal that the acceleration amplitudes in the three directions on the third floor are more significant than the stone base. This result can also be observed in Table 5, in which the root mean square (RMS) values of the accelerations and listed. In future research, the transfer ratios between the vibration source and the foundation (stone base) and between the foundation and the upper timer frame can be established. The vibration response of the structure can be predicted and analyzed.

Table 5 RMS of measuring points on the first floor and third floor

Position	RMS (mm/s^2)		
	East-west direction	North-south direction	Vertical direction
The first floor	0.3074	0.2533	0.5511
The third floor	1.4229	0.9691	2.3972

(a) West-east direction of the first floor and third floor (b) North-south direction of the first floor and third floor



(c) The vertical direction of the first floor and third floor

Fig. 33 The time histories of accelerations

5. Conclusions

The implementation and operation of SHM systems is an effective method to detect and evaluate the structural condition through the processing and analysis of data collected from transducers and sensors. The SHM system for heritage buildings is much more demanding than modern structures because of the need to protect and respect the heritage and cultural value of the structure. This paper presents the design of the SHM system and its implementation in a multi-story heritage timber building. Conclusions and suggestions that are expected to guide the implementation of monitoring systems on similar structures are described as follows:

- The service life of the heritage building structure is usually long, and most of the structures have various kinds of existing damage and structural safety problems, as was the case for the Feiyun Wooden Pavilion. The behavior of heritage building structures is complicated to assess because of the uncertainties in material parameters, geometrical configurations, mechanical properties, and non-documented retrofits and repairs. Therefore, monitoring the health of important heritage building structures is necessary to evaluate their condition and provide scientific support for management and maintenance decisions. Short-term monitoring is often not sufficient because of the complexity of the structures, such that long-term monitoring is necessary. The long-term monitoring also enables warnings of abnormal behavior of the structure to be sent out in time by analyzing the environmental actions and the degradation law of the structures. This is of great significance to maintaining the cultural value of the building heritages.
- An intelligent, integrated, stable, and durable SHM system is important to guarantee the long-term performance of the structure. The design and implementation of an effective SHM system on a heritage building involve sensing, communication, computer systems, signal processing, information, and cultural heritage protection technologies. This paper introduces the architecture design and subsystem implementation of the SHM system in the Feiyun Wooden Pavilion. A total of 104 sensors of 6 types, which were carefully selected considering the timber characteristics, the indestructibility of heritage buildings, and other factors, are installed to collect information on environmental effects and structural responses. Various data transmission approaches consisting of wired and wireless transmission are adopted to fulfill different requirements. The data management and processing subsystem provides data storage, read, processing, analysis, display, inquiry, and early warning based on a multi-level database and developed online software.
- The efficacy of the developed SHM system is demonstrated by the preliminary monitoring results, including environmental temperature and humidity, wind speed and direction, structural temperature and strain of the main columns, and its relationship and the dynamic response. Some notable observations are reported, e.g., the high correlation between temperature and strain of the structural components, the time-varying effect of column inclination angle that may be caused by wind load, and the amplification effect and transmission regularity of the vibration from the base stone to the top of the building. For the condition assessment of the building, both data-driven analysis methods and model-based updating methods are recommended and should be combined. Identifying the fundamental properties and their underlying mechanisms in this heritage timber building requires further research and would be investigated in subsequent studies.

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