Application Scheme Of Fiber Bragg Grating Sensor In Prefabricated Building

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Abstract. Prefabricated building has the advantages of low energy consumption, high resource utilization and fast construction speed, which is the key technology for the development and upgrading of the future construction industry. In this paper, based on the existing shortcomings of prefabricated buildings, as well as the characteristics of anti-electromagnetic interference and strong corrosion resistance of fiber Bragg grating sensors, an application scheme is proposed to improve the safety of prefabricated buildings by utilizing the stress detection functions of fiber Bragg grating sensors.

1. Introduction
China is in the stage of rapid development of the construction industry, and compared with traditional buildings, there are some outstanding characteristics in prefabricated buildings, such as reducing labor cost, shorter time consumption and higher resource utilization, which meet the requirements of “Construction of Ecological Civilization”. The construction industry must take steps to achieve industrialization, which saves resources and energy and reduces environmental pollution. In the next few years, prefabricated buildings will become the direction of key development to the construction industry [1]. However, they still have some shortcomings not to be ignored. First, prefabricated building refers to the transfer of a large number of on-site work in the traditional construction mode to the factory, where the construction components and accessories are processed and manufactured. Then they are transported to the construction site, and assembled and installed there. Therefore, prefabricated building lacks the integrity of the building structure, which is directly related to the seismic performance of buildings. As China is a multi-earthquake country, this problem must be taken into account. Second, in prefabricated buildings, the shrinkage of precast concrete is almost over when these elements are poured, but the shrinkage of cast-in-place concrete has not yet begun. Therefore, the shrinkage degree of the concrete of cast-in-place components and precast components will be inconsistent in some way, resulting in large tensile stress, and then cracks, affecting the building safety [2].

2. Research Status at Home and Abroad
In the 1950s, foreign countries have already implemented the application of first-generation safety technology detection on bridges [3]. In 1987, the United Kingdom has begun to build the first complete monitoring system on the Foyle bridge to detect the vibration, deflection response and corresponding stress changes of the main beam of the Foyle bridge under the action of wind, driving
vehicles and self-weight. Data of surroundings is shared in real time [4]. In 2006, the State of Florida built a bridge with an intelligent structure-Easy Bay Bridge. Fiber optic intelligent sensors are distributed on the permanent data acquisition system on the bridge to achieve remote communication.

The domestic start is slow, but some achievements have also been made. In the monitoring project of Runyang Yangtze River Bridge in Jiangsu Province, Li Aiqun and others deployed optical fiber strain sensors and temperature sensors on the beams, which transmitted the temperature, displacement and stress changes of the main beam to the bridge monitoring center through the optical fiber transmission network for data analysis. The final conclusion is that the sensor measurement results are consistent with the resistance strain gauge and vibrating wire strain gauge measurement results [5]. The National Laboratory for Optical Fiber Sensing Technology of Wuhan University of Technology successfully implemented large-scale optical fiber-based sensing technology in Qingchuan Bridge, the Second Yangtze River Bridge, Yangluo Yangtze River Highway Bridge, Jingyue Yangtze River Highway Bridge, etc. In Wuhan, the bridge monitoring system has formed technical solutions for safety monitoring to different targets, different bridge types and different bridge age [6]. In 2018, Jiang Shanchao et al developed a new type of FBG earth pressure sensor applied to soil and constructed a barometric pressure calibration system [7]. Li Zhihua and others have used fiber grating technology to successfully implement a stress detection and analysis system on shear walls [8].

The application of FBG sensors have experienced the application from the initial bridge monitoring to soil and shear. It can be seen that the civil engineering industry is gradually integrating with the Internet of Things technology, and the building monitoring system is gradually developing towards real-time, automation and integration. Stress monitoring of building structure can not only reduce maintenance costs, but also an effective measure to ensure building safety.

3. Theoretical Basis

3.1. Fiber Grating Sensor

3.1.1 Principle of Grating Measurement

The first grating was produced by Hill et al. in 1978 using the standing wave writing method. After decades of development, with the gradual completion of existing grating manufacturing technology, the photosensitivity of the grating has been greatly improved. The grating has now become one of the most promising and representative passive devices. The main structure of Bragg grating is shown in figure 1.

A mixed beam of light with various wavelengths enters the fiber. Part of the light of a specific wavelength will be reflected by the Bragg grating, while light of other wavelengths can pass through the grating without influence, as shown in Figure 2. The wavelength of light of a specific wavelength reflected is called the center wavelength of the Bragg grating, and is denoted as $\lambda_b$. 
3.1.2. Theoretical Calculation of Grating Measurement

The relationship between the central wavelength $\lambda_b$ of the Bragg grating and the effective refractive index of the fiber core is as follows:

$$\lambda_b = 2n_{\text{eff}} \Lambda$$  \hspace{1cm} (1)

Where:
- $\lambda_b$ - central wavelength of Bragg grating
- $n_{\text{eff}}$ - effective index of propagation mode of optical fiber
- $\Lambda$ - Bragg grating period

The peak reflectivity and transmittance of Bragg wavelength are as follows:

$$R = \tanh^2 \left( \frac{\Delta n_{\text{max}} L}{\lambda_b} \right)$$  \hspace{1cm} (2)

$$T = \cosh^{-2} \left( \frac{\Delta n_{\text{max}} L}{\lambda_b} \right)$$  \hspace{1cm} (3)

Where:
- $R$ - peak reflectivity
- $T$ - transmissivity
- $\Delta n_{\text{max}}$ - maximum variation of refraction
- $L$ - grating length

When a certain variable of the external environment changes, such as temperature, stress, strain, etc., the effective refractive index $n_{\text{eff}}$ and grating period $\Lambda$ of the grating will change, and the central wavelength $\lambda_b$ of the grating will also change, as shown in the following formula [10].

$$\Delta \lambda_b = \lambda_b (K_T \Delta T + K_e \Delta \epsilon)$$  \hspace{1cm} (4)

According to formula (4), we can get:

When there are changes in temperature only:

$$\Delta \lambda_b = \lambda_b (\alpha + \xi) \Delta T$$  \hspace{1cm} (5)

When there are changes in strain effect only:

$$\Delta \lambda_b = \lambda_b \left( 1 - \frac{n_{\text{eff}}^2}{2} \left( \rho_{12} - \nu (\rho_{11} - \rho_{12}) \right) \right) \Delta \epsilon$$  \hspace{1cm} (6)

Where:
- $\Delta \lambda_b$ - the center of the Bragg grating wavelength variation
- $K_T$ - Temperature sensitivity of Bragg grating
- $K_e$ - Strain sensitivity of Bragg grating
- $\Delta T$ - Temperature variation
- $\Delta \epsilon$ - Strain variation
\( \alpha \) – Thermal expansion coefficient of optical fiber material  
\( \xi \) – Thermal optical coefficient of optical fiber material  
\( \rho_{11}, \rho_{12} \) – Components of strain tensor in optical fiber  
\( \nu \) – Poisson's ratio  

Based on (4) to (6), we can know that by recording the change of grating wavelength, we can deduce the change of temperature and stress, and realize the perception of FBG sensor to the outside world.

3.2. ZigBee Wireless Network

3.2.1. Selection of Data Transmission Mode

The commonly used wireless transmission methods are as follows:

|                | Power consumption | Frequency             | Lag    | Data transmission distance (Adjacent node) | Network scale | advantages                      |
|----------------|-------------------|-----------------------|--------|------------------------------------------|--------------|---------------------------------|
| ZigBee         | very low          | 865MHz, 915MHz, 2.4Ghz | 0.03s  | over 1-100m                               | 255 or 65000 | Extremely low power consumption, low cost, reliable |
| Wi-Fi          | high              | 2.4GHz, 5GHz          | 3s     | 1-100m                                   | 32           | High speed                      |
| Bluetooth      | medium            | 2.4Hz                 | 3-10s  | over 1-10m                               | 7            | Low cost, easy                  |
| UWB            | low               | 3.1-10.6 GHz          | low    | over 1-10m                               | node to node | High speed                      |

ZigBee can form a more powerful mesh network. Its communication coverage increases with the number of nodes, and the network scale can be expanded as needed. At the same time, the terminal node and the routing node can be arbitrarily connected, so that the data is free to choose paths to avoid the faulty node, and retain a kind of "self-healing" function.

Considering the characteristics of the large number of detection nodes and wide range required for prefabricated buildings, combined with the transmission distance, stability, power consumption, cost and other factors of the wireless network, ZigBee wireless network communication is the most suitable.

3.2.2. ZigBee Positioning Technology

Since the layout of nodes in a prefabricated building is a targeted layout, the positioning algorithm is only an auxiliary method. When the stress exceeds the threshold, the system automatically alarms, and the staff can quickly find the location of the alarm node according to the positioning result. Therefore, we can use a relatively simple three-sided positioning method to achieve this node positioning function.

Let the three reference nodes be \( P_1(x_1, y_1), P_2(x_2, y_2), P_3(x_3, y_3) \) and the unknown node be \( Z(x_4, y_4) \). The distance between the reference node and the unknown node is D1, D2 and D3 respectively.
Figure 4. Schematic diagram of trilateral positioning method

Solving equations:

\[
\begin{align*}
\sqrt{(x - x_1)^2 + (y - y_1)^2} &= d_1 \\
\sqrt{(x - x_2)^2 + (y - y_2)^2} &= d_2 \\
\sqrt{(x - x_3)^2 + (y - y_3)^2} &= d_3
\end{align*}
\]  

(7)

Then we can find out the coordinates of unknown nodes. In the same way, by adding another node, the trilateral positioning method can be extended to three-dimensional space. At the same time, increasing the number of nodes can also reduce the positioning error.

4. System Architecture

The detection system for grating stress designed in this paper is composed of several fiber grating sensors, ZigBee modules (divided into terminal nodes, routers, and coordinators), power supply, and main control terminal PC, as shown in Figure 5. After the sensor detects the data, it converts the detected analog signal into a digital signal and transmits it to the microcontroller in the ZigBee module through the ZigBee interface. If the detected stress value exceeds the preset threshold, the controller drives the alarm to issue a warning. The digital signal is transmitted to the next node through wireless transmission after being processed by the microcontroller. Through multiple transfers between nodes, the information finally reaches the PC in the main control room. The network topology diagram is shown in Figure 6.
5. Application Prospects

This application has the following advantages:

1. It can monitor the joints of the key components of the prefabricated building to play an early warning function. Indirectly improve the safety of prefabricated buildings.
2. The network structure is a mesh structure, which has a certain "self-healing" function and is relatively reliable.
3. Zigbee has low energy consumption and can monitor the building for a long time.
4. With automatic alarm function.

The shortcomings of the application program:

1. When there are too many external factors, it will affect the accuracy of the sensor detection data to a certain extent.
2. Although the energy consumption of the terminal node is low, the battery on the node needs to be replaced regularly.
3. The positioning algorithm is relatively simple, so the positioning accuracy is not high enough.
4. The function is not perfect, lack of data evaluation, and can only function as an alarm, not able to predict data.

The application scheme is suitable for the connection of components and main load-bearing structures of prefabricated buildings. In the future, the sensor types of nodes (such as humidity and temperature sensors) can be added to achieve other functions. At the same time, data analysis can be added to make predictions and promoted to other buildings.

6. Conclusion

Through theoretical calculation and analysis, this paper proposes a scheme for the application of fiber grating sensors based on ZigBee wireless network in prefabricated buildings. The application scheme can perform stress monitoring on the joints of key components of prefabricated buildings, thereby indirectly improving the safety of prefabricated buildings. When the stress exceeds the threshold or the structure is deformed, it can function as an alarm. It plays a certain auxiliary role in the development of prefabricated buildings.
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“Respectable qualities and behaviors make one follow willingly. Though one cannot reach the height as the master does, one always keeps it in mind.” From now on, I will always keep my faith in heart, work hard, move forward and never to be restrained by the surrounding.

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