Value, Function, Cost Volume 2 Issue 2 (2022) **doi: 10.54517/vfc.v2i2.2584**

Original Research Article

Construction and Engineering Example of Safety Monitoring System for Shear Structure House

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Abstract: With the continuous development of my country's economic construction, the structural safety of old houses has become increasingly prominent, which is related to people's life safety and social stability. Through the application of sensor technology, Internet of Things technology, and big data analysis, the safety management, monitoring and early warning of houses are realized. Based on an engineering example, this paper deeply explores the safety monitoring system of shear structure buildings and its construction application.

Keywords: House; Structural safety; Dynamic monitoring; Shear structure.

1. Engineering Background

The example residential building in this paper is located in Shanghai, built in 1998, the structure type is masonry structure, the floor adopts partially prestressed hollow plates and cantilevered plates, and the ring beams and structural columns are set according to the seismic requirements. Each house has 3 or 4 units, a ladder of two households, and the overall structural plane has a large aspect ratio. The safety performance of the houses in the community has been tested, including the detection of complete damage, deformation and material strength, and the detection found that there are different degrees of damage in the residential buildings in the community, including wall cracks, uneven settlement, the overall tilt of the house, etc. Some houses have been seriously damaged and there are relatively large security risks, so further house safety monitoring.

The project monitoring object is selected as a 4-unit residential building, the westernmost unit of which is also the one with the most serious damage. Considering that the damage of masonry structure is usually more serious at the bottom, the cracks of the wall are generally gradually aggravated from top to bottom. In addition, masonry houses belong to rigid structures, and the walls at both ends of the houses will produce greater temperature stress when the temperature changes, and are also prone to serious damage. It is reasonable to select the end unit as the monitoring object, and select the bottom and top monitoring at the same time. Figure 1 and Figure 2 are sensors and acquisition terminals.

Figure 1 Seam gauges and acquisition terminals.

Figure 2 Acceleration sensors and seam gauges.

Received: 4 September 2022 Accepted: 27 September 2022 Available online: 8 October 2022

2. Security Monitoring System Architecture

The building safety monitoring system can obtain the measuring point data of the structure through the sensor in real time, and convert it into the safety index through calculation, and directly indicate the health state of the structure. To meet this requirement, the system needs to:

(1) Select the appropriate sensor and arrange it in a reasonable position;
(2) Reliable enough wireless transmission mode to ensure real-time and accurate data transmission;
(3) Optimize the configuration of the database so that data can be stored and extracted quickly and stably;
(4) Supporting energy supply devices;
(5) An information release platform that facilitates the operation of end users.

The architecture of the security monitoring system of the house is shown in Figure 3.

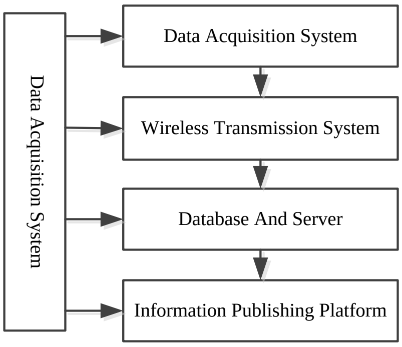


Figure 3 Housing safety monitoring system architecture.

2.1 Sensor Arrangement

The data acquisition system can be divided into two parts: sensing element and data acquisition equipment, which is responsible for real-time and uninterrupted monitoring of the data information of the measurement point. In the part of data acquisition system design, it is necessary to select the appropriate sensor according to the monitoring focus and optimize the arrangement of measuring points, so as to obtain the most structural information with the least measuring points. Among them, the sensor selected seam gauge, inclination meter, static level and acceleration sensor, each sensor is configured with the corresponding data acquisition node, the collected information is summarized to the gateway.

Crack expansion is measured by a seam gauge, 10 measuring points are laid on the wall with serious cracks at the bottom, and 1 measuring point is laid on the top. The sensor uses a Jikang BGK4420-12.5 crack meter, and the monitoring results are indicated by a vibrating string reading instrument with a measuring range of 0-25mm.

The relative settlement of the two walls is obtained by monitoring the change of the liquid level of the static level. A total of four measuring points are set outside the first-layer structure, and the points with fewer cracks in the periphery are selected as reference points, and the data difference between the other three static level and it is calculated as the settlement monitoring result. The sensor adopts Kikang BGK4675-100 static level, and the monitoring data is also indicated by vibrating string reading instrument, with a measuring range of 0-100mm. Since the relative settlement can rise or fall, we need to adjust the liquid level to the appropriate position when deploying the sensor to avoid the situation that the liquid level is too low to exceed the minimum range.

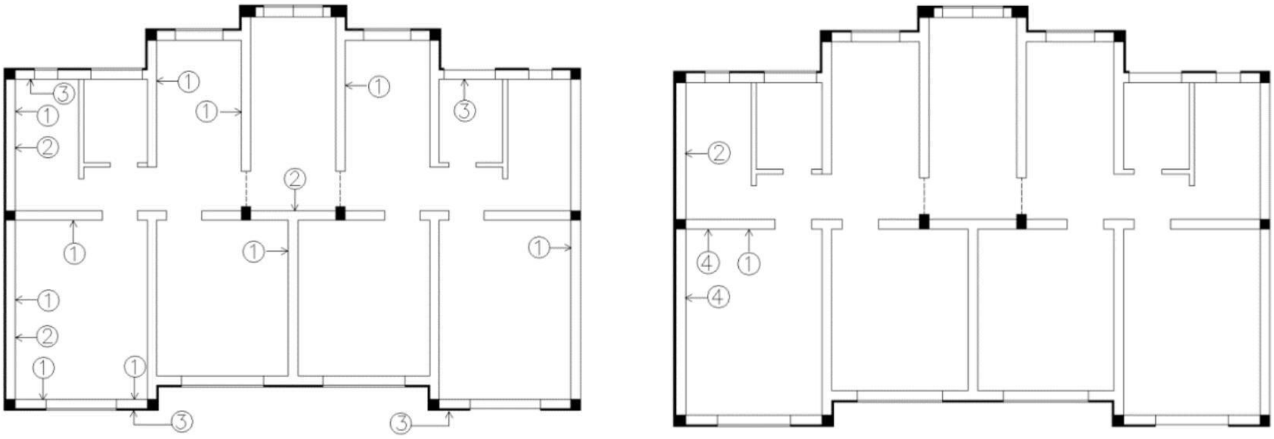
Two two-way acceleration sensors are arranged on the two vertical walls of the top layer, using the French LC0132T built-in IC piezoelectric acceleration sensor, the frequency range is 0.05-500Hz, the resolution is 6×10^{-7} g.

The dipmeter takes the gravity line as a reference, and can measure the change value of the Angle, because the Angle change is very small, θ (radian) is approximately equal to the inclination rate — $\tan\theta$, and the inclination change value of the wall can be obtained by installing an X/Y bidirectional dipmeter on the wall of the house. Three measuring points are arranged at the bottom, and one measuring point is arranged at the top. The range is $\pm 15^\circ$ and the resolution is 1.3×10^{-30}.

The layout information of sensors is shown in Table 1, and the position diagram is shown in Figure 4. In the figure, (1) indicates the joint gauge, (2) indicates the inclinometer, (3) indicates the static level, and (4) indicates the acceleration sensor.

Table 1 Sensor arrangement information.

Sensor type	Deployment location	Quantity
Seam gauge	Wall surfaces with cracks on the top and bottom layers	11
Inclinometer	Wall surfaces with cracks on the top and bottom layers	4
Static level	Bottom wall surface	4
Accelerometer	Top wall surface	2



(a) Ground floor layout plan

(b) Top floor layout plan

Figure 4 Sensor arrangement schematic.

2.2 Wireless Transmission

Select different transmission forms according to different sensor types. The two vibrating string reading instruments indicate that the data sensor is first transmitted through ZigBee, connected in series, and then the data information is summarized to the gateway; The dipmeter sends data to the gateway via 2G network; The acceleration sensor also uses wireless networking, sending data to the gateway through the 3G network, and then uploading data through the gateway through GPRS wireless signal.

The gateway uses the ZG-01 GPRS gateway to encapsulate the monitoring data packet of the local monitoring subnet into a standard Internet protocol package, which is transmitted to the cloud service platform through the Internet, and plays the conversion and bridge function between the collection subnet and the existing Internet network. Taking into account the signal coverage, a gateway is set up in each house, a total of 3.

2.3 Databases and Servers

The data is received and processed by the service program and saved to the database for further data analysis and processing. Two years of monitoring time will produce a large number of monitoring data, long-term uninterrupted operation encountered unstable servers may lead to server crash. The stable storage and call of data requires the system to be equipped with a reliable database. The data is uploaded to the server in real time through GPRS, and the user can view the monitoring data at any time through the computer or smart phone to monitor the structure safety. If there are many types of monitoring project data and more complex processing is required, the data can be uploaded to the cloud service platform for processing through the network.

2.4 Information Dissemination Platform

Real-time release of monitoring information is a major advantage of security monitoring system compared with traditional wireless sensor networks. If the monitoring content selected by the system can directly reflect the health status of the structure, and the safety index is obtained without complicated calculation, the early warning value of the monitoring content can be set in advance according to the relevant specifications and actual engineering experience, and the user can view the on-site structure monitoring information at any time to monitor whether the structure is in a safe state. If more complex indicators are selected as the basis for early warning, the safety monitoring system website can be set up, and the monitoring data and calculation results are displayed in tables or graphs. When the structure is damaged, the user can obtain the detailed information of the damage more intuitively, and timely maintenance processing when the damage occurs, so as to achieve the purpose of real-time intelligent monitoring.

3. Static Monitoring Data Processing and Structural Safety Analysis

For the safety monitoring system of shear structure building, the follow-up data processing and structural safety analysis are mainly divided into two parts: static monitoring data and dynamic monitoring data analysis. Among them, static monitoring is mainly to obtain the local damage information of the structure or the overall physical indicators of the structure under a certain transient state, and generally locates the sensor at the location where the damage has occurred, such as the uneven settlement monitoring of the structure, the crack width monitoring and the wall tilt monitoring, which is the non-vibration signal monitoring of the structure. In this project, when the safety monitoring system started to work, the structure had already been damaged. Therefore, non-vibration monitoring data such as cracks, tilt and settlement of the building should be set with initial values, and the data after a period of stable working time should be used as the initial data. During monitoring, the change value of measurement data is mainly monitored. In the initial stage of data processing, it is believed that if the measurement point data does not fluctuate significantly for a short time, the damage will converge and there will be no expansion trend. If the monitoring data increases rapidly, it is considered that the damage is aggravated, and maintenance measures should be taken quickly. Due to the huge amount of data, the non-vibration data (including crack width, overall incline of the house and uneven settlement) in June 2016 is selected as an example for analysis.

3.1 Crack Situation Analysis

Crack is one of the key damage forms in this project, so it is necessary to set a seam gauge at the position where the crack is more serious to monitor whether the crack has a trend of expansion. According to the provisions of 5.3.3 in JGJ 125-2016, the early warning standard is selected, that is, based on the initial value of the crack, there is an increment of 0.5mm to reach the early warning value. The data collection interval was 1 hour. Figure 5 shows the incremental change of the width of a crack relative to the initial value. It can be seen that there was no expansion trend of the crack during the observation time, nor did it exceed the warning limit, and there was no development trend of local damage.

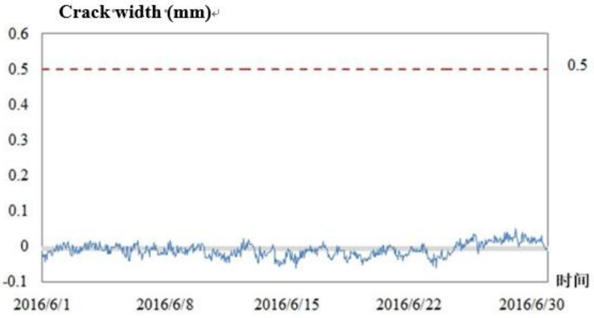


Figure 5 Plot of incremental change in crack width.

3.2 Overall Tilt Analysis of the House

The slope of the wall can be used as the basis for judging the overall slope of the house. According to the provisions of 5.3.3 in JGJ 125-2016, the wall tilt increment reaches 0.7% to reach the warning value, that is, 0.007 (radian). The data collection interval is 30 seconds. FIG. 6 shows the incremental variation of the longitudinal tilt of the top wall along the building. It can be seen that the tilt value does not exceed the warning limit during the observation time, indicating that the overall tilt of the wall is in good condition and there is no inclination trend.

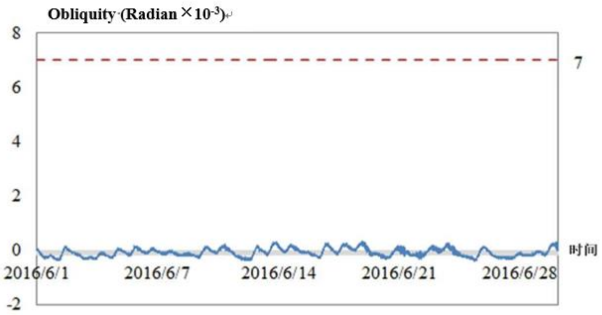


Figure 6 Tilt increment change chart.

3.3 Structural Uneven Settlement Analysis

The uneven settlement of the structure will lead to greater local stress concentration, produce cracks and affect the integrity of the structure. According to the provisions of article 5.3.4 in GB50007-2011 of the national standard “Code for Design of Building Foundation”, 70% of the monitoring alarm value is taken as the monitoring and warning value, that is, the settlement difference monitoring and warning value of the adjacent column base of the building $\leq 0.0014L(0.002L \times 70\% = 0.0014L)$ (L is the center distance (mm) of the adjacent column base), and the example warning value is 7mm. The data collection interval is 1 hour. Figure 7 shows the elevation variation of the two walls on the north side of the ground floor. It can be seen that the warning limit is not exceeded, that is, there is no large relative elevation variation.

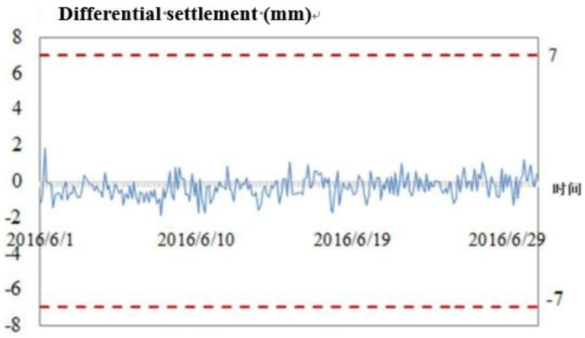


Figure 7 Relative elevation change map.

4. Dynamic Monitoring Data Processing and Structural Safety Analysis

For the safety monitoring system of shear structure building, vibration data can usually reflect more structural information, and the damage that cannot be observed by external structural observation instruments such as crack meter, dipmeter and static level can be reflected by vibration information. For the vibration signal part, the acceleration response of the structure is mainly considered. For the acceleration response, the damage identification method of the paper is used to identify the damage of the structure. Due to the huge amount of data, the acceleration data of the middle four days from July to November 2016 is selected as an example for analysis.

According to the analysis of the static detection data of the system, it is found that the uneven settlement of the structure increases slightly after September, and two cracks show obvious data changes after October, indicating that the damage of the structure has intensified to a certain extent during this period. Therefore, the two sets of data before September are selected to verify the system performance of the structure without damage expansion. Comparing the performance of the monitoring system after 10 months, it shows that the system can identify structural damage.

Two bidirectional acceleration sensors are arranged on the top layer. Six sets of data on July 5, 2016, three sets of data on August 31, three sets of data on October 9, and three sets of data on October 31, 2016 are selected for analysis. Each set of data contains four columns of acceleration time-history response, and each column time-history response contains 6000 data points. That is, each set of data forms a 4×6000 signal matrix.

The data were compared by principal component analysis. Figure 8 to Figure 11 respectively show the time histories of the four columns of acceleration data in the first group of data. It can be seen that the average amplitude of acceleration data shown in Figure 8 and Figure 10 is larger than that shown in Figure 9 and Figure 10, which indicates that there is a significant gap between the bidirectional vibration amplitude of the structure, and the health status of the structure can be comprehensively analyzed from two perpendicular directions.

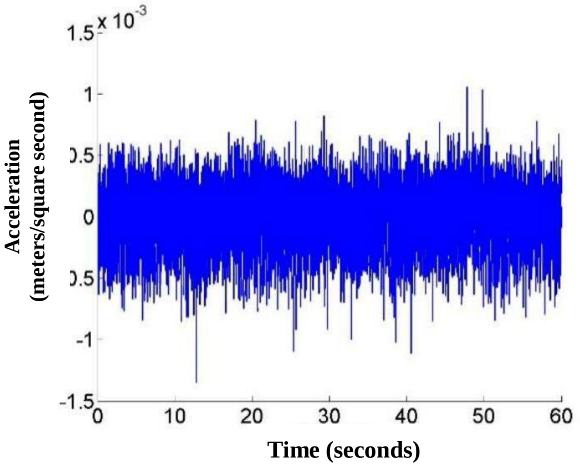


Figure 8 Acceleration time diagram 1.

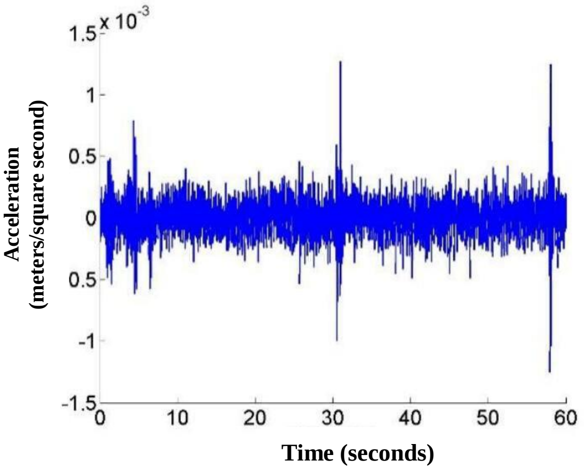


Figure 9 Acceleration time diagram 2.

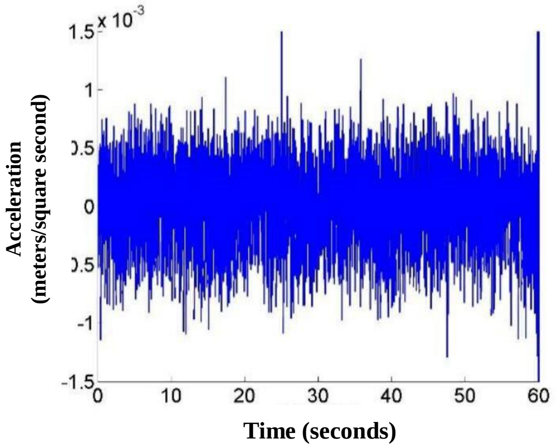


Figure 10 Acceleration time diagram 3.

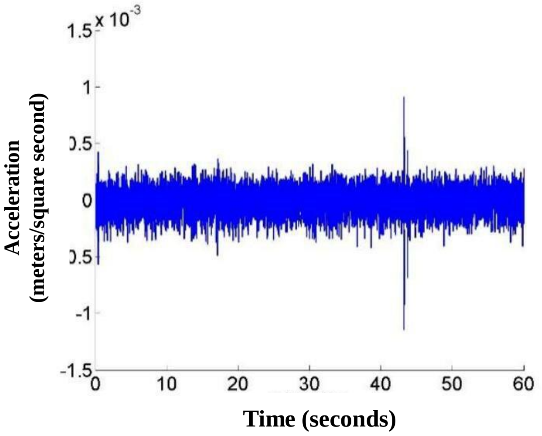


Figure 11 Acceleration time diagram 4.

The first set of data on July 5, 2016 is taken as the reference signal, and the wavelet packet energy spectrum distance between the second set of data and its calculated principal component residual is taken as the reference index. Since the structure generally does not have major damage in a short period of time, the index calculated by the last four groups of data and the reference signal on that day is taken as the control index. If there is little difference between them and the reference index, it can be considered that the damage identification algorithm is effective, the wavelet function and the number of decomposition layers are properly selected, and the monitoring system works normally. In addition, 9 groups of measured data are processed to obtain the wavelet packet energy spectrum distance from the principal component residual of the reference signal, so as to judge whether the structure has damage expansion. As shown in Table 2, the corresponding date of each observation data group and the type and quantity of sample signals contained in each observation data group are respectively shown. The group number and sample number are used to represent the observed sample signals in the following words. Among them, the reference indicators are calculated from samples 1-1 and 1-2.

Table 2 Sensor arrangement information.

Observation data group number	Signal acquisition date	Sample category	Sample quantity
1	July 5th	Standard sample	2
2	July 5th	Reference sample	4
3	August 31st	Sample to be tested	3
4	October 9th	Sample to be tested	3
5	October 31st	Sample to be tested	3

As shown in Figure 12 to Figure 23, the comparison histograms between the reference indexes obtained through the acceleration responses of different measurement points of the structure and the damage indexes under other conditions to be measured are respectively.

From the above figure, we can get:

(1) Sample 2.1 to 2.4 calculated damage indicators and reference indicators compared to most of the difference is not large, only sample 2-2 and sample 2-4 of the No. 4 sensor observation signal damage indicators obtained by the deviation is larger, consider that because of the short-term structure is subjected to a large excitation, the vibration energy change is larger, or a single sensor is subjected to a short period of time larger vibration, and therefore, in the vicinity of the sample collection time, the observed signal at this location Therefore, near the sample collection time, the damage indexes obtained from the observed signals at this location do not fluctuate significantly, and the overall indexes do not change much, so it can be determined that the damage state of the structure has not changed, or the damage extension has not occurred.

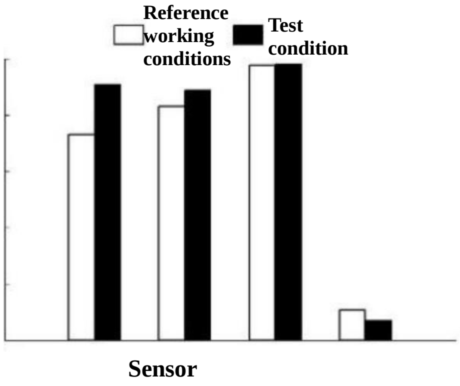


Figure 12 Sample 2-1 vs. reference indicator.

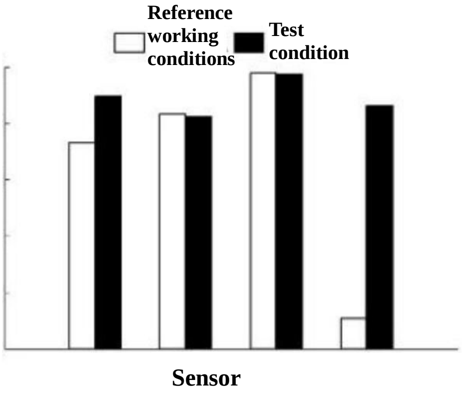


Figure 13 Sample 2-2 vs. reference indicator.

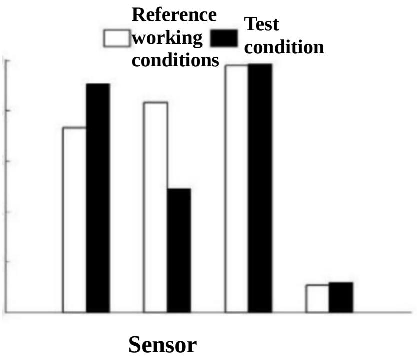


Figure 14 Sample 2-3 vs. reference indicator.

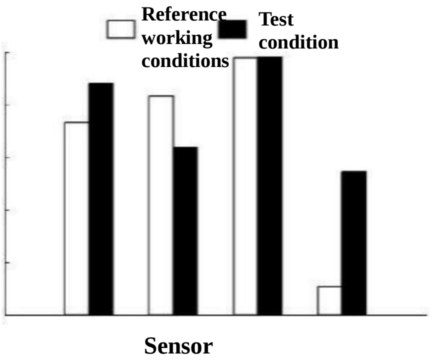


Figure 15 Sample 2-4 vs. reference indicator.

(2) It can be seen from the damage indicators calculated from samples 3-1 to 3-3 that most of them have little difference compared with the reference indicators, only the indicators of sensor No. 1 and No. 4 in samples 3-2 increase significantly at the same time, and the two sensors have the same measurement direction, so it can be considered that there is a large environmental incentive in this direction in a short time, causing the observed signal energy to increase significantly. Considering the performance of the three consecutive groups of samples, it is concluded that the structure of the group of samples did not suffer great damage when they were collected.

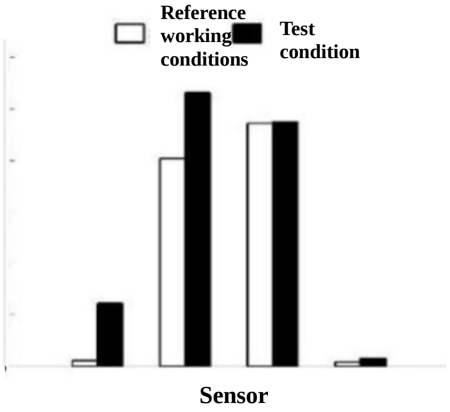


Figure 16 Sample 3-1 vs. reference indicator.

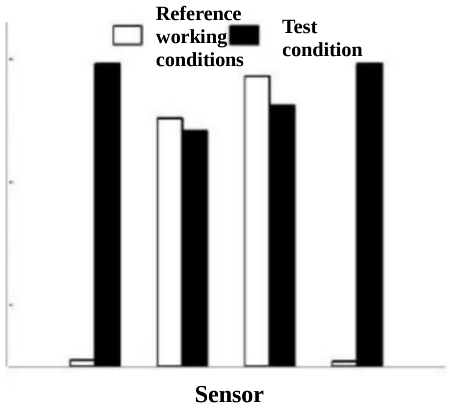


Figure 17 sample 3-2 vs. reference indicator.

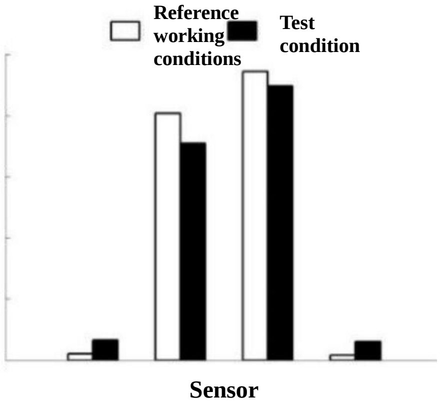


Figure 18 sample 3-3 vs. reference indicator.

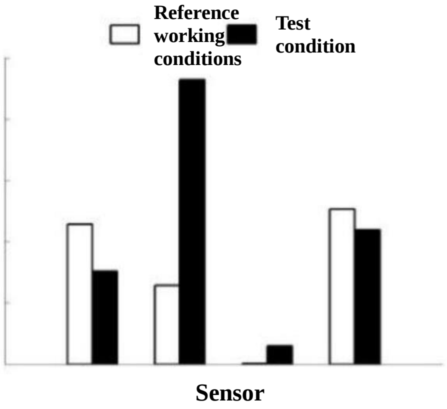


Figure 19 sample 4-1 vs. reference indicator.

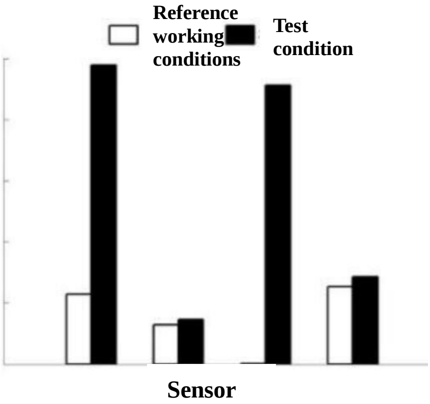


Figure 20 sample 4-2 vs. reference indicator.

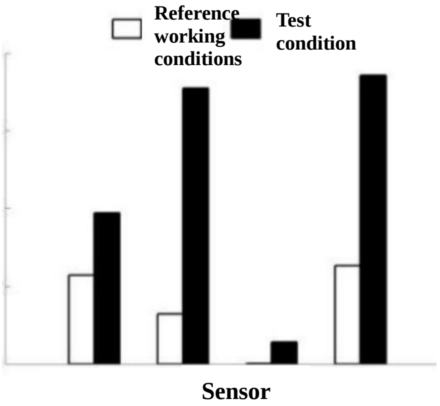


Figure 21 sample 4-3 vs. reference indicator.

(3) It can be seen from the indicators calculated from samples 4-1 to 4-3 and 5-1 to 5-3 that, different from the first two groups of indicators, many of the signal damage indicators in the two groups have significant changes compared with the reference indicators, especially in the sample group 5-1 to 5-3, 2 to 3 of the 4 indicators have significant increases. After referring to the analysis of static monitoring data in the safety

monitoring system, it was found that the uneven settlement of the structure increased slightly after September, and two cracks showed obvious data fluctuation after October, among which a crack on the first floor had a maximum expansion of 0.3mm. Another crack located near the acceleration collection point on the sixth floor began to shrink by 0.5mm and expand by 0.8mm within 36 hours from November 22, indicating that the structure has multiple unstable damage and the trend of damage intensification. However, the damage indexes of the two groups of acceleration data in October have been sensitively characterized, which indicates that the damage recognition algorithm is effective and the monitoring system is working normally.

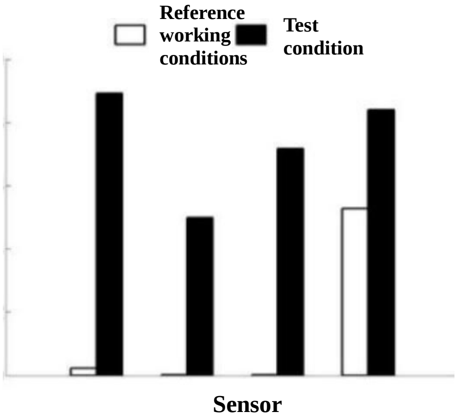


Figure 22 sample 5-1 vs. reference indicator.

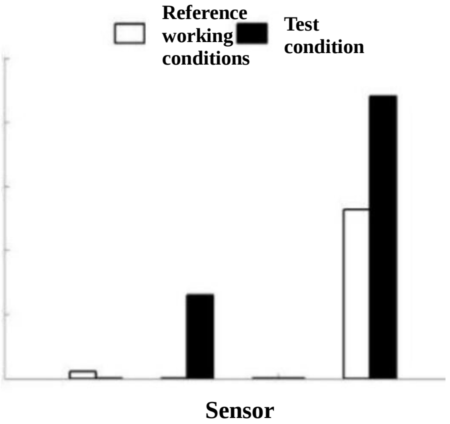


Figure 23 sample 5-2 vs. reference indicator.

5. Conclusion

This paper introduces a building safety monitoring system based on the Internet of Things, and combines the damage identification method to monitor the existing structure. Through real-time acquisition of information such as structural crack width change, tilt, uneven settlement and top acceleration, the system obtains the data we need and guides us to judge and identify the damage. Taking a residential building in Shanghai as an example, the validity and applicability of the damage identification algorithm are verified, and the construction method of the safety monitoring system of the shear structure building is expounded. This system has been put into use since May 2016, which can not only guarantee the structural safety of the project, but also further guide the theoretical research of the safety monitoring system in the future.

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