# Full-life Monitoring and Performance Analysis of the Dongying Yellow River Bridge

TONG ZHANG[1] AND JINPING OU[1, 2]

[1]School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, P. R. of China [2]Dalian University of Technology, Dalian, 116024, P. R. of China

**Abstract:** Dongying Yellow River Bridge is a long span bridge, whose main structure is continuous rigid-jointed frame. During the course of engineer monitoring, the construction monitoring system, system of loading test and health monitoring system are integrated firstly in China. In this paper, the basic information of each subsystem is introduced briefly. Optical fiber sensors are widely used in this system to measure strain and temperature. Data of internal force, leveling and vibration were collected in some key operating modes. In addition, the mechanical situations of vital area of the structure are monitored in these modes and main results recoded by monitoring system are presented in this paper. The corresponding theoretical data are also shown orderly. Based on this comparison, the performance of the bridge, such as linearis, strength, stiffness, bearing capacity and vibration in overall process is analyzed and the security of the structure is assessed. The validity and importance of the integrated monitoring system are then verified.

**key words:** Bridges; construction supervision; loading test; health monitoring; optical fiber sensor

## 1. INTRODUCTION

The Dongying Yellow River Bridge is located in Dongying city, Shandong province. This bridge is an important component part of national trunk highway networks and main frame of synthetical transportation network of Shandong province.

Fig. 1: The figure of Dongying Yellow River Bridge.

This bridge is built according to the GB criterion of expressway, whose overall length is 2743.1m and total width is 26m with 4 lanes in two ways. The design running speed is 100Km/h, design load is vehicle-20. The main bridge is a prestressed concrete continuous rigid frame bridge and the spans of it are 116+200+220+200+116m. It includes two breadth of separate bridge. The superstructure is full pre-stressing concrete box girder and the concrete grade is C55. The main pier is a kind of double thin wall pier, whose wall thickness is 1.8m and the center distance is 8m. The others are solid piers whose cross sections are rectangular. All the foundation footing adopts the bored piles. The main bridge sketch map is showed in Fig.1.

## 2. THE NECESSITY OF FULL-LIFE MONITORING

The scale of this bridge is very large and the construction period is very long (3 years). The bridge was divided into 286 elements to be constructed. Furthermore, it went through many times of structure system transformation. So the construction procedure is quite complicated. There are many uncertainty factors existing in construction, such as the discretion of material property and formwork dimension, the error of oil-pressure gauge of jack, temporary load, wind load and temperature field. These uncertainty factors would give rise to the change of structure controlling parameters, such as weight, dimension and rigidity of the girder, effective prestress, even led to the deviation of internal force states from the designed theoretical trajectory because of the accumulative action of these errors [4]. For the purpose of avoiding it and ensuring that structure internal force and deformation exist in safety range, the construction supervision must be carried out.

During the period of operation, this bridge structure sustains many loads, such as vehicles, the acting force of concrete shrinkage and creep, the impact force, centrifugal force and braking force of vehicles, platform trailer and tracked vehicle. In view of the particularity of hydrology, geology weather of this area, wind load, flowing water pressure, ice pressure, earthquake force, hitting force of ship, environment corrosiveness and temperature variation etc all have a notable effect on the structure [5]. The service environment of this bridge is very bad. Additionally, many disadvantageous factors, such as the action of fatigue and corrosion, the aging effect of materials and overloading etc all make it unavoidable for the structure to raise damage accumulation and resistance attenuation [6]. Therefore, it is necessary to set up the online health monitoring system, and then continuously monitor the status of internal force, vibration and deformation. On the basis of damage identification and state analysis, we can carry out the model correction and safety assessment.

Furthermore, loading test should be performed for a new bridge before it is open to traffic, in order that we can examine the quality of design and construction, grasp the actual bearing capacity of this bridge and testify the validity and rationality of these assumptions used in design and calculation. Loading test can also accumulate basic data for the health monitoring.

The full-life monitoring of long span bridge has become more and more necessary in the world [6] [7]. Construction supervision, loading test and health monitoring are the indispensable components of the engineering monitoring for large bridge. For keeping the integrity of all monitoring information and acquire the full-life monitoring data, in term of the triune pattern, the construction supervision, the loading test and the health monitoring system were integrated as one uniform engineering monitoring system to be carried out.

## 3. THE CONSTRUCTION SUPERVISION

### 3.1 THE METHOD AND FLOW

As mentioned above, there are many disadvantage factors and errors existed in the process of construction. We can leach away the influence of these uncertainty factors and identify those factors that can deflect the real state of structure and their deviation from the design. After analyzing them, we can forecast and guide the next operating condition [4]. During construction, we repeat the process: measuring-filtering-identification- correcting- forecast and then attain our purpose of control. This process is showed in Fig.2. These monitoring and controlling also provide basic data for FEM model (see Fig. 3).

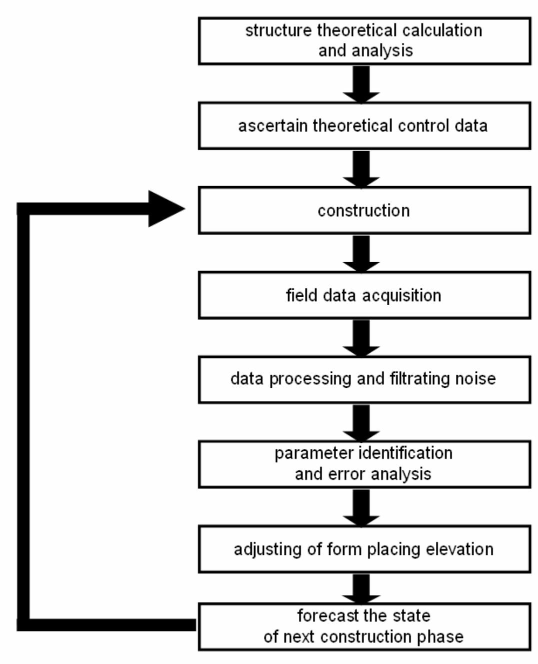


Fig. 2: The flow of construction monitoring and control.

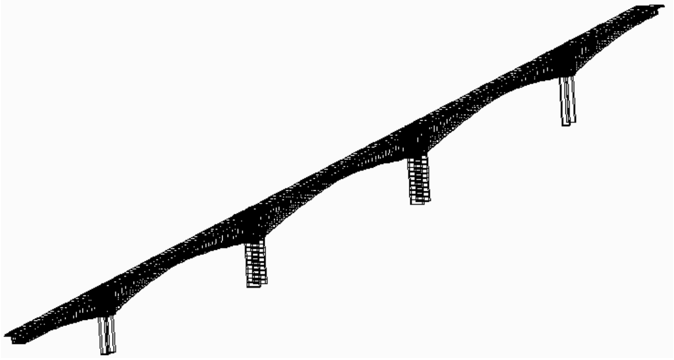


Fig. 3: The FEM model.

### 3.2 THE MAIN MONITORING CONTENT

The construction monitoring includes many items. The most important are as follows:

the deflection measurement of girder during construction, the stress and strain measurement, the temperature field measurement, the collection and processing of basic data, such as the modulus of elasticity and the compression strength of concrete in different period, the elongation indicator of prestressed steel strand, the hydrologic and meteorologic data.

The elevation points were set at the front end of girder sects and each one had two elevation points. The high accuracy water level was used to take the height measurement. The purpose of this measurement is to ascertain the change of deflection of these elevation points, especially the influence of the concrete placing and prestressing force.

The FBG sensors were adopted to measure strain and stress because of their series of merits, such as excellent durability and high precision. Experimental research shows that encapsulated FBG sensors can realize the resolution of 1με for strain sensor and 0.1℃ for temperature sensor [1] [2]. According to FEM analysis and monitor experience of the homogeneous bridges [3], we set 37 control sections of internal force along the longitudinal direction and they are showed in Fig.4. 1-20 is the monitoring section in girders; 25-32 is the monitoring section in the double thin wall piers; 21-24 and 33-36 is the monitoring section in temporary piers (used in the construction supervision); 37 is the monitoring section in bearing pier. Fig.5 shows the longitual strain sensor that was installed in the box girder.

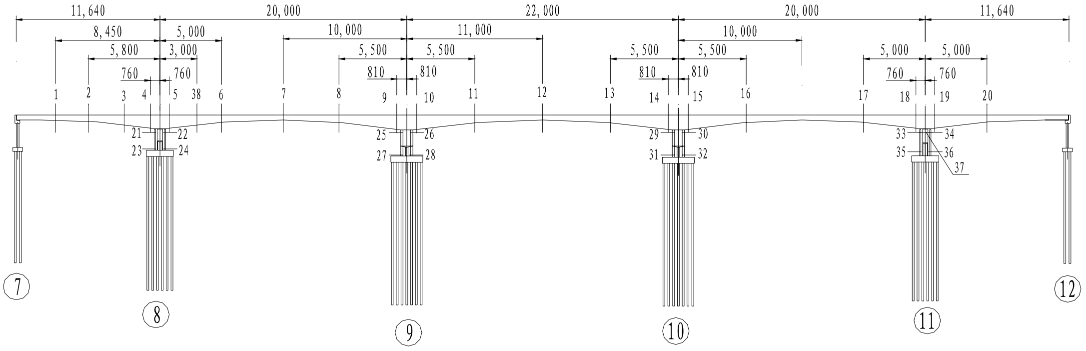


Fig. 4: Longitudinal distribution of monitoring sections of internal force.

Fig.5: The optical fiber strain sensor installed in the girder.

### 3.3 SOME MONITORING RESULTS

During the construction of this bridge, a lot of data was acquired. Fig.6 shows the total deflection of all elevation points in case of healing (the point denote the measured value). In some typical operation modes, the longitudinal strain measuring data of some sections in cantilever of pier11 is showed in table 1. The unit of strain is με and compressive strain is plus. For comparison, this table also arranges the theoretical computed data.

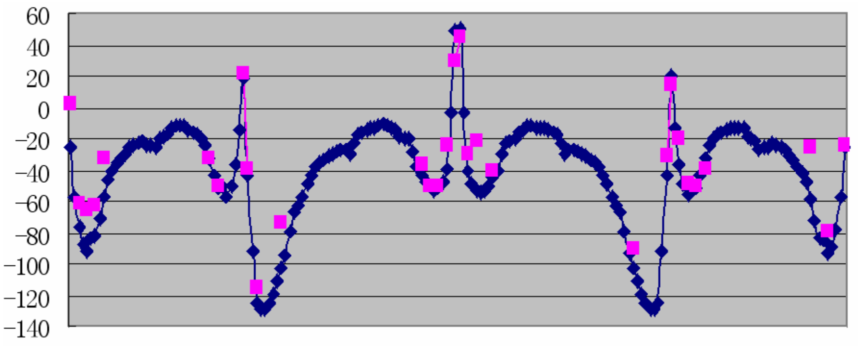


Fig.6: The deflection of the whole bridge in case of healing.

Table 1: Comparison table between measured value and theoretical value.

| operation mode<br>section (position) | | Cantilever construction (16#segment concrete placement) | | The max cantilever (21#segment concrete curing) | | Completion all the prestressing | | Some mode of static loading test | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Measured value** | **Theoretical value** | **Measured value** | **Theoretical value** | **Measured value** | **Theoretical value** | **Measured value** | **Theoretical value** |
| 17(11#pier south 13#segment) | Top plate | 244.9 | 240.9 | 331.5 | 309.4 | 531.5 | 523.1 | 8.2 | 11.7 |
| | neutral axis | 178.3 | 185.6 | 408.5 | 424.0 | 568.5 | 552.1 | -0.5 | 0.0 |
| | Bottom plate | 93.6 | 95.8 | 547.3 | 538.7 | 586.5 | 598.7 | -13.6 | -16.9 |
| 18(11#pier south 1# segment) | Top plate | 690.5 | 680.0 | 643.0 | 610.0 | 743.0 | 706.4 | -14.3 | -18.5 |
| | neutral axis | 522.7 | 532.3 | 637.5 | 643.4 | 682.0 | 665.9 | 1.0 | 0.0 |
| | Bottom plate | 379.0 | 365.9 | 605.5 | 629.6 | 611.0 | 620.4 | 19.2 | 22.9 |

## 4. LOADING TEST

The purpose of static loading test of this bridge is to determine the internal force and deformation under the effect of static load, and then verify whether the actual working condition accords with the expectation. It is the most direct and available approach to examine the performance of bridge structure, such as strength and stiffness.

### 4.1 TEST CONTENT

By analyzing the mechanical characteristic of this bridge and combing some relative test items, we select section 2, 7, 10, 12, 13, 17, 18, 28 (see Fig.4) as the control sections of internal force. The main test contents are as follows: testing the bearing capacity of section 2, 7, 12 to resist positive bending moment; testing the bearing capacity of section 10 to resist negative bending moment, testing the bearing capacity of section 13, 17, 18 to resist shear force and the bending strength of section 28.

### 4.2 DESIGN OF TEST LOAD AND OPERATING MODE

Considering the designing live load, some type of tipper was used as the test substitute load. According to the statical equivalent principle, the test loads were arranged in the most disadvantageous place of influence line and then the max internal force value of each control section was calculated. The ratio of the test internal force to the design internal force is the coefficient of efficiency (η) of the static test load. The operating modes of static test were designed on the basis of lots of calculation. Table 2 shows all the operating modes. From table 2 we can see that the coefficients of efficiency of these modes are between 0.90 and 0.98, which are satisfied the concerned requirement of ***test method of long span concrete bridge***. Fig.7 shows the longitudinal and transverse layout of test load of operating mode 2.

Table 2: operating modes of static loading test.

| **Num** | **Operating modes** | **Equivalent internal force** | **coefficient of efficiency** |
|---|---|---|---|
| 1 | The max positive bending moment of 12-12(including the max deflection operating mode) | 33677kN·m | 0.96 |
| 2 | The max shear force of 13-13 | 2396 kN | 0.98 |
| 3 | The max bending moment of 28-28 | 10275 kN·m | 0.93 |
| 4 | The max positive bending moment of 7-7(including the max deflection operating mode) | 35588 kN·m | 0.94 |
| 5 | The max positive bending moment of 2-2(including the max deflection operating mode) | 43102 kN·m | 0.90 |
| 6 | The max negative bending moment of 10-10 | -150577 kN·m | 0.92 |
| 7 | The max shear force of 17-17 | 1885 kN | 0.95 |
| 8 | The max shear force of 18-18 | 2903 kN | 0.94 |

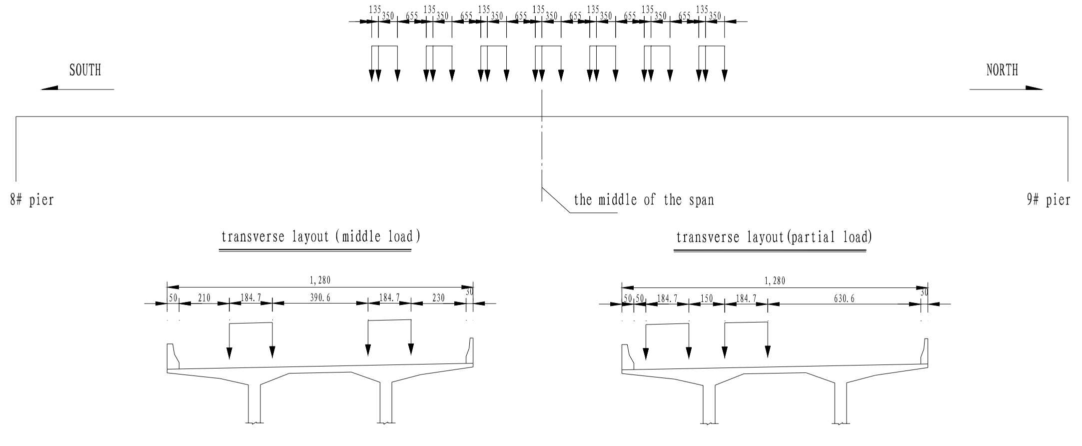


Fig.7: the layout of test load of operating mode 2

### 4.3 DATA ANALYSIS AND CONCLUSION

Table 3 shows the max measured strain values and the corresponding theoretical values of control sections under all these loading modes (tensile strain is positive and the unit of strain is με, the unit of shear force is MPa). Table 4 shows the measured deflection, theoretical deflection, and residual deflection of the midpoint of loading span(the downward deflection is positive and the unit of deflection is mm ). Their checkout coefficients are also arranged in table 2 and 3. From table 3 we can see that all the max strain values of these control sections are less than the theoretical ones in all of these modes and the max checkout coefficient of structure is 0.97. More analysis indicates that all the checkout coefficients of strain are between 0.7-1.0, which reach the concerned standard of ***test method of long span concrete bridge***. The local and whole strained regulations are accord with the design and the bridge structure has adequate strength and bearing capacity. From table 4 we can also see that all the measured deflection is less than the theoretical calculate value and the max checkout coefficient of deflection is 0.66, which testifies that the stiffness of the structure is more than that of the design and the bridge can satisfy the requirement of using. Besides, the effect of partial loading and residual deformation is not obvious. Therefore, the mechanical property of this bridge is safety and rational.

Table 3: check list of measured and theoretical internal force.

| **Loading mode** | **control section** | **position** | **Max measured value** | **Theoretical value** | **Checkout coefficients** |
|---|---|---|---|---|---|
| 1（middle load） | 12 | Top plate | -43.3 | -51.6 | 0.84 |
| | | Bottom plate | 72.5 | 79 | 0.92 |
| 2（middle load） | 13 | The shear force of centroid | 0.41MPa | 0.42MPa | 0.97 |
| 4（middle load） | 7 | Top plate | -46 | -52.5 | 0.88 |
| | | Bottom plate | 67.5 | 78.2 | 0.86 |
| 4（partial load） | 7 | Top plate | -43.3 | -52.5 | 0.82 |
| | | Bottom plate | 70.0 | 78.2 | 0.89 |
| 6（middle load） | 10 | Top plate | 41.2 | 42.8 | 0.96 |
| | | Bottom plate | -33.3 | -44.2 | 0.75 |
| 6（partial load） | 10 | Top plate | 38.3 | 42.8 | 0.90 |
| | | Bottom plate | -43.0 | -44.2 | 0.97 |
| 8（middle load） | 18 | Top plate | 14.7 | 18.5 | 0.80 |
| | | Bottom plate | -20.8 | -22.9 | 0.91 |
| | | The shear force of centroid | 0.23 MPa | 0.24 MPa | 0.96 |
| 5（middle load） | 2 | Top plate | -35.8 | -44.6 | 0.80 |
| | | Bottom plate | 54.6 | 72.1 | 0.76 |
| 7（middle load） | 17 | Top plate | -9 | -11.7 | 0.77 |
| | | Bottom plate | 14.2 | 16.9 | 0.84 |
| | | The shear force of centroid | 0.35 MPa | 0.36 MPa | 0.97 |

Table 4: check list of measured and theoretical deflection

| **Loading mode** | **Measured deflection** | **Theoretical value** | **Checkout coefficient** | **residual deflection** | **Relative Residual deflection** | **Measured Partical Loading coefficient** |
|---|---|---|---|---|---|---|
| 1（middle load） | 42 | 71.8 | 0.58 | 1 | 0.02 | / |
| 4（middle load） | 36.5 | 78.7 | 0.46 | 1 | 0.03 | / |
| 4（partical load） | 34 | 78.7 | 0.43 | 1 | 0.03 | 1.09 |
| 6（middle load） | 41.5 | 62.9 | 0.66 | 3 | 0.07 | / |
| 6（partical load） | 41.5 | 62.9 | 0.66 | 3 | 0.07 | 1.08 |
| 8（middle load） | 19 | 56 | 0.34 | 1 | 0.05 | / |
| 5（middle load） | 14 | 38.6 | 0.36 | 1 | 0.07 | / |
| 7（middle load） | 19 | 72.6 | 0.26 | 3 | 0.05 | / |

## 5. STRUCTURE HEALTH MONITORING

### 5.1 SYSTEM INTEGRATION

There were too many FBG sensors (1868) installed in this bridge at the three successive monitoring stages (construction supervision, loading test and the off-line health monitoring). We only added 184 key sensors to the real-time online health monitoring system for the purpose of reducing the cost on the premise of satisfying the monitoring requirement. Besides, we install 32 acceleration sensors to monitor the vibration. These sensors will monitor the mechanical status of the structure continuously. And then the healthy record of this bridge is set up.

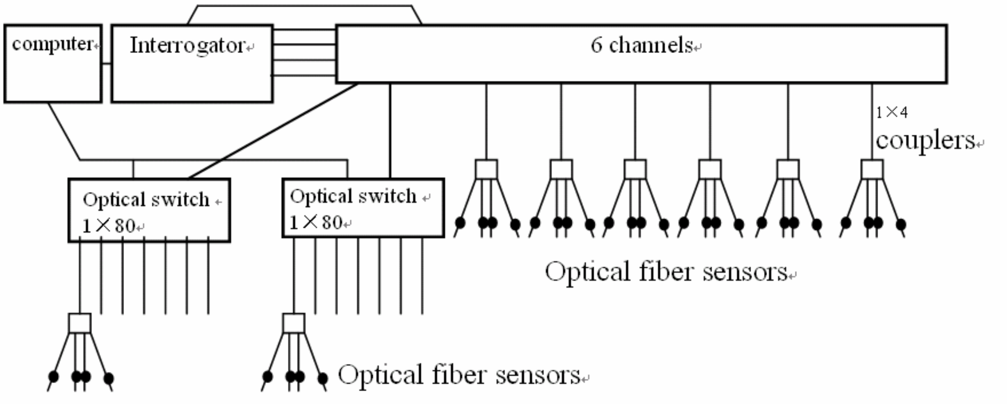


Fig. 8: The optimization layout of optical fiber sensors integration.

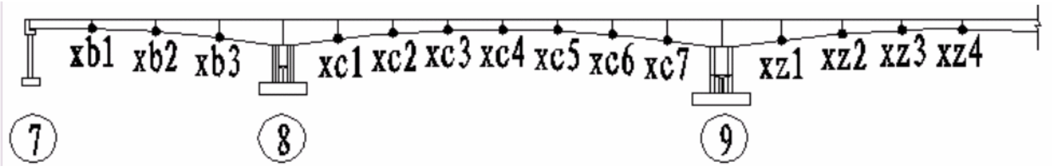


Fig.9: The distribution of acceleration sensors.

In the part of optical fiber sensors integration, we adopted the following optimization mode of connection: sensors—coupler-- optical switch—interrogator. The optimization integration layout is showed in Fig.8. Fig.9 shows the distribution of acceleration sensors of half bridge.

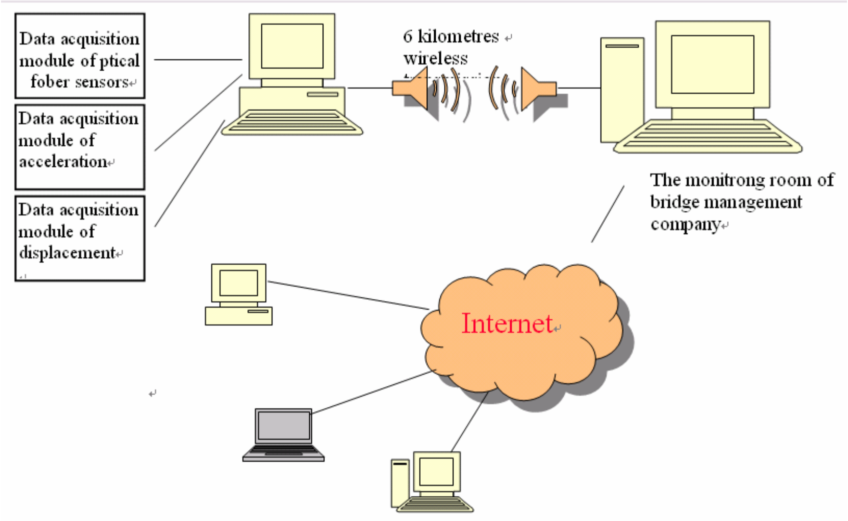
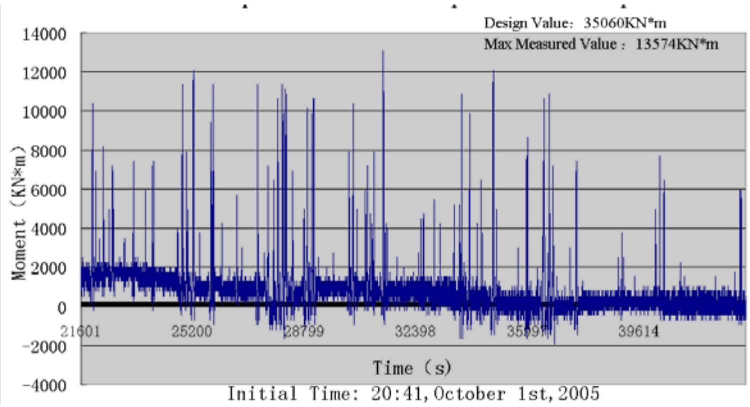


Fig.10: The data acquisition, transmission and display mode of the SHM system.

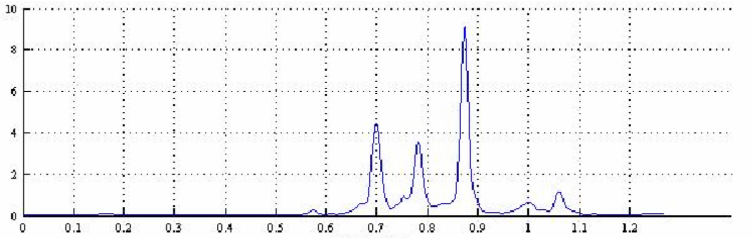
The internal force monitoring subsystem (mentioned above), the vibration monitoring subsystem, the displacement monitoring subsystem and the weighing subsystem were integrated into the real-time online health monitoring system. All the strain data, the acceleration data and the displacement data will be saved into the health records of this bridge. The mode of data acquisition, data transmission and real-time display is showed in Fig.10.

## 5.2 SOME MONITORING RESULTS

The acquisition of strain, temperature data and acceleration data is the basic function of the health monitoring system. Analyzing the data of strain, we can get the bending moment, shear force and axial force of key sections; we can also figure out the information of vibration mode, such as mode shape, frequency by processing the acceleration data. All of these can be displayed in the webpage of the system simultaneously (see Fig.11).



a) The bending moment spectrum.



b) The power spectrum of vibration.

Fig.11: Some monitoring results of SHM system

## 6. CONCLUSION

The Dongying Yellow River Bridge is the unique project in which the construction supervision, loading test and health monitoring are integrated as one whole monitoring system firstly in China. The full-life heath record will be formed on the basis of SHM system. Comprehensively analyzing the overall process of the integrated system, we find that the full-life monitoring of large bridge is not only benefic, but also necessary. The integrated system design saves monitoring cost in large quantities, especially the cost of sensors. Moreover, it makes the three monitoring stages linked up in time sequence. As a result, all the monitoring information is fully used.

The monitoring system of large civil structure comprises many subsystems and involves many fields such as smart sensor and system integration, data acquisition and processing, parameter and damage identification, modeling correction, health consultation, safety assessment. This research has the character of interdisciplinary and need many researchers of different subjects to cooperate closely.

## REFERENCES

1. Ou J. P. and Zhou Z. Encapsulation techniques for FBG and smart monitoring for bridges with FBG sensors. Proceedings of 4th International Workshop on Structural Health Monitoring, Stanford, CA, USA, 2003

2. Zhou Z, Tian S z and Ou J. P. Applications of optical fiber sensors in civil engineering. Building Structure,2005,(2)

3. Hu F. Q, Xiang Y.Q, YAO Y.D and ZHU W.G. Loading test and evaluation of Zongze bridge In Yiwu city. Journal of Highway and Transportation Research and Development,2003,(02):43-46

4. Xu J. L. The construction supervision of long span bridge. China Communications Press, Beijing, China, 2000

5. Fan L.C. Bridge Engineering. China Communications Press, Beijing, China, 1986

6. MO S.H and Wang D.F. Research of new technique of intelligent health monitoring for reinforced concrete bridge structures. Bridge Construction, 2003, (03):73-77.

7. Han D.J, Xie J. State of Arts of Health Monitoring Techniques for Long pan Bridge. Bridge Structure, 2002, (6):69-73.