DISTRIBUTED REMOTE WIRELESS BRIDGE MONITORING SYSTEM

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There has been a series of bridge collapses in China recently. Most of them are related to serious illegal overloading. In these accidents of bridge collapses, most of the bridges are found to be large bridges, medium bridges or small bridges. Their spans are not long and the ages of them are mostly under twenty years. But many overloaded trunks cross them in the night due to their locations and the lack of effective monitoring measures. In order to add a safeguard against accidents and to solve the problem of managing and maintaining these bridges which are currently the majority of bridges in total, this paper discusses an economical distributed remote wireless bridge monitoring system that is carried out in Hangzhou, China. The main reason for bridge stricture's fatigue and damage is overloaded trunks. Accordingly, the core of the system is analyzing qualitatively the trunks' loads, counting the numbers of heavily loading trunks and finding the patterns of traffic flow. And considering the characteristics of the highway network in Hangzhou, one or several typical bridges in one road are chosen. Several points are chosen to represents the line of the road, therefore the cost of the system is lowered but the aim of overall monitoring the state of every bridge in the highway network is achieved. The paper focuses on the overall structure of the distributed wireless bridge monitoring system in Hangzhou and the field installation, and then discusses and analyzes the strain sensors in the system and their performance. In the end of the paper, the actual testing results of the sensors installed in bridges verify that this kind of sensors could be used to analyze qualitatively the numbers of heavy trunks crossing bridges, to discover the patterns of traffic flow and to improve the bridge management and maintenance in the dynamic bridge safety monitoring and managing system.

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ABSTRACT: There has been a series of bridge collapses in China recently. Most of them are related to serious illegal overloading. In order to add a safeguard against accidents and to solve the problem of managing and maintaining large, medium and small bridges which are currently the majority of bridges in total, this paper discuss an economical distributed wireless bridge monitoring system that is carried out in Hangzhou, China. The main reason for bridge stricture's fatigue and damage is overloaded trunks. Accordingly, the core of the system is analyzing qualitatively the trunks' loads, counting the numbers of heavily loading trunks and finding the patterns of traffic flow. And considering the characteristics of the highway network in Hangzhou, one or several typical bridges in one road are chosen. Several points are chosen to represents the line of the road, therefore the cost of the system is lowered but the aim of overall monitoring the state of every bridge in the highway network is achieved. The paper focuses on the overall structure of the distributed wireless bridge monitoring system in Hangzhou and the field installation, and then discusses and analyzes the strain sensors in the system and their performance. In the end of the paper, the actual testing results of the sensors installed in bridges verify that this kind of sensors could be used to analyze qualitatively the numbers of heavy trunks crossing bridges, to discover the patterns of traffic flow and to improve the bridge management and maintenance in the dynamic bridge safety monitoring and managing system.

1 INTRODUCTION

A series of bridge collapsing and breaking accidents has happened in China recently. Most of them are related to serious illegal overloading. There are some common characteristics in these bridge collapsing accidents: firstly, most of these bridges are large bridges, medium bridges or small bridges and their spans are not long; secondly, the ages these bridges are mostly under twenty years; thirdly, the number of overloaded trunks crossing the bridges in the night is bigger due to the location of the bridges; Fourthly, there is a lack of effective measures supervising overloaded trunks crossing bridges.

From the above analysis, most of these bridges are in the initial stage of their operating life. There is no structural health monitoring (SHM) because they are large bridges, medium bridges, small bridges or the approaches of grand bridges. Therefore, the maintenance and management of these bridges relied on human regular check. However, with the rapid development of Chinese economy and the fast growth of traffic volume, these bridges have some structural safety problem in an early time due to the heavy load. How to supervising these bridges effectively is a big problem facing the people responsible for bridge maintenance and management. If the SHM can be installed in these medium bridges and small bridges to improve the supervising level of bridge safety, the problem of feeble bridge management and maintenance could be partly solved. When the number of overloaded trunks crossing these bridges is found to rise, an early inspection and assessment of the bridge structural condition could be carried out according to the actual situation. Besides, according to the useful statistics relevant law enforcement departments could be asked to strictly check overloaded crossing trunks to avoid the aggravation of the bridge structural conditions.

However, there are several problems in the current SHM. Firstly, most bridge SHM systems are aimed at grand bridge. Designing and constructing grand bridges cost much. When accidents happen, the social effect is great. Grand bridges often have complicated structures and are hard to maintain and manage, so it is necessary to build intelligent SHM systems in order to reduce the burden for the maintenance personnel. For example, Tsing Ma Bridge in Hong Kong, China, Jiangyin Yangtze River Highway Bridge, Runyang Yangtze River Bridge, Humen Bridge in Guangdong, Lupu Bridge in Shanghai, and Hangzhou Bay Bridge in the mainland of China are all equipped with SHM. Secondly, most of current long-term bridge SHM systems are wired. Although the technique of wireless telecommunication is mature, the long-term SHM is still mainly using wired transmission such as serial transmission, Ethernet and optical fiber transmission. Thirdly, the statistical exception function of the current bridge SHM system is mainly working in the assessing system in the background server instead of in the foreground device that collecting statistics from sensors. As a result, the background server has a heavy workload and burden.

From the above analysis, current bridge safety monitoring systems are only suitable for grand bridges and cost much. For the large bridges, medium bridges and small bridges which are in the majority of bridges and are scattered, the traditional large SHM systems are obviously inappropriate. However, in Hangzhou bridges in the county roads amount to more than two thousand. Among them, there are 292 large bridges, 692 medium bridges and 1398 small bridges, which in total account for 99 percent of all bridges. It is not realistic to find, deal with and control the damage to these bridges that caused by overloaded trunks only through current personnel doing field checking. What's more, it will be a huge project and will cost much to install the expensive bridge SHM systems in these bridges. The situation requires an advanced and economical monitoring system to help the maintenance and management departments to monitoring these bridges and to improve supervising measures. Monitoring the patterns and numbers of crossing overloaded trunks on these bridges in real time will provide reliable statistics for the bridge maintenance and management and other decision.

To solve the current problem in the maintenance and management of large bridges, medium bridges and small bridges, this paper discusses an economical distributed wireless bridge monitoring system that is carried out in Hangzhou, China. The main reason for bridge stricture's fatigue and damage is overloaded trunks. Accordingly, the core of the system is analyzing qualitatively the trunks' loads, counting the numbers of heavily loading trunks and finding the patterns of traffic flow. And considering the characteristics of the highway network in Hangzhou, one or several typical bridges in one road are chosen. Several points are chosen to represents the line of the road, therefore the cost of the system is lowered but the aim of overall monitoring the state of every bridge in the highway network is achieved. The paper focuses on the overall structure of the distributed wireless bridge monitoring system in Hangzhou and the field installation, and then discusses and analyzes the strain sensors in the system and their performance. In the end of the paper, the actual testing results of the sensors installed in bridges verify the feasibility of the system.

2 THE OVERALL FRAMEWORK OF THE SYSTEM

The distributed wireless bridge monitoring system in Hangzhou is a comprehensive project that integrates the techniques of bridge engineering, sensor, wireless telecommunications, computer network, database, Web service and GIS. Figure 1 shows the functional block diagram of the distributed wireless bridge monitoring system in Hangzhou. As it shows, the system could be logically divided to 2 layers. The down layer consists of truck monitoring sensors distributed on different bridges. The sensors transmit the statistics of overloaded trucks that surpass a given threshold to the up (or remote) database server through the Internet by the technique of wireless GPRS data transmission. The personnel of bridge maintenance and management could get their accounts and passwords through the system administrator and use an Internet browser to login the GIS system and Web server. Then the personnel could acquire the traffic patterns of trucks on the roads of their own districts and thus decide whether to further check and enforce the components of the bridges in their districts. What's more, because the statistics of overloaded trucks transmitted to the servers are all in real time, the system will give a warning about a heavy load crossing some bridge. The supervising personnel in the system monitoring center could contact the personnel of the road maintenance and management in that district immediately and ask them to go to the precise site or the whole road to check whether the structure of each bridge in the road is damaged permanently. At the same time, the supervising personnel could request relevant law enforcement departments to stop the very overloaded truck on the road that the truck is going to follow. As a result, the truck could not damage the structures of other bridges in the road network.

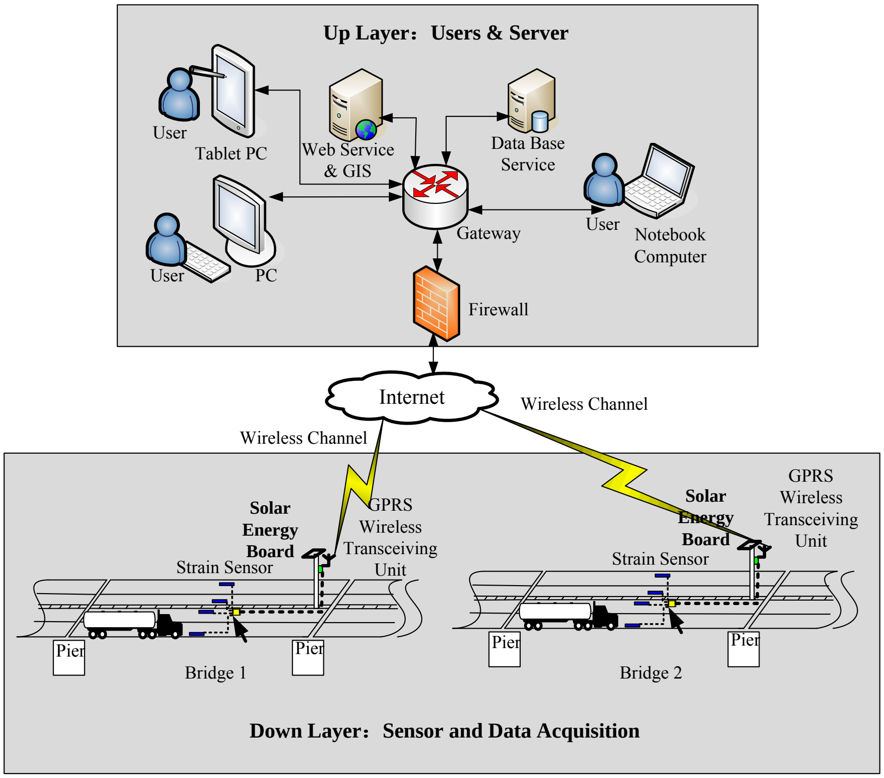

Figure 1 The functional block diagram of the distributed wireless bridge monitoring system in Hangzhou

Figure 2 shows the GIS map of the distributed wireless bridge monitoring system in Hangzhou based on Web. In the figure, the red and green lines represent the road network of county roads and higher level roads in Hangzhou. The big blue dots represent the bridges with load monitoring sensors. Actually each road has many bridges (represented by the small blue dots), but only some typical bridges were chosen to install the monitoring sensors.

Figure 2 The GIS map of the distributed wireless bridge monitoring system in Hangzhou

It has already been researched in many papers to recognize mobile loads through bridges' dynamic responses. Considering the complication of establishing equations of the dynamics of the bridge structure and the influence of the roughness of the bridge road , the velocities of the mobile loads and coupling between loads and bridges, it is obviously unrealistic to have precisely quantitative recognition of the mobile loads on bridges through a single parameter of dynamic responses. Therefore, in this system, the influence of some factors such as velocity of loads and roughness of the road are neglected, and the mobile loads are not recognized quantitatively. Assuming that the shock responses from mobile loads to bridges are liner, the system analyzes qualitatively the loads crossing bridges and discovers the traffic patterns. On this base, the system speculates the possible damage that loads have done to the structures of bridges so that the ability of bridge maintenance and management is improved.

The costs of this system are lowered not only through reducing monitored bridges but also the following measures. The early stage of the realization of the system costs less when typical bridges in the road network are chosen to reduce monitored bridges. At the same time, the power consumption of devices is firstly lowered. The low power consumption of devices means that the supply capacity of the solar power system could be decreased, thus the costs of power devices are lowed. The main way to lower power consumption is to replace the strain resistor of 120Ω in the traditional experiment with one of 1kΩ. The power consumption of each bridge could decrease by 15% according to the calculation. Secondly, sensitivity of sensors is improved. High sensitivity could help reduce the complication of realizing signal conditioning circuits and lower the realizing cost of data acquisition circuits. Thirdly, the foreground sensors are smarter and their processing ability is enforced. The accuracy of recognizing overloaded trucks is improved. Only the statistics over a given threshold are transmitted so that the data traffic is diminished. Because the telecom operators charge for transmitting data into the Internet by GPRS, the decrement of data traffic will lower the cost of the maintaining system operation greatly.

3 THE STRUCTURE OF THE STRAIN SENSOR AND THE TEST OF ITS PERFORMANCE

This part mainly analyzes and tests the performance of the strain sensor. When it comes to the distributed wireless bridge monitoring system in Hangzhou, in order to improve the accuracy of the loads' statistics qualitatively analyzed by the supervising system, at first the good elasticity and repeatability of the structure of the strain sensor on the foreground and the good linearity in the measuring range should be ensured. Figure 3 shows the structure of the strain sensor. Its profile is an arc. In the center of the arc there is a round hole. On the up and down surfaces of the hole, a simple arc bridge strain sensor could be realized according to the location of strain gauges in Figure 3 and the circuit in Figure 4. The strain gauges are close to the hole in the arc so that the four bridge strain gauge concentrate stresses, thus the overall sensitivity of the arc strain sensor is improved.

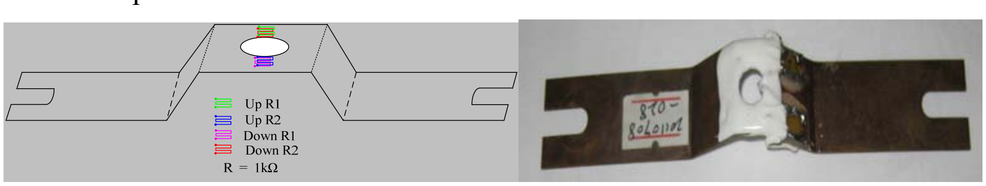

Figure 3 The arc bridge strain sensor

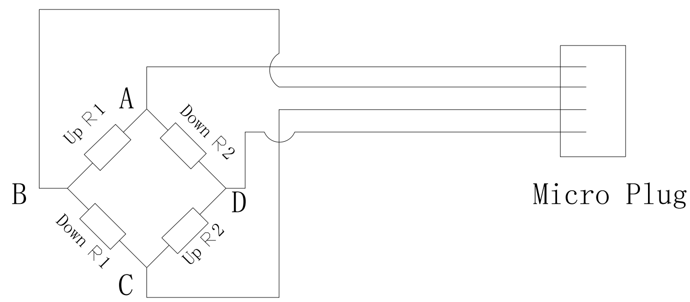

Figure 4 The circuit of the bridge strain sensor

In order to verify the strain performance of the arc sensor, the testing system shown in Figure 5 is used to mark all arc strain sensors in the project of the distributed wireless bridge monitoring system. The mechanical device on the left is a stress calibration frame. It is installed with a dial gauge to test the strain from braking wheels when the wheels is forwarding or backing. Pin A and C of the arc strain sensor connect to a power supply with a constant voltage of 2 volt and the digital multimeter of high precisions used to test the output voltage of Pin B and D.

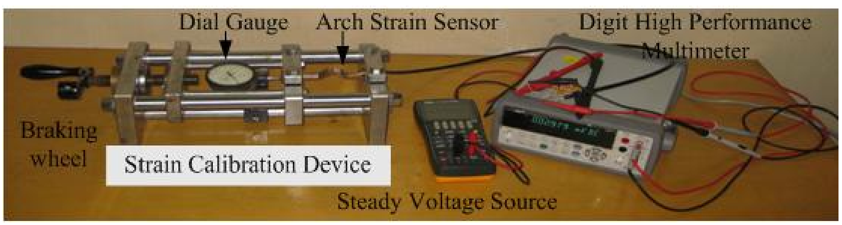

Figure 5 The strain sensor marking system

In the experiment, the strain ranges from -1000με to +1000με and each strain sensor loops for four times. In each time the change of the strain due to each step of the braking wheel is 100με. Table 1 lists the testing result. According to eh testing results in Table 1, Figure 6 draws four groups of curves corresponding to the statistics. From the testing curves, the repeatability of arc strain sensors is good, Then the linear deviation of the arc strain sensors will be analyzed according to the testing results in Table 1 (The influence on the test from changing temperature is neglected at the moment).

Table 1 The relation between the strain and the voltage of the arc strain sensor.

Variation of stresses （με）	Voltage 1 (mV)	Voltage 2 (mV)	Voltage 3 (mV)	Voltage 4 (mV)
1000	4.937	4.942	4.933	4.945
900	4.825	4.83	4.821	4.835
800	4.71	4.708	4.706	4.715
700	4.596	4.596	4.592	4.598

600	4.48	4.482	4.476	4.485
500	4.362	4.37	4.363	4.375
400	4.248	4.257	4.248	4.264
300	4.137	4.136	4.132	4.144
200	4.021	4.022	4.014	4.026
100	3.906	3.91	3.898	3.909
0	3.785	3.794	3.78	3.79
-100	3.663	3.676	3.663	3.673
-200	3.544	3.556	3.547	3.554
-300	3.427	3.438	3.43	3.437
-400	3.308	3.318	3.311	3.321
-500	3.191	3.202	3.193	3.202
-600	3.072	3.086	3.078	3.082
-700	2.953	2.966	2.956	2.965
-800	2.836	2.843	2.836	2.844
-900	2.723	2.726	2.721	2.729
-1000	2.604	2.615	2.61	2.613

The calculation of the nonlinear deviation of the arc strain sensor through the ideal straight lime method:

1）Average the travel distance of each sensor in the calibrating loops to get a mean line;

2）Establish n equations according to n stress ladders:

$u_1=p_1*m+b$, $u_2=p_2*m+b$, $u_3=p_3*m+b$, ……, $u_n=p_n*m+b$ ……（1）

In the equation: n is the number of stress ladders; u is the output voltage; p is the value of strain; m is the slope; b is the intercept.

3）Divide the n equations to 2 groups and equations of each groups add to each other to get 2 equations. Here n = 21.

$$\left\{\begin{array}{l} u_1 = p_1 * m + b \\ u_2 = p_2 * m + b \\ u_3 = p_3 * m + b \\ \cdots\cdots\cdots\cdots \\ u_{10} = p_{10} * m + b \end{array}\right\} \ldots\ldots(2) \qquad \left\{\begin{array}{l} u_{11} = p_{11} * m + b \\ u_{12} = p_{12} * m + b \\ u_{13} = p_{13} * m + b \\ \cdots\cdots\cdots\cdots \\ u_{21} = p_{21} * m + b \end{array}\right\} \ldots\ldots(3)$$

m and b can be computed through by uniting Equations (2) and (3).

4）Because the value of the stress ladder is fixed, p_n , m, and b are now known. Replace them in $u_n=p_n*m+b$, each $u_n^{'}$ can be get by the ideal straight method.

5）Subtract each u_n from of n groups in the same stress ladder and get the difference ΔL of each measured value.

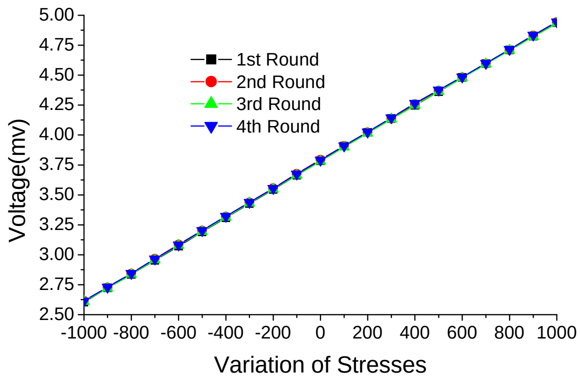

Figure 6 The result of performance test

6）Calculate the maximum deviation of the output un and .

$$\Delta L_{\max} = \frac{\left|+\Delta L_{\max}\right| + \left|-\Delta L_{\max}\right|}{2} \quad \ldots\ldots (4)$$

7）Calculate the nonlinear deviation

$$L_N\% = \frac{\Delta L_{\max}}{u_n - u_1} * 100\% \ldots\ldots (5)$$

Note: Here（$u_n - u_1$） is taken as the output value of the full measuring range.

According to Equation (1), (2), (3), (4) and (5), the calculated maximum nonlinear deviation of the four groups of output values in the Table 1 are respectively 0.5%, 0.4%, 0.3% and 0.5%. Considering output stresses are not conditioned and amplified and are directly measured by digital multimeter, the actual nonlinear deviation of the full measuring range is smaller. Because the strain sensors are mainly used to analyze loads qualitatively, the used arc strain sensors can meet the requirement of this experiment.

4 THE ACTUAL TEST AND VERIFICATION

Among more than two thousand bridges in Hangzhou, most are of simply supported beam structure. In the distributed monitoring system, the bridges of simply supported beam structure account for more than 80% of the bridges installed with monitoring sensors. Therefore, this part takes bridges of simply supported beam structure as an example and verify the reliability of using dynamic stain sensor to analyze loads qualitatively. Figure 7 shows the schematic diagram of the installation of the sensors and cameras at the system testing field. In the figure, the dynamic strain sensor is installed in the outside lane and on the bottom in the middle of the span. The location is where wheels push the road most possibly. In the qualitative analysis of loads on the system, the loads are divided into three levels according to the actual requirement of the system and the possible extent of loads' damage to the bridge structure: Level A includes vehicles from 10 tons to 30 tons; Level B includes vehicles from 30 tons to 50 tons; Level C includes vehicles more than 50 tons.

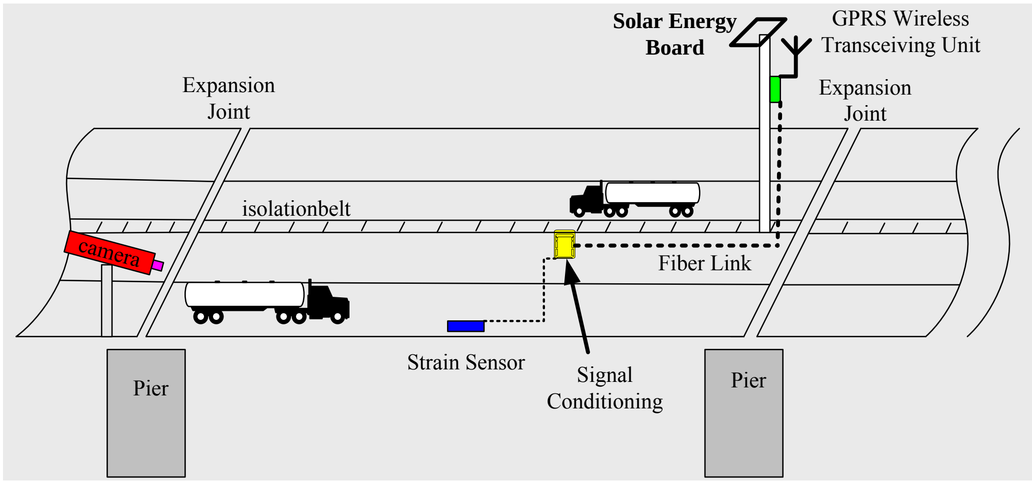

Figure 7 The schematic diagram of the installation of the sensors and cameras at the system testing field.

Figure 8 (a), (b), (c), (d),(e) and (f) show pictures and variation of stresses when 6 different loaded vehicles crossing the bridge. The variation of stresses is a relative value without a unit (The reason is that in the process of installation and adjustment, the arc strain sensors can change the extent by which signals are amplified to achieve the optimal testing results according to the field situation.) The level of the mobile loads in Figure 8 (a) and (b) is Level A; the level in Figure 8 (c) and (d) is Level b; the level in Figure 8 (e) and (f) is Level C. From the 6 following figures, the differences among the three levels of loads are relatively obvious. Here the variation of stresses from 3.5 to 12 belongs to Level A; the variation form 12 to 20 belongs to Level B; the variation above 30 belongs to Level C.

From the 139 testing results in that night, the accuracy of analyze loads qualitatively can reach more than 95%. The main error is because the parallel vehicles on two lanes and vehicles occupying two lanes. Parallel vehicles cause the increment of the variation of stresses, as a result loads of low level are recognized as those of high level. For vehicles occupying two lanes, loads of high level are recognized as those of low level due to the traverse distributed stresses. The classification errors caused by these two situations cannot be avoid because the strain sensors are installed under bridge.

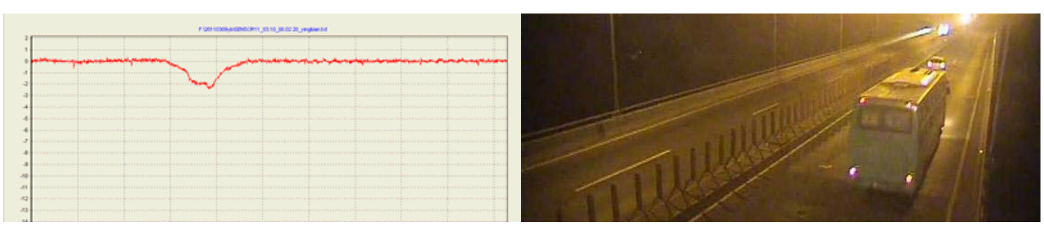

Figure 8 (a) Time: 0:02:39; Maximum variation of stresses: 6.25; Kind of Vehicle: Bus

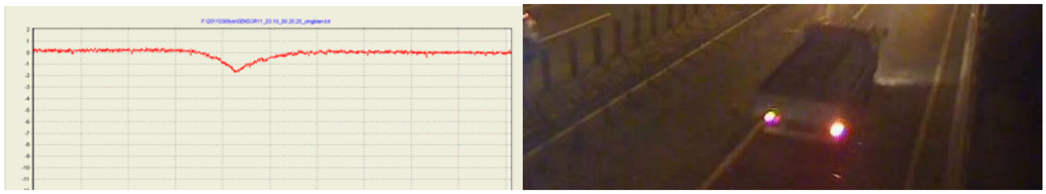

Figure 8 (b) Time: 0:20:56; Maximum variation of stresses: 5; Kind of Vehicle: truck

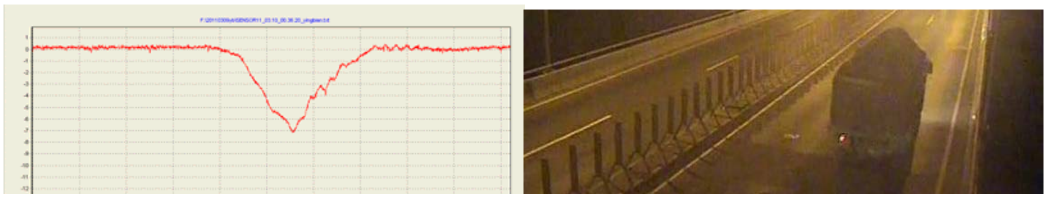

Figure 8(c) Time: 0:36:50; Maximum variation of stresses: 18.5; Kind of Vehicle: truck

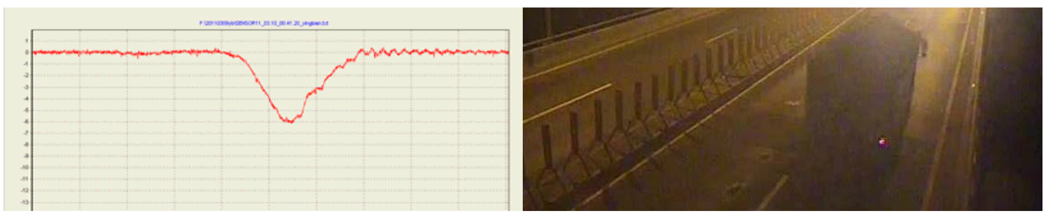

Figure 8 (d) Time: 0:42:01; Maximum variation of stresses: 15.5; Kind of Vehicle: truck

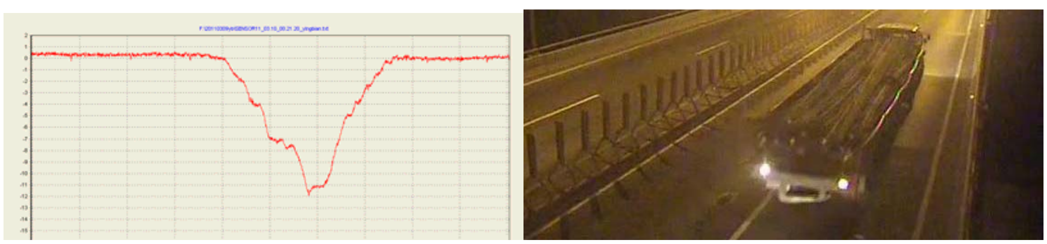

Figure 8 (e) Time: 0:21:45; Maximum variation of stresses: 30.5; Kind of Vehicle: truck of 6 axles

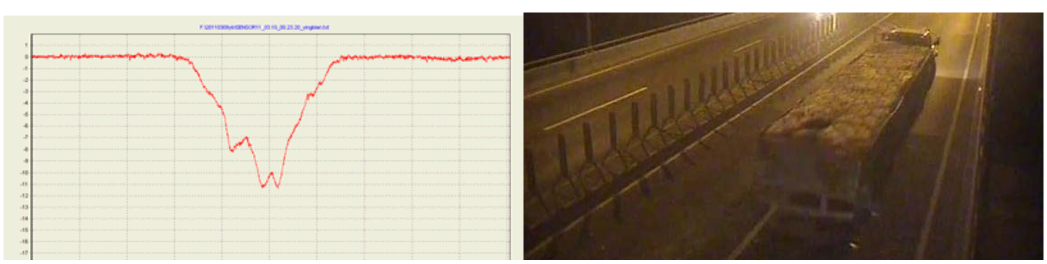

Figure 8 (f) Time: 0:23:56; Maximum variation of stresses: 29; Kind of Vehicle: truck of 6 axles

Figure 8 The testing pictures and corresponding maximum variation of stresses

5 CONCLUSION

Due to the increasing transport loads, more than two thousand bridges in the county roads or higher level roads in Hangzhou face the problem of being more fatigued and damaged in a shorter time. To solve the problem in the current maintenance and management of large bridges, medium bridges and small bridges which in total are in the majority of all kinds of bridges, Hangzhou carried out a distributed wireless bridge monitoring system, which integrates the techniques of bridge engineering, sensor, wireless telecommunications, computer network, database, Web service and GIS. This paper focuses on the discussion, research and verification of the feasibility of using sensors of dynamic response to qualitatively recognize mobile loads on bridges and discover the traffic patterns of overload trucks. The experiment demonstrates that this kind of sensor could be used to qualitatively analyze the number of crossing overloaded trucks and to discover their traffic patterns in the Hangzhou dynamic bridge safety supervising system. The realization of this system will improve the ability of the maintenance and management of large bridges, medium bridges and small bridges greatly, and reduce the heavy burden carried by the personnel of bridge maintenance and management.

This project has some further work. Firstly, the scalability of this system can be improved. To achieve this aim, the function of online updating programs should be added to the sensors of the down layer. So the system can upgrade software in the remote terminal devices according the latest research development in order to improve the performance of the devices and improve the maintainability of devices. Secondly, systematic errors should be diminished to improve the accuracy of recognizing loads in different road lanes. In the above experiment, although the sensors were installed in the outside of a road lane, the measured value from the sensor was still high when an overloaded truck cross the other road lane. Therefore, further research should be done on how to use the relation of the transverse stresses on bridges to reduce the mutual influence between loads from different lanes. Thirdly, the focus of the subsequent projects should include how to use the statistics of overloaded trucks from the distributed wireless bridge monitoring system to speculate the influence on bridge structures' aging and being damaged from mobile loads, how to use the statistics to further assess the condition of the structures of other bridges in the road network and concluding the maintaining and supervising measures of the overall bridge structures under the influence of heavy loads.

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