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Methodology of Long-Term Real-Time Condition Assessment for Existing Cable-Stayed Bridges

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Abstract: Difficulty in measuring the total stress of bridge girders in service (due to dead, live, and environmental loads) raises a significant problem in assessing existing cable-stayed bridges without a complete monitoring record from construction to service. To address this problem, this paper develops a practical monitoring methodology that needs to focus only on the variation of the bridge condition during the service period. In the proposed methodology, the variation of the bridge condition is considered with respect to two sub-conditions: the long-term load condition and the service live load condition. Using the varying cable forces as a reflection of the long-term load condition, the effect of time-dependent loads can be entirely traced back from the present to the bridge's completion. The service live load condition is real-time monitored using strain sensors distributed across different cross-sections. Specific bridge design codes are used to set up the assessment criterion by specifying the stress threshold envelopes for checking each sub-condition of the bridge. By using a three-dimensional solid finite element model in the study of service live load condition, it becomes feasible to arrange measurement stations at the exactly same positions as those on the real structure. A case study is conducted through which the advantages of the proposed methodology are demonstrated.

Key words: condition assessment, existing cable-stayed bridge, variation of bridge condition, long-term load condition, service live load condition, specific bridge design codes, finite element model.

1. INTRODUCTION

In recent years, there has been growing concerns about the health of existing bridges. Bridges in service today are deteriorating due to many factors, such as unexpected accidental loads, varying environmental condition, deferred maintenance, etc. (Sasmal and Ramanjaneyulu 2008). A common problem for bridge owners/managers is the need to assess the condition of the existing bridge in service (O'Connor and Enevoldsen 2007). For this purpose, a large amount of data concerning the bridge condition from its construction stage to the time of assessment should be available in order to track and identify the pre-existing stresses of the structure at any time in the past. However, a majority of existing bridges lack such complete data (Tan 2005), which raises a significant challenge for bridge owners, managers, and researchers. While a typical bridge monitoring system can measure the incremental stress, the pre-existing stresses of the structure are usually not easily obtained.

In the past decades, significant efforts have been made to study the condition assessment of existing bridge structures (Aktan *et al*. 1996, 1997, 1998; Ferregut *et al*. 1995; Natke *et al*. 1995; Ng and Fairfield

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2002; Mazurek and DeWolf 1990; Sasmal and Ramanjaneyulu 2008; O'Connor and Enevoldsen 2007; Kim *et al*. 2001). Different methodologies have also been proposed in the literature including the visual observation method, in-situ testing method, fuzzy logic-based approach, and probability-based approach; however, all of them have some disadvantages. The visual observation method is too subjective to provide an accurate result. The in-situ test is not only expensive but it also causes some unexpected damage to the structure; besides, it is only good for short-term condition assessment. Though the fuzzy logic-based and probability-based approaches are becoming more and more popular in recent years, their application procedures are quite complicated; and these approaches do not offer a deterministic result. As a result, all of these assessment approaches are not widely applicable in bridge engineering practice.

Cable-stayed bridges are a unique type of structure in terms of both mechanical properties and construction process. The stress condition of a cable-stayed bridge before being put into operation (will be called "dead load condition" hereafter) is always controllable by altering the sequence of erection stages and adjusting the forces in stay cables during the construction process (Wang *et al*. 2004). Due to the way cable-stayed bridges are constructed, the total stresses in the girders are usually difficult to be determined accurately during the in-service period if no sensors were installed from the very beginning stage. This raises a significant problem for assessing the condition of existing cable-stayed bridges without a complete monitoring record from construction to service; however, these problems could be prevented if the knowledge of the dead load condition of the bridge is not necessary or can be alternatively derived. As a matter of fact, in practice it is generally safe to assume that the dead load condition can well follow the design scheme and that most of the structural deteriorations occur only after the bridge construction is finished. As a result, engineers can now only focus on the variation of bridge condition since being put into operation, which is the basic idea behind the proposed methodology in this paper. Hereafter the variation of bridge condition refers to the variation after the bridge is put into operation unless specifically noted otherwise.

The proposed methodology for long-term real-time condition assessment of existing cable-stayed bridges in the present study aims at the cable-stayed bridges without a complete monitoring record from construction to service and the total stress of whose girders during the service period are difficult to be measured. In this approach, the variation of bridge condition is the sole focus during the entire assessment process and the need of the information of total stresses in girders can be avoided. The long-term load condition and service live load condition are the two objectives of assessment. The cable force, which can be easily measured and traced back from the present to the bridge's completion, was selected to reflect the long-term load condition while the measured stresses of girders were chosen to represent the service live load condition. The bridge responses in the two sub-conditions were then compared with the stress threshold envelopes obtained according to specific bridge design codes, and conclusions were drawn upon the condition of the bridge. The advantages of the proposed methodology were demonstrated by applying it to the condition assessment of Zhao Bao Shan Bridge, an existing cable-stayed bridge in Zhejiang Province of China.

2. CONCEPT AND PRINCIPLE OF THE PROPOSED METHODOLOGY

In the proposed methodology the variation of the bridge condition from its dead load condition is considered with respect to two sub-conditions that exclude the dead load effects: the long-term load condition and service live load condition. The long-term load condition is defined as the bridge condition under the effects of long-term loads such as creep and shrinkage-induced loads and long-term varying loads caused by temperature change, etc. The service live load condition is defined as the bridge condition under the effects of service live loads such as vehicle loads, pedestrian loads, wind loads, and short-term varying loads caused by temperature change, etc. The service live load condition can be real-time monitored using strain sensors. In contrast, due to the time-dependent feature of the long-term loads, the long-term load condition should be recorded ever since the operation of the bridge, which is difficult if no sensors were installed at the initial stage, as discussed earlier. To address this problem, this study proposed using the variation of cable force as a reflection of the long-term load condition. The main reason of selecting the cable force is that the cable force can be easily traced back all the way from the present to the bridge's completion. When the cable-stayed bridge is subjected to the long-term loads, the corresponding deformation of the bridge structure would be partially restrained by stay cables. As a result, the forces in the stay-cables would be re-distributed to satisfy deformation compatibility in the entire structure. Therefore, the variation of cable forces could be considered to be a good reflection of the long-term load condition. In other words, the long-term load condition can be equally judged by checking the varying cable forces.

2.1. Long-Term Load Condition Assessment

To exclude the effect of the service live loads on the cable forces, the measurement of cable forces should be performed when minimum traffic is present. The variation of cable forces can be then directly calculated by subtracting the measured stay cable forces from the design cable forces or from measured cable forces at the completion of construction. As a result, the long-term load condition such as girder stresses can be predicted by applying the variation of the cable forces as internal forces on the bridge structure model. To do this, a two-dimensional (2D) frame finite element (FE) bridge model was used in the present study. For convenience, in practice the resulted stresses of girders from the FE analysis are usually used as the parameter to check the condition of the bridge by comparing them with the pre-set stress threshold envelopes.

In the present study the loads specified in specific bridge design codes, which could cover all possible long-term loads in reality, are used to develop the allowable stress envelopes that are used to check the long-term load condition of the bridge. The stress envelopes can be predicted by applying the code-specified long-term loads to the FE model of the bridge.

Since the specific bridge design codes cover all possible long-term loads in real life, the predicted stresses due to the varying cable forces should be within the predicted stress threshold envelopes when the long-term load condition of an existing cable-stayed bridge remains safe or normal. This is used as the criterion of the proposed methodology to assess the long-term load condition of existing cable-stayed bridges.

The long-term load condition assessment over a long period of time can be easily ensured by a long-term (not necessarily continuous) measurement of cable forces. The flow chart for the proposed approach of assessing the long-term load condition is illustrated in Figure 1.

2.2. Service Live Load Condition Assessment

Service live load condition of a bridge is referred to as the bridge condition under the effects of service live loads such as vehicle loads, pedestrian loads, wind loads, and short-term varying loads caused by temperature change, etc. Compared with the long-term load condition, the service live load condition varies much more frequently and significantly in a short period of time, and it therefore usually draws more attention. To gain a better view of the structural condition, a good measurement strategy is needed. In most cases a good measurement system would be one such that it uses as few sensors as possible while being able to collect all information needed for assessing the bridge condition. In the present study this can be done by installing sensors only at the critical locations or cross-sections of girders where the responses of the girders vary significantly or the stress is very close to the stress threshold specified in the specific bridge design codes. The critical locations or cross-sections of girders can be determined by performing a static analysis on the FE model of the bridge structure.

Due to the shear lag effect found in concrete bridge structures, it is common that the stresses at different locations across a cross-section differ from each other, which is the so-called spatial distribution of stress. This phenomenon could be significant for cable-stayed bridges under service live load condition mainly subjected to bending and torsion. To be able to consider the spatial distribution of stress across the cross sections, sensors should not only be installed at different cross-sections along the longitudinal direction of the bridge but also at different positions along the cross-sections. In the corresponding numerical analysis, a 3D solid FE model is used for the bridge, making it feasible to arrange measurement stations at the exact positions where the sensors are installed on the real structure. Unlike for the long-term load condition, where only the average stress needs to be checked for one cross section because the bridge girders are mainly subject to axle loads leading to only weak spatial distribution of stress, the stresses due to the service live load condition at different locations across a cross-section should all be checked. As a result, stress threshold envelopes should be developed individually for each sensor location across the cross-sections.

Similar to the long-term load condition, the stress threshold envelopes for each measurement stations for the service live load condition assessment can be predicted by applying the worst load condition using the code-specified service live loads onto the 3D solid FE model of the bridge. If a cable-stayed bridge can stay in a safe and normal service live load condition

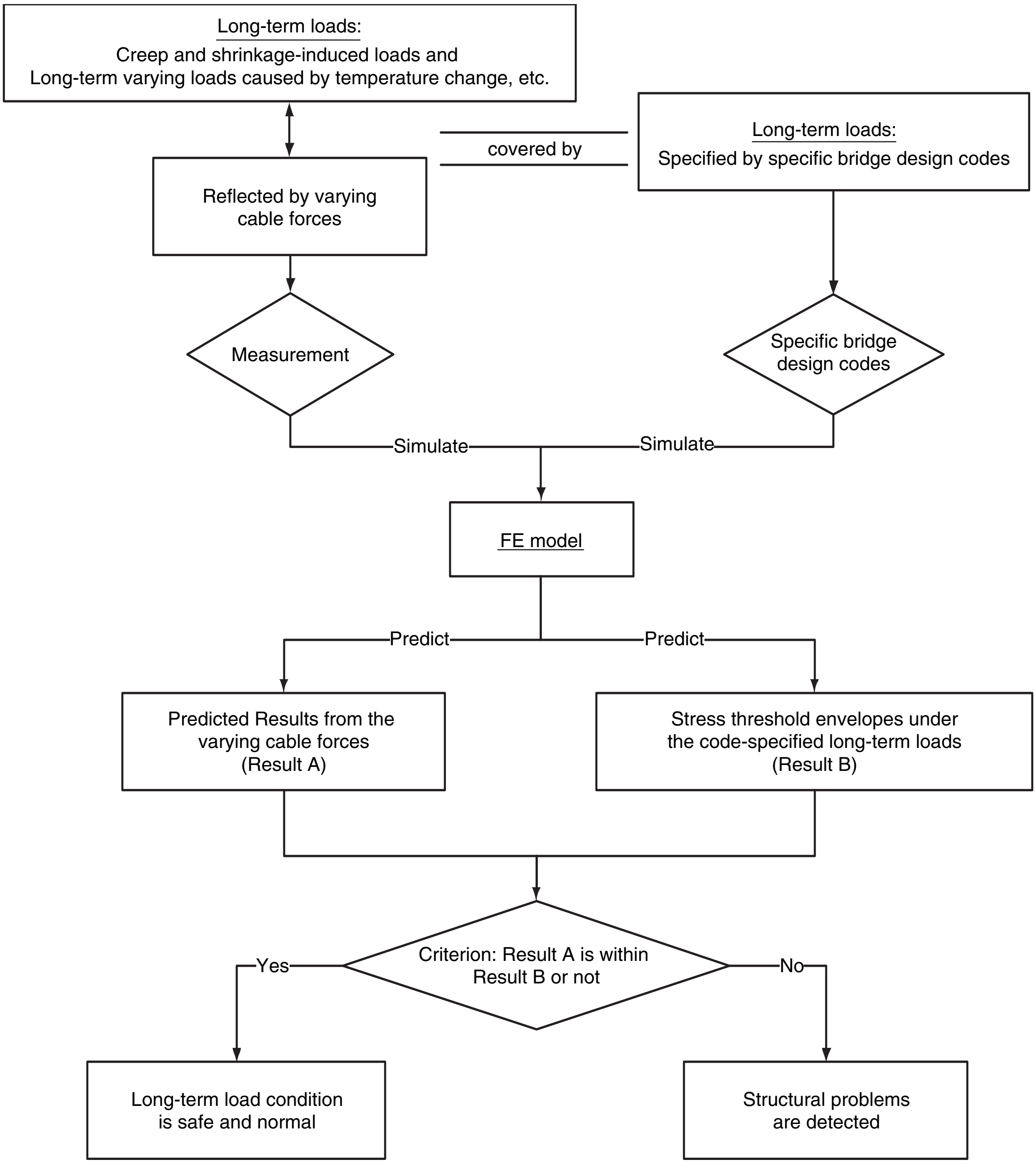


Figure 1. Flow chart of the proposed methodology for long-term load condition assessment

during the service period, the measured stresses from each sensor should be within the corresponding stress envelopes predicted using specific codes.

The long-term feature of the service live load condition assessment can be easily ensured by a continuous real-time stress measurement in a long period of time. However, in the process of collecting real-time data, to differentiate the unwanted effect due to concrete creep, shrinkage, and long-term temperature change from that caused by the service live loads and reduce these effects to the minimum, initialization should be performed setting the initial value of the stress sensors to zero. The flow chart for the proposed methodology of service live load condition assessment is given in Figure 2. It should be noted that the focus of the proposed methodology is for the condition of the entire bridge superstructure rather than any single structural member.

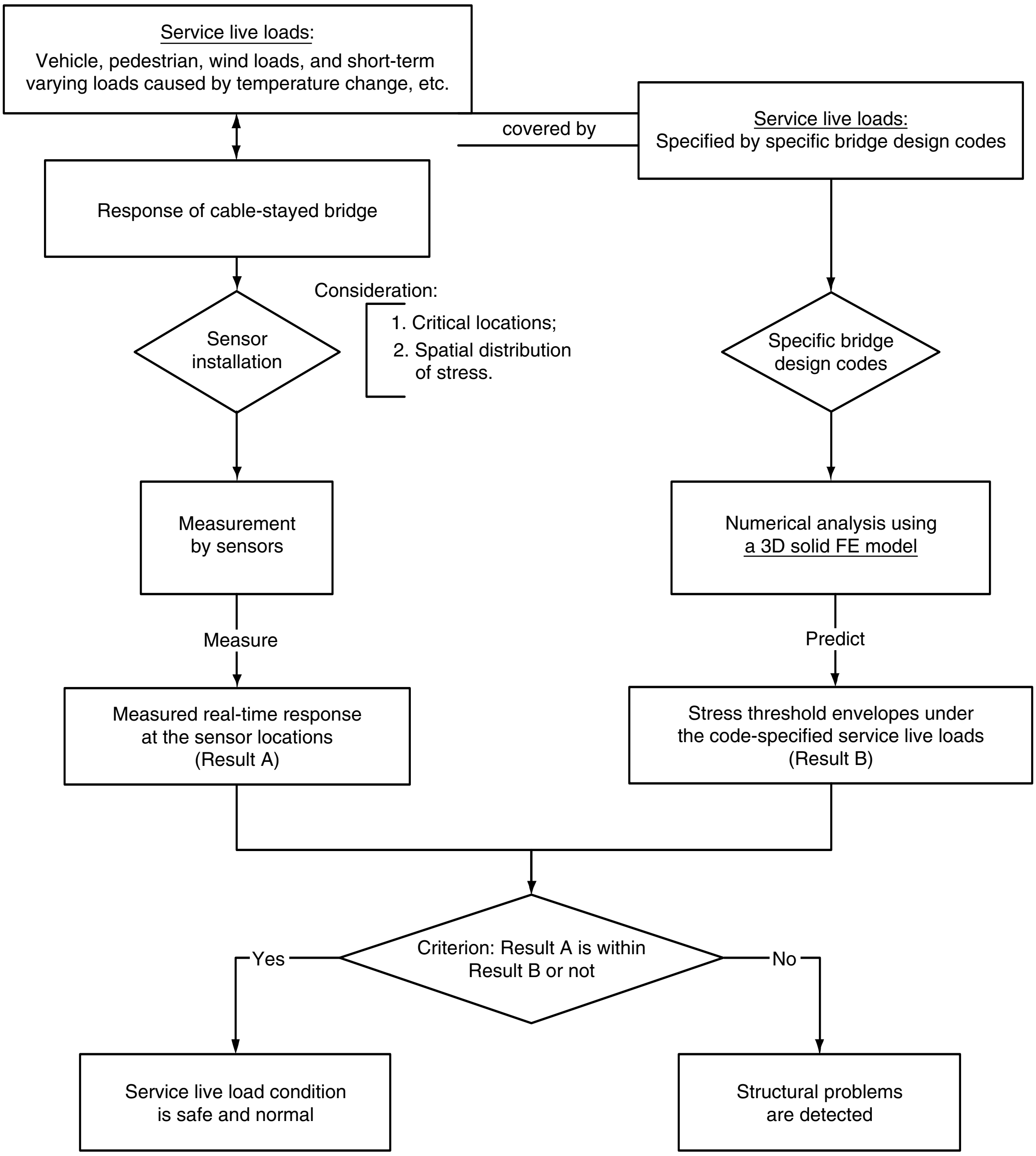


Figure 2. Flow chart of the proposed methodology for service live load condition assessment

3. A CASE STUDY

An existing cable-stayed bridge in China is taken as an example to demonstrate how the proposed methodology can be used to assess the condition of cable-stayed bridges. The tested bridge, Zhao Bao Shan Bridge (Figure 3), is located in Zhejiang province, China (Huang *et al*. 1998; Lv *et al*. 2001). When the cable forces were measured, and assessment of the condition of this bridge was performed in 2005, the bridge had been in service for four years since 2001.

This bridge has two main spans along with a side span, each measuring 258 m (846.46 ft), and 234.5 m (769.36 ft), and 74.5 m (244.42 ft) respectively, as shown in Figure 4. The side span is a continuous-girder structure connected to the main structure. To increase the in-plane flexural rigidity of the bridge, two intermediate piers were constructed dividing the main span into three sub-spans of 102 m (334.65 ft), 83 m (272.31 ft), and 49.5 m (162.40 ft), as shown on the right hand side in Figure 4. Six typical cross-sections labeled

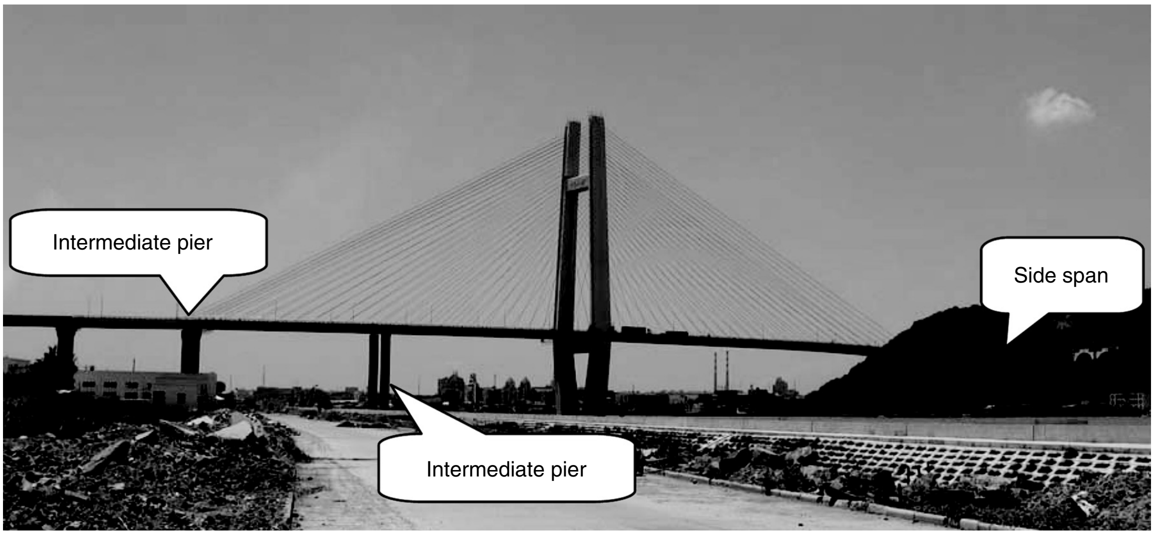


Figure 3. Profile of Zhao Bao Shan bridge

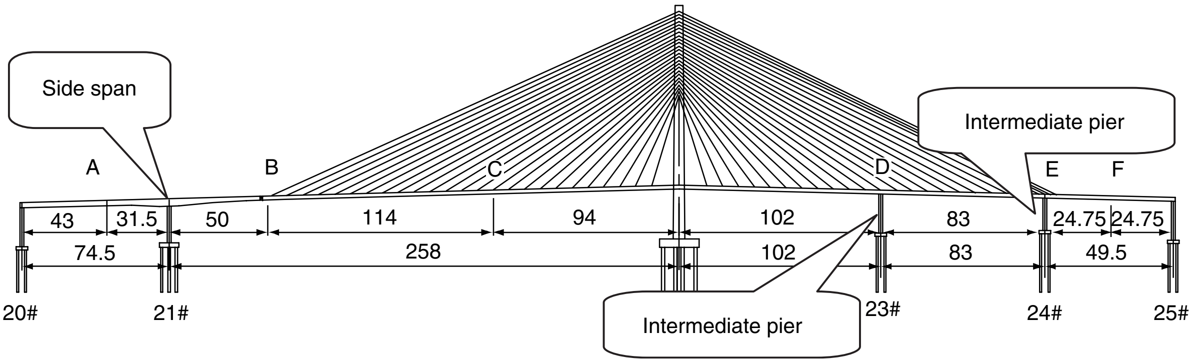


Figure 4. Profile of the study bridge (engineering drawing of design scheme, unit: m)

A, B, C, D, E and F, whose locations and configurations are shown in Figures 4 and 5, were selected as the critical cross-sections for monitoring based on a static analysis for this cable-stayed bridge and were used to assess the condition of the bridge.

3.1. Step 1: Building the FE Model

Based on the engineering drawings of the bridge, a 2D frame FE model and a 3D solid FE model for this bridge were created using the MIDAS and ANSYS programs, respectively. For the 3D solid FE model (Figure 6), the bridge decks, girders, and transverse beams were all modeled using solid elements, which have three translational degrees-of-freedom (DOFs) for each node. The stay cables and steel tendons were modeled using link elements, which have two translational DOFs for each node. In order to reduce computation effort, the single pylon was modeled using beam elements.

The sequence of erection stages during the construction was ignored when creating both the FE bridge models because of two reasons: first, the constructed bridge is assumed to be in safe condition according to the specific bridge design codes; second; the only focus of this study is the variation of the bridge condition after the bridge was put into operation. Also, it should be noted that the FE bridge models were built based on the engineering drawing and field test before in-service period of the bridge and were considered to be acceptable only for this project. For other applications of the proposed methodology, a calibration procedure, such as model updating, for the FE models is very necessary to ensure the accuracy of modeling.

3.2. Step 2: Long-Term Load Condition Assessment

The cable force is the key parameter in the long-term load condition assessment. In order to exclude the effect of the service live load, the measurement of cable forces was performed at night when there was minimum traffic. Accelerometers were used to capture the

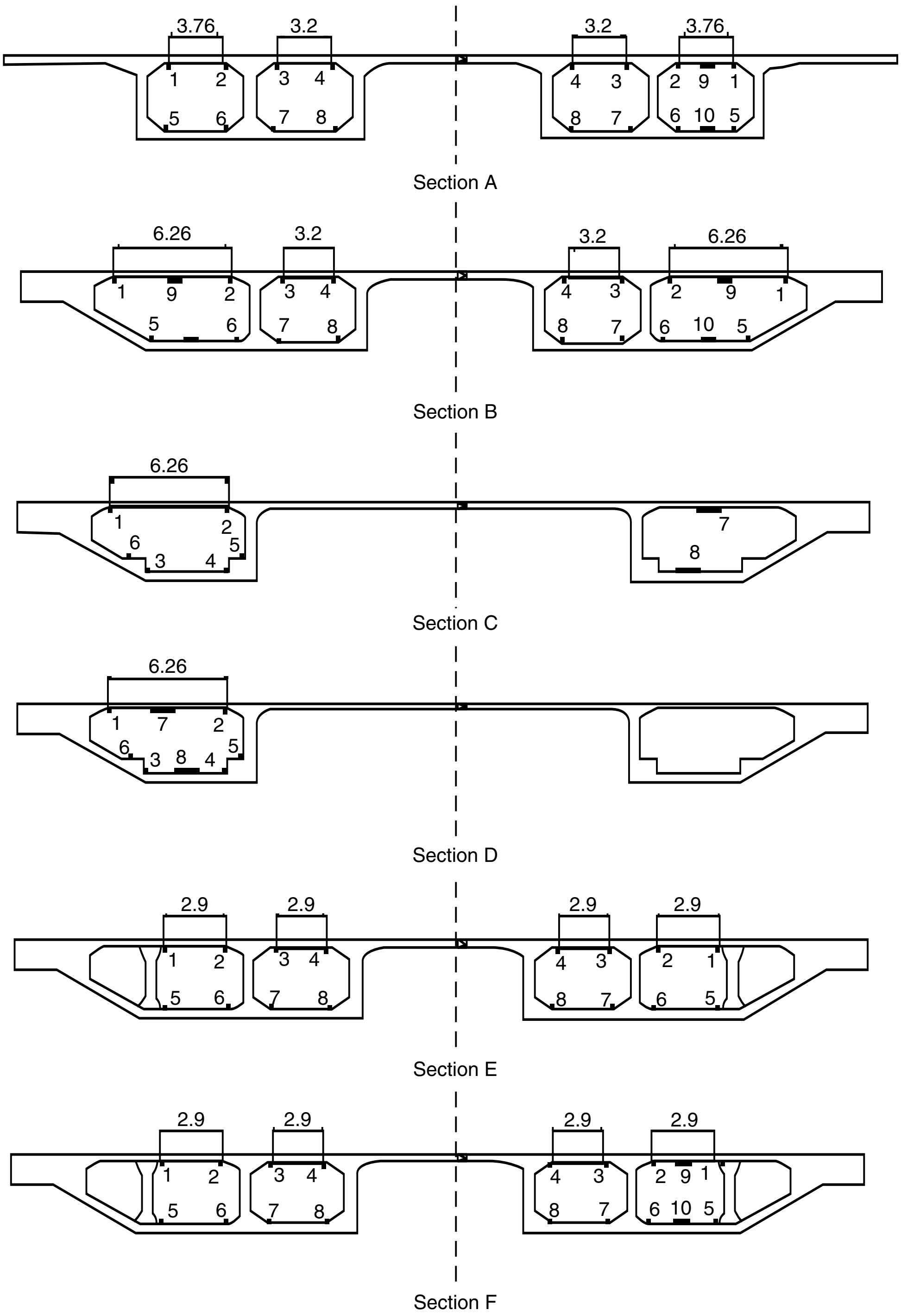


Figure 5. Profile of the critical cross-sections (engineering drawing of design scheme, unit: m)

vibration frequencies of the stay cables (Figure 7). The tensile force in each stay cable was then calculated using the equation as follows:

$$T = Kf^2 \tag{1}$$

where T = measured stay cable force; K = a specific coefficient from the technical manual of the JMM-268 (model number of the accelerometers); and f = measured vibration frequency.

Since the stay cables are symmetric about the tower, for the purpose of convenience the number C0-C25 and C1'-C25' were used to mark the stay cables on one plane, as shown in Figure 8. It should be noted that the stay cables on the other plane are marked using the same numbers. The measured cable forces during the years

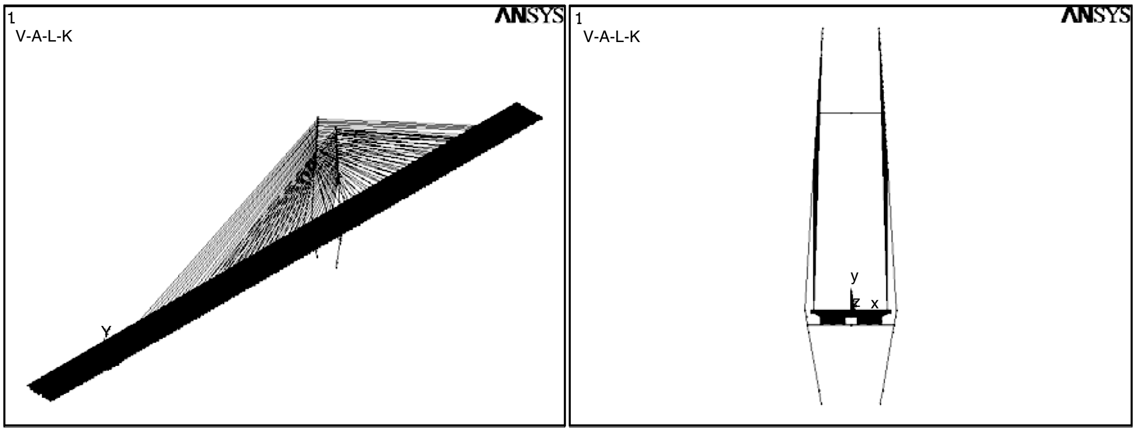


Figure 6. 3D solid FE model of the bridge under study

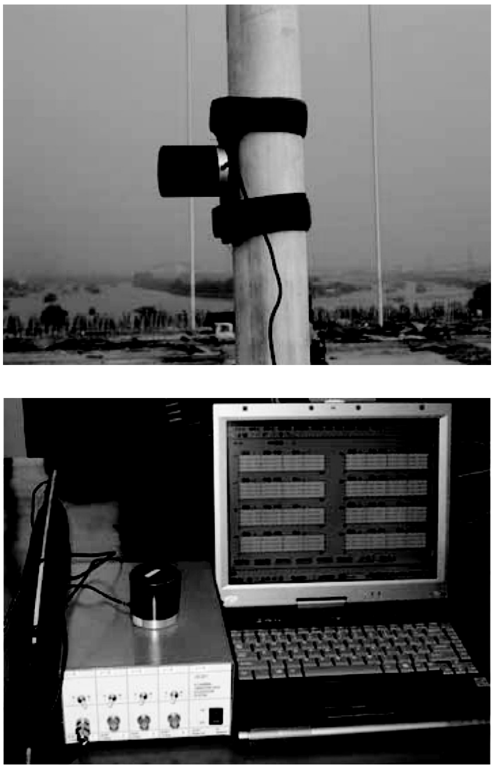


Figure 7. Accelerometers and analysis system

between 2001 and 2005 are shown in Figure 9 where the diamond line represents the design cable forces while each other line represents the measured cable forces in all stay cables along the bridge at a specific time of each year. However, in the present study only the data measured in the year 2005 was used for the condition assessment. By reasonably assuming the initial cable forces were equal to the design values, the variation of stay cable forces can be easily obtained by subtracting the measured cable forces from their design values.

As discussed earlier, the long-term load condition can be equally judged by checking the bridge condition in term of the stresses of girders under the varying cable forces. If the variations of cable forces are applied as internal forces onto the 2D frame FE model of bridge structure, the long-term load condition of the bridge can be then predicted using the resulted stresses of the girders along the whole length of the bridge. The dash lines in Figure 10 show the results under the variations of the cable forces.

Next, the stress threshold envelopes were calculated by applying the code-specified long-term loads onto the 2D frame FE model of the bridge structure. In the present study the long-term loads were decided according to the Chinese specific bridge codes (JTG D62 2004; JTG D60 2004). These codes have considered all possible loads when the bridge is in service, such as vehicle loads, pedestrian loads, wind loads, and short-term varying loads caused by temperature change, etc. The predicted stress threshold envelopes at both the top and bottom flanges of the girders along the whole length of the bridge are shown in Figure 10.

To draw a conclusion on the long-term load condition, the resulted stresses of the girders in the long-term load condition along the whole length of the bridge are compared to the corresponding stress threshold envelopes, as shown in Figure 10, where the resulted stresses are within the stress envelopes except for a few points. Under this situation, structural problem may or may not exist on the structure since any non-structural problem such as a measurement error could contribute to this problem. To confirm the conclusion, assessment should be performed again using another set of measurement data; if the stresses still exceed the stress threshold envelopes at the same positions, we may conclude there is a strong sign for a defection in the structure. In this case, it was found that if the

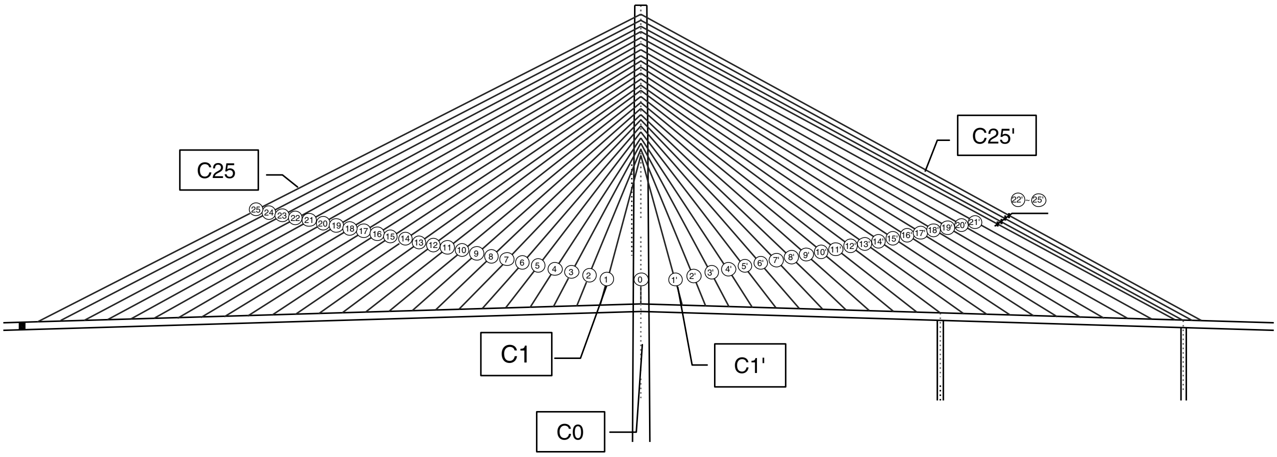
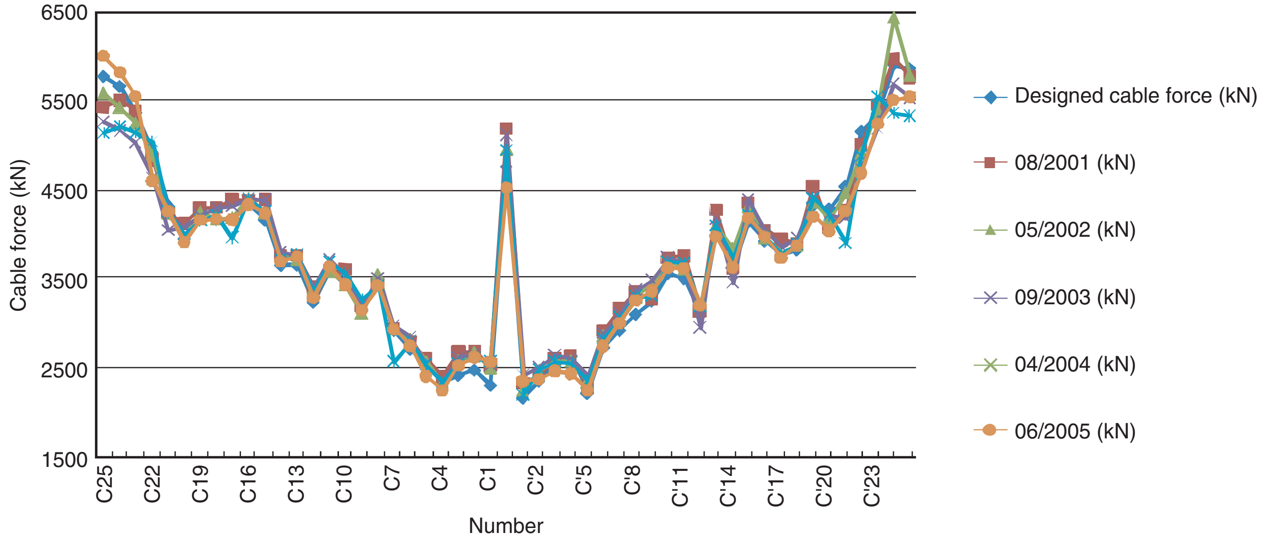
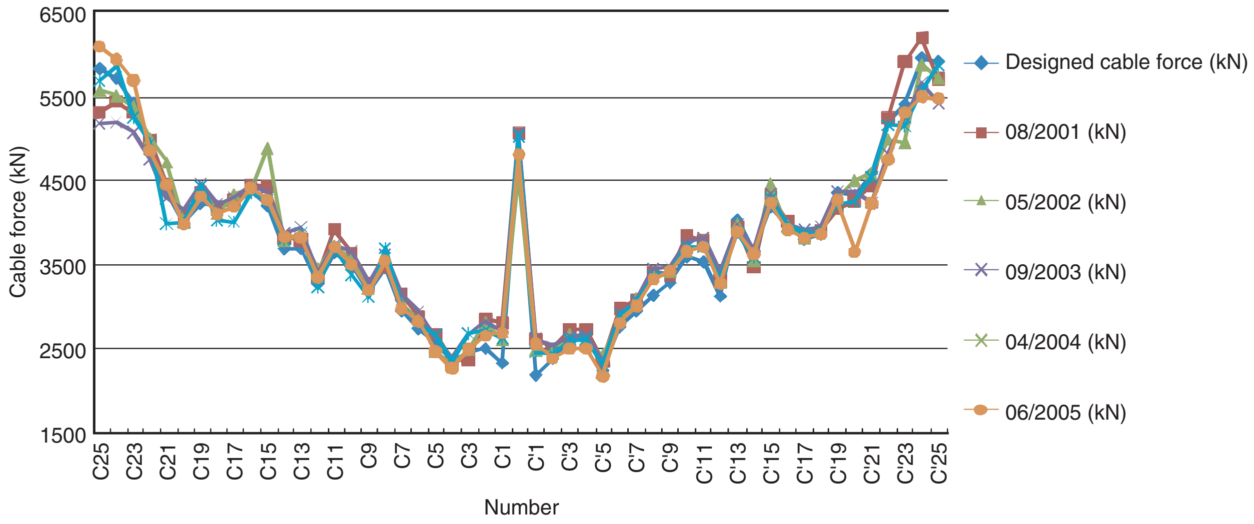


Figure 8. Serial numbers of the stay cables

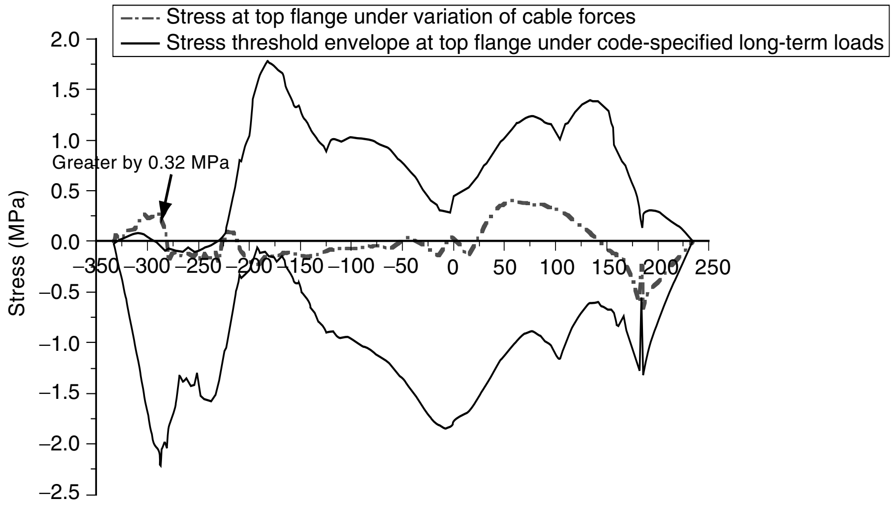


(a) Cable forces in the plane of upper stream side

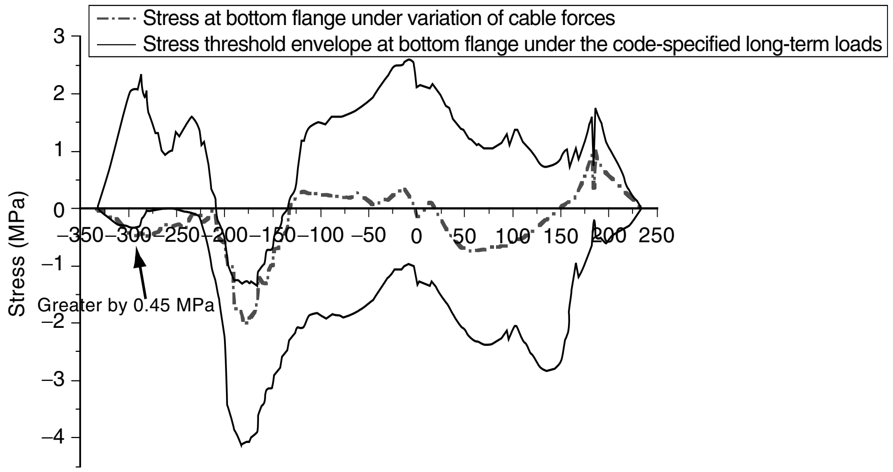


(b) Cable forces in the plane of lower stream side

Figure 9. Distributions of cable forces



(a) Comparison at the top flange



(b) Comparison at the bottom flange

Figure 10. Comparative analysis of stresses for the long-term load condition assessment

assessment procedure was repeated using another set of measurement data, the stresses at all positions were all within the stress threshold envelopes. On the other hand, the stress level at the concerned area is very low. Therefore, it was concluded that the long-term load condition of this existing cable-stayed bridge was in a safe and normal level. A more quantitative criterion is more desirable.

3.3. Step 3: Service Live Load Condition Assessment

As discussed earlier, to capture a whole picture of the condition of a cable-stayed bridge under service live loads sensors need to be installed on different locations across selected critical cross sections. The locations of the six measured cross-sections (A-F) along the longitudinal direction are shown in Figure 4 while the detailed locations of the sensors installed on the six cross-sections are shown in Figure 5.

The data acquisition and transmitting plan used for this project are shown in Figure 11. This data acquisition system satisfies the requirements of the proposed method because of its capability of performing real-time monitoring. Real-time stress data measured at each cross-section was transmitted to the lab and then recorded on a daily basis, as shown in Figure 12. It should be noted that the frequency of transmitting and recording the stress data was set to be three times per 24 hours, and only the maximum of the three stress values measured during a 24-hour period was used for the plots in Figure 12.

To obtain the stress threshold envelopes for assessing

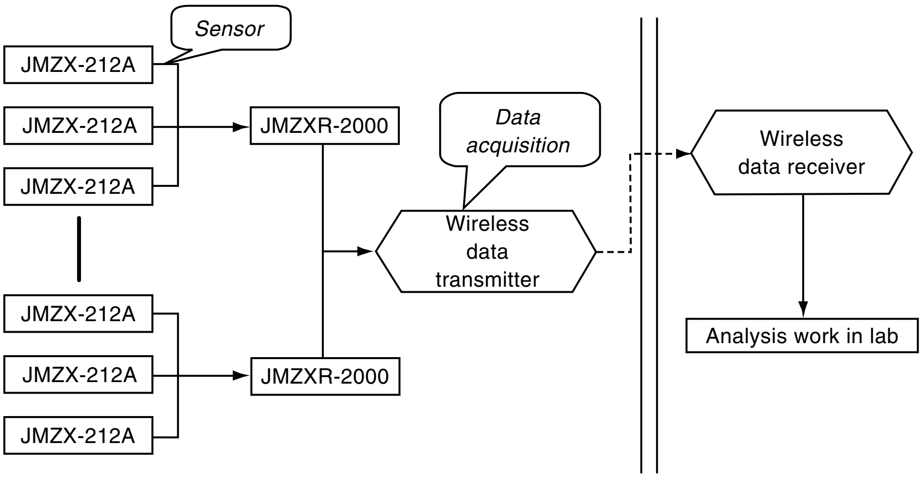


Figure 11. Data acquisition and transmitting plan

the service live load condition, again the service live loads specified in the Chinese specific bridge design codes (JTG D62 2004; JTG D60 2004) were used.

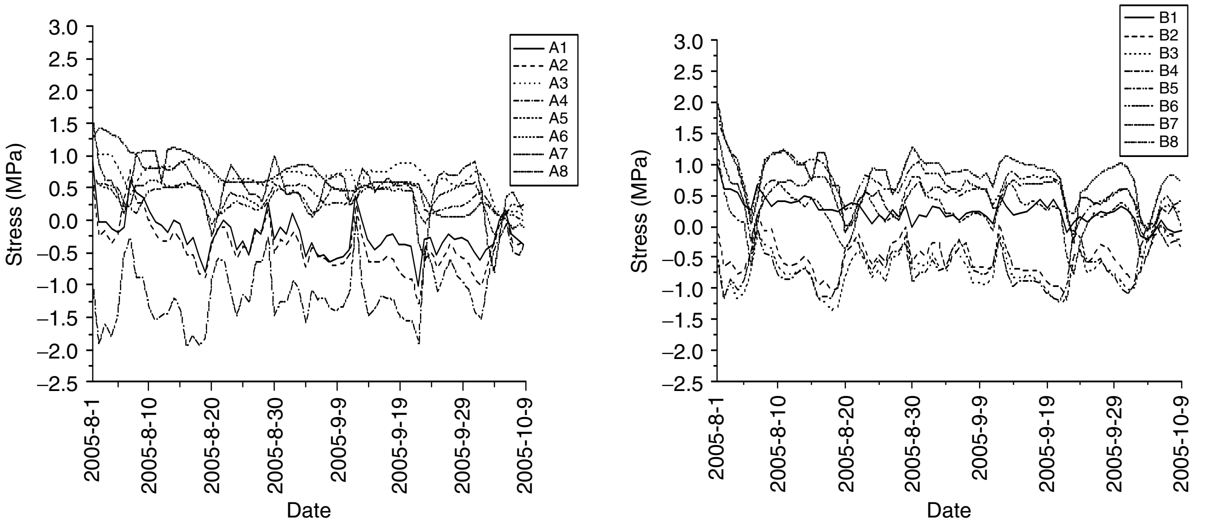
Since it is usually very complicated to directly obtain the stress threshold envelopes in the ANSYS program because of the difficulty in applying moving loads on a 3D solid FE model, a simple 2D frame FE model (could also use the 2D frame FE model previously used for long-term load condition assessment) was first constructed using another bridge structural analysis program MIDAS. Based on the numerical analysis results using the MIDAS, the worst possible loading condition for each of six cross-sections can be obtained. Then, the obtained worst case loading condition for each critical cross-section was applied onto the 3D solid FE bridge model using the ANSYS program (Figure 6). By doing this the stress threshold envelope of every assigned cross-section can be obtained while a lot of computation effort can be reduced. Figure 13 shows the stress threshold envelopes obtained for sections A-F individually, where the x axis represents different sensors across each cross section with their numbers corresponding to the sensor locations marked in Figure 5.

To draw a conclusion on the service live load condition, measured stresses at each cross-section were compared to the corresponding stress threshold envelopes as plotted in Figure 14. It should be noted that the measured stresses used in the drawing are the maximum/minimum stresses measured during the in-service period. It can be clearly seen that the maximum/minimum measured stresses for each critical cross section are within the stress threshold envelopes. Therefore, the service live load condition of the bridge is within a safe and normal level. The difference between the stresses for different locations across the same cross section, as shown in Figure 14, also indicates that the spatial distribution of stress exists and is significant in every cross-section.

3.4. Condition Assessment Results

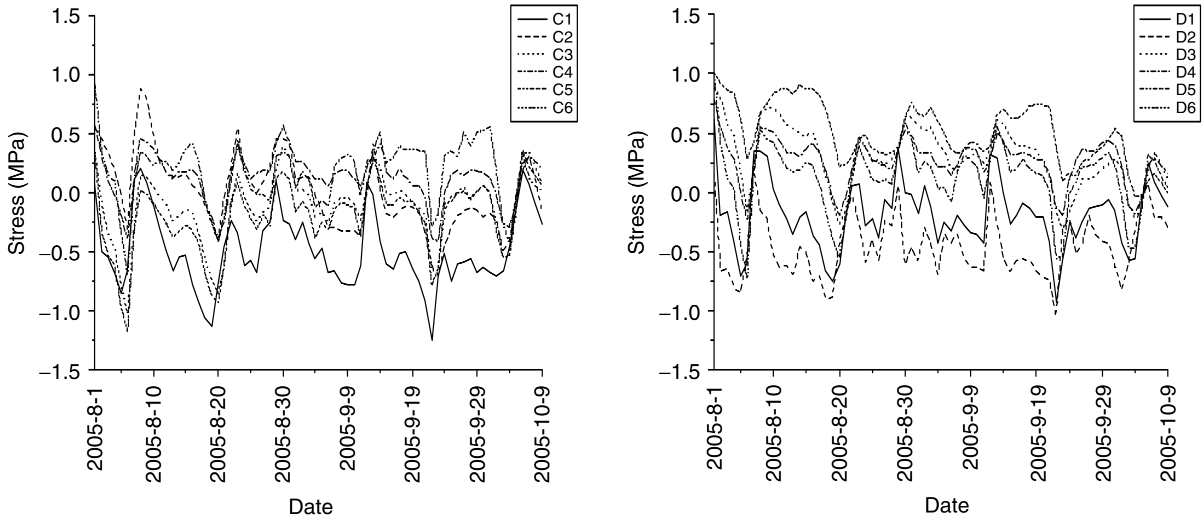
Based on the condition assessment results of the project, it can be concluded that this cable-stayed bridge, from the view of entire structure, was still in a good and safe condition and can still satisfy the requirements of the specific bridge design codes.

The bridge condition assessment of the bridge, including both long-term load condition and service live load condition assessment, has been carried out within the past 3 years. For the long-term load condition assessment if the difference between the current cable forces and the measured cable forces in the last assessment was less than a pre-set threshold value, which was usually decided by experienced engineers, it could be judged that the long-term load condition did not vary significantly from the condition upon the last measurement. As a result, the long-term load condition could still be seen as safe and acceptable. In cases when the difference was close to the threshold value, to confirm the conclusion the assessment process could be repeated. This pre-set threshold value can be determined by the experience from repeating the assessment of long-term load condition. For the service live load condition, the real-time monitoring provided sufficient amounts of data to be used in a condition assessment of a long period of time. A new service live load condition assessment could be easily



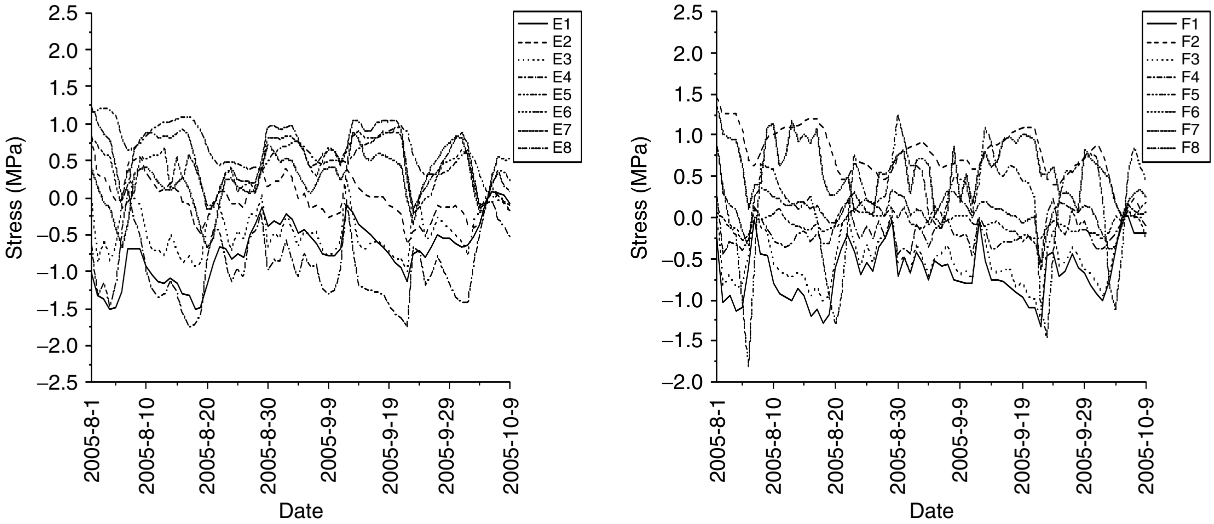
Section A

Section B



Section C

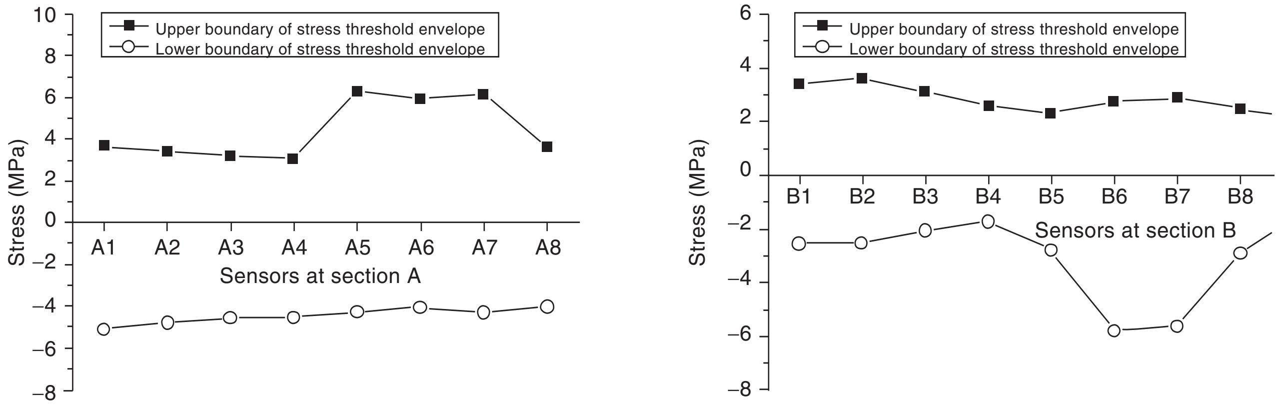
Section D



Section E

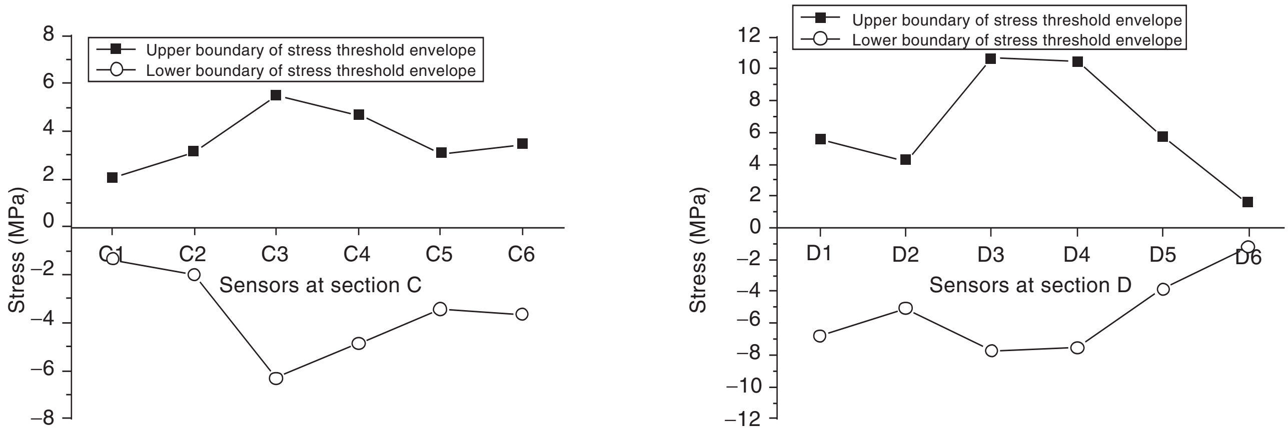
Section F

Figure 12. Real-time monitoring results



Section A

Section B



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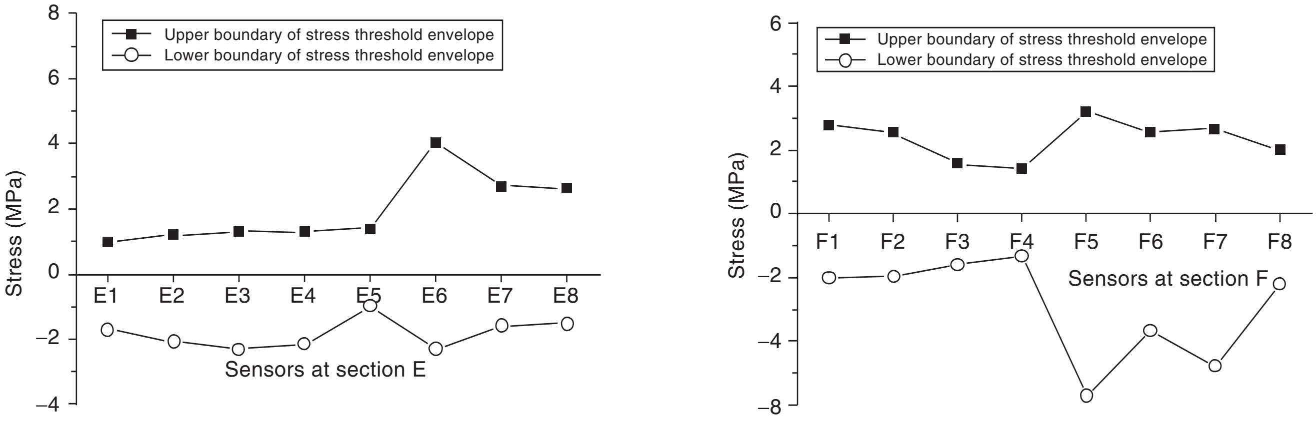

Section E

Section F

Figure 13. Stress threshold envelopes at every sensor in the six cross-sections

implemented by repeating the proposed process with the newly-measured data.

It should be noted that if a more reliable conclusion is needed, more comprehensive measurements should also be performed to obtain the girder deformation, pylon deflection, foundation settlement, local damage etc. The proposed methodology is intended to provide a quick assessment of bridge global performance that is useful for online monitoring.

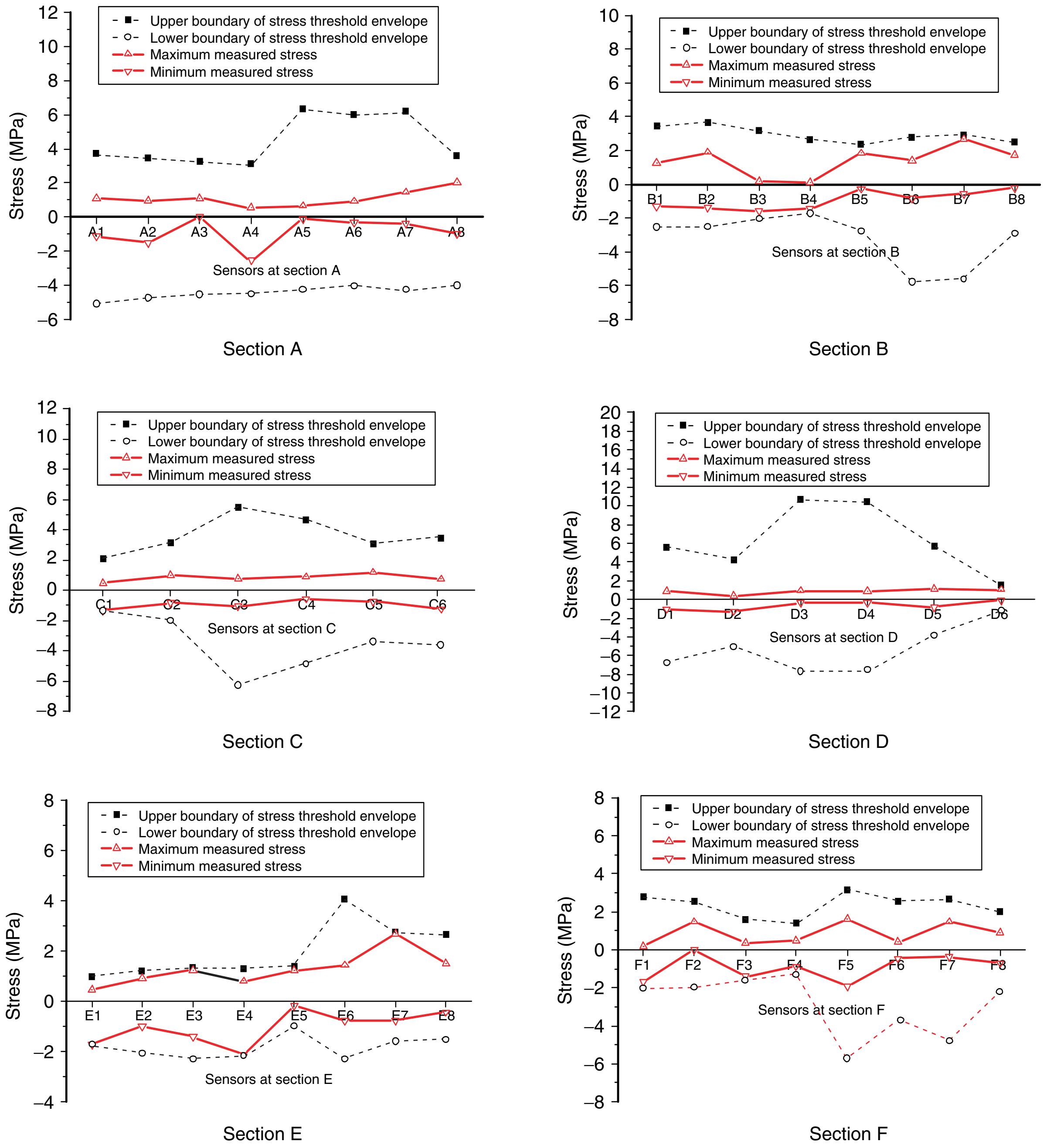

Figure 14. Comparative analysis

4. CONCLUSIONS

The present study has developed a new methodology of assessing the long-term real-time condition of existing cable-stayed bridges. This methodology is particularly useful when a complete monitoring record of the bridge from construction to service is not available. Also, the total stresses of the bridge girders during the service period are difficult to be measured. To deal with this problem, the proposed methodology focuses only on the variation of bridge condition, which can be reflected by field measurement data. In this methodology, the variation of the bridge condition is considered with respect to two sub-conditions: the long-term load condition and service live load condition. To avoid the measurement of total stresses by sensors in the entire service period, the varying cable forces are selected as the reflection of the long-term load condition; as a result, the effect of time-dependent loads could be traced back from the present to the time of bridge's completion. The service live load condition of the bridge can be real-time monitored using strain sensors. The safety of the bridge condition can be ensured if both of the sub-conditions are in safe condition according to specific bridge design codes. A case study demonstrated that the proposed method works well and its advantages over other methods are obvious.

It should be pointed out that the large amount of computation effort needed due to the use of a 3D solid FE bridge model and possible errors with field measurement data may affect the application of this methodology in engineering practices. However, solutions to these problems are now available with the dramatic development in computing techniques and more advanced measurement devices. In summary, the proposed methodology provides a practical and convenient tool for engineers to quickly assess the global performance of existing cable-stayed bridges, such as online monitoring.

REFERENCES

Aktan, A.E., Farhey, D.N., Brown, D.L., Dalal, V., Helmicki, A.J., Hunt, V.J. and Shelley, S.J. (1996). "Condition assessment for bridge management", *Journal of Infrastructure Systems*, ASCE, Vol. 2, No. 3, pp. 108–117.

Aktan, A.E., Farhey, D.N., Helmicki, A.J., Brown, D.L., Hunt, V.J., Lee, K.L. and Levi, A. (1997). "Structural identification for condition assessment: experimental arts", *Journal of Structural Engineering*, ASCE, Vol. 123, No. 12, pp. 1674–1684.

Aktan, A.E., Catbas, N., Turer, A. and Zhang, Z. (1998). "Structural identification: analytical aspects", *Journal of Structural Engineering*, ASCE, Vol. 124, No. 7, pp. 817–829.

Ferregut, C.M., Osegueda, R.A. and Ortiz, J. (1995). "Artificial neural networks for structural damage detection and classification", *Proceedings of SPIE - The International Society for Optical Engineering*, San Diego, Ca., U.S.A., pp. 68–80.

JTG D60 (2004). *General Code for Design of Highway Bridges and Culverts*, China Communications Press, Beijing, China. (in Chinese)

JTG D62 (2004). *Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts*, China Communications Press, Beijing, China. (in Chinese)

Huang, D.J., Xu, L.P., Han, Z.P., He, M. and Qian, Y.L. (1998). "Zhao Bao Shan bridge design", *13th Annual Domestic Bridge Conference,* Shanghai, China, pp. 64–70. (in Chinese)

Kim, S. H., Lee, S.W. and Mha, H.S. (2001). "Fatigue reliability assessment of an existing steel railroad bridge", *Engineering Structures,* Vol. 23, No. 10, pp. 1203–1211.

Li, Z.X., Chan, T.H.T. and Ko, J.M. (2002). "Determination of effective stress range and its application on fatigue stress assessment of existing bridges", *International Journal of Solids and Structures*, Vol. 39, No. 9, pp. 2401–2417.

Lv, Z.D., Qin, S.Q., Zhu, H.M. and Meng, Q.B. (2001). "Research on the project of partial-dismantling and rehabilitation of the main bridge of Zhaobaoshan bridge in Ningbo", *Bridge Construction*, No. 3, pp. 1–7. (in Chinese)

Mazurek, D.F. and DeWolf, J.T. (1990). "Experimental study of bridge monitoring technique", *Journal of Structural Engineering*, ASCE, Vol. 116, No. 9, pp. 2532–2549.

Ng, K.H. and Fairfield, C.A. (2002). "Monte Carlo simulation for arch bridge assessment", *Construction and Building Materials*, Vol. 16, No. 5, pp. 271–280.

Natke, H.G., Doll, H. and Hildebrandt, P. (1995). "Bridge condition assessment using an expert system", *Structural Engineering Review*, Vol. 7, No. 3, pp. 165–180.

O'Connor, A. and Enevoldsen, Ib (2008). "Probability based modeling and assessment of an existing post-tensioned concrete slab bridge", *Engineering Structures*, Vol. 30, No. 5, pp. 1408–1416.

Sasmal, S. and Ramanjaneyulu, K. (2008). "Condition evaluation of existing reinforced concrete bridges using fuzzy based analytic hierarchy approach", *Expert Systems with Applications*, Vol. 35, No. 3, pp. 1430–1443.

Tan, D.L. (2005). *Key Studies of Bridge Structural Condition Assessment Based on Monitoring*, PhD Thesis, Tongji University, Shanghai, China, pp. 1–8. (in Chinese)

Wang, P.H., Tang, T.Y. and Zheng, H.N. (2004). "Analysis of cable-stayed bridges during construction by cantilever methods", *Computers and Structures*, Vol. 82, No. 4–5, pp. 329–346.