4D Multi-Scale Analysis of the Hybrid Zone for Cable-Stayed Bridges with Steel-Concrete Hybrid Girders

Meng Zhou[1,2], Xiao-Xv Ning[1,2], Jian-Sheng Fan[1,2], Jian-Guo Nie[1,2], Xiao-Gang Yang[3]

[1]Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Beijing, 100084, China;
[2]Department of Civil Engineering, Tsinghua University, Beijing, 100084, China;
[3]China Road and Bridge Corporation, Beijing, 100084, China;
email: zhoum07@mails.tsinghua.edu.cn

ABSTRACT

The cable-stayed bridge with steel-concrete hybrid girders is one of the most widely used bridge types in China. As the key sub-structure of this kind of bridge, the hybrid zone which consists of girders in the region jointing the steel girder and the concrete girder plays an important role securing the safety and good serviceability of the entire bridge, and consequently the study on the mechanical behavior of the hybrid zone is essential for both the analysis and design of the whole bridge. However, due to the strong dependence of the Saint-Venant Principle and significant influence of the Fuzzy Region which cannot be quantitatively determined, the traditional local-elaborate modeling method for the study is limited by its dim Saint-Venant Region-Fuzzy Region boundary, leading to unreliable analysis results and enormous trial and error works. To tackle this problem, the multi-scale modeling method is introduced in this paper, employing the flexible boundary conditions (flexible BCs) for the simulation of the complex boundary condition of the hybrid zone. The fourth dimension is time. In order to gain results closer to the realistic behavior of the bridge at the finished date, it is considered to model the construction process. A 4D multi-scale model of the hybrid zone is then established according to the prototype of an actual cable-stayed bridge project in Chongqing, China. Simultaneously, a local-elaborate model is built for comparison. Comparison study of the finite element models demonstrates that analysis results of the 4D multi-scale model are reliable without the influence of the Fuzzy Region. The model is more accurate, reliable and hence widely applicable. It is concluded that the 4D multi-scale modeling method may offer a new approach for the analysis and monitor of the hybrid zone for cable-stayed bridges with steel-concrete hybrid girders in the future.

INTRODUCTION

Four dimensions are involved in real bridge engineering: 3 spatial dimensions and 1 temporal dimension. The 3 spatial dimensions determine the scale of a bridge, whereas the temporal dimension reflects the construction process. In numerical simulations, models of different scales are established based on different theories and focused on various investigated object (Fish and Shek 2000). As shown in Figure 1, stud scales within decimeters and its mechanical behaviors obey the material mechanics; hybrid zone scales to dozens meters and its predicted performance relies on Saint-Venant principle and material mechanics; cable-stayed bridges scale to hundreds meters and the theory of structures becomes its basic theory.

Besides, in finite element analysis (FEA), detailed consideration of the construction process is essential to ensure the simulating accuracy of the bridge, especially for cable-stayed bridges (Li *et al.* 2007). As shown in Figure 1, since the hybrid zone is constructed from a single hybrid box to the hybrid zone and the bridge is erected section by section and finally transforms from two separate tower-cantilever girder systems into one complete cable-stayed bridge system (Liu *et al.* 2012), neglecting its construction process not only loses the analysis results during the construction, but also brings significant errors to the final result of the servicing performance of the complete bridge. Once the global performance of the entire bridge is miscalculated, the predicted behaviors of the hybrid zone become unreliable. Hence, two critical issues of the numerical study on cable-stayed bridges with hybrid girders are characterized: scale diversity and construction-process reliability. An overall consideration of these two issues is required for the numerical simulation to secure its accuracy and reliability. On this purpose, a 4D multi-scale modeling method is proposed in this paper based on the platform of the FE package *midas FEA*.

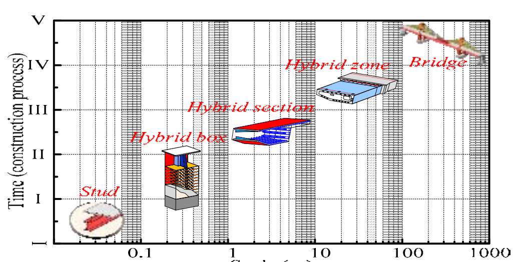

Figure 1. 4D multi-scale modeling of cable-stayed bridges.

METHODOLOGY: 4D MULTI-SCALE MODELING METHOD

The unreliability region in traditional local-elaborate models is pointed out by

Nie and Tao *et al.* (2011) in researches on the cable anchorage system of self-anchored suspension bridges. The unreliable region is then determined as the Fuzzy Region on the contrary to the Saint-Venant Region by Nie and Zhou *et al*. (2013). The Saint-Venant Region (Region S) is determined as the region where the analysis result is reliable according to the Saint-Venant Principle. The principle is widely used in elaborate finite element (FE) models and known as saying that “the analysis result is reliable for regions far from the short boundary”, whereas the original state of the principle is “the different between the effects of two different but statically equivalent loads becomes very small at sufficiently large distances from load”. On the contrary, results of the regions which are not far enough from the short boundary are unreliable. These regions are between the Saint-Venant Region and the short boundary and determined as the Fuzzy Region (Region F). Significant influence of the Fuzzy Region in traditional local-elaborate models is further observed in study on the key sub-structures for bridges covering a range of bridge types (Zhou and Nie 2013), like the arch feet of arch bridges with steel truss and tie-beam, and the steel-concrete hybrid zone of cable-stayed bridges with hybrid girders *et al.*.

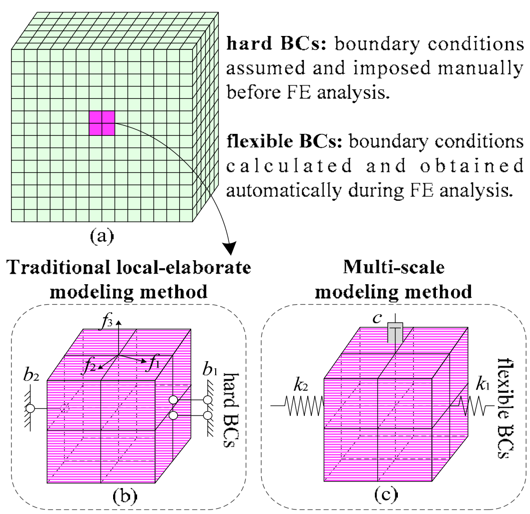

Figure 2. Multi-scale modeling method. (a) real structure; (b) traditional local-elaborate model; (c) multi-scale model.

The short boundary aforementioned is the boundary where the traditional local-elaborate model is separated from the global structure. The general geometric continuity and mechanical properties are destroyed on the short boundary. It is on the short boundary that the hard boundary conditions (BCs) are assumed and imposed, as shown in Figure 2. The hard BCs are generally comprised of direct force conditions and displacement conditions. And they are required to be settled down before FE analysis.

This aggravate the influence of the Fuzzy Region, since the hard BCs are such strong boundary assumptions that the dependence on the Saint-Venant Principle is strengthened, leading to a wider Fuzzy Region. To tackle this problem, the flexible BCs are proposed by Nie and Zhou *et al*. (2013) using multi-scale modeling method. As shown in Figure 2 (c), the flexible BCs are a kind of generalized BCs, which introduce a global scale model of the entire bridge to the elaborate model of the investigated local key sub-structure to simulate the complex BCs, like the springs in the figure. Besides, the flexible BCs are calculated and obtained automatically during FE analysis. It has been validated that the flexible BCs enable the FE model free from influence of the Fuzzy Region, resulting in good accuracy and reliability.

In order to simulate the construction process of the bridge, the platform of the FE package *midas FEA* is selected, for its reliable construction process modeling ability. Thus, the basic strategy of the 4D multi-scale modeling method is built. With an actual cable-stayed bridge case, Yonrchuan Bridge in Chongqing, China, the 4D multi-scale modeling method is applied and compared with the traditional local-elaborate model.

APPLICATION

Case: Yongchuan Bridge. The Yongchuan Bridge, which is a typical three-span double –tower cable-stayed bridge with steel-concrete hybrid girders, is studied as a case for the research. The bridge has a total length of 1005m over the Changjiang River in China. The main feature of the Yongchuan Bridge, as shown in Figure 3, has a main span of 608m and side spans of 198.5m.

Figure 3. Yongchuan Bridge.

FE models. By applying the preceding modeling method, a 4D multi-scale model of the Yongchuan Bridge is established on the platform of the FE package *midas FEA*. Meanwhile, a traditional local-elaborate model of its hybrid section is built for comparison. Figure 4(a) shows the traditional local-elaborate model. The model is comprised of the hybrid zone and a couple of cables. The hybrid zone is 3.5m in height, 37.6m in width, and 7.795m in length. Of the 7.795m long hybrid zone, the concrete section takes 4.75m, and the steel section takes 5.045m of which 2m is hybrid with the concrete section. The short boundary of the concrete section is set to be fixed, whereas the short boundary of the steel section is used to apply forces transferred from the main girder. Cable tension force is applied through the couple of cables.

Figure 4(b)-(f) illustrates the typical construction processes of the 4D multi-scale model. The model is made up of two parts: model in local scale and model in global scale. The former is identical with the traditional local-elaborate model, whereas the latter is a typical beam-truss model of the entire cable-stayed bridge. 89 construction processes are included in the model, of which six typical processes (*P-I* to *P-VI*) are selected and studied in this paper. *P-I* (Figure 4(b)) is the first selected process in which the concrete section of the hybrid zone is lifted up and erected. *P-II* (Figure 4(c)) is the process by which the hybrid section and steel section have been erected and the hybrid zone has been accomplished. *P-III* (Figure 4(d)) is the process by which the 9^{th} group of cables have been placed and tensioned and the corresponding girders have been erected. *P-IV* (Figure 4(e)) is the process by which the last group of cables have been placed and tensioned and all girders except the final girder at the middle of the main span have been erected. *P-V* (Figure 4(f)) is the process by which the last girder has been lifted up and erected and the main structure of the entire bridge has been constructed. Figure 4(f) also represents the geometry of the *P-VI*. Its difference with *P-V* is the loads: *P-VI* contains the loads for service while *P-V* not.

ANALYSIS AND RESULTS

Comparison study on multi-scale model and traditional local elaborate model. Figure 5 compares the distribution of the third principal stress of concrete section, including the concrete part in the hybrid section, of the two FE models at *P-IV*. The Fuzzy Region mainly occurs near the short boundary of the concrete section in the traditional local-elaborate model, where the compressive stress is unreasonably high and the distribution appears like cantilever beam.

Discussion on 4D multi-scale modeling method. 4D multi-scale model enable researchers to study and monitor the mechanical behaviors of the hybrid zone for cable-stayed bridges during the entire process: from the beginning of the construction to the final state when the bridge is on service. Figure 4 and 5 illustrates the change and development of stress distributions of the concrete section and the steel section from construction to use. Preceding six selected processes are used. It is observed that the stress level of P-IV is higher than that of P-V both in the concrete and steel section. This demonstrates that the erecting of the final girder at the middle of the main span strengthen the mechanical performance of the bridge by transforming the separate two tower-cantilever girder system into a complete cable-stayed bridge system. And the stress level of P-VI shows no significant increase, since the complete cable-stayed bridge system has formed. So it might be not only interesting but also meaningful and essential to simulate and monitor the mechanical behaviors of the hybrid zone during the construction, since the control state may occur in one of the construction process.

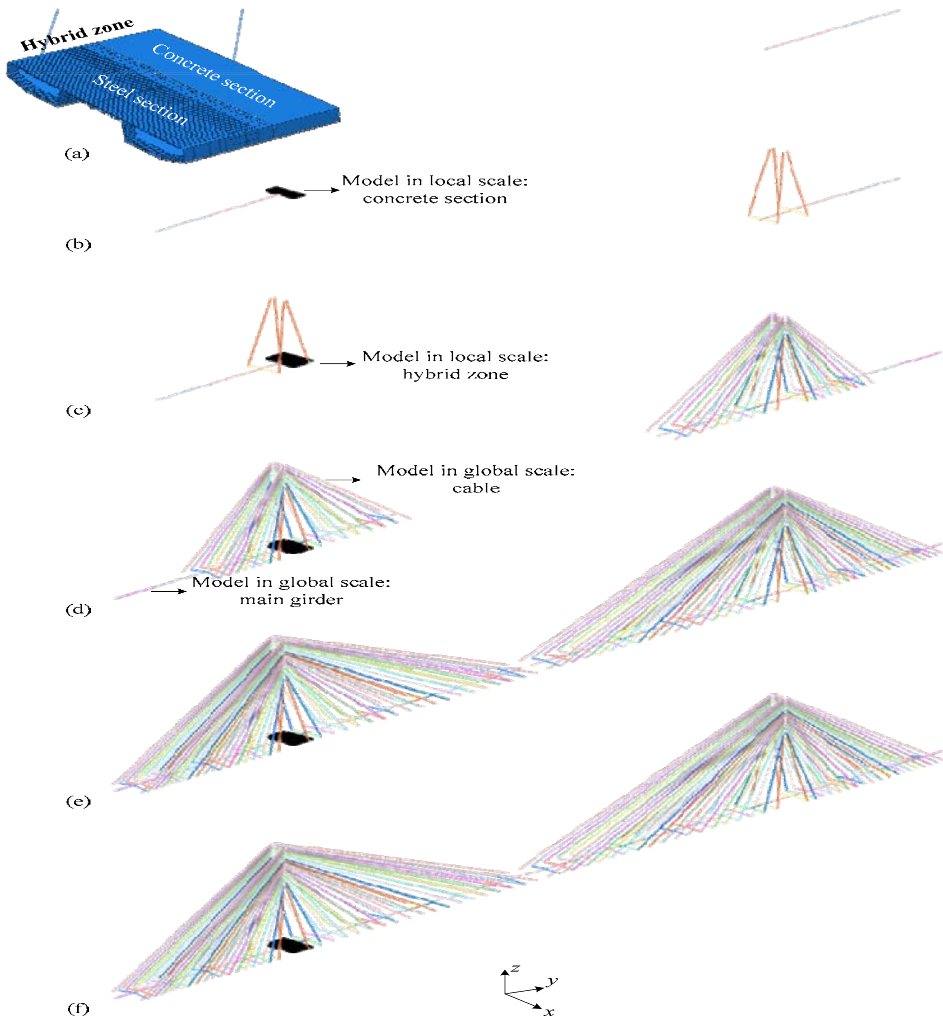

Figure 4. FE models. (a) traditional local-elaborate model; (b) 4D Multi-scale model, *P-I*: concrete section up; (c) 4D Multi-scale model, *P-II*: steel section up; (d) 4D Multi-scale model, *P-III*: 9th cable on; (e) 4D Multi-scale model, *P-IV*: last cable on; (f) 4D Multi-scale model, *P-V* and *P-VI*: bridge complete and on service.

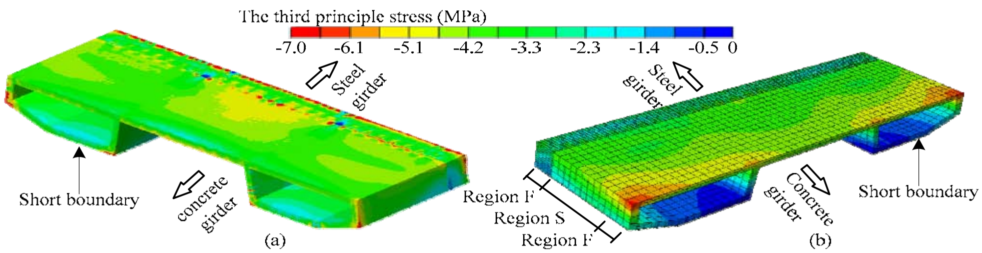

Figure 5. Distribution of the third principal stress of concrete section in hybrid zone at *P-IV*. (a) 4D Multi-scale model; (b) traditional local-elaborate model.

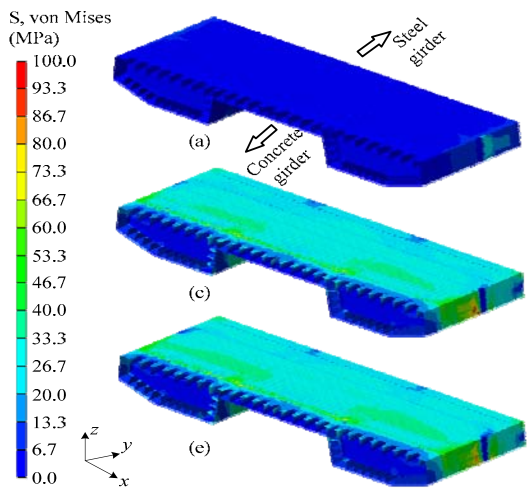

Figure 6. Distribution of von Mises stress of steel section in hybrid zone using 4D multi-scale modeling method. (a) *P-II*: steel section up; (b) *P-III*: 9th cable on; (c) *P-IV*: last cable on; (d) *P-V*: bridge complete; (e) *P-VI*: bridge on service.

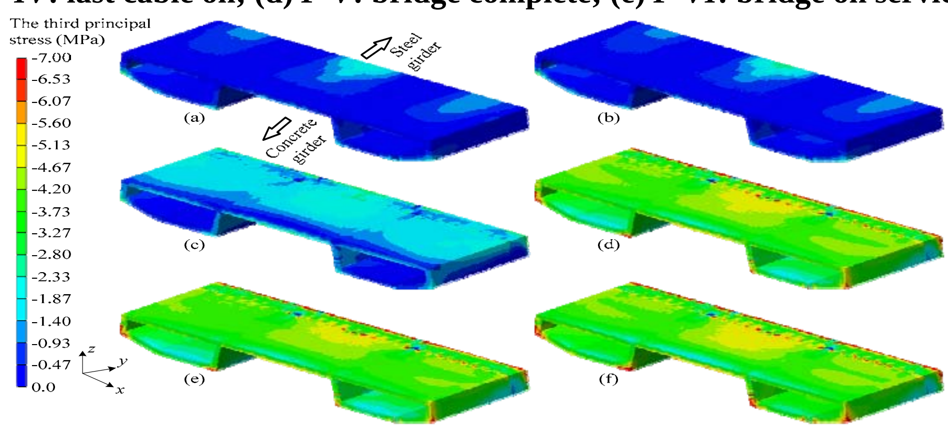

Figure 7. Distribution of the third principal stress of concrete section in hybrid zone using 4D multi-scale modeling method. (a) *P-I*: concrete section up; (b) *P-II*: steel section up; (c) *P-III*: 9th cable on; (d) *P-IV*: last cable on; (e) *P-V*: bridge complete; (f) *P-VI*: bridge on service.

CONCLUSION

The cable-stayed bridge with steel-concrete hybrid girders is one of the most widely used bridge types in China. The mechanical behavior of its key sub-structure, the hybrid zone, is studied in this paper. A 4D multi-scale FE model is established based on the prototype of the Yongchuan Bridge in Chongqing, China. A traditional local-elaborate FE model is built for comparison. Comparison study shows that Fuzzy Region affects the result of the traditional local-elaborate model. A discussion of the development of the stress distributions of the hybrid zone from construction to use is given. It is concluded that the 4D multi-scale modeling method enables researchers to accurately simulate and monitor the mechanical behaviors of the hybrid zone during the entire process: from construction to use.

ACKNOWLEDGEMENT

The writers gratefully acknowledge the financial support provided by the National Science Fund of China (51222810, 51138007) and the National Science & Technology Support Program of China (2011BAJ09B02).

REFERENCES

Fish J. and Shek K. (2000). “Multiscale Analysis of Large Scale Nonlinear Structures and Materials.” *International Journal for Computational Civil and Structural Engineering*, 1(1), 79-90.

Li Z. X., Zhou T. Q., Chan T. H. T. and Yu Y. (2007). “Multi-scale Numerical Analysis on Dynamic Response and Local Damage in Long-Span Bridges.” *Engrg. Struct.*, 29(6), 1507-1524.

Liu M. H., Tan H., Xu G. P. and Zhao C. H. (2012). “Closure technique for the hybrid girder cable stayed bridge of Edong Bridge.” *Engrg. Sciences*, 10(4), 51-56.

Nie J. G., Tao M. X., and Fan J. S. (2011). “Research on cable anchorage systems for self-anchored suspension bridges with steel box girders.” *J. Bridge Engrg.*, ASCE, 16(5), 633-643.

Nie J. G., Zhou M., Wang Y. H., Fan J. S., and Tao M. X. (2014). “Research on cable anchorage system modeling methods for self-anchored suspension bridges with steel box girders.” *J. Bridge Engrg.*, ASCE, 19(2), 1-13.

Zhou M., Nie J. G., Xu L. Y., and Fan J. S. (2013). “Multi-scale analysis of the key sub-structure for large-span bridges.” *10th Pacific Structural Steel Conference*, Singapore, 138-144.