# Experimental Study on Prestress Loss of Short Tendons Applied in the Cable-Stayed Bridge PC Pylon

Nannan Cui, Xiaolin Yu, Buyu Jia, Jintu Zhong, and Quansheng Yan
School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, China
Email: annatreecivile@sohu.com, 280304690@qq.com, {ctjby, cvqshyan}@scut.edu.cn, zhongjintu@gmail.com

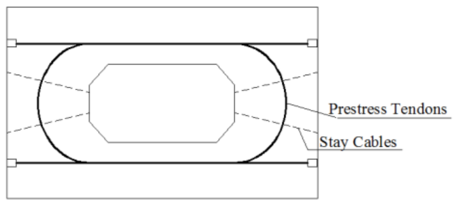
***Abstract*—A new layout of prestress tendons named as "one-way tendons", instead of traditional "U tendons", was applied in the PC box pylon of a long span cable-stayed bridge. The length of these prestress tendons was only 5m-7m, the contribution of each prestress loss source was different from tendons with common length, which added the difficulty to construction control. This paper presents a full-scale segment model test to determine the prestress losses of these short tendons, especially focuses on instantaneous losses due to anchorage set and friction. Test result shows that the average losses is 26%, anchorage set leads to more than 50% of total losses, friction leads to 30% which should not be ignored as most articles and code recommend.**

***Index Terms*—short prestress tendons, prestress loss, PC pylon, cable-stayed bridge**

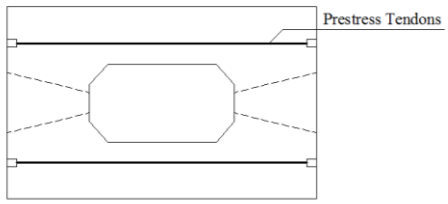
## I. Introduction

Because of its excellent mechanical performance and economical saving, PC box pylon is commonly used in cable-stayed bridge. The prestress loss is an important factor related to its serviceability. A poor estimate of prestress loss in PC pylon can result in cracks and undesirable deflection; even endanger the safety of the bridge.

Xijiang Waterway Bridge in Guangdong province, China, which supports the research of this paper, is a double PC box pylon cable-stayed bridge, with a main span of 400 m (57.5 m+172.5 m+400 m+172.5 m+57.5 m). Given the complex force status, the cable anchorage zone of PC box pylon has attracted great attention of the designers and researchers, especially in the way of prestress tendons layout. Traditionally, "U tendons", as described in fig.1, is selected to use in the PC pylon, but limited by sectional dimension, "U tendons" unavoidably has small curvature radius, which brings difficulties to site orientation, prestress losses estimate and construction control (for great difference between actual elongation and theoretical value) [1], [2]. In china, a full-scale segment model test would be set up almost every time when the constructors wanted to apply "U tendons", which have waste much construction resources. More unfortunately, it is difficult to get generally applicable conclusions by those tests, for many random uncertainties of small curvature radius tendons. Considering the shortcoming of "U tendons", the designers of Xijiang Waterway Bridge purposed "one-way tendons", as described in Fig. 1 Prestress tendons only arranged on longitudinal direction wall, the shear in transverse direction wall produced by stay cable force just resisted by the thick concrete wall.




(a)




(b)

Figure 1. The way of prestress tendons layout:(a) U tendons; (b) one-way tendons

This "one-way tendons" layout makes the PC box pylon clearer in force status, simpler to construct. But meanwhile another question has been put forward, whether the one-way prestress tendons, consists of 16 steel strands, as short to 5m-7m limited by the sectional dimension, can analyze and construct like common length prestress tendons. Existing literatures about short prestress tendons showed that the prestress loss pattern of short tondons was indeed different from common length tondons. [3], [4]. But the conclusions from those literatures were limited to prestressed steel bars used vertical tendons in the concrete box-girders, not the steel strands this paper mentioned. Given the "one-way tendons" characterized by short steel strands and large-tonnage prestress is first applied in the cable-stayed bridge PC pylon, it is necessary to experiment the prestress loss pattern and discuss the construction technology.

Manuscript received March 19, 2015, revised July 25, 2015.


doi: 10.18178/ijscer.4.3.259-264

There are several sources of prestress loss in post-tensioned construction. Losses due to anchorage set, friction, and elastic shortening are instantaneous, whereas losses due to creep, shrinkage, and relaxation are time-dependent. This paper focuses on instantaneous loss.

## II. RIMENT

### A. The Design of Test Model

One typical segment containing a pair of stay cables and seven of prestress tendons was selected for the experiment. In order to conveniently simulate the oblique load of stay cables, the group designed a PC trapezoidal pedestal at the bottom of the model, which could be used as the reaction beam of cables. The sizes of the test model are showed in Fig. 2. The arrangement and serial number of prestress tendons is showed in Fig. 3. All material parameters of the test model were consistent with actual bridge. Every prestress tendon consists of 16 steel strands (nominal diameter=15.2mm, fpk=1860 MPa, Ep＝$1.95\times10^5$ MPa), and is tensioned at single-end. Plastic corrugated pipes (D104/90mm) were used for prestress duct.

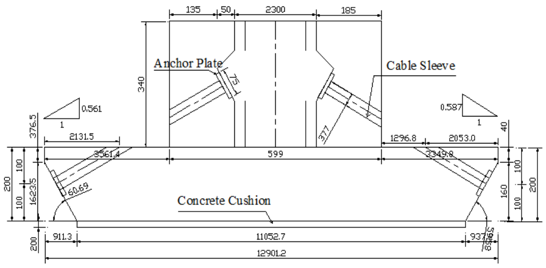
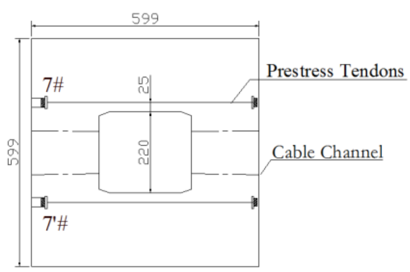
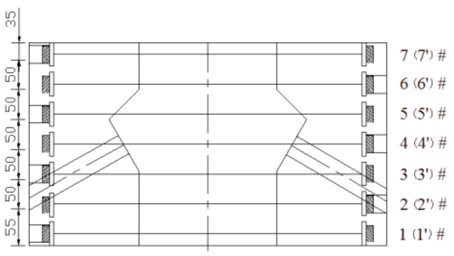



Figure 2. Details of the test model (mm)




(a)




(b)

Figure 3. The layout of prestress tendons (cm): (a) plan view (b).side view

### B. The Experiment of Ducts Friction Loss

Ducts friction loss means the loss due to the friction between internal prestress tendons and the duct (plastic corrugated pipe). In order to get the value of this loss, 2 # and 2' # prestress tendons were choosed for the experiment. Resistance strain gauges (120Ω, built-in temperature compensation) were pasted in the steel strand in order to measure prestressed strain (stress) in the process of tensioning. Five measure points were set on one strand, and the specific size is showed in Fig. 4. Each point was pasted with two strain gauges for checking each other.

the relationship between stress and strain of the steel strand was ascertained in advance in the laboratory .When the prestress tendons were installed to the steel skeleton of test model, the group cut the plastic corrugated pipe, pasted the strain gauges, then sealed the plastic corrugated pipe, and check carefully to ensure no grout leakage. The ducts friction loss can be calculated by testing the tension in different location of a steel strand.

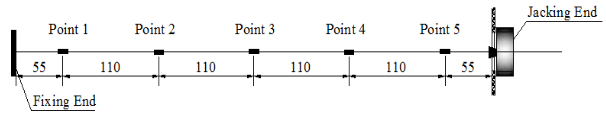



Figure 4. The arrangement of measure points on a steel strand

### C. The Experiment of Anchorage Head Friction Loss

The prestress loss which was caused by friction between anchorage head and steel strand is called the anchorage head friction loss. 4 # and 4' # prestress tendons were selected for the experiment. Two pressure sensors were installed inside and outside of the anchorage head respectively. The difference value between two sensors in the process of tension is the anchorage head friction loss. The installation of sensors is showed in Fig. 5.

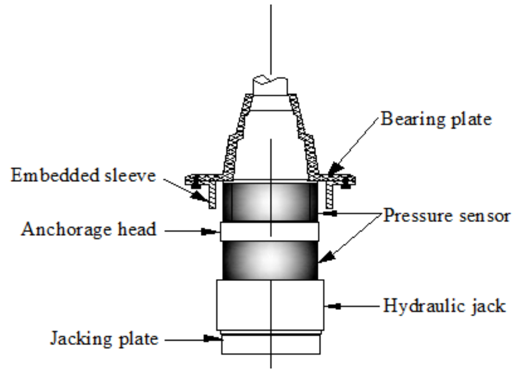



Figure 5. The installation diagram of test for anchorage head friction loss

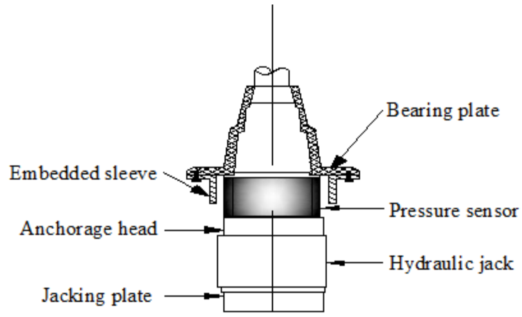



Figure 6. The installation diagram of test for anchorage head friction loss

### D. The Experiment of Anchorage Set Loss

Anchorage set loss is caused by the movement of the tendon prior to seating of the wedges or the anchorage gripping device [5]. 4 #, 4' #, 6 # and 6' # prestress tendons were selected for the experiment. One pressure sensor were installed between anchorage head and bearing plate (Fig. 6). The anchorage set loss can be measured by calculate the pressure difference before and after loading.

### E. The Experiment of Loss due to Concrete Elastic Shortening

Suggested by [6], this kind of loss needs to use the elastic mechanics theory to calculate according to the real structure and arrangement of prestress tendons.

Recording the pressure under the anchorage set before and after the next tendons tensioned, the value of this loss can be calculated.

## III. Experimental Results and Discussion

### A. Ducts Friction Loss

Code [6] proposes that the effective prestressing force at any point under consideration may be taken as:

$$P_x = P_k e^{-(\mu\theta + kx)} \tag{1}$$

where:

$P_x$- The effective prestressing forcet any point under consideration

$P_k$- The force at the jacking end

$\theta$ - Total horizontal angular change of prestressing steel path from jacking end to a point under consideration (rad.)

$x$ - Length of prestressing tendon from the jacking end to any point under consideration (m)

$\mu$ - Coefficient of friction

$k$ - Wobble friction coefficient

Change the form of Eq.1:

$$A = P_x / P_k = e^{-(\mu\theta + kx)} \tag{2}$$

Take the natural log of both sides:

$$-lnA = \mu\theta + kx \tag{3}$$

Let $Y= -lnA$, then a series of Eqs. Can be written at different point:

$$\mu\theta 1+kx1-Y1=0$$
$$\mu\theta 2+kx2-Y2=0$$
$$\cdots\cdots$$
$$\mu\theta n+kxn-Yn=0$$

Because of the errors exist in experiments, the right sides of the Eqs. above are not always zeros:

$$\mu\theta 1+kx1-Y1=\triangle F1$$
$$\mu\theta 2+kx2-Y2=\triangle F2$$
$$\cdots\cdots$$
$$\mu\theta n+kxn-Yn=\triangle Fn$$

Use Least-Square Method here:

$$(\mu\theta_1 + kx_1 - Y_1)^2 + \cdots + (\mu\theta_n + kx_n - Y_n)^2 = \sum_{i=1}^{n}(\Delta F_i)^2 \tag{4}$$

$\sum(\Delta F)^2$ will meet the minimum when both of the following Eqs. are satisfied:

$$\frac{\partial\sum(\Delta F_i)^2}{\partial\mu} = 0,\ (4)\ \frac{\partial\sum(\Delta F_i)^2}{\partial k} = 0 \tag{5}$$

$$\begin{cases} \mu\sum\theta_i{}^2 + k\sum x_i\theta_i - \sum Y_i\theta_i = 0 \\ \mu\sum x_i\theta_i + k\sum x_i{}^2 - \sum Y_i x_i = 0 \end{cases} \tag{6}$$

For the straight prestressing tendons: $\theta=0$,

$$k\sum x_i{}^2 - \sum Y_i x_i = 0 \tag{7}$$

$k$ can be solved from Eq.7

Resistance strain gauges are set on the internal prestress tendons to measure the force of specific points. Every point's effective coefficient $A$ and its $Y$ can be calculated. Given the oil-pressure gauge of hydraulic jack can't show the force accurately, the force of point 5 is taken to be as $P_k$, and x is the length of point 5 to the investigating point. Details of the prestress force and calculated $k$ are summarized in Table I.

From Eq.7, the actual factor $k$ is 0.0059, on average.

TABLE I. Measured Force of Internal Tendons

| Tendon no. | Load level | Actual force (kN) | | | | | $k$ | $k$ (Average) |
|---|---|---|---|---|---|---|---|---|
| | | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | | |
| 2# | 1.0P | / | 3022.86 | 3042.47 | 3058.23 | 3079.46 | 0.0056 | 0.0059 |
| | 0.8P | / | 2434.05 | 2449.73 | 2462.33 | 2478.38 | | |
| | 0.5P | / | / | / | 1499.58 | 1512.75 | | |
| 2'# | 1.0P | 2943.98 | 2964.02 | 2981.16 | 3002.73 | 3023.06 | 0.0062 | |
| | 0.8P | 2351.01 | 2367.95 | 2381.67 | 2397.96 | 2410.34 | | |
| | 0.5P | 1467.72 | 1477.8 | 1488.53 | 1500.08 | 1514.24 | | |

Note: "/"means that the gauges may be broken

Code [6] proposed wobble friction coefficient $k$=0.0015(for plastic corrugated pipe). There are seldom researches on $k$ about straight prestressing tendons. Relevant researches study the coefficient of friction μ in curvilinear prestress tendons, however, they treat $k$ as code proposed [7].Statistics show that the $k$ on this test is close to the existing bridges. The $k$ of Hangzhou Bay Bridge is 0.005, the $k$ of Guangzhou Bridge is 0.0069, and the $k$ of Wuhan Junshan Yangtze River Bridge is 0.003.

Because of uncertainty factors in the construction, it is easy to wobble the duct, which cause the steel strands squeezing the duct, and then led to more friction. As the number of strands increasing, they twine around each other, therefore, the friction between strands increase as well as the friction between strands and the ducts wall. Results on this test show that, the actual $k$ is larger than the one recommended by [6].

On this test, the applied force is 3124.8 kN. If $k = 0.0015$ (Code recommended value), the loss of prestress at fixing end is 25.63 kN, which is 0.8% of the applied force. If $k = 0.0059$ (actual value), the loss is 99.59 kN, which is 3.19% of the applied force. That means the Code recommended $k$ is less-safety, a larger $k$ should be highly suggested when calculatingWithin three days after the prestress tendons anchorage, recording the measured force under the anchorage set, then deducting the loss due to concrete elastic shortening, we can get the loss due to steel relaxation.

### *B. Loss due to Anchorage Head Friction*

Data of loss due to anchorage head friction are summarized in Table II. Data displays that, the loss is more than 5% of applied force. This type of loss is not clearly defined in Code [6], but according to the test, it seems should not be ignored when calculating the total loss.

TABLE II. LOSS DUE TO FRICTION ON ANCHORAGE HEAD

| Tendon no. | Load level | Force inside anchorage head (kN) | Force outside anchorage head (kN) | Prestress losses (kN) | ratio |
|---|---|---|---|---|---|
| 4# | 1.0P | 2951.95 | 3113.06 | 161.11 | 5.16% |
| 4'# | 1.05P | 3082.76 | 3258.11 | 175.35 | 5.34% |

Note: ratio = $\dfrac{outside - inside}{1.0P(1.05P)} \times 100\%$

### *C. Loss due to Anchorage Set*

Results of test on loss due to anchorage set are summarized in Table III.

TABLE III. LOSS DUE TO ANCHORAGE SET

| Tendon no. | Load level | Force before anchored (kN) | Force after anchored (kN) | Prestress losses (kN) | Ratio % |
|---|---|---|---|---|---|
| 4# | 1.0P | 2951.95 | 2545.47 | 406.48 | 13.01% |
| 6# | 1.0P | 2962.00 | 2498.00 | 464.00 | 14.85% |
| 4'# | 1.05P | 3082.76 | 2625.33 | 457.43 | 13.94% |
| 6'# | 1.05P | 3073.90 | 2631.89 | 442.01 | 13.47% |

Note: ratio= $\dfrac{Before - After}{1.0P(1.05P)} \times 100\%$

As shown in Table III, loss due to anchorage set is relatively larger. Generally, the reverse friction of ducts should be considered when calculating this loss. The reverse friction reduces this loss along the tendons from jacking end to fixed end, then the loss may became 0 when leave a certain distance away the jacking end. For the straight-short tendons, the reverse friction is much smaller than long or curvilinear tendons; this loss exists in the whole tendons. On the other hand, the elongation of straight-short tendons is small while the shortening of anchor set is a constant (rated 6mm, Code [6]). Therefore, straight-short tendons are more sensitive to anchor set loss comparing to long tendons. References [8], [9] propose that double-tensioned anchor can reduce this loss a lot.

### *D. Loss due to Concrete Elastic Shortening*

Fig. 7 shows the loss of tendons no.4# after other tendons extending. When the nearest group of tendon was extended, the loss was found to be 8 kN. When jacking the tendons in the region out of *1m*, the loss of tendons no.4# was found to be about 1 kN. The total loss due to concrete elastic shortening of tendons no.4# was 29.45kN, 0.94% of the applied force. The results of tendons 4'#, 6#, 6'# are 20.90 kN (0.64%), 13.00 kN (0.42%) and 12.73 kN (0.39%).

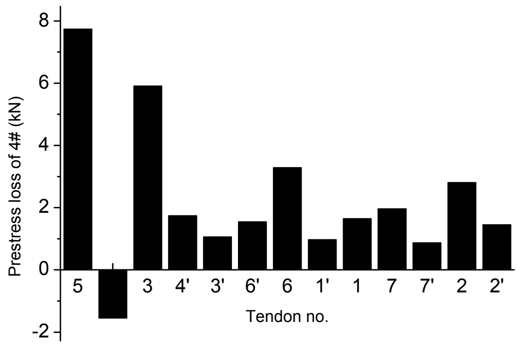



Figure 7. Loss of tendon no.4# due to concrete elastic shortening

### *E. The Total Losses*

All of the prestress losses above are summarized in Table IV. As can be seen from the data, in all the types, the loss due to anchorage set accounts for the largest portion, about 50% of the total losses, which is an important characteristic of the straight-short tendons. The double-tensioned anchor which will reduce this loss a lot should be considered. Overstressing technique also can compensate this loss, but it easily leads to broken strand, especially when the number of strands in one tendon is large and strands are intertwined, so the application of overstressing should be cautious. Duct friction loss and anchorage head friction loss are about 30% of the total losses, which should not be neglected. The proportion of loss concrete elastic shortening is smallest, only 1%-3% of total losses. In the experiment, 4# and 6# tendons were non-overstressed, 4'# and 6'# were overstressed by 1.05P. From the data, the two ways have a regular difference only in the steel relaxation loss; the loss of overstressing is slightly larger. Effective prestress of overstressed tendons is 50-100 kN larger than non-overstressing ones. The total losses are about 26% of applied force.

TABLE IV. TOTAL LOSS

| | Tendon no. | Ducts friction loss (k=0.0059) | Anchorage haed friction loss | Anchorage set loss | Concrete elastic shortening loss | Time-dependent loss (calculated ultima value) | Total losses |
|---|---|---|---|---|---|---|---|
| Prestress losses (kN) | 4# | 94.99 | 161.11 | 406.48 | 29.45 | (75.9) | 767.93 |
| | 4'# | 99.74 | 175.35 | 457.43 | 20.90 | (145.74) | 899.16 |
| | 6# | 94.99 | (161.11) | 464.00 | 13.00 | (106) | 839.10 |
| | 6'# | 99.74 | (175.35) | 442.01 | 12.73 | (116) | 845.83 |
| Loss ratio of the applied force (%) | 4# | 3.04% | 5.16% | 13.01% | 0.94% | 2.43% | 24.58% |
| | 4'# | 3.04% | 5.34% | 13.94% | 0.64% | 4.44% | 27.40% |
| | 6# | 3.04% | 5.16% | 14.85% | 0.42% | 3.39% | 26.86% |
| | 6'# | 3.04% | 5.34% | 13.47% | 0.39% | 3.54% | 25.78% |
| Loss ratio of the total losses (%) | 4# | 12.37% | 20.99% | 52.93% | 3.82% | 9.88% | - |
| | 4'# | 11.09% | 19.49% | 50.87% | 2.34% | 16.21% | - |
| | 6# | 11.32% | 19.21% | 55.28% | 1.56% | 12.63% | - |
| | 6'# | 11.79% | 20.72% | 52.26% | 1.51% | 13.72% | - |

Note: the date in () means calculated according to the Code [6], not obtained from the experiment

## IV. CONCLUSION

This paper has tested the straight-short tendons applied on the cable-stayed bridge PC pylon. The following is concluded:

1. The total loss of short prestress tendons in this experiment is 26% of the applied force.

2. The loss due to anchorage set is larger than any other types of loss. It accounts for about 50% of the total losses, which is different from long or curve tendons. This loss can be reduced a lot by double-tension anchor as well as overstressing. For the risk of steel strands snapping during overstressing, double-tension anchor are recommended.

3. 12% of the total loss is the loss due to friction between prestress tendons and ducts wall. It cannot be neglected as most literatures and code suggested for straight tendons. The *k* of actual test is 0.0059, which is larger than the proposed 0.0015 in Chinese code. Another considerable loss is the loss due to anchorage head friction which contributes 20% of the total losses.

4. Only 1%-3% of the total loss is due to elastic shortening of concrete. So, constructors can arrange the tensioning sequence just by construction convenience, and ignore to consider of minimizing loss due to concrete elastic shortening.


## ACKNOWLEDGMENT

This work was financially supported by project management of Guangzhongjiang Highway, Natural Science Foundation of China (50808180, 51478193) and the Fundamental Research Funds for the Central Universities (2014ZZ0019).


## REFERENCES


[1] S. F. Xiong, "Research of construction control of u-shap loop prestressing in anchorage zone in pylon of Nancang cable-stayed bridge in Tianjin," *Bridge Construction*, vol. 4, pp. 71-75, Feb. 2011.

[2] G. Q. Chang, W. U. Bo, K. Liu, and F. Zhang, "Discussion on non-uniformity of u-looped prestressing tendons elongation at tower anchorage zone," *Journal of Chongqing Jiaotong University (Natural Science)*, vol. 5, pp. 826-829, May 2009.

[3] Z. Fang and J. Wang, "Vertical prestressing loss in the box girder of long-span PC continuous bridge," *China Civil Engineering Journal*, vol. 5, pp. 78-84, May 2006.

[4] H. Huang, X. B. Tang, K. Y. Zhang, *et al*., "Numerical simulation on vertical prestressed effect and experimental studies on presstressed loss," *Journal of Wuhan University of Technology (Transportation Science & Engineering)*, vol. 5, pp. 922-924, May 2007.

[5] AASHTO, *AASHTO LRFD Bridge Design Specification*, 2012.

[6] China P R. Ministry of Communications, *Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridge and Culverts*, (JTG D62-2004), 2004.

[7] Y. Li and J. L. Fu, "Circular prestress tension experiment for tower of cable-stayed bridge," *Journal of Shijiazhuang Tiedao University (Natural Science)*, vol. 3, pp. 53-56, Mar. 2010.

[8] X. Shao, R. Pan, and H. Zhao, "Prestress loss of a new vertical prestressing anchorage system on concrete box-girder webs," *Journal of Bridge Engineering*, vol. 19, pp. 21-219, Feb. 2013.

[9] L. Bin, "Research on technology of twice tension applied in web's vertical prestress of box beam," Hunan University, 2009.

[10] C. Liu, "Research on the shear properties and prestress losses of transversely prestressed concrete beams," South China University of Technology, 2010.

[11] Y. Yang and J. Myers, "Prestress loss measurements in missouri's first fully instrumented high-performance concrete bridge," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1928, pp. 118-125, Jan. 2005.



**Nannan Cui** was born in Yantai, Shandong, China in 19 Dec. 1987. She is a PhD student of School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong, China. She obtained a bachelor's degree in civil engineering from Ludong university in 2010. She has completed the full-scale model test of pre-stressed cable-pylon anchorage zone of cable-stayed bridges named Xijiang Waterway Bridge, in Guangdong, China. The test is directed by her tutor Quansheng Yan. Her areas of interest are large span bridge design, prestressed concrete structure, and strut-and-tie model theory.

**Xiaolin Yu** was born in 1978. She is a lecturer of School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong, China. She obtained a bachelor's degree in civil engineering from Zhongnan university in 2000, obtained a master's degree in bridge and tunnel engineering from Zhongnan university in 2003, earned her doctorate in bridge and tunnel engineering from South China University of Technology in 2011.

Her areas of interest are large span bridge structure reliability, construction control and health monitoring.

**Buyu Jia** was born in 1983. He is an assistant researcher of School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong, China. He obtained a bachelor's degree in civil engineering from Zhongna university in 2006, earned her doctorate in bridge and tunnel engineering from South China University of Technology in 2011.

His areas of interest are large span bridge structure reliability, construction control and health monitoring.

**Quansheng Yan** was born in 1968. He is a professor of School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong, China. He obtained a bachelor's degree in civil engineering from Changsha Railway University in 1985, obtained a master's degree in bridge and tunnel engineering from Changsha Railway University in 1988, earned her doctorate in bridge and tunnel engineering from Changsha Railway University in 1994.

His areas of interest are bridge structure calculation and construction monitoring