Scientific Research

Stage-by-Stage Prestressing Arrangement Design in the Design of Bridges with Hybrid Internal and External Prestressing Tendons

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Abstract: In the design scheme of a bridge with external prestressing tendons and hybrid internal and external tendons, the internal tendons can bear the load in cantilever casting construction, the external tendons can bear the superimposed dead load and the service load, and the external prestressing tendons are easy to inspect and replace in the service stage. However, in the design of prestressing tendons and hybrid tendons, different tendon arrangement schemes will lead to differences in the layout and number of internal and external prestressing tendons and determine the stress state of the bridge. This paper optimized different tendons in an engineering project during the construction process based on the principle that the internal tendons bear the load in the construction stage while the external tendons bear the superimposed dead load and the service load, highlighted the arrangement schemes of different internal prestressing tendons and the corresponding design of external prestressing tendons, and determined the final bridge design scheme and bridge stress state. The relevant design process can provide references for similar prestressed continuous girder or continuous rigid-frame bridges with hybrid tendons.

Keywords: external prestressing; hybrid tendons; stress state

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1 Introduction

Improving the reliability of bridge structural quality and prestressing level, the durability of structure and prestressing system, and the comprehensive economy during the reference period is an inevitable trend in the development of modern prestressed bridges. Although traditional bridge design and construction methods are relatively mature, there still exists a significant gap compared to modern prestressed bridges in terms of structural construction, prestressing technology, and construction processes due to limitations imposed by technology and techniques.

In terms of structural design, prestressed concrete (PC) has experienced a development process from fully prestressed to partially prestressed. Through the development of theory and practice and on the basis of the design and use experience of reinforced concrete, prestressing design theory is becoming increasingly perfected. Internationally, the rationality and economy of PC, especially partially PC, have been accepted by engineering circles worldwide [1-3]. Particularly, in structural engineering, partially PC has been successfully applied in small- and medium-span bridges and even long-span bridges in the past 20 years. In the synchronous development process with partially PC, the externally PC structural system has changed from its application in retrofit engineering to a new structural system due to its own advantages and has become a hot topic in the concrete engineering field in recent years [4-6].

For structural systems, simply supported beams have always been the main load-bearing system due to the low strength and durability of concrete material used in the early stage and the backward construction technology. However, with the increase in concrete strength, continuous girder and continuous rigid-frame bridges have been gradually demonstrating their advantages in bridge construction due to their favorable mechanical characteristics (such as small deformation, good structural stiffness, and high seismic resistance) and application benefits (fewer structural expansion joints, easy maintenance, and conduciveness for smooth driving). However, before the 1950s, due to the relatively backward construction technology and concrete technology, the spans of such bridges were all less than 100 meters, and the advantages of prestressed continuous girders and continuous rigid frames were not obvious. In the past 50 years, combined with the development of prestressing technology and high-strength materials, continuous girder and continuous rigid-frame bridges have become optimal bridge design solutions for long-span bridges [7-9]. With improvements in concrete technology, prestressing technology, and construction technology, the structural forms of continuous girder and continuous rigid-frame bridges have developed.

Much research on prestressed continuous rigid-frame bridges has been conducted in various countries on the basis of theory, practical experience and tests. The structural mechanical characteristics of prestressed continuous rigid-frame bridges are very clear, calculations and analyses related to their construction can be completely automated, and the calculations and design of the continuous rigid-frame bridge are no longer problems. However, when external prestressing technology is used in long-span continuous rigid-frame bridges, the mechanical performance of the structures may not coincide with the internal prestressing [7, 9, 10].

From the perspective of construction quality and the reliability of the prestressing level of the bridge structure, the densely arranged internal prestressing tendons with complex shapes tend to conflict with the construction of common steel bars and make the on-site installation of tendons challenging. In addition, dense internal prestressed pipes increase the difficulty of pouring concrete. These factors have an adverse effect on the reliability of concrete construction quality. External prestressing technology is used to arrange prestressing steel tendons outside the concrete structure to protect the concrete construction from the influence of dense pipes, thereby improving the structural construction and making the structural integrity more reliable. More importantly, the construction of prestressing tendons inside the pipes is prone to cause problems, which directly affects the reliability of prestressing. In contrast, the external prestressing system is a “visible and tangible” prestressing system that can be conveniently inspected, adjusted, or even replaced during the service period, thus ensuring the reliability of structural prestressing [1, 2].

From the perspective of the durability of the bridge structure, the external prestressing system has its own protective functions. For example, the use of a single epoxy-coated unbonded steel strand with multilayer anti-corrosion coating prevents the deterioration of grout caused by insufficient grouting and voids in the pipes and the damage to conventional internal prestressing tendons caused by concrete carbonation and cement grout cracking; because the corrosion of prestressed steel under high stress will lead to stress corrosion and fracture, the durability of prestressed steel is an important guarantee for the durability of prestressed structures [3, 11]. If the external prestressing system is adjustable, detectable, and replaceable, its durability is more reliable than that of the conventional internal prestressing system.

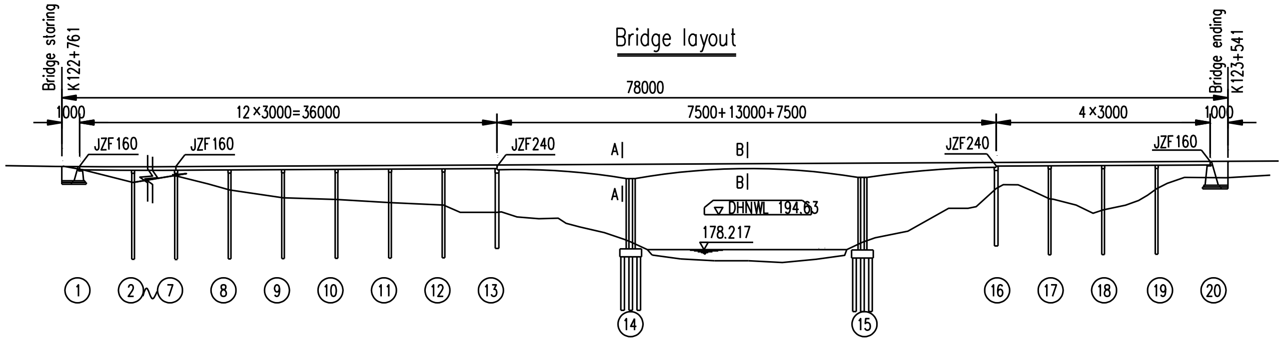
From the economy of the bridge structure during the service period, the externally prestressed structure can minimize the size of the non-load-bearing portion of the structure and reduce the structural weight and the material usage of the upper and lower structures. Compared with internally prestressed structures, the maintenance and retrofit costs of externally prestressed structures during their service period are much lower. Therefore, the lifetime economy of externally prestressed structures is better than that of internally prestressed structures.

Although the development advantages of externally prestressed bridges have been fully revealed in bridge construction as a new type of structural system, there are still many urgent problems to be solved in the study of design theory and methods. The study of the design theory and methods of externally PC bridges and the development of adjustable, detectable, and replaceable external prestressing systems are the key and foundation for the application and development of externally prestressed bridges.

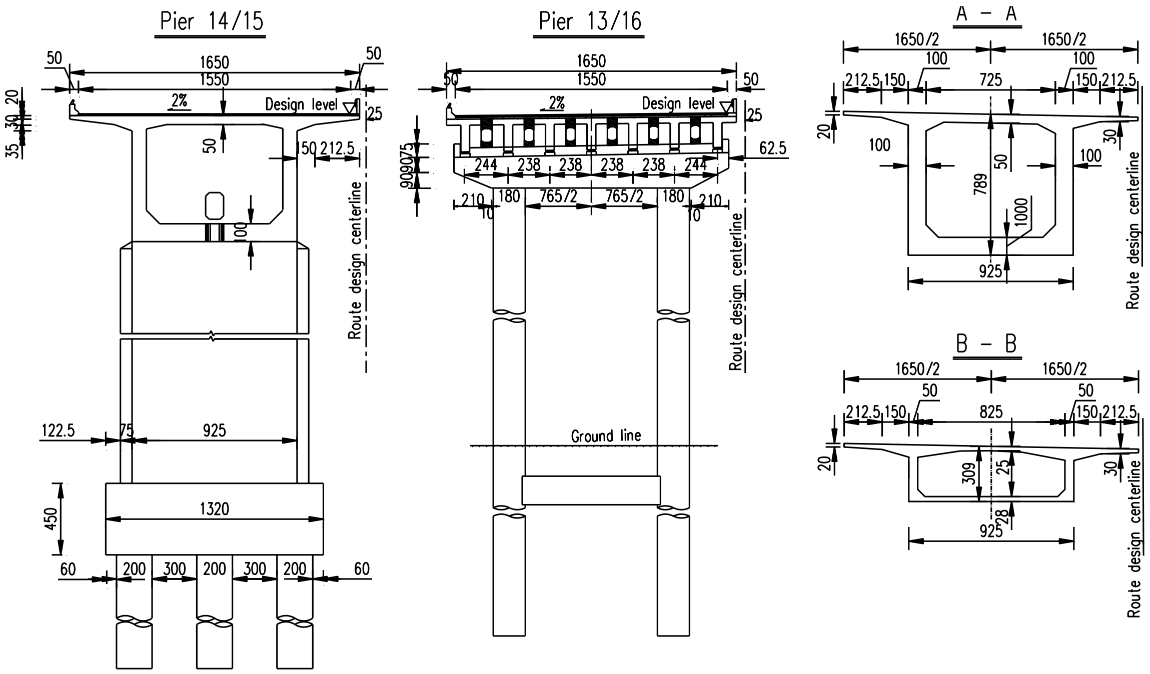
This paper aims to study the design theory of externally prestressed bridges, to recommend the design method of corresponding externally prestressed systems, and to validate the design with a real bridge. More mature bridge types are chosen for the research and practice of external prestressing technology and the technical characteristics of the application of external prestressing technology in long-span bridges are summarized to provide a theoretical basis and engineering experience for the design of similar bridge types.

2 Introduction to the Engineering Background

The Chongqing Xintan Qijiang Highway Bridge is a project supported by the Technological Research Project of Western Transportation Construction “Research on the Design and Construction Technology of Externally Prestressed Bridges” of the Ministry of Transport of the People's Republic of China. According to the topographic, geological, geomorphic, and hydrological conditions of the bridge location, the main bridge is arranged as a PC continuous rigid-frame structure with three spans (75+130+75 meters), with a total length of 280 m. The main piers are double thin-walled flexible piers. A junction pier is present between the main bridge and the approach bridge at each bank. The main bridge is designed as a two-way six-lane bridge and is composed of a pair of twin bridges, each 16.50 m wide. The continuous rigid frame of the left half of the twin bridges is an internal prestressing system. The continuous rigid frame of the right half is a hybrid internal and external prestressing system, in which the first-stage and second-stage steel tendons are the internal and external prestressing systems, respectively, and the box-girder web is free of vertical prestress. This bridge is the first long-span bridge in China that was constructed using external prestressing technology. Figure 1 shows the overall arrangement and the constructional dimensions of the key cross-sections of the bridge.



(a) Bridge elevation layout



(b) Structural diagram of key cross-sections

Figure 1 Bridge layout diagram (Unit: cm)

This study uses Bridge Doctor software for calculations, carrying out the design for both ultimate limit state and serviceability limit state during construction, completion, and usage phases. Both the main girder and piers are modeled using beam elements, neglecting the longitudinal and transverse slope of the bridge. Fixed constraints are applied at the bottom of piers, while vertical constraints are applied at both ends of the main girder. The overall bridge model is illustrated in Figure 2.

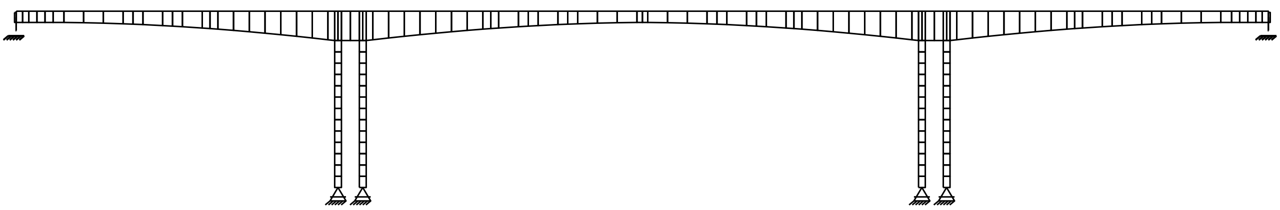


Figure 2 Bridge overall model

3 Design and Analysis of the Externally Prestressed Continuous Rigid Frame Bridge

On the basis of the design of the continuous rigid-frame bridge in the supported project, the left and right halves of the twin bridges were used for comparative analysis and design in the design process of the externally prestressed continuous rigid-frame bridge:

(1) To fully grasp the characteristics of external prestressing technology and to compare and summarize the differences between external prestressing technology and internal prestressing technology through engineering design, it is necessary to carry out a comparative design, which is conducted on the basis of the principle of comparability. Considering that the bridge is composed of a pair of twin bridges, in actual design, a comparative design was used; that is, the design results of the left and right halves of the twin bridges were compared to summarize their differences and similarities, thus comprehensively comparing the implementation effects of internal and external prestressing techniques.

(2) A reasonable prestressing tendon layout analysis was performed, a corresponding feasibility design for hybrid internal and external reinforcement was

conducted, and the techniques that maximize the use of external prestress were analyzed in the case of changing the alignment of longitudinal prestressing tendons or not using vertical prestressing tendons.

(3) Conventional internal prestressing reinforcement was used in the left half of the twin bridges. The number and alignment of prestressing tendons used in the left half are basically the same as those of the conventional continuous rigid-frame bridges. Specifically, there is one straight tendon and one curved tendon for each segment: the bottom-slab tendons and closure tendons in the side-span closure segment, and the bottom-slab tendons and closure tendons in the mid-span closure segment.

(4) For the hybrid external and internal prestressing reinforcement, the advantages of external prestressing technology are fully utilized through optimization design to achieve the optimal configuration as much as possible so as to obtain empirical values.

Considering the improvement of the shear performance of the structure by external prestressing, the vertical prestressing tendons were optimized to maximize the effect of external prestressing tendons and reduce the usage of longitudinal and vertical internal prestressing tendons, which is also conducive to saving manpower, improving concrete construction quality, shortening the construction period, and thus improving the economy and safety of the bridge.

3.1 Optimization Principle of Longitudinal Prestressing Tendons

If the vertical prestressing tendons are removed, the number of prestressing tendons used in the web will be greatly reduced, and on this basis, the construction of vertical downward-bending prestressing tendons will be very easy. Although the removal of vertical prestressing tendons will lead to more downward-bending tendons, the removal of vertical prestressing tendons is practical considering its benefits.

The actual downward-bending arrangement of longitudinal prestressing tendons is determined by the structural stress and the number and arrangement of external tendons. The number and steering angles of the external tendons determine the size of the vertical force component that can be provided by the external tendons. When the number and the steering angle of external tendons used is large, the use of downward-bending internal tendons can be minimized.

As mentioned above, the configuration and number of internal tendons are based on the requirements of the construction stage, and they and external tendons together bear the load in the service stage. Therefore, in the actual design process, the distribution of longitudinal internal prestressing tendons is directly related to the arrangement of external tendons.

Because the local forces on the anchor points of the external tendons are large and the anchor points of external tendons should not be concentrated, the number of external tendons is limited to some extent, and the steering angle is also limited by the alignment of the bottom slab of the main girder. Therefore, the vertical component force that can be provided by the external tendons must have an upper limit. Taking this factor into consideration, a certain number of internal tendons is required to cooperatively provide the vertical component force and reduce the principal tensile stress. The number of downward-bending tendons must be determined based on the number and alignment of the external tendons in the later configuration process. Therefore, this parameter is an uncertain proportional value and needs to be determined through cyclic calculation.

In the design of the Xintan Bridge, after many adjustments, it was finally determined that, for each segment, a set of straight tendons and a set of downward-bending tendons were installed on the webs on both sides to supplement the insufficient vertical component force of the external tendons. Under the joint action of the vertical straight tendons, the vertical downward-bending tendons and the external tendons, the reasonable normal stress and principal stress values of the cross section are the adjusted values required.

Based on the above evidence, a feasible solution for the internal and external prestressing tendons of the Xintan Bridge was designed. In the early stage of design, it was assumed that only straight tendons were needed, while downward-bending tendons were unnecessary and external tendons only needed to pass through one steering block in a T configuration. In this case, the number of internal tendons and the construction of downward-bending tendons would be reduced, and the number of steering gears for external tendons would be greatly reduced. With the determined number and alignment, under the joint action of the internal and external tendons, the load-bearing capacity of the structure should meet the requirements. In consideration of construction convenience and reinforcement experience, in the transverse half of the bridge (the same for the others), a total of 8 bundles of external tendons are arranged. The longitudinal layout of the external tendons starts from one side's cross-beam, turns through the top of the other side's pier, and is anchored.

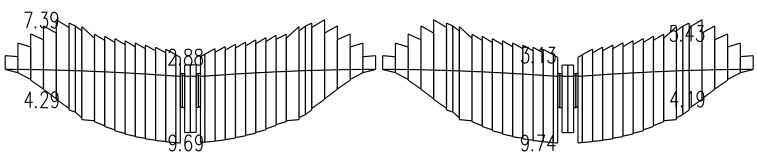
The internal tendons were arranged as follows: two sets of straight tendons were installed in each segment and were locally bent down at the anchorage end to facilitate construction. In addition, two sets of straight tendons were installed in the five segments further away from the pier to compensate for the insufficient compressive stress caused by the insufficient number of longitudinal prestressing tendons. This is due to the restriction in the selection of the types and sizes of the internal and external tendons and the restriction in the number of external tendons sets by the end anchorages and tendon branches.

During the feasibility design analysis of longitudinal prestressing tendons, the number of prestressing tendons was optimized when the internal and external prestressing tendons were in the above-described alignments. In this case, because the reinforcement construction is relatively simple, the construction of external prestressing tendons is easy, and the material usage is relatively economical.

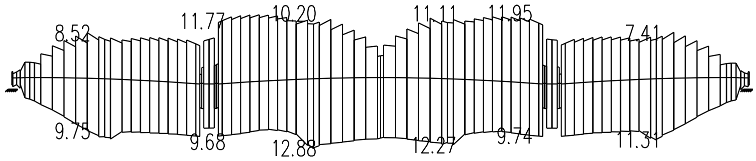
In the schematic design stage, the configuration of the internal prestressing tendons (single-T half-width bridge) shown in Table 1 was determined through preliminary analysis. The external tendon specification is 15-27 (The diameter of the steel strand is 15.2mm, with a total of 27 steel strands forming one bundle, the same below), with a total of 8 sets for the half-span bridge. The total weight of prestressing tendons used was 255 t (excluding the tensile segment), including 98.7 t external tendons and 156.3 t internal tendons. The corresponding stress state is shown in Figure 3.

Table 1 The preliminary tendon arrangement scheme

Segment Number	**0-10**	**11-12**	**13-15**
Downward-bending tendons	15-22	15-22	15-22
Straight tendons	/	15-25	15-22



(a) Stress envelope during the construction of the segment ("+" represents the compressive stress)



(b) Stress envelope diagram of the initial completion stage of the bridge

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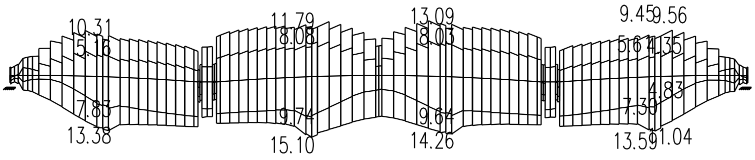
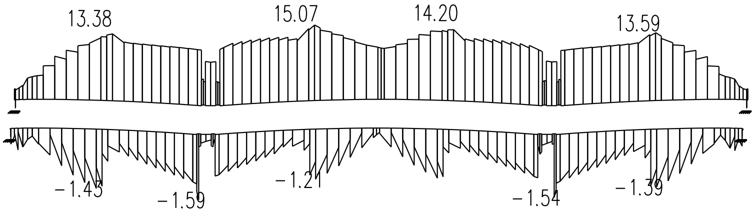


(c) Envelope diagram of the normal stress for the most unfavorable combination II



(d) Envelope diagram of the principal stress for the most unfavorable combination II

Figure 3 Stress state of the original design scheme (Unit: MPa)

From the point of view of the stress state, this prestressing tendon scheme meets the requirements of the code during both the construction stage and the service stage. However, from the perspective of the construction stage, the number of internal tendons used was larger, which led to the smaller role of external tendons. As a result, the prestressing effect of external tendons was not fully exerted, and the purpose of making full use of external prestressing technology was not realized. The above conclusions can only confirm the feasibility of canceling the vertical prestress by using external prestressing technology. The vertical component of the external tendons is mainly used to overcome the excessive principal stress caused by the shear force. To fully play the prestressing role of the external tendons, the number and alignment of the internal tendons must also be optimized. As mentioned earlier, the use of downward-bending internal tendons can give full play to the synergistic effect of internal and external prestressing without increasing the amount of material used or the difficulty of construction.

3.2 *Optimization Design and Analysis*

The optimization design of the externally prestressed bridge on the right half of the Xintan Bridge mainly includes the following aspects:

(1) The optimization design of the number and alignment of the internal tendons mainly aims to minimize the number of internal tendons, use them to ensure the load bearing capacity in the construction stage, and then use the external tendons to meet the load bearing requirements in the service stage. The optimization goals included the optimization of the number and alignment of internal tendons.

(2) Since the number of external tendons and the number and locations of the steering blocks are limited inside the box girder, the number of internal tendons and the change in the cross-sectional stress due to the internal tendons will greatly change the corresponding external tendon arrangement. Therefore, the optimization was mainly performed in terms of segmentation, continuity, combination, and size of the external tendons.

3.2.1 Optimization of the Number of Internal Tendons

According to the principle that the internal tendons bear the load in the construction stage and the external tendons bear the superimposed dead load and service load, the optimization design was performed based on the original feasibility scheme in the design process of the Xintan Bridge.

In the internal tendon arrangement equation to ensure the success of the construction stage, there are two feasible schemes:

Option A: Because the negative bending moment generated in the segment at the pier edge is small, relatively thin tendons are used to ensure that the stress meets the code requirements. Although the dead weight of the far segment is light, the moment arm against the 0# block is increased and the negative bending moment increases faster, so thicker tendons are used.

Option B: Thick tendons are used for the segment at the pier edge, and thin tendons are used for the segment farther from the pier because the dead weight of the segment is less. However, the increase in the corresponding negative bending moment must be considered when the segment is far from the pier.

The goal of tendon arrangement is to distribute the compressive stress evenly on the upper edge of each segment during the construction stage after the tensioning and grouting of the last cast-in-place segment and the internal tendons are completed, although the compressive stress on the upper edge of each segment during the construction stage is lower than that of conventional internally prestressed bridges.

Based on the above two tendon arrangement schemes, optimization analysis under various scenarios was performed. Notably, the optimization of the internal tendons only focused on the number of tendons without changing their alignment, and the alignment of the original scheme was still used. The alignment of the external tendons also followed the original scheme.

(1) Option A: Arrangement scheme from thin tendons to thick tendons

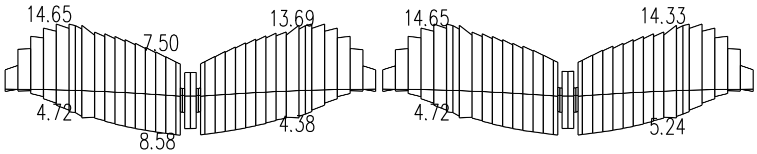
Notably, this type of tendon arrangement scheme is not unique. During the optimization process, limited by the number and alignment of the external tendons used in the second stage and the influence of the principal tensile stress in the service stage, there are various feasible arrangement schemes for internal tendons. The main results of the optimization are the decrease in normal stress and the increase in principal tensile stress. Only one scheme is described below. Table 2 lists the number of tendons required when the structural stress state is considered without considering the actual number of finished tendons.

The external tendon specification is 15-27, with a total of 8 sets for the half-span bridge. The total weight of the tendons was 339 t (excluding the tensile segment), including 98.7 t external tendons and 240.3 t internal tendons. Compared with the original scheme, the internal tendons were 84 t heavier. The corresponding stress state is shown in Figure 4.

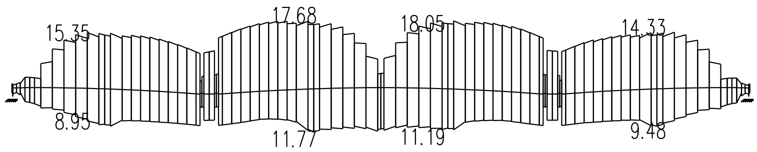
Table 2 An optimized tendon arrangement scheme

Segment Number	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Downward-bending tendons	0	15-3	15-7	15-10	15-13	15-16	15-19	15-23
Segment Number	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Downward-bending tendons	15-26	15-29	15-33	15-49	15-62	15-76	15-92	15-107

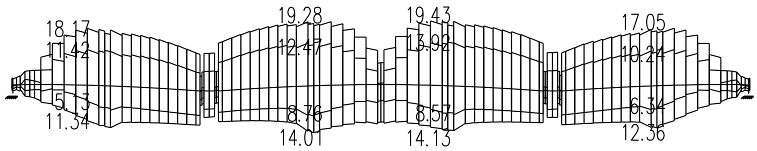
Figure 4 shows the calculation results for the scheme that uses thin tendons first and then thick tendons. Figure 4(a) is the segmental stress envelope when the construction of the last segment is completed. It can be seen from the diagram that although a small number of tendons are used in the early stage, in the later stage, due to the influence of the negative bending moment generated by the dead weight of the segment farther from the pier, thicker tendons must be used to provide the compressive stress at the pier top; this offsets the negative bending moment at the pier top, although the subsequent segment does not require thick tendons due to its light dead weight. As a result, the compressive stress at the upper edge of the segment far from the pier top is much larger than the compressive stress at the pier top. Another adverse effect is that, due to the longer tendons used in the segment farther from the pier, the number of prestressing tendons also significantly increases. Figure 4(b) shows that under the joint action of external prestressing tendons, the compressive stress at the upper edge in the cross-sectional stress state is relatively stable. As shown by the normal stress and principal stress envelope diagrams of the most unfavorable combination II in Figure 4(c) and 4(d), because too many internal tendons were used in the segment near the closure segment during construction, the compressive stress at the upper edge of the cross-section under the joint action of the external tendons was too large, approaching the limit specified in the bridge code.



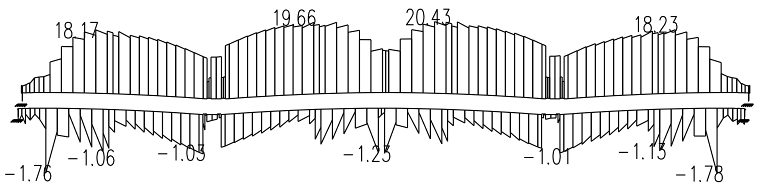
(a) Stresses in the construction stage of the segment



(b) Normal stress in the initial completion stage of the bridge



(c) Normal stress of the most unfavorable combination II



(d) Principal stress of the most unfavorable combination II

Figure 4 Stress diagram of the optimization scheme (Unit: MPa)

Compared with the original design, this scheme uses more internal tendons, mainly to reduce the principal tensile stress through the increased number of internal tendons. However, the design calculation results show that the addition of more internal tendons does not fundamentally reduce the principal tensile stress. Of course, this is based on the scheme without vertical prestressing tendons. Hence, when the alignment of internal prestressing tendons is fixed, it is not an economical solution to increase the number of internal prestressing tendons to improve the load-bearing capacity. The reason is that the principal tensile stress is dominated by shear force, and the increase in the number of internal tendons may change the maximum principal tensile stress at the position of the cross-section height.

(2) Option B: Arrangement scheme from thick tendons to thin tendons

In theory, to make the negative bending moment area have a larger compressive stress reserve, it is more advantageous to use thicker tendons in the segment near the 0# block and use smaller tendons in the segment near the closure segment, which can reduce the usage of prestressed rebars. Based on the analysis of the design data of the existing continuous rigid-frame bridges, it is found that many bridges use this tendon arrangement scheme. In the later analysis, it was concluded that the principal tensile stress of the box girder was large under the influence of the lateral shear stress of the pier, and the adoption of this tendon arrangement scheme was more conducive to reducing the principal tensile stress at the pier edge. Therefore, this tendon arrangement scheme was selected as the external prestressing tendon arrangement scheme for the right half of the Xintan Bridge.

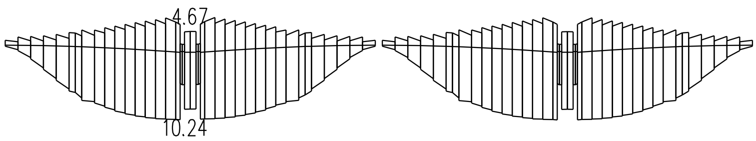
Similarly, due to the difference in the number of prestressing tendons and considering its interaction with the second-stage external tendons, there are multiple options for this tendon arrangement scheme. Only one of them is described below. Table 3 lists the number of prestressing tendons used in this tendon arrangement scheme.

The external tendon specification is 15-27, with a total of 8 sets for the half-span bridge. The total weight of the tendons was 219 t (excluding the tensile segment), including 98.7 t external tendons and 120.3 t internal tendons. Compared with the original scheme, the internal tendons were 36 t lighter. The corresponding stress state is shown in Figure 5.

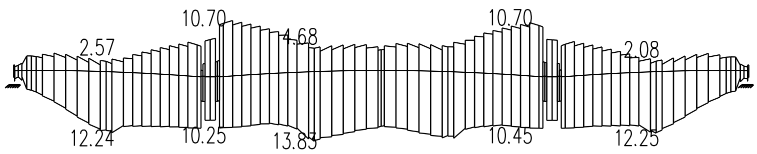
Table 3 An optimized tendon arrangement scheme

Segment Number	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Downward-bending tendons	0	15-37	15-35	15-33	15-33	15-30	15-30	15-30
Segment Number	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Downward-bending tendons	15-30	15-33	15-30	15-26	15-24	15-20	15-20	15-20

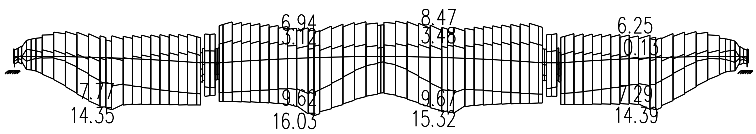
The stress calculation results of this tendon arrangement scheme show that the internal tendons only meet the construction requirements. During the construction of the segment, the maximum compressive stress at the upper edge was within 5 MPa. At the early stage of bridge completion under the combined action of second-stage external tendons, the compressive stress state at the pier top was ideal, but the compressive stress reserve at the upper edge of the cross-section at the side span midpoints and the main span quarter-points (that is, the cross-section at the turning positions of the external tendons) was insufficient; as a result, in the most unfavorable combination II, a small amount of tensile stress appears in the minimum stress envelope at the upper edge. The examination of the principal compressive stress and the principal tensile stress shows that the principal tensile stress at the same position basically reaches the limit specified in the bridge code.



(a) Construction stress of the segment



(b) Stress in the initial completion stage of the bridge



(c) Normal stress under the normal use of combination II

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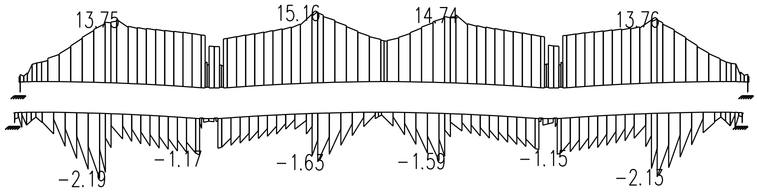


(d) Principal stress under the normal use of combination II

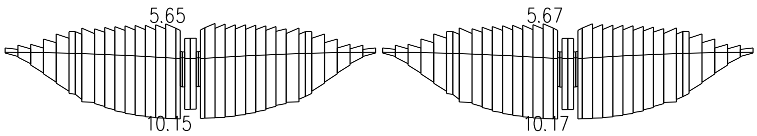
Figure 5 Stress in the optimized tendon arrangement scheme (Unit: MPa)

Since the abovementioned tendon consumption schemes do not consider the actual models of finished tendons, when the finished tendon models are classified for the abovementioned tendon consumption schemes, the number of some tendons should be increased correspondingly considering that the stress level in combination II is low. For the segments with more tendons, the tendons were divided into two parts considering the actual construction operation; one part consisted of horizontal tendons, and the other part was still anchored after being locally bent down at the anchorage locations as designed in the original scheme. Table 4 lists the tendon specifications.

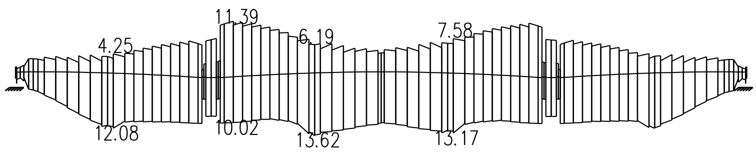
Table 4 An arrangement scheme for finished tendons

Segment Number	0-1	2-8	9-12	13	14-15
Downward-bending tendons	15-22	15-30	15-22	15-22	15-19
Straight tendons	15-15	/	15-15	/	/

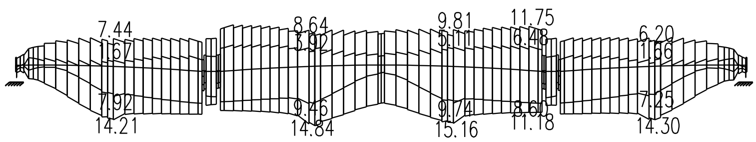
At this time, the number and alignment of the external tendons were the same as those designed in the original scheme. The weight of external tendons was 98.7 t, and the weight of internal tendons was 232 t, for a total of 330.7 t, which was 32 t lighter than that in the original design. The corresponding stress state is shown in Figure 6.



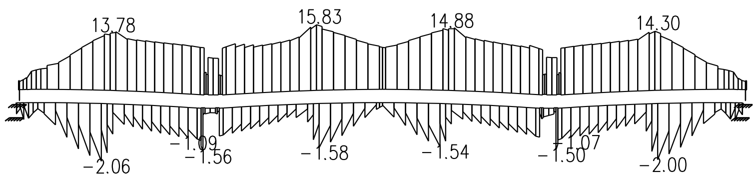
(a) Construction stress of the segment



(b) Stress in the initial completion stage of the bridge



(c) Normal stress under the normal use of combination II



(d) Principal stress under the normal use of combination II

Figure 6 Stress in the arrangement scheme for the finished tendons (Unit: MPa)

From the normal stress state under the normal use of combination II in the figure above, the normal stress in the mid-span of the side span of the upper edge, i.e., the position of the steering block, is only 1.58 MPa, while the principal tensile stress at the same position reaches 2.06 MPa. The normal stress can be increased by three methods: adjusting the number and eccentricity of the external tendons, increasing the number of internal tendons in the top and bottom slabs, and increasing the internal tendons in the longitudinal web.

However, the eccentricity of the external tendons determines their angle in the overall arrangement, which will affect their shear performance. Therefore, it is not suitable to increase the normal stress in the top slab by reducing the eccentricity. In contrast, increasing the eccentricity may be beneficial in reducing the principal tensile stress but may be unfavorable for normal stress, and the turning positions of the external tendons in the calculation scheme are already at the lowest part in the construction. Based on their role over the full length of the bridge and the influence of anchorage stress and construction costs, the number of external tendons should not be increased.

Adding top-slab and bottom-slab tendons will add too much construction difficulty and workload, and the top slab and the bottom slab affect the normal stress and the principal stress, respectively, so this approach is only used as one of the alternative measures.

The simple solution is to further increase the number of the longitudinal internal tendons, especially the number of the longitudinal internal tendons in the several segments near the closure segment. In addition, considering that the above tendon arrangement schemes have various tendon types 15-15, 15-19, 15-22, 15-30, and 15-27, which are beneficial to construction, the internal tendons of several segments near the closure section increased from 15-19 to 15-22 to improve the stress state of segment 11, where the normal stress and the principal tensile stress were only 1.58 MPa and 2.06 MPa, respectively, and the total weight of prestressing tendons only increased by 3 t. The corresponding tendon arrangement scheme is shown in Table 5, and the stress state is shown in Figure 7.

Table 5 An adjusted tendon arrangement scheme

Segment Number	0-1	2-8	9-12	13-15
Downward-bending tendons	15-22	15-30	15-22	15-22
Straight tendons	15-15	/	15-15	/

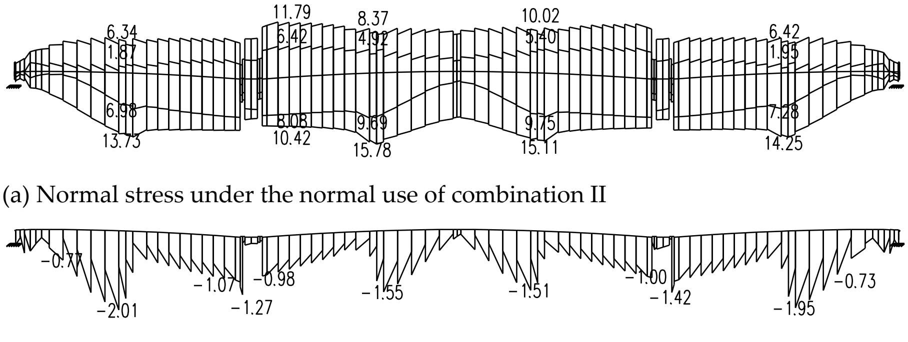


Figure 7 Stress state of the adjusted scheme (Unit: MPa)

Comparison of the results of the above adjusted scheme shows that, in combination II, the minimum compressive stress of the upper edge is improved by approximately 0.5 MPa, but the maximum principal tensile stress basically does not decrease. Therefore, there is not much room for readjustment of the internal tendons. At this point, the optimization of the internal tendon number is basically completed. The remaining work will involve the simultaneous alignment optimization of both internal and external tendons based on the principal stress. Due to the combined action of internal and external tendons, further optimization of the internal tendon number may also be necessary.

3.2.2 External Tendon Alignment Optimization

(1) Comparison of the effect of the capped rebars by moving the turning positions of the external tendons

Based on the effect and principle of shear resistance provided by capped rebars, the turning positions of the external tendons were locally adjusted to determine whether the total principal tensile stress should be reduced by introducing capped rebars or directly using the shear resistance of the external tendons.

Figure 9 shows the calculation results when the turning positions of external tendons are shifted by one segment towards the 0# block. The calculation results show that the principal tensile stress in the segment from the turning positions to block 0# is slightly reduced, but the effect is far inferior to the expected effect. The main reason is that the moment range of the external tendons must be limited. The external tendons cannot move too much to ensure the stress in the normal service stage; the angle of the external tendon cannot change much, and the principal tensile stress is not reduced much. In addition, the principal stress between the steering block and the closure segment rises instead of declining. To take advantage of the shear resistance of external tendons, the effect of internal tendons needs to be integrated. In addition, the external tendons can be turned at multiple positions, which can ensure the prestressing effect in the positive bending moment region of the mid-span while partly reducing the principal stress effect from the steering block to the pier edge.

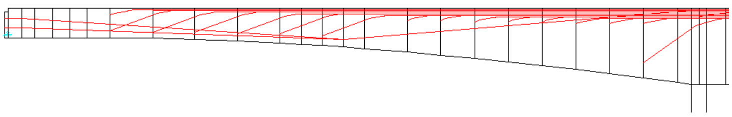


Figure 8 Alignment after offsetting external tendon turning positions by one segment

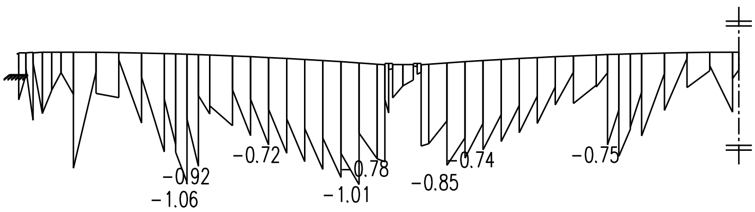


Figure 9 Principal tensile stresses of the corresponding alignment under the normal use of combination II (Unit: MPa)

(2) Turning external tendons at different locations

Based on the conclusion reached by the calculation in (1) by moving the turning positions of the external tendons, the external tendons can effectively reduce the principal tensile stress in most areas of the bridge to a certain extent. The more the turning positions of some external tendons are moved toward the pier, the larger the increase in the corresponding vertical angle is, and the function of the capped rebars is fulfilled to a certain extent. Therefore, the effect of turning external tendons at different locations was reanalyzed in the design calculation. During the calculation, the turning positions move 11.0 m toward the pier, as shown in Figure 10, and the corresponding principal tensile stress is shown in Figure 11. The calculation results showed that the effect of turning external tendons separately was close to the expected effect. Therefore, in the design, the external tendons were turned separately.

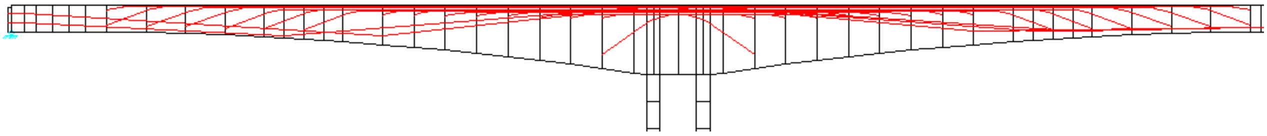


Figure 10 Alignment after turning external tendons separately

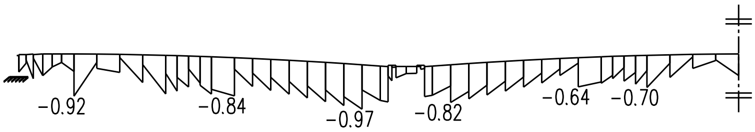


Figure 11 Principal tensile stress corresponding to the alignment under the normal use of combination II (Unit: MPa)

3.2.3 Final design Scheme

Based on all the aforementioned optimization calculation results, the cross-sections with larger local stresses were partially revised, including the edge closure segment and the mid-span closure segment, and the alignment and number of the top- and bottom-slab tendons were adjusted to ensure that the principal tensile stress and the principal compressive stress were within 0.8 MPa (the allowable range) and 15 MPa, respectively. The final numbers of all types of longitudinal internal prestressing tendons are shown in Table 6. The corresponding alignments are shown in Figures 12 and 13, and the calculation results are shown in Figure 14.

After several rounds of iterative optimization, the final hybrid cable arrangement has a total cable quantity of 268 tons, with 83.6 tons used for external cables and 184.4 tons used for internal cables. In contrast, the left bridge only uses internal prestressed tendons, with 273 tons used for longitudinal tendons and 70 tons used for vertical tendons, totaling 343 tons. By adopting the hybrid cable arrangement of internal and external tendons, the cable usage can be reduced by 75 tons, approximately 22%.

Table 6 The number of tendons used in the implementation scheme

Segment Number	**0**	**1**	**2**	**3-8**	**9-15**
Downward-bending tendons	15-22	15-22	15-30	15-30	15-22
Straight tendons	**15-17**	**15-17**	**15-17**	**15-17**	**15-17**
Capped tendons	15-22	/	15-22	/	/

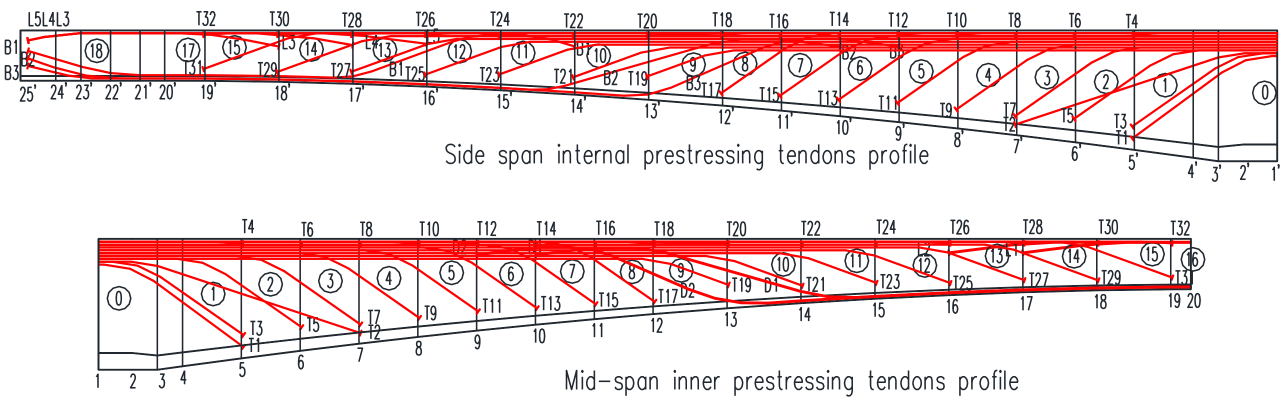


Figure 12 Alignments of longitudinal internal prestressing tendons for the half span

https://doi.org/10.59238/j.pt.2023.02.002

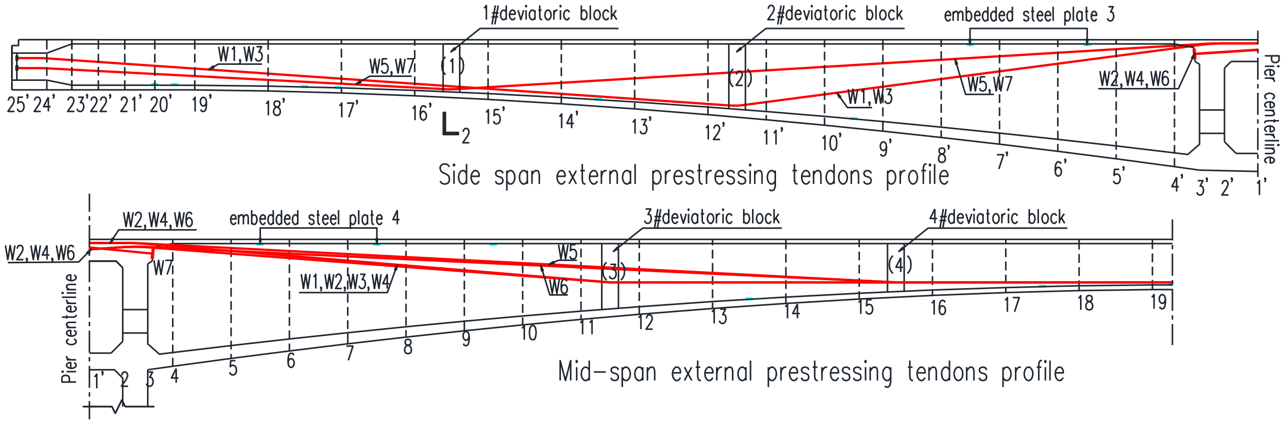
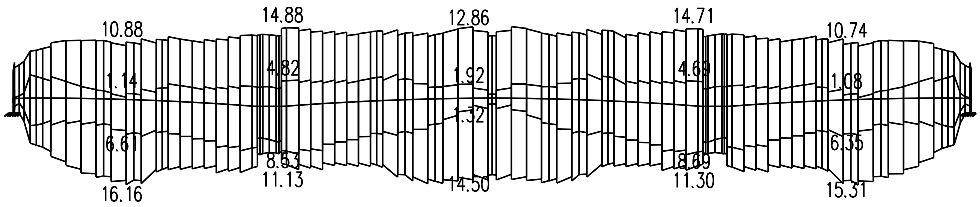
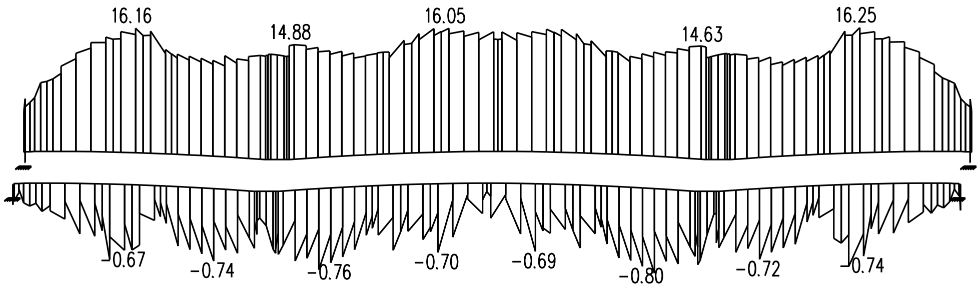


Figure 13 Alignments of external prestressing tendons for the half span



(a) Normal stress under normal use of Combination II



(b) Principal stresses under normal use of combination II

Figure 14 Stress state in the final design (Unit: MPa)

4 Conclusions

To compare and summarize the differences and commonalities between external prestressing technology and internal prestressing technology, it is necessary to carry out a comparative design. In design, the advantages of external prestressing technology were fully improved through optimization design. Feasibility design was performed to achieve the optimal configuration as much as possible and obtain the empirical values, and the requirements of local and construction design in the application of external prestressing technology were analyzed. The specific research contents include the following:

(1) Determination of comparative design schemes: In the selection of comparative projects, the differences and similarities were summarized through the design comparison of the left and right halves of the twin bridges;

(2) Feasibility design: Reasonable alignment and arrangement of internal tendons and reasonable number and arrangement of external tendons.

(3) Optimization design: Tendon type design: Adjustment of internal tendons (optimization of quantity), alignment of internal tendons (adjustment downward-bending and flat bending of tendons, and capped rebars), alignment and number of external tendons (segmentation, continuity, combination, number), and spare tendon settings;

(4) Structural and local design of external tendons: steering, anchoring, shock isolation, construction, etc., and material and anti-corrosion treatment required by external tendon characteristics.

Based on the above reinforcement methods, the authors designed the Xintan Bridge. As a continuous rigid-frame bridge with the largest span in China at the time, the Xintan Bridge is still in good condition after many years of normal operation, which proves that the relevant conclusions are correct and reasonable.

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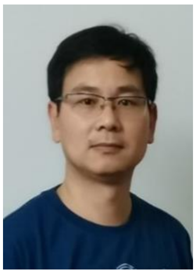
	**Zhichao Wang** B.E, Engineer. Tongji University Architectural Design (Group) Co., LTD. Research Direction: Prestress Technology. Email: dutwzc@163.com		**Fangyuan Li** Ph. D., Professor, Department of Bridge Engineering, Tongji University. Research Direction: Bridge Engineering, 3D Print and New Material New Technology. Email: fyli@tongji.edu.cn