Optimization of Suspender Tension Scheme of Cast-in-Situ Tied Arch Bridge with Support

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Abstract: The suspender tension sequence and construction cable force of tied arch bridges have a greater impact on the internal force and deformation of the structure. In order to obtain a reasonable suspender tension plan, make sure that the internal force of the structure meets the specific requirements and is evenly distributed during the construction process to avoid the excessive internal force mutation, seven suspender tension schemes were proposed. Combined with the example of a half-through concrete-filled steel tube tied arch bridge project, this scheme introduces the "kurtosis coefficient" evaluation index, and compares and analyzes the changes in the internal force of the structure under different suspender tension schemes. In this paper, the pros and cons of each scheme/part were also discussed. The results show that the difference between the internal force of the bridge and the cable force during the bridge completion stage of each scheme is relatively small, which has a greater impact on the internal force of the bridge during the construction phase. Among them, the symmetrical sequential tension scheme is convenient for construction, but the local position (such as arch foot, arch top, 1/4 arch rib) the internal force changes obviously, and there will be a large peak value, which will affect the safety of the structure during the construction process; the symmetrical interval tension plan can improve the structural force condition and reduce the internal force peak value, but the overall trend is basically unchanged; the internal force distribution of the symmetrical alternating tensioning scheme is uniform, without major sudden changes, and no obvious peaks, so that the safety of the bridge construction process is more guaranteed.

1. Introduction
The concrete-filled steel tube tied arch bridge is widely used. The tied beam (main longitudinal beam) can bear the horizontal thrust of the arch foot and is suitable for various geological conditions. This kind of arch bridge is an externally statically indeterminate and internally indeterminate system [1]. During construction, the tension sequence and cable force of the suspender will have varying degrees of influence on the internal force distribution and magnitude of the structure [2]. In addition, studies have shown that the most unfavorable state of structural forces in actual engineering does not necessarily appear in the operation stage, and the controlling mechanical state often appears in the construction process [3]. The installation and tensioning of the suspender are key link in the construction of a tied arch bridge. The excessive local stress caused by the unreasonable suspender tensioning scheme will bring safety hazards to the construction and affect the safety of the structure after the completion of the bridge [4].

Based on this, this article combined engineering examples to propose seven different suspender tensioning schemes for cast-in-place tied arch bridges with supports, and introduced the "Kurtosis Coefficient" evaluation index to quantitatively evaluate the pros and cons of the schemes. By comparing
and analyzing the internal force state of the structure during construction and after completion of the bridge, a relatively optimal suspender tension plan and construction cable force were expected to obtain.

2. Project examples

2.1. Project overview

The Lushui River Bridge in Anfu County is located in the northwest area of the city. The upper part adopts a mid-through tied arch structure. The main bridge has a total length of 156m and a combined span of (28+100+28) m. The overall layout of the bridge is shown in Figure 1. The upper arch rib is made of steel tube concrete, the lower arch rib is made of reinforced concrete, the main arch is made of Q345qD steel, and C50 shrinkage compensation concrete is poured into the pipe.

The upper part of the bridge deck is a dumbbell-shaped section, and below part of the bridge deck is a rectangular solid section. The arch rib is 3.0m high and 1.8m wide. The collar beam has a rectangular cross-section and adopts a C55 prestressed concrete structure with a height of 2.2m and a width of 2.0m. The suspenders are all made of 37-Φ15.2 steel stranded wire, with a distance of 4.5m~5.0m, a total of 32 (16 pairs).

![Figure 1. The layout of the main bridge of the Lushui River Bridge Unit (cm)](image)

2.2. Full bridge finite element model

MIDAS Civil was used to establish a finite element model of the full bridge, and the construction phase was simulated according to the construction process. The full bridge has a total of 2522 units and 2514 nodes. The steel tube arch rib is simulated by the joint section of construction, the suspender is simulated by a truss element only under tension, the beam, concrete arch rib and substructure are all simulated by beam element, and the support system is simulated by elastic connection only under compression. The pile-soil section is simulated by soil spring.

3. Suspender tensioning plans

3.1. Stretching sequence of suspender

When the steel tube arch bridge is constructed by the cantilever method, the slings are generally stretched sequentially from the arch foot to the middle of the span. However, this bridge uses the bracket method to construct the main girder. The suspender tensioning sequence can be comprehensively selected according to the internal force, deformation, and construction convenience, etc. of the main arch and main beam. The suspender tensioning plan is mainly composed of two factors, the tension sequence and the tension control force [5]. In order to determine the reasonable suspender tensioning plan of this type of bridge, this paper proposes 7 types of suspender tensioning construction plans. The suspender numbers are shown in Figure 1. It is agreed that the horizontal bridges will be constructed at the same time with the same number of suspenders.
Table 1. Suspender tensioning sequence under different schemes

| Construction stage | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 5 | Scheme 6 | Scheme 7 |
|--------------------|---------|---------|---------|---------|---------|---------|---------|
| S1                 | D1      | D8      | D4      | D1      | D8      | D4      | D4      |
| S2                 | D2      | D7      | D5      | D3      | D6      | D1      | D2      |
| S3                 | D3      | D6      | D3      | D5      | D4      | D7      | D6      |
| S4                 | D4      | D5      | D6      | D7      | D2      | D2      | D5      |
| S5                 | D5      | D4      | D2      | D2      | D7      | D6      | D3      |
| S6                 | D6      | D3      | D7      | D4      | D5      | D3      | D7      |
| S7                 | D7      | D2      | D1      | D6      | D3      | D5      | D1      |
| S8                 | D8      | D1      | D8      | D8      | D1      | D8      | D8      |

3.2. Calculation of tension control force of suspender

The bridge cable force is a target cable force, which is the prerequisite for determining the suspension rod tension control force. When the suspension rod construction sequence is determined, the corresponding suspension rod tension control force should be calculated to ensure that the suspension rod cable force can reach the target cable force.

Usually following methods are used to determine the reasonable state of the bridge: unconstrained cable force optimization, constrained cable force optimization, and influence matrix method [6-7]. Among them, the influence matrix method is mostly used for secondary cable adjustment, and the representative of the unconstrained cable force optimization method is the minimum bending energy method and the minimum bending moment method. In this paper, the minimum bending energy method is used to determine the bridge cable force. The minimum bending energy method is used to minimize the bending strain energy of the structure by adjusting the suspender cable force. At this time, the suspender cable force is the target cable force in a reasonable bridge state. The implementation of MIDAS Civil is as follows: amplify the axial stiffness of the tie beam, main arch, and suspender (usually by $10^4$ times), and perform a bridge calculation. Now, the value of the suspender cable force is the desired target cable force.

After the target cable force value is determined, the inverted disassembly method and the forward installation iterative method can be used to solve the construction cable force [8]. The inverted disassembly method is simple in thinking, unable to consider time parameters, and cannot calculate the time effects of materials such as shrinkage and creep, but it can be completed by only one calculation; the formal installation method requires iteration, the calculation cost is high, and the result is relatively reliable. This paper adopts the formal installation iteration method.

4. Results and analysis

4.1. Tension control force of suspender

According to the minimum bending energy method and the forward installation iterative method, the target suspender cable force and suspender tension control force are shown in Table 2.

Table 2. Suspender tension control force under different tension schemes

| Suspender number | Target cable force of suspender/kN | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 5 | Scheme 6 | Scheme 7 |
|------------------|-----------------------------------|---------|---------|---------|---------|---------|---------|---------|
| D1               | 970                               | 1105    | 915     | 870     | 1130    | 905     | 1000    | 865     |
| D2               | 950                               | 870     | 860     | 705     | 765     | 1010    | 855     | 830     |
| D3               | 925                               | 710     | 860     | 675     | 905     | 700     | 655     | 570     |
| D4               | 995                               | 745     | 930     | 1095    | 680     | 1050    | 1065    | 1080    |
| D5               | 980                               | 775     | 885     | 960     | 995     | 675     | 640     | 770     |
The following conclusions can be drawn from the results in Table 2.

1. Even if the target cable force is the same, there are still quite differences in the suspender cable force during the construction process with different suspender tensioning schemes. For example, the suspender D1 in scheme 1 and scheme 3, when the target cable forces is 970kN, the suspender tension control forces are 1105kN and 870kN respectively.

2. The suspender tension control force in scheme 1 (stretching the suspender symmetrically from the spandrel to the vault) varies greatly (1105kN at the maximum, 560kN at the minimum and 790kN on average). The tension control force of the suspender in scheme 2 (stretching the suspender symmetrically from the vault to the spandrel) is relatively uniform (915kN at the maximum, 735kN at the minimum and 860kN on average). The specification and sling model of the suspender tension equipment can be relatively uniform. The rules of symmetrical interval tension and symmetrical alternate tension scheme (scheme 4-7) are consistent with symmetrical sequence tension scheme, that is, the tension control force of suspender is more uniform under the scheme stretching the suspender symmetrically from the spandrel to the vault.

3. Comparing sequential tensioning suspender (scheme 1 ~ scheme 3) and interval tensioning suspender (scheme 4-7), it can be seen that the tension control force of suspender in interval tensioning suspender scheme is more discrete. Combined with suspender tension sequence, the construction convenience of interval tensioning suspender scheme is less than sequential tensioning suspender scheme.

4.2. Structural internal force during construction

The bridge is constructed by bracket method, and the collar beam bracket is removed after the suspender is tensioned. In the process of suspender tensioning, the change of internal force and displacement of collar beam is not obvious, but it has a great impact on the internal force of main arch. Then, the internal force of arch rib in the construction process is compared and analyzed.

4.2.1. Internal force envelope of steel tube arch rib. In each construction scheme, the envelope of the maximum and minimum bending moment at each longitudinal bridge position of the steel tube arch rib in the construction process were shown in Figure 2 and Figure 3.
According to the results of Figure 2 and Figure 3, it can be concluded that.

1) Symmetrical sequential tensioning of the suspender is likely to cause local stress to be too large, and sequential tensioning from the spandrel to the vault (scheme 1) is likely to cause the tensile stress on the upper edge of the spandrel to be too large (the minimum bending moment at spandrel in scheme 1 is -10365.96 kN.m); sequential tensioning from the vault to the spandrel (scheme 2) tends to cause greater tensile stress on the lower edge of the vault (the maximum bending moment at the position of...
vault in the scheme 2 is 5635.99 kN.m); sequential tensioning from 1/4 arch rib to spandrel and vault (scheme 3) tends to cause greater tensile stress at the lower edge of the 1/4 arch rib (the maximum bending moment at the 1/4 arch rib in scheme 3 is 4771.06 kN.m).

2) Comparing the symmetrical interval tensioning suspender scheme with the sequential tensioning scheme, the internal force of the local position caused by the interval tensioning scheme is smaller than that of the sequential stretching scheme. For example, from the spandrel to the vault, the maximum bending moments generated at the spandrel are -10365.96 kN.m and -8313.95 kN.m respectively. This shows that stretching the suspenders at intervals is better than stretching the suspenders in sequence.

3) Comparing the maximum bending moment envelope diagrams of the arch ribs under seven different suspender tensioning schemes, it is better to stretch the suspender from the 1/4 arch rib than the other two methods (tension from the spandrel and from the vault), especially under the suspender tensioning sequence of Scheme 7, the maximum and minimum bending moments of the steel pipe arch ribs are more stable and even.

4.2.2 Changes in internal force at key section positions of steel tube arch ribs. Take the structural internal force changes at the three key sections of the arch foot, 1/4 arch rib and dome for analysis. The internal force changes at the key sections under seven different schemes are shown in Figure 4, 5, and 6. Introduce the kurtosis coefficient $K$ [9] to quantitatively evaluate the uniformity of the internal force of the structure during the construction of different suspender tensioning schemes (the larger the kurtosis coefficient, the more uneven the internal force distribution of the structure, and vice versa). The definition of kurtosis coefficient $K$ is as follows.

$$K = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^4 \left(\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{-3}$$

where $x_i$ represents the bending moment at any section of the steel pipe arch rib, $\bar{x}$ represents the average value, and $n$ represents the number of sections when dividing the unit. The kurtosis coefficient changes under different schemes are shown in Figure 7.
The construction phases S1–S8 in Figure 4–7 respectively represent the various phases of successively stretching the suspender. S9 and S10 represent the phase of removing the collar beam bracket and the completion of the bridge considering shrinkage and creep. It can be seen from Figure 4–7.

(1) There is "convergence" in the suspender tensioning schemes. When the state of the bridge is determined, the sequence of tensioning will not affect the internal forces of the structure after completion of the bridge. After the last suspender of each scheme is tensioned, the internal force state of the whole bridge will tend to be consistent. However, the tension control force of the suspender varies by 23% under different tensioning schemes, such as D1 suspender in scheme 4 and scheme 7.

(2) The changes of internal forces of the structure under the sequentially tensioning scheme (scheme 1 ~ 3) show the characteristics of "continuity", while the interval tensioning scheme shows the characteristics of "reciprocity". For example, the bending moment at the spandrel in scheme 1 (sequentially stretch the suspender from the spandrel to the vault) increases continuously from -5597.18kN.m in stage S1 to -10365.96kN.m in stage S4, and then continues to decrease to the target state. Such internal force change is obviously disadvantageous to the structure.

(3) Combining figure 4–6 and figure 7, the internal force of interval tensioning of the suspenders is more uniform than the sequential tensioning of the suspenders. Especially in the seventh plan, the internal force changes in spandrel, 1/4 arch rib and vault are small without sudden changes, and the internal force distribution of the steel pipe arch rib is also relatively uniform. The variation of the internal force kurtosis coefficient of the steel tube arch rib in scheme 7 is between -1.13 and 0.1 during the S1~S6 stage.

5. Conclusion
This paper takes the concrete-filled steel tube tied arch bridge as the research target, compared and analyzed the tension control force under each tension scheme and the structural internal force during the construction phase. The following can be obtained in conclusion.

(1) Different suspender tensioning schemes have "convergence", that is, when the target bridge state is determined, the corresponding construction cable force is used for tensioning. The tension sequence does not affect the internal force of the bridge, but due to the suspender tensioning force of different schemes, it can be seen that the difference is quite big.

(2) From the analysis of construction convenience, the symmetrical sequential stretching of the suspender is better than the symmetrical interval stretching. Among them, the suspender is stretched sequentially from the vault to the spandrel without moving the stretching equipment back and forth, and

![Figure 6. Structural internal force change diagram at 1/4 arch rib](image)

![Figure 7. Variation of kurtosis coefficient of each scheme](image)
the tension control of the suspender is also relatively uniform.

(3) From the analysis of structural forces, symmetrical and sequential tensioning of the suspenders can easily cause excessive internal forces at local locations (spandrel, vault, 1/4 arch rib), such as sequential tensioning of the suspenders from the spandrel to the vault can easily cause the internal force at the spandrel to be too large. Then the symmetrical interval tensioning of the suspender will slightly improve the structural force, but the overall trend remains the same.

(4) Analyzed from the internal force distribution, the internal force of the structure generated by the interval tensioning of the suspender rod is more uniform than that of the sequential tensioning of the suspender, especially under the symmetrical alternating tensioning suspender scheme, the internal force of the structure is evenly distributed during the construction process, and no mutation is generated. The change is conducive to the structural stress and the safety of the bridge under construction.

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