Study on Asymmetric Closure Scheme of Rigid Frame-Continuous Beam Composite System Bridge

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Abstract. The rigid frame-continuous beam composite system bridge has many spans, and the pier layout is different, and the demolition of temporary anchorage of pier and beam needs to undergo system transformation. Therefore, different closure sequence and the demolition time of temporary anchorage of pier and beam will have certain influence on the internal force and alignment of the main girder after completion of the bridge. Based on the practical engineering of the rigid frame-continuous beam composite system bridge constructed by asymmetric closure, four closure schemes were designed from two aspects: asymmetric closure sequence and temporary anchorage and demolition sequence. Based on the finite element model, the internal force and alignment of the main girder of the four closure schemes were compared and analyzed, and the general rules of closure of this type of bridge construction were summarized. The analysis and comparison results showed that the internal forces of the main girders are basically the same with different closure schemes, and the final linear shape of the main girders is different with different closure sequence. The results of this study can provide technical reference for similar bridge construction decision-making and closure scheme determination.

1. Introduction
The rigid frame-continuous beam composite system bridge is a complex statically indeterminate structure with partial pier and beam are connected by support and partial pier and beam are anchored. It takes into account the advantages of continuous beam bridges and continuous rigid frame bridges in terms of structural stress and applicability. In recent years, It is favored by bridge engineers [1-2]. Because the bridge span, the number of spans, and the form of the cross section of the main beam are different, the arrangement of the piers of the rigid frame bridge section and the continuous beam section are generally different. The bridge closure schemes in actual projects are also different. Different closure sequence and the demolition time of temporary anchorage of pier and beam will affect the structure after completion of the bridge, and will affect the internal force, linear shape and subsequent redistribution of internal forces of the main beam[3]. In recent years, many experts and scholars have studied the construction closure of multi-span bridges and achieved some results[4-9]. Studies at home and abroad show that different bridges should choose a suitable closure scheme for the bridge according to their own structural characteristics. Therefore, it is of great engineering application value to find the optimal closure scheme to guide the construction decision of the main beam closure stage.

Taking a six-span asymmetric closure rigid frame-continuous beam composite bridge as the engineering background, This paper proposes another closure sequence based on this asymmetrical closure, by changing the order of tensioning the pre-stressing tendon and releasing the temporary anchorage, four closure schemes were designed. The finite element software Midas/Civil is used to carry
out construction simulation, by analyzing and comparing the effects of the four types of closure schemes on the deformation of the main beam, the most reasonable closure scheme is determined to provide a reference for the selection of the closure sequence of such bridges.

2. Calculation model

2.1. Project overview

The layout of the main bridge of a six-span rigid frame-continuous beam composite bridge is (82.68m +4×152m+82.80m). The elevation of the main bridge is shown in Figure 1. The upper part of the main bridge is a single-box single-cell section (see Figure 2), The top plate width is 15.75m, the bottom plate width is 8m, the flange plate cantilever length is 3.875m, and the beam height of the main pier root to the mid-span closing section adopts a 1.7 parabolic variation from 9.5 m to 3.4m high, Piers are in the form of rectangular hollow piers, numbered 8# ~14 #, where the 8 # pier is the pier at the junction of the main bridge and the approach bridge, the 14# pier is the main bridge splitting pier, and the 9 #, 12 #, 13 # pier are continuous pier with steel ball surpport, 10 # and 11 # are rigid frame pier anchored with main beam. The main bridge box girder adopts the double cantilever hanging basket symmetrical beam cast-in-place construction method.

![Figure 1. Elevation drawing of main bridge (unit: cm).](image)

![Figure 2. Cross-sectional drawing of main girder (unit: cm).](image)

| Strength grade | Elastic modulus (MPa) | Bulk density (KN·m⁻³) | Liner expansion coefficient | Standard value fₐ/MPa | Design value fₐ/MPa |
|---------------|----------------------|-----------------------|----------------------------|-----------------------|---------------------|
| C55           | 3.55e+04             | 26                    | 1.00e-05                   | 35.5                  | 2.74                |
| C40           | 3.25e+04             | 26                    | 1.00e-05                   | 26.8                  | 2.40                |

* The concrete bulk density has taken into account the effects of prestressed steel bundles, steel bars, tooth plates, anchors and other factors. The calculation parameters of concrete shrinkage and creep are based on Reference 11[11].
2.2. Materials and calculation parameters

Parameters:

(1) Concrete: The cast-in-place box girder is made of C55 concrete, and the pier body is made of C40 concrete. See Table 1 for specific materials and calculation parameters.

(2) Prestressed steel: The national standard GB / T 5224-2014 high-strength low-relaxation steel stranded wire is used. The standard values of tensile strength is $f_{pk}=1860$MPa, elastic modulus is $E_y=1.95\times10^5$MPa, relaxation coefficient is $\xi=0.3$, The Finished deformed bar’s elastic modulus is $E_s=2.0\times10^5$MPa, and the relaxation rate is $\rho=0.035$.

2.3. Establishment of finite element model

The finite element model was established using Midas / Civil. The whole bridge was separated into a total of 276 units and the lower pier was a total of 50 units. In the treatment of the boundary of each pier bottom, consolidation constraints are adopted at the pier bottom. Each rigid frame pier and the main beam are rigidly connected in elastic connection, each continuous pier and the main beam are hinged, the continuous pier and the main beam are temporarily consolidated before closure, and vertical displacement hinge constraints are used after closure. The Midas / Civil finite element model is shown in Figure 3.

![Figure 3. Midas/Civil finite element model.](image)

2.4. Super-structure construction sequence

The main beam adopts double cantilever hanging basket symmetrical beam-by-beam construction. The main construction sequence of the superstructure is as follows:

(1) Block 0 construction: No. 0 block is poured on the bridge pier; after the concrete reaches 90% of the design strength, tension the corresponding pre-stressing tendon of the roof and web; Temporarily anchor the No.9, No.12, No.13 piers.

(2) Hanging basket cast-in-cantilever construction: Move the hanging basket forward → Set up the mold and bind the steel bars → Cast the No.n beam segment concrete symmetrically from block 0 to both sides in proper sequence → After the concrete reaches 90% of the design strength, tension the corresponding roof and web prestressed steel beam → Grouting → Move the hanging basket forward.

(3) Construction of the closure section.

(4) Remove the full bridge hanging basket.

(5) Bridge deck system construction.

2.5. Research on main beam closure Scheme

Put forward the following four schemes for comparative analysis. Based on the two closing sequences, change the order of tensioning the pre-stressed steel bundles in the closure section and the removal of the temporary anchoring of closure section. The construction procedures of specific scheme are as follows:

Scheme I: No.3 closure section → Tension prestressed steel bundle of No.3 closure section→ No.2, No.4 closure section → Tension the longitudinal pre-stressing tendon on the top and bottom of the No.2 and No.4 closure sections → Release the temporary anchorage of the No.9 and No.12 pier→ No.1, No.6 closure section→ Tension the longitudinal pre-stressing tendon on the top and bottom of the No.1 and No.6 closure sections → Release the temporary anchorage of the No.8 and No.14 pier→ No.5 closure section→ Tension the longitudinal pre-stressing tendon on the top and bottom of the No.5 closure sections→ then release the temporary anchorage of the No.13 pier.
Scheme II: Keep the same closing sequence as in Scheme I. When construction is carried out on No.1, No.2, No.4, No.5, No.6 closure sections, change the order of tensioning the pre-stressed steel bundles in the closure section and the removal of the temporary anchoring of closure section.

Scheme III: No.2, No.3 closure section → Tension the longitudinal pre-stressing tendon on the top and bottom of the No.2 and No.3 closure sections → Release the temporary anchorage of the No.9 pier → No.4, No.5 closure section → Tension the longitudinal pre-stressing tendon on the top and bottom of the No.4 and No.5 closure sections → Release the temporary anchorage of the No.12 and No.13 pier → No.1, No.6 closure section → Tension the longitudinal pre-stressing tendon on the top and bottom of the No.1 and No.6 closure sections → Release the temporary anchorage of the No.8 and No.14 pier.

Scheme IV: Keep the same closing sequence as in Scheme III. When construction is carried out on No.1, No.2, No.4, No.5, No.6 closure sections, change the order of tensioning the pre-stressed steel bundles in the closure section and the removal of the temporary anchoring of closure section.

3. Influence of different closure schemes on the force of the main beam

3.1. The influence of different closure schemes on the stress of the main beam

After the four schemes of the full bridge are folded and the second-phase dead load construction is completed, extract the stress values of the upper and lower flanges of all nodes of the main beam under the serviceability limit state (frequency combination), and draw the stress curve shown in Figure 4.

![Stress Curve](image)

(a) Upper flange compressive stress of main girder. (b) Lower flange compressive stress of main girder.

Figure 4. Compressive stress curve of upper and lower flanges of main girder (full bridge).

Analysis of Figure 4 shows: (1) The variation law of the stress on the upper and lower flanges of the main beam caused by the four closure schemes is almost the same, and they are all compressive stress. The maximum compressive stress on the upper flange of the main beam appears on the cantilever root section of each pier corresponding to the main beam, and decreases gradually to the side span and the mid-span closure section, and the minimum compressive stress appears on the mid-span closure section; The stress of the lower flange of the main beam varies greatly, but all are compressive stress reserves, and the locations of the stress extremes appear at the same place, the maximum extremes appear near the cross section of the L/4 or 3L/4 beams, the minimum extremes appear near the top of the pier and the mid-span closure section. (2) It can be known that Compressive stress curve of upper and lower flanges of main girder in schemes I and II are basically the same, and schemes III and IV are basically the same. According to the stress curve diagram, the closure sequence has a greater impact on the stress levels of the upper and lower flanges of the main beam. However, the stress differences of the flanges of the four schemes on the main beams of the corresponding spans are less than 0.88 MPa, the stress difference between the lower flanges of the main beams of the corresponding spans has the largest difference in the closure section of the fourth midspan, but it is only 1.4 MPa.

The calculation results show that the stress of the upper and lower flanges of the cross-section of the main beam of the four closure schemes are all compressive stress reserves, the extreme points of the
stress curve are close, and the difference between the stress values is small. Therefore, different closure schemes have no significant effect on the stress level of the bridge girder. The stress level of the cross-section of the girder mainly depends on the structural characteristics of the bridge.

3.2. Influence of Different Closure Schemes on Internal Forces of Piers

See Tables 2 for the bending moments and reactions at the bottom of the pier of No.9 ~ No.13 when the bridge is completed and ten years after completion.

| Position | Scheme I | Scheme II | Scheme III | Scheme IV |
|----------|----------|-----------|------------|-----------|
|          | Postcs   | Ten years later | Postcs | Ten years later | Postcs | Ten years later | Postcs | Ten years later |
| 9#       | 0        | 0          | 0          | 0          | 0        | 0          | 0        | 0          |
| 10#      | 1.92e+04 | 3.75e+04  | 1.88e+04  | 3.73e+04  | 2.76e+04 | 4.48e+04  | 2.76e+04 | 4.42e+04  |
| 11#      | 1.51e+04 | 3.69e+04  | 1.48e+04  | 3.66e+04  | 1.86e+04 | 3.91e+04  | 1.82e+04 | 3.80e+04  |
| 12#      | 0        | 0          | 0          | 0          | 0        | 0          | 0        | 0          |
| 13#      | 0        | 0          | 0          | 0          | 0        | 0          | 0        | 0          |

By comparing and analyzing the data in Table 2, we can see that: (1) The influence of the four closure schemes on the bending moment at the bottom of the pier is basically the same. The maximum negative bending moment at the bottom of the pier appears at the No.10 pier, and the maximum positive bending moment at the bottom of the pier appears at the No.11 pier. The bottom bending moments of the remaining piers are zero. (2) The construction order of tensioning the pre-stressed steel bars and releasing the temporary anchorage has a small influence on the bending moment at the bottom of the pier constructed in the same closure sequence, however, the sequence of closure has a greater effect on the bending moment at the bottom of pier, four schemes under the second-stage dead load in the Postcs phase, bending moment at the bottom of the No.10 pier scheme II decreased by 2.1% compared to scheme I, schemes III and IV increased by 43.8% and 43.8% respectively compared to scheme I; Under the second-stage dead load in the Postcs phase, bending moment at the bottom of the No.11 pier scheme II decreased by 2.0% compared to scheme I, schemes III and IV increased by 23.2% and 20.5% respectively compared to scheme I. But the effect of the sequence of tensioning the prestressed steel beams and releasing the temporary anchorage 10 years after the completion of the bridge on the bending moment at the bottom of the pier constructed in the same closure sequence is significantly reduced, however, the sequence of closure has a greater effect on the bending moment at the bottom of pier. (3) In comparison, schemes I and II have smaller bending moments at the bottom of the pier than schemes III and IV, and their forces are more reasonable.

4. Influence of different closure schemes on the linear shape of the main beam

4.1. Influence of different closure schemes on horizontal displacement of pier top

When the bridge was built and ten years after the bridge was built the absolute values of the horizontal displacements of the control points of the main beams corresponding to the tops of the No.9 ~ No.13 pier are shown in Table 3.

| Position | Scheme I | Scheme II | Scheme III | Scheme IV |
|----------|----------|-----------|------------|-----------|
|          | Postcs   | Ten years later | Postcs | Ten years later | Postcs | Ten years later | Postcs | Ten years later |
| 8#       | 1.53     | 8.32      | 1.52       | 7.93      | 0.83     | 7.56      | 0.77     | 7.34      |
| 9#       | 4.01     | 9.10      | 4.21       | 9.01      | 5.75     | 10.78     | 5.87     | 10.78     |
| 10#      | 1.10     | 2.80      | 1.21       | 2.82      | 1.81     | 3.49      | 1.85     | 3.49      |
| 11#      | 0.57     | 2.41      | 0.68       | 2.38      | 0.20     | 1.64      | 0.22     | 1.55      |
As can be seen from Table 3: (1) The variations of the horizontal displacement of the pier tops of the four schemes when the bridge was built and ten years after the bridge was built are basically consistent. Ten years after the completion of the bridge, the horizontal displacement is significantly larger than when the bridge was completed. The No.11 pier top has the smallest horizontal displacement, followed by the No.10 pier, and the other piers top have larger horizontal displacements, the No.10 and No.11 pier are rigid frame pier, which can better limit the horizontal displacement of the pier top. (2) The construction order of tensioning the pre-stressed steel bars and releasing the temporary anchorage has a small influence on the horizontal displacement of main beam constructed in the same closure sequence, however, the sequence of closure has a greater effect on the horizontal displacement of main beam. Scheme III and IV have larger horizontal displacements at other piers except for No.11 piers compared to scheme I and II. According to the construction sequence of releasing the temporary anchorage after tensioning pre-stressing tendon, scheme III is increased by 1.73cm (No.9 Pier) and reduced by 0.37cm (No.11 Pier) compared to scheme I, according to the construction sequence of tensioning pre-stressing tendon after releasing the temporary anchorage, scheme IV is increased by 1.66cm (No.9 Pier) and reduced by 0.45cm (No.11 Pier) compared to scheme II. It can be seen that the closure sequence of scheme I and II is more conducive to controlling the horizontal displacement of the pier top.

4.2. Influence of different closure schemes on vertical displacement of main beam

The vertical displacement maps of all nodes and the maximum vertical displacement values of each span of the main beam after completion of the bridge are shown in Figure 5. The directions are positive upward and negative downward.

![Figure 5. The vertical displacement of the main girder in the Postcs.](image)

From Figure 5: (1) The law of the deflection curve of the main beam is: The maximum cumulative vertical upward displacement of the main beam appears at the closure section of each span, the cumulative vertical downward displacement of the main beam reached the maximum at the closure section of both sides of the span, and the vertical displacements on both sides of each pier showed "M"-shaped downward displacement. (2) Scheme I and II except for the vertical displacement of the fifth span is large, and the vertical deformation of other spans is more uniform, scheme I and III have greater up deflection values than those of schemes II and IV in the midspan closure section of most spans, and schemes I and III have lower maximum down deflections than most schemes II and IV in most spans. The construction sequence of tensioning the pre-stressing tendon before releasing the temporary anchorage is more reasonable. (3) The deflection curves of the first four spans of the four schemes are basically the same, the fifth and sixth spans are quite different, and the position where the maximum value appeared was inconsistent, the maximum vertical displacement value difference between Option III and Option I in the same location reached 111 mm (fifth span). The final linear shape of the bridge after closure will vary with the closure sequence, the vertical difference of the same position caused by
different closing orders cannot be ignored, and it will have an unadjustable effect on the elevation control when the main beam is closed. Therefore, once the full bridge closure sequence is determined, it should not be changed after construction.

5. Conclusion
This paper discusses the changes in the force and linear shape of the four closure schemes for a six-span pier type asymmetric rigid frame-continuous beam composite bridge after completion, it can be seen from the comparative analysis:

(1) The closure sequence has a greater impact on the bending moment of pier bottom, vertical displacement and horizontal displacement. However, the construction sequence of tensioning the pre-stressing tendon and releasing the temporary anchorage has little effect on the force and linear shape of the main beam after the bridge is completed. During construction, any scheme of removing the temporary anchorage can be adopted.

(2) From the force on the beam body, the four types of closure schemes caused the same change in the stress on the upper and lower flanges of the main beam and the internal force at the bottom of the pier. After the bridge is completed, the stress level of the main beam depends mainly on the characteristics of the structure itself. In comparison, the bending moments at the bottom of the pier in scheme I and II are smaller and the forces are more reasonable.

(3) Judging from the linear shape of the beam after the bridge is formed, the closure sequence of scheme I and II is more conducive to controlling the horizontal displacement of the pier top. However, the vertical displacement of scheme I is larger than that of scheme II on the mid-span closure section, and smaller than the maximum downward deflection value on both sides of the closure section. Therefore, scheme I was finally selected as the closure scheme.

(4) Different order of closure sequence will lead to inconsistency of the final linear shape after bridge formation, and the vertical difference at the same position cannot be ignored. Therefore, once the closure sequence of the whole bridge is determined, it should not be changed after construction.

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