Study on the Efficiency of Prestressing Application in Prestressed Composite Bridges

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Abstract. In order to study the proportion of prestressing between concrete slab and steel girder in different forms of prestressed composite bridges, this paper analysed the distribution of prestressing between concrete slab and steel girder when conventional prestressing method and post-tensioned prestressing method were used in the negative moment region respectively, against the background of a certain project. The results showed that 43.65% of the total prestressing applied by the conventional prestressing method was transferred to the steel girder, and nearly half of the prestressing tendons failed to reduce the tensile stresses in the concrete slab; the use of post-tensioned prestressing reduced the number of prestressing tendons by 65.6% relative to the traditional prestress application method.

Keywords. Composite bridges, prestress efficiency, post-tensioned prestress, FE analysis.

1. Introduction

The continuous composite bridges can be divided into positive moment region and negative moment region according to the stress condition in their service stage. The area around the middle support is in the negative region, in which case the concrete is easy to crack because of tensile stress and the bottom flange of steel girder is prone to buckle under compressive stress. At present, the main design methods to deal with the problem of concrete cracking in the negative moment zone are as the followings [1-3]: (1) allow the concrete of the deck slab to crack, but control the crack width within the allowable range by proper allocation of reinforcement; (2) do not allow the concrete to crack, and take corresponding measures to reduce the tensile stress of the concrete slab to prevent it from cracking [4-6].

Engineering practice shows that for continuous composite girder bridges with spans under 40 m, the method of controlling the crack width by appropriate reinforcement can achieve better economy; however, for continuous girder bridges with spans over 40 m, the method of controlling the crack width often requires larger concrete slabs and more steel reinforcement, therefore, its economy decreases with the increase of span. For continuous composite girder bridges with spans over 50 m, better economy is achieved by applying prestressing in the negative moment zone [7-8].

Post-tensioned prestressed steel-concrete composite bridge is a brand-new construction technology, thus there are few relevant engineering examples. Furthermore, the key technical research on design and construction is not yet mature, so it is necessary to study the relevant issues in its construction.
2. Engineering Background and Calculation Model

2.1. Engineering Background
The span of this composite bridge is 3×70 m, with the height of 4000 mm. As shown in figure 1, for concrete slab, it is 12500 mm wide, 280 mm thick between two steel girders, 200 mm and 500 mm thick at two cantilever ends respectively, and its cantilever length is 2150 mm. As for steel girder, the top flange and bottom flange are 1500 mm and 1600 mm wide respectively, with thickness varying from 40-50 mm and 50-70 mm respectively. Thickness of steel webs varies from 16-24 mm. An ordinary crossbeam is set at an interval of 7000 mm between two steel girders, and at each location of support a strengthened cross beam is applied.

![Figure 1. Cross section of composite bridge.](image)

2.2. Introduction to Finite Element Model
The Finite Element Method (FEM) was used to calculate the stress condition of this composite bridge. As shown in figure 2, the FEM of the continuous composite girder is built by simulating prestressing tendons with link elements, steel structure with shell elements, and concrete slab with solid elements. The transverse and longitudinal slopes of the bridge are not considered in this model. While the slip between the concrete slab and the steel top flange of the composite bridge slab were taken into account, and spring elements were built to simulate the studs. For each stud, simulated with two horizontal spring elements and one vertical spring element, the shear stiffness of a single stud is $4.13 \times 10^5$ kN/m and the pull-out stiffness is $2.50 \times 10^7$ kN/m according to the test.

![Figure 2. FEM of continuous composite bridge.](image)
To set up the boundary condition, solid elements were applied at the corresponding locations of the steel bottom supports to simulate the bearings. The axial stiffness of the solid elements was used to simulate the vertical stiffness of the bearing. For the simulated bearing solid elements, their faces share the same nodes with the lower flange of the steel bottom flange; nodes in the bottom face of the elements were constrained with the vertical freedom and the corresponding horizontal freedom as shown in figure 3.

![Diagram of bearings](image)

Figure 3. Layout of the bearings.

In order to facilitate the description of structural stress condition, the support and span of continuous composite bridge are numbered, and the illustration is shown in figure 4.

![Diagram of support and span](image)

Figure 4. Number of support and span.

2.3. Calculation Loads

According to General Specification for Design of Highway Bridges and Culverts (JTGD60-2015) [9] in China, the calculation loads are listed as following:

1. Dead load: the uniformly distributed load of railing at each side is 12 kN/m, and the pavement layer is calculated as 100 mm asphalt pavement.
2. Vehicle load: calculated according to highway class I lane load.
3. Differential settlement: \( L/3000 \text{ mm}=7000/3000 \text{ mm}=23.3 \text{ mm} \), where \( L \) equals to the length of single span.
4. Temperature load: the highest and lowest overall temperature variations are 20 ℃ and -20 ℃ respectively; gradient temperature increases from 5.5 to 14 ℃ while drops from -7 to -2.75 ℃.
5. Shrinkage and creep: the concrete is loaded from 6 months; the shrinkage and creep effect at 10 years is calculated.

2.4. Construction Procedure

The two different methods for prestressing application correspond to different construction steps which are shown in table 1.
Table 1. Construction procedure.

| Construction stage | Traditional prestressed composite bridge | Post-tensioned prestressed composite bridge |
|--------------------|-------------------------------------------|---------------------------------------------|
| Stage 1            | Incrementally launching steel girder      | Incrementally launching steel girder        |
| Stage 2            | Laying of precast concrete slab            | Laying of precast concrete slab              |
| Stage 3            | Forming composite section in positive moment region | Forming composite section in positive moment region |
| Stage 4            | Forming composite section in negative moment region | Tensioning prestressed steel strand in negative moment region |
| Stage 5            | Dropping back 20 cm at support II and III  | Forming composite section in negative moment region |
| Stage 6            | Tensioning prestressed steel strand        | Dropping back 20 cm at support II and III    |
| Stage 7            | Construction of pavement and ancillary facility | Construction of pavement and ancillary facility |

3. Calculation Results

3.1. Calculation Section

In terms of concrete slab, the negative moment zone is mainly considered. One section in longitudinal direction (location of support II), five sections in transversal direction is monitored, which are shown in figure 5. The longitudinal stress under combination (including fundamental combination of actions, frequent combination of actions, quasi-permanent combination of actions) at the above selected point and width of crack are calculated on the basis of Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG 3362-2018) [10]. As for steel girder, 3 sections are considered in the longitudinal direction, which are midspan of span I and span II and support II. For each location at the selected section, 3 section in the transversal location are monitored as shown in figure 5.

![Figure 5. Monitoring point in transversal direction](image)

3.2. Static Behavior of Traditional Prestressed Composite Bridge

A total of 288 prestressing tendons with diameter of 15 mm were used in traditional prestressed composite bridge, including 48 prestressing tendons each of 158 m, 144 m, 130 m, 116 m, 32 m and 18 m in length, for a total length of 28,704 m.

Considering the action of dead load, settlement, prestress, vehicle load, temperature, shrinkage and creep, the width of crack and stress condition at 10th year are shown in table 2. It’s obvious that under
frequent combination of actions and quasi-permanent combination of actions, both top face and bottom face of concrete slab are in tensile stress. The maximum tensile stress occurred on the top face at the location of F, which is 2.16 MPa, and the corresponding crack width is 0.08 mm less than 0.1 mm. Therefore, crack width meets the Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTJ D362-2018).

Table 2. Longitudinal stress and crack width of concrete in negative moment region.

| Transversal location |  | Fundamental combination of actions (MPa) | Frequent combination of actions (MPa) | Quasi-permanent combination of actions (MPa) | Crack width (mm) |
|----------------------|----------------|--------------------------------------|--------------------------------------|---------------------------------------------|------------------|
|                      | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | |
| D                    | 2.83 | -0.95 | 1.16 | -1.06 | 0.61 | -1.38 | 0.03 |
| E                    | 3.39 | -1.18 | 1.46 | -1.18 | 0.86 | -1.47 | 0.05 |
| F                    | 4.88 | -2.45 | 2.16 | -1.63 | 1.39 | -1.75 | 0.08 |
| G                    | 2.56 | -1.60 | 0.88 | -1.44 | 0.32 | -1.71 | 0.03 |
| H                    | 1.78 | -1.96 | 0.49 | -1.63 | 0.01 | -1.87 | 0.01 |

In terms of steel girder, as shown in table 3, under fundamental combination of actions, at the location of midspan in span I the minimum compressive stress of top plate is -215.7 MPa, the maximum tensile stress of bottom plate is 184.2 MPa; at the location of midspan in span II, the minimum compressive stress of top plate is 135.0 MPa, the maximum tensile stress of bottom plate is 113.1 MPa; at the section of support II, the maximum tensile stress of top plate is 157.9 MPa, the minimum compressive stress of bottom plate is -276.4 MPa.

Table 3. Longitudinal stress of steel under fundamental combination of actions.

| Longitudinal location | Location A (MPa) | Location B (MPa) | Location C (MPa) |
|-----------------------|------------------|------------------|------------------|
|                       | Top | Bottom | Top | Bottom | Top | Bottom | |
| Midspan of span I     | -206.3 | 178.8 | -161.6 | 167.7 | -215.7 | 184.2 |
| Midspan of span II    | -126.5 | 108.1 | -88.9 | 99.4 | -135.0 | 113.1 |
| Support II            | 157.9 | -186.7 | 140.7 | -276.4 | 155.6 | -190.4 |

3.3. Static Behavior of Post-Tensioned Prestressed Composite Bridge

In the case of post-tensioned prestressed composite bridge, a total of 260 prestressing tendons with diameter of 15 mm were used, including 160 with a length of 24.5 m and 100 with a length of 59.5 m, for a total of 9870 m.

By extracting the relevant results at support II, it shows that the total prestress is 37952.1 kN, while the prestress in concrete is 21386.1 kN, i.e., 43.65% of the prestress is transferred to steel girder. Therefore, a post-tensioned prestressing method is considered to reduce cracking of concrete slab which can fully improve the efficiency of the use of prestress and reduce the number of prestressing tendons.

In the case where prestress is not taken into account, the stress condition of composite bridge is calculated and the crack width of concrete in the negative moment region is obtained, so as to calculate the reasonable application range of prestress strand. In the longitudinal direction from midspan of span I (0.55L, where L is the length of single span) to midspan of span II (1.5L), 20 sections (1 section for every 3.5 m interval) are extracted. In the transversal direction, selected sections are shown in figure 5. The width of crack is calculated on the basis of Code for Design of Highway reinforced concrete and prestressed concrete bridges and culverts (JTJ D62-2018) as shown table 4.

The results in table 4 show that the crack width is over 0.1 mm from 0.65 L to 1.5 L. Consequently, the prestress should be applied between 0.65 L to 1.5 L in concrete to control the width of crack. After the prestressing force is applied, the crack width is shown in table 5, from which it is clear that the
maximum crack width is 0.076 mm, far less than 0.1 mm, and the crack width at support II is 0.058 mm.

Table 4. Longitudinal crack width of concrete without prestress.

| Longitudinal location (L = 70 m) | Transversal location (crack width: mm) | D  | E  | F  | G  | H  |
|----------------------------------|----------------------------------------|----|----|----|----|----|
| 0.55L ^b                         |                                        | 0.006 | 0.009 | 0.037 | 0.065 | 0.062 |
| 0.6L                             |                                        | 0.028 | 0.037 | 0.064 | 0.043 | 0.045 |
| 0.65L                            |                                        | 0.037 | 0.058 | 0.087 | 0.063 | 0.064 |
| 0.7L                             |                                        | 0.055 | 0.085 | 0.113 | 0.086 | 0.088 |
| 0.75L                            |                                        | 0.075 | 0.116 | 0.146 | 0.117 | 0.117 |
| 0.8L                             |                                        | 0.098 | 0.152 | 0.188 | 0.151 | 0.152 |
| 0.85L                            |                                        | 0.120 | 0.190 | 0.238 | 0.190 | 0.189 |
| 0.9L                             |                                        | 0.143 | 0.226 | 0.279 | 0.226 | 0.225 |
| 0.95L                            |                                        | 0.169 | 0.266 | 0.328 | 0.266 | 0.261 |
| L (support II)                   |                                        | 0.196 | 0.316 | 0.417 | 0.293 | 0.279 |
| 1.05L                            |                                        | 0.173 | 0.272 | 0.334 | 0.272 | 0.267 |
| 1.1L                             |                                        | 0.151 | 0.238 | 0.294 | 0.239 | 0.237 |
| 1.15L                            |                                        | 0.133 | 0.210 | 0.260 | 0.210 | 0.208 |
| 1.2L                             |                                        | 0.116 | 0.181 | 0.220 | 0.179 | 0.179 |
| 1.25L                            |                                        | 0.098 | 0.153 | 0.188 | 0.152 | 0.152 |
| 1.3L                             |                                        | 0.083 | 0.130 | 0.163 | 0.129 | 0.130 |
| 1.35L                            |                                        | 0.070 | 0.110 | 0.141 | 0.112 | 0.113 |
| 1.4L                             |                                        | 0.060 | 0.094 | 0.123 | 0.097 | 0.098 |
| 1.45L                            |                                        | 0.052 | 0.081 | 0.109 | 0.086 | 0.086 |
| 1.5L                             |                                        | 0.006 | 0.009 | 0.101 | 0.074 | 0.076 |

^a L refers to the length of single span.
^b 0.55L means the distance between support I and the pointed location.

Table 5. Longitudinal crack width of concrete with post-tensioned prestress

| Longitudinal location (L = 70 m) | Transversal location (crack width: mm) | D  | E  | F  | G  | H  |
|----------------------------------|----------------------------------------|----|----|----|----|----|
| 0.65L                            |                                        | 0.039 | 0.003 | 0.025 | 0.000 | 0.041 |
| 0.7L                             |                                        | 0.003 | 0.011 | 0.000 | 0.000 | 0.000 |
| 0.75L                            |                                        | 0.004 | 0.007 | 0.007 | 0.006 | 0.006 |
| 0.8L                             |                                        | 0.031 | 0.043 | 0.047 | 0.042 | 0.042 |
| 0.85L                            |                                        | 0.000 | 0.000 | 0.076 | 0.000 | 0.000 |
| 0.9L                             |                                        | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.95L                            |                                        | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| L (support II)                   |                                        | 0.014 | 0.030 | 0.058 | 0.014 | 0.000 |
| 1.05L                            |                                        | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.1L                             |                                        | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.15L                            |                                        | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.2L                             |                                        | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.25L                            |                                        | 0.031 | 0.044 | 0.049 | 0.044 | 0.043 |
| 1.3L                             |                                        | 0.010 | 0.017 | 0.023 | 0.017 | 0.021 |
| 1.35L                            |                                        | 0.039 | 0.003 | 0.025 | 0.000 | 0.041 |
| 1.4L                             |                                        | 0.003 | 0.011 | 0.000 | 0.000 | 0.000 |
| 1.45L                            |                                        | 0.004 | 0.007 | 0.007 | 0.006 | 0.006 |
| 1.5L                             |                                        | 0.031 | 0.043 | 0.047 | 0.042 | 0.042 |
As for steel girder, in the longitudinal direction, considering the location at midspan of span I and span II, and the location at support II, the stress condition of steel girder are shown in table 6. Under the fundamental combination of actions, the minimum longitudinal compressive stress of top plate at the location of midspan in span I is -205.8 MPa, while the maximum tensile stress of bottom plate at the same section is 201.5 MPa; at the section of midspan in span II, the minimum compressive stress of top plate is -104.4 MPa, the maximum tensile stress of bottom plate is 153.8 MPa; at the section of support II, the maximum tensile stress of top plate is 199.6 MPa, the minimum compressive stress of bottom plate is -252.8 MPa.

| Longitudinal location | Location A (MPa) | Location B (MPa) | Location C (MPa) |
|-----------------------|------------------|------------------|------------------|
|                       | Top   Bottom     | Top   Bottom     | Top   Bottom     |
| Midspan of span I     | -195.8 196.1     | -152.6 183.4     | -205.8 201.5     |
| Midspan of span II    | -94.0   148.9     | -61.4  135.8     | -104.4 153.8     |
| Support II            | 199.6   -166.3    | 175.3 -252.8     | 192.8 -170.8     |

4. Conclusion

According to the above analysis, the following conclusion can be drawn: For the traditional prestressing application method, 43.65% of the total stress is transferred to steel girder, while in terms of post-tensioned prestressing application method, all the prestress is applied to concrete slab if not considering shrinkage and creep. For the traditional prestressing application method, the whole length of prestress tendon is 28704 m, while in post-tensioned prestressing application method, the whole length is 9870 m, reducing 64.6% for the number of prestress tendon.

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