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Study on the Reasonable Alignment of the Steel Truss Concrete Composite Continuous Rigid Frame Bridge

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Abstract

The alignment of steel truss concrete composite continuous rigid frame bridge (STCR in short) has a significant influence on the distribution of internal bending force, the research concerning the reasonable alignment, however, is very limited. In the negative bending moment section of STCR, the bottom chords are in compression state, in addition, the secondary moment caused by the joint stiffness of STCR is too significant to be neglected, therefore, these bottom chords are compression and bending members, which mechanical characteristics are somehow similar to that of the main arch of the open spandrel arch bridge, with the difference lies in that the bottom chord of STCR in the mid-span is in tension while the arch in the mid-span of open spandrel arch bridge is still in compression. On the basis of the method that determine the reasonable alignment of open spandrel arch bridge, a segmental pressure line method is proposed to determine the reasonable alignment of STCR: (1) Select an initial approximate reasonable axis for the bottom chord and a specific load condition, and calculate the internal force of members through finite element model analysis; (2) Select the compressed bottom chord as the research object, make the internal force of the adjacent members as external force to the research object and apply them to the corresponding position, repeat the iterative calculation, and get the discrete node coordinates that approximate the real pressure line; (3) Take the discrete nodes and the bottom chord node in the mid-span as the controlling nodes, using the curve fitting method to get the parabola alignment that can be applied to practical engineering. To validate this method, a detailed engineering application was introduced. Results of the example show that the proposed method is simple and efficient, it can significantly reduce the internal bending force of each member, and improve the internal force distribution state of STCR.

Keywords: reasonable alignment, segmental pressure line method, steel truss concrete composite, continuous rigid frame bridge

1. Introduction

The alignment reasonability of the steel truss concrete composite continuous rigid frame bridge (STCR in short) has a significant influence upon the value and the distribution of the internal force in each section of steel truss. The most optimal alignment should coincide with the pressure line resulted by all of the loads acting upon the bottom chord in the section where the bottom chord is in compression state, thus the bottom chord is subjected to axial force merely, no bending moment or the bending moment is very small, in this way, the force is distributed evenly in each section and the material strength could be fully developed. However, because the influence of other factors such as the action of live load, the change of temperature, the shrinkage of material and so on, the most optimal alignment cannot be obtained, therefore, the alignment should make the bottom chord in the compression section to approximate the real pressure line as far as possible, and that is the expected reasonable alignment of STCR.

Unfortunately, the current research or report that concerning this topic is very limited. Some similar researches and reports were found, documentation by Xu and Sun (2011) indicated that for a continuous truss girder, large negative bending moment appears in the supports section, it is economical to make the truss height proportional to the square root of the bending moment. So in many cases, the truss height in the supports section is appropriately increased, such as Chongqing Niujiaotuo Bridge as shown in Figure 1 (Xu & Sun, 2011). In the reports of Bao, Chen and Lu (2005), they analyzed the influence of steel truss alignment upon the secondary bending force, the report indicated that the influence is significant, and they also analyzed the regularity of the change of the secondary force in accordance with the change of the truss alignment, and preliminarily discussed the cause of the above regularity (Bao, Chen, & Lu, 2005). However, none of these documentation has put forward the determination method of the reasonable alignment of such height-varying steel truss, it would be necessary to have an effective method to determine the reasonable alignment of STCR.

Figure 1. Chongqing Niujiaotuo Bridge

In the negative bending moment section of STCR, the bottom chords are in compression state, in addition, the secondary moment caused by the joint stiffness of STCR is too significant to be neglected. These bottom chords are compression and bending members, which mechanical characteristics are somehow similar to that of the main arch of the open spandrel arch bridge, with the difference lies in that the main arch of open spandrel arch bridge is basically in compression state in each section, while in STCR, the bottom chord is in tension in the mid-span section and then turns into compression in about 1/4 of the span length. As for the open spandrel arch bridge, Yang, Li and Peng (2001) proposed the determination method of the reasonable arch axis by simplify the whole bridge to an arch with external force acting upon it and then to calculate the pressure line according to the simplified external force (Yang, Li, & Peng, 2001); Lin, Huang and Ren (2007) further improved this method by adding a factor to increase the iteration speed (Lin, Huang, & Ren, 2007). However, the method that determine the reasonable axis of open spandrel arch bridge is no longer appropriate for the alignment determination of STCR because of the differences mentioned earlier. This paper discussed the method to determinate the reasonable alignment of STCR on the basis of the works and theories mentioned above.

2. Determination Method of the Reasonable Arch Axis of the Open Spandrel Arch Bridge

Yang, Li and Peng (2001) proposed the determination method of the reasonable arch axis of the open spandrel arch bridge, the details are as follows: The arch rib of arch bridge bears not only the self-weight but also the concentrate load of the column, due to the existence of concentrate load, the pressure line of arch rib may no longer be a smooth curve but with some turning points corresponding to the action points of concentrate load. In the practical design work, catenary or parabola curves are generally used as the arch axis of the open spandrel arch bridge. The "5 points coincidence method" is used to determine the value of arch axis coefficient *m* of catenary arch, and that is to make 5 points on the arch (the crown, two 2 L / 4 points and 2 arch foot points) coincide with the real pressure line merely. But in fact, the pressure line of arch rib is related to the boundary conditions of a structure, many researches show that the arch axis determined by "5 points coincidence method" has a certain deviation with the pressure line of the corresponding hingeless arch, and that results in some secondary bending moment in the vault and the arch foot. At the same time the deviation from the arch axis to the real pressure line in each section cannot be evaluated accurately, and that usually results in a significant deviation in some sections when the arch rib is subjected to load (Yang, Li, & Peng, 2001).

At present, the finite element model (FEM) analysis theory and computer assistant calculation have been widely used in the bridge design. Therefore, the arch axis can be discrete as a series of bar element based on the pre-selected arch axis, by using the FEM analysis and the powerful calculation ability of modern computer, the discrete nodes that approximate the real pressure line of arch under a certain load condition can be obtained (Lin, Huang, & Ren, 2007).

The detailed procedures are as follows: Select an initial approximate reasonable arch axis, calculate the internal force of columns under the specific load condition by using FEM analysis;

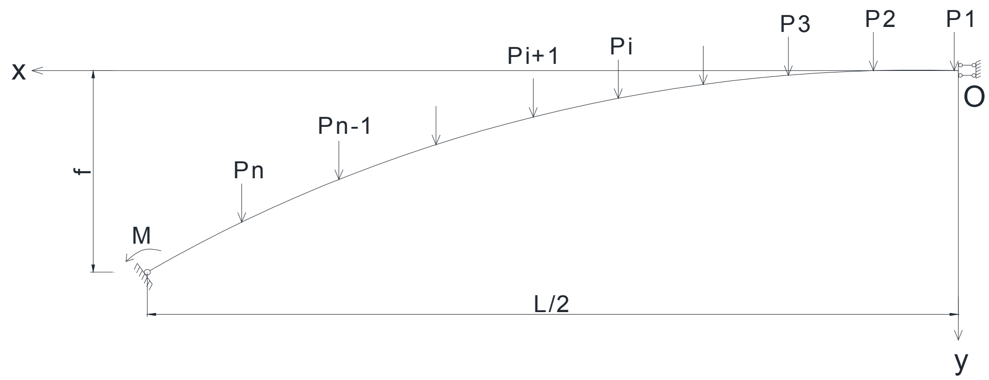


Figure 2. Calculation diagram of the open spandrel arch axis

Due to the symmetrical characteristic of arch, a half of the arch is taken as the research object as is shown in Figure 2; discrete the arch as a series of bar element and mark down the initial node coordinates (x_{i0}, y_{i0}); make the internal force of columns as external force to arch and apply them to the corresponding position on the research object, using the basic theory that determine the pressure line to obtain (x_{i1}, y_{i1}), then replace (x_{i0}, y_{i0}) as (x_{i1}, y_{i1}) to get the new node coordinates through iteration method; repeat the above steps till the node coordinates are approximate to the real pressure line; integrate the discrete points as the arch axis with simple equation expression such as high order parabola curves through curve fitting method. It should be noticed that the horizontal coordinates of each node remain constant during the whole process.

As for the open spandrel arch bridge, the main arch is basically in the compression state, while for STCR, the bottom chord in the mid-span is in tension and then gradually turns into compression with the approaching from mid-span to pier; in addition, the secondary internal force of truss bridge is significant, so that the internal force of web members cannot be neglected any more, and the method that determine the reasonable axis of open spandrel arch bridge is no longer appropriate for the alignment determination of STCR, therefore, the segmental pressure line method was proposed to determine the coordinates of discrete node that are approximate to the real pressure line, and then take the obtained nodes and the bottom chord node in the mid-span as the controlling points, and finally obtain the reasonable alignment of STCR through curve fitting method.

3. Determination Method for the Reasonable Alignment of STCR—Segmental Pressure Line Method

3.1 Segmental Pressure Line Method

In the STCR, the bottom chord is in tension state in the mid-span, and turns into compression state with the approaching from mid-span to pier. Therefore, a reasonable alignment of the compressed bottom chord must exist that could make the internal force distribution of the whole bridge approximate an optimal state. To get the reasonable alignment of the compressed bottom chord, the bottom chord that in tension sate can be ignored temporarily, and just select the section with compressed bottom chord as the research object. The detailed procedures are as follows:

Step 1: Select an initial approximate reasonable arch axis and a certain load condition, calculate the internal force of columns by using FEM analysis;

Step 2: Select the section with compressed bottom chord as the research object, make the internal force of adjacent members as external force to the research object and apply them to corresponding position on research object. Repeat the iteration calculation to obtain the discrete nodes that approximate the real pressure line;

Step 3: Take the obtained nodes and the bottom chord node in the mid-span as the controlling points, and finally obtain the reasonable alignment of the bottom chord through curve fitting method.

3.2 Selection of the Specific Load Condition and the Creation of the FEM

Generally, the rationality of an arch axis depends on the proximity between it and the pressure line of arch rib under a specific load condition (generally the dead load or the dead load and a half of the live load), the one that proximate the pressure line most is assumed as the optimal arch axis (Gu & Xiang, 2012). So as for STCR, the pressure line with the load condition of the dead load and a half of the live load could be assumed as an approximate reasonable alignment of the bottom chord. Due to the load is distributed evenly in STCR, the secondary parabola curve could be assumed as the initial alignment of the bottom chord, which is given by

(Figure 3).

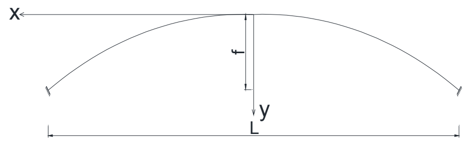


Figure 3. The secondary parabola alignment

$$y = \frac{4f}{l^2}x^2 \tag{1}$$

To simplify the calculation, a single piece of steel truss can be adopted for research during the creation of FEM, the cross section of each members in the preliminary design should be adopted. The load conditions could be the dead load and a half of the live load, the alignment of the bottom chord should be an approximate reasonable one such as a secondary parabola. To simulate the real situation as far as possible, the deck and the prestress used in the preliminary design should be created in the FEM.

3.3 Selection of the Research Object

According to the calculation results by FEM analysis, divide the bottom chord into two segments in terms of tension and compression state, ignore the segment with tension bottom chord temporarily, take a half of the segment with compression bottom chord as the research object, make the internal force of adjacent members as external force to the research object and apply them to corresponding position on research object. In addition, assume that when the small deformation of the bottom chord is occurred, the internal force of web members remain constant. The calculation diagram of the segmental pressure line is shown in Figure 4.

In which: m_i $m_i^{'}$——the bending moment of the vertical and the tilted web members in the i^{th} node, respectively;

p_i, $p_i^{'}$——the axial force of the vertical and the tilted web members in the i^{th} node, respectively;

s_i, $s_i^{'}$——the shear force of the vertical and the tilted web members in the i^{th} node, respectively;

θ_i——the angle between the member and the horizontal line in the i^{th} node.

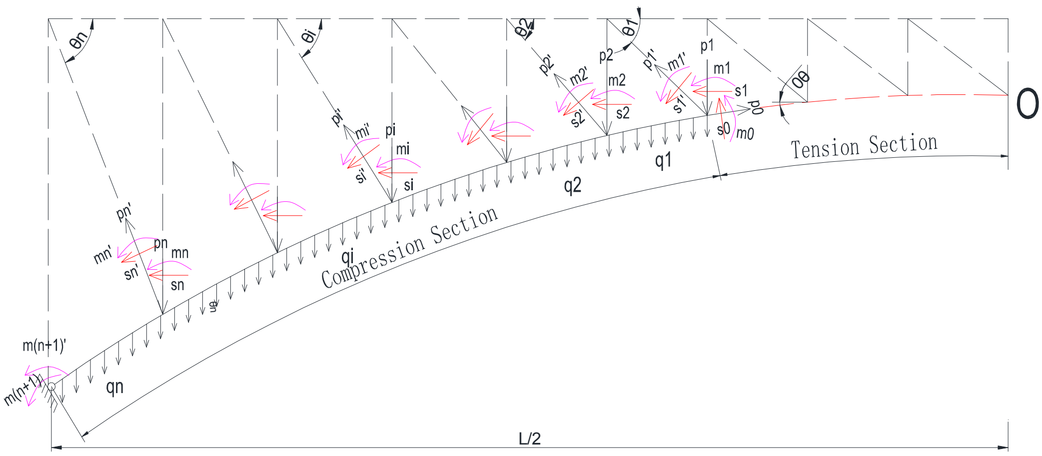


Figure 4. The calculation diagram of segmental pressure line

To simplify the calculation process, all the loads can be decomposed to two directions of the Cartesian coordinates system as is shown in Figure 5 through Equations (2)~(7).

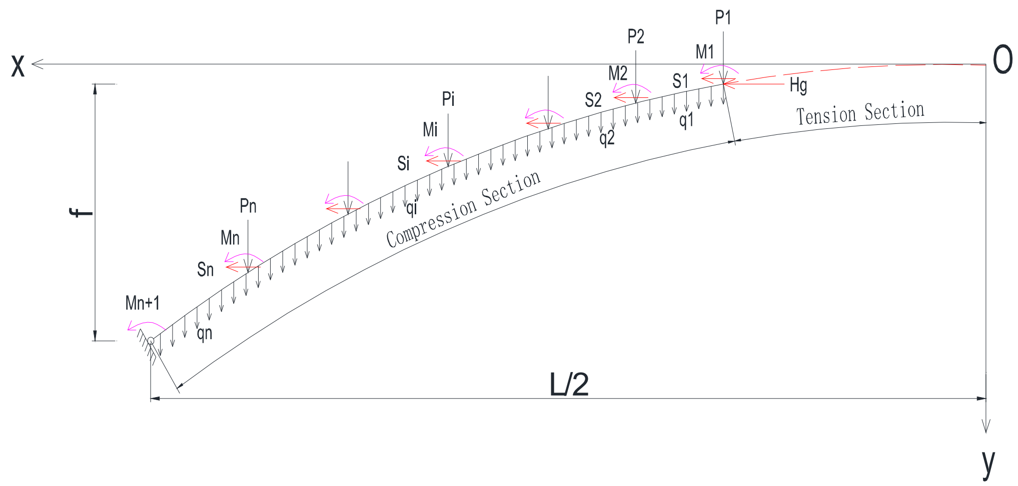


Figure 5. The simplified calculation diagram of segmental pressure line

$$S_1 = p_1^{'} \cos\theta_1 + s_1^{'} \sin\theta_1 + s_1 - p_0 \cos\theta_0 + s_0 \sin\theta_0 \tag{2}$$

$$M_1 = m_0 + m_1 + m_1^{'} \tag{3}$$

$$P_1 = -p_1^{'} \sin\theta_1 + s_1^{'} \cos\theta_1 + p_1 - p_0 \sin\theta_0 + s_0 \cos\theta_0 \tag{4}$$

$$S_i = p_i^{'} \cos\theta_i + s_i^{'} \sin\theta_i + s_i \tag{5}$$

$$M_i = m_i + m_i^{'} \tag{6}$$

$$P_i = -p_i^{'} \sin\theta_i + s_i^{'} \cos\theta_i + p_i \tag{7}$$

In which: P_i, S_i and M_i are the concentrate force in the i^{th} node, $i = 2 \sim n+1$.

Assume the coordinate system is as shown in Figure 5, the horizontal force caused by external force in the top end of the research object is assumed as H_g, calculate the bending moment of the lower end section, then the H_g is given by,

$$H_g = \frac{\sum M_j}{f} \tag{8}$$

In which: $\sum M_j$ ——the moment of the external loads to the lower end section of the research object;

H_g ——the horizontal force caused by external force (without consideration of the elastic compression);

f ——Vector height of the research object.

Calculate the bending moment of each section caused by external force, then

$$y_{i1} = \frac{M_x}{H_g} \tag{9}$$

M_x ——the bending moment of each section caused by the right side external force of the research object;

y_{i1} ——longitudinal coordinate of the i^{th} node after the first iteration.

Then replace (x_{i0}, y_{i0}) as (x_{i1}, y_{i1}) in the FEM and the calculation process to get the new node coordinates through iteration method. Repeat the above steps till the node coordinates are approximate to the real pressure line. It should be noticed that the horizontal coordinates of each nodes remain constant during the whole process.

3.5 Stop Criteria of Iteration

When any of the following conditions is met, iteration can be stopped.

Condition 1:

$$\max\left|(\mathrm{M}_{i,n} - \mathrm{M}_{i,n-1}) / \mathrm{M}_{i,n-1}\right| \le 5\% \tag{10}$$

When meet Equation (10), it can be assumed that the internal force state of the bottom chord has been basically stable.

Condition 2:

$$\max\left|(y_{i,n} - y_{i,n-1}) / y_{i,n-1}\right| \le 5\% \tag{11}$$

When meet Equation (11), it can be assumed that the alignment of the bottom chord has been basically stable.

3.6 Fitting of the Reasonable Alignment

Select the group of discrete nodes that could make the internal force distribution of STCR in an optimal sate as the basis of curve fitting. Take the obtained discrete nodes and the bottom chord node in the mid-span of intermediate span as the controlling points, integrate these controlling points by an arch axis with simple equation expression such as high order parabola curves through curve fitting method. As for the curve fitting method, many effective methods are available such as least square method (Li, Zhang, & Jiang, 2005).

4. The Engineering Application

To validate the feasibility of segmental pressure line method, we applied to a real STCR. Figure 6 shows a steel truss concrete composite continuous rigid frame bridge with a span arrangement of 41+70+41 m, the height of girder is 2 m and 6 m in the mid-span of intermediate span and the pier, respectively, the secondary parabola was selected as the alignment of the bottom chord in the preliminary design, The side span within the length of half intermediate span is symmetric with the half intermediate span, and the rest of the side span is a height-constant truss girder with the height same as that of the mid-span in the intermediate span.

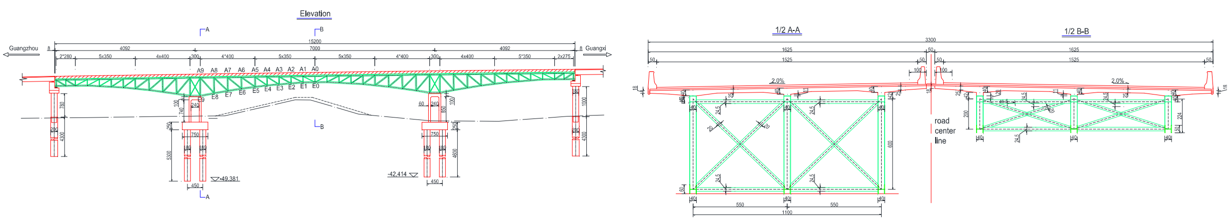


Figure 6. General layout of a STCR (cm)

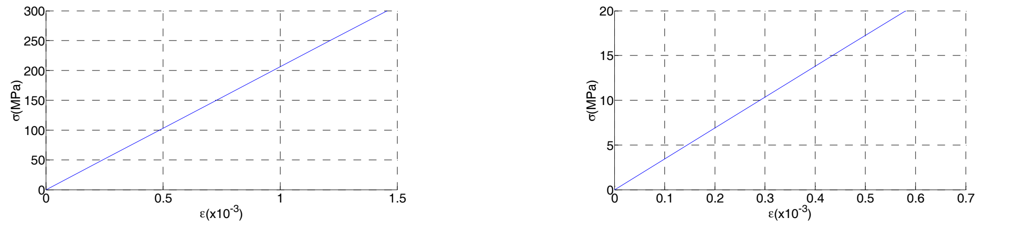
The top chords cross section was fabricated as build-up box with plates measuring 400 mm wide by 14 mm thick; using Q345 steel. The web members cross section was fabricated as build-up members with flange plates measuring 200/300 mm wide by 14/22 mm thick; the web plates measured 380 mm tall by 12 mm thick; using Q345 steel. The bottom chords cross section was fabricated as build-up members with flange plates measuring 500 mm tall by 14~30 mm thick; the web plates measured 380mm wide by 14~30 mm thick; using Q345 steel. The precast deck is 5m long by 16.25 m wide, using C50 concrete.

In the whole analysis process, the following assumptions are made:

1) The steel and concrete are assumed as isotropic, homogeneous and elastic materials, material nonlinearities do not taken into account. The constitutive model of both materials are assumed as $\sigma = E\varepsilon$, as is shown in
2) Table 1 and Figure 7.
3) The elements used in the FEM are elementary beam element, met the assumption of plane section.
4) The shear lag of the deck does not taken into account, assume that there is no slippage between the deck panels and the steel truss.
5) Assume that when the small deformation of the bottom chord is occurred, the internal force of each member remains constant in a single iteration step.

Table 1. The arguments of Q345 steel and C50 concrete

Materials	Young's modulus (N/mm^2)	Poisson ratio	Density (N/mm^3)
Q345 Steel	2.06×10^5	0.3	7.698×10^{-5}
C50 Concrete	3.45×10^4	0.2	2.5×10^{-5}



a) Stress-strain relationship of Q345 steel b) Stress-strain relationship of C50 concrete

Figure 7. The stress-strain relationship of Q345 steel and C50 concrete

For the convenience of calculation, only a single piece of steel truss is created as the research object, the load condition is dead load and a half of the live load, integral gusset plate is adopted in the bridge, due to the significant joint stiffness, the members are connected through common node. To simulate the real situation as far as possible, the deck and the prestress used in the preliminary design are created in the FEM as is shown in Figure 8.

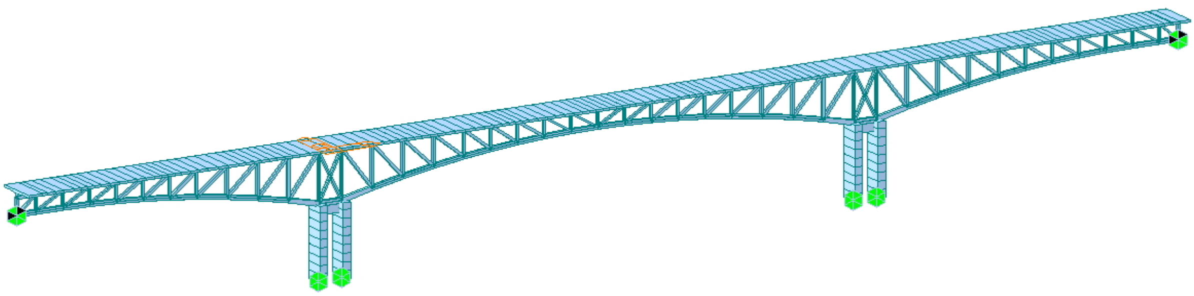


Figure 8. The FEM of a single piece of steel truss

According to the initial calculation results of FEM analysis, for a half of the intermediate span, the bottom chord in the three sections from E0~E1 are in tension state, and the rest are in compression, therefore, the final calculation diagram of segmental pressure line can be simplified as Figure 9.

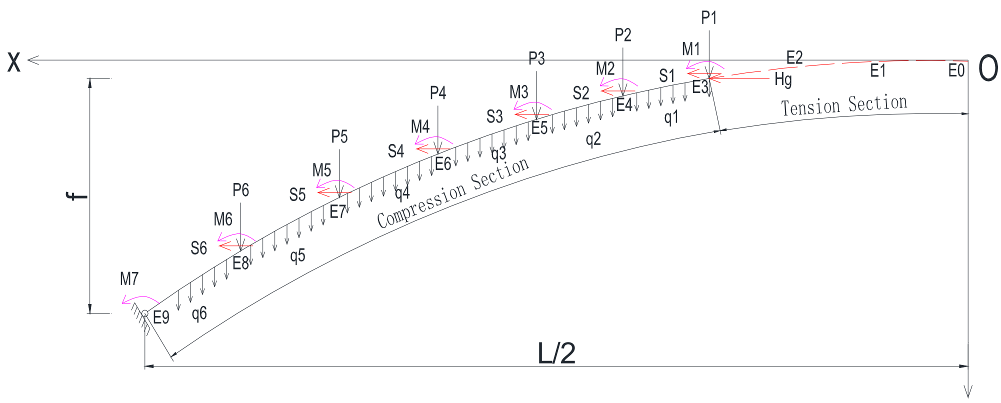


Figure 9. The final simplified calculation diagram

In accordance with the iteration method described in part 3. Assume that the coordinate system is shown as in Figure 10, the obtained coordinates of the discrete nodes are show in Figure 10, the obtained coordinates of the discrete nodes are show in Table 2. In which represents the horizontal coordinate of each node, represents the longitudinal coordinate of each node on the secondary parabola, and represents the longitudinal coordinate of each node after the iteration.

Table 2. Node coordinates of bottom chord within 1/2 intermediate span in each alignment (m)

Node	x	y_0	y_{i1}	y_{i2}	y_{i3}	y_{i4}	y_{i5}	y_f
E9	1.5	0	0	0	0	0	0	0
E8	5.5	0.8982	1.1093	1.0962	1.1653	1.1492	1.1572	1.1616
E7	9.5	1.6823	1.9821	1.9735	2.0219	2.0173	2.023	2.0601
E6	13.5	2.3524	2.7179	2.7208	2.7514	2.7559	2.7596	2.7323
E5	17.5	2.9084	3.1885	3.2167	3.235	3.2427	3.2473	3.2144
E4	21	3.3014	3.4734	3.5136	3.5322	3.5414	3.5443	3.5092
E3	24.5	3.607	3.6493	3.6695	3.6788	3.6834	3.6849	3.7109
E2	28	3.8254	3.8254	3.8254	3.8254	3.8254	3.8254	3.844
E1	31.5	3.9563	3.9562	3.9563	3.9563	3.9563	3.9563	3.9329
E0	35	4	4	4	4	4	4	4

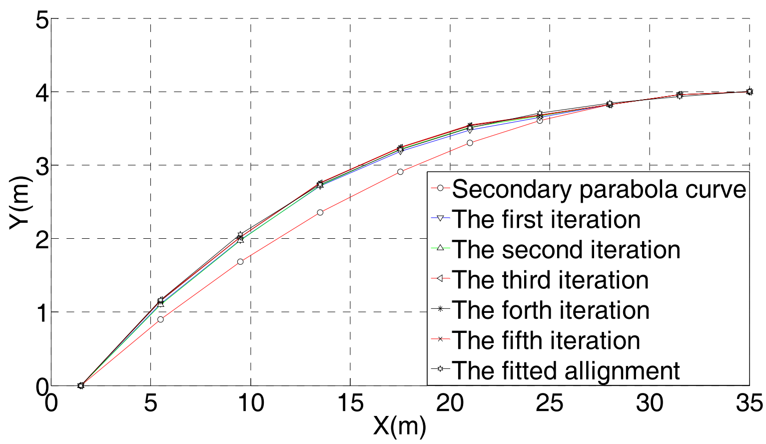


Figure 10. Comparison of each alignment

Table 2 and Figure 10 indicate that the change of longitudinal coordinate of nodes are relatively large in the first two iterative calculations, after the third iteration calculation, the longitudinal coordinate change of nodes begin to decrease and gradually meet the stop criteria of iteration. According to the preliminary comparison, the third group of discrete nodes make the internal force distribution of the whole bridge in an optimal state, so they are selected as the basis of curve fitting. It has been found that the cubic parabola is enough to meet the accuracy requirement, and the final fitted alignment is given by:

$$y_f = 9.504\times10^{-5}\times(x-1.5)^3 - 0.009358\times(x-1.5)^2 + 0.3263\times(x-1.5) \tag{12}$$

The final selected alignment is substituted in the FEM to analysis the mechanical behavior of the whole bridge, and the internal bending moment distribution comparison is obtained as is shown in Table 3. In STCR, a certain prestress are arranged inside of deck, and part of the prestress is applied to the top chord of steel truss through shear connector, and results a significant reduction of the internal force of top chord, in addition, the internal force of intermediate span is relatively large than that of the side span, therefore, they are not the controlling parts, here only the bending moment of the controlling section within 1/2 intermediate span are presented in terms of the web members and bottom chords, respectively. In which L is the length of intermediate span.

Table 3. Bending moment comparison in the controlling section ($KN \bullet m$)

Type	Section	Element	Position	Secondary parabola (M_1)	The final alignment (M_2)	$\frac{M_2 - M_1}{M_1} \times 100\%$ (%)
Bottom Chord	1/8L	E9-E8	I	-1194.36	-1057.65	-11.45
			J	150.97	112.32	-25.60
	1/4L	E7-E6	I	-71.24	-67.31	-5.52
			J	29.68	22.99	-22.54
	3/8L	E4-E3	I	-19.87	-20.61	3.72
			J	32.68	35.29	7.99
	1/2L	E1-E0	I	25.17	27.3	8.46
			J	9.35	9.27	-0.86
Web Member	1/8L	A9-E8	I	10.33	8.26	-20.04
			J	-29.19	-25.49	-12.68
		A8-E8	I	44.98	40.95	-8.96
			J	-52.7	-47.42	-10.02
	1/4L	A7-E6	I	11.95	9.22	-22.85
			J	-19.41	-17.35	-10.61
		A6-E6	I	58.88	68.4	16.17
			J	-57.03	-65.56	14.96
	3/8L	A4-E3	I	8.12	7.92	-2.46
			J	-7.85	-7.14	-9.04
		A3-E3	I	32.3	32.71	1.27
			J	-32.75	-33.05	0.92
	1/2L	A1-E0	I	1.64	1.78	8.54
			J	-1.58	-1.62	2.53

Table 3 indicates that the fitted alignment effectively reduced the bending moment of both the bottom chords and the web members in the segment with large internal force, in the 1/8L section, the bending moment reduction reaches the maximum of 25.06%, in the segment with small internal force, the bending moment increased a little.

5. Discussion

The calculation results indicate that the segmental pressure line method is simple and effective, it can improve the internal force distribution state of STCR, but this method did not considered the elastic deformation of members, while it has a significant influence upon the internal bending force distribution of the whole bridge, therefore, how to take into account the elastic deformation of members requires further study.

6. Summaries and Conclusions

The alignment of steel truss concrete composite continuous rigid frame bridge has a significant influence on the distribution of internal bending force, however, the research upon the reasonable alignment is very limited. In the negative bending moment section of STCR, the bottom chords are in compression state, in addition, the secondary moment caused by the joint stiffness of STCR is too significant to be neglected. Therefore, these bottom chords are compression and bending members, which mechanical characteristics are somehow similar to that of the main arch of the open spandrel arch bridge, with the difference lies in that the bottom chord of STCR in the mid-span is in tension while the arch in the mid-span of open spandrel arch bridge is still in compression. Therefore, some theories established upon the open spandrel arch bridge can be applied to STCR with certain modifications. The results of this research can be concluded as follows:

(1) On the basis of the method that determining the reasonable alignment of arch bridge, the segmental pressure

line method was proposed to determine the reasonable alignment of STCR, and then the detailed calculation procedures was introduced. According to this method, the reasonable alignment of an application bridge was derived as shown in Equation (12).

(2) The segmental pressure line method is simple and efficient, the whole process can be performed by the combination of EXCEL and the FEM analysis, in addition, only with 3 to 4 times of iteration, the discrete nodes that approximate the real pressure line can be obtained.

(3) The calculation results indicate that fitted alignment effectively reduced the bending moment of both the bottom chords and the web members in the segment with large internal force, in the 1/8L section, the bending moment reduction reaches the maximum of 25.06%, in the segment with small internal force, the bending moment increased a little. Thus improved the internal force distribution state.

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