Assistant pullback technique for main span closure of Sutong Bridge

Chen Ming[1], Luo Chengbin[1], Wu Qihe[1,2], Zhang Yongtao[1,2], You Xinpeng[1,2]
(1. CCCC-Second Harbour Engineering Company Limited, Wuhan 430014, China;
2. Key Lab of Large-span Bridge Construction Technology, Ministry of Communications, Wuhan 430071, China)

Abstract: Sutong Bridge is a cable-stayed steel box girder bridge with a main span of 1 088 m. The erection of upper structure adopts geometry control method and requires no change to the unit's size and the structure's none-stress geometry. Before main span closure, the cantilever of girder reaches 540.8 m, the structure state is noticeably influenced by external circumstances, the main span closure face great difficulty. By abstracting the advantage of the pullback method abroad and the domestic temperature-cutting method, a new assistant pullback method have put forward and bring into practice actually. In this paper, the analysis key point of practice conditions, key parameter of practice, main measures of the method and the performance is introduced.

Key words: Sutong Bridge; assistant pullback; main span closure; geometric control methord; construction technology

1 Introduction

Sutong Bridge is a cable-stayed steel box girder bridge which has two towers and double cable planes, and the span layout of the main bridge is $(2 \times 100 + 300 + 1088 + 300 + 2 \times 100)$ m, as shown in Fig. 1. Sutong Bridge is the largest among the same type of suspension bridges in the world. The steel box girder utilizes fully welded streamline form flat-structure, the breadth of the containing wind beak is 41 m, and the height of the center line is 4 m. The main girder was installed by deck derrick crane, before the closure of the main span, unsupported length of the main girder reached 540.8 m.

Due to the flexibility of structure, the component geometric control method has been applied in the construction control, the geometry size of the members and the stressless alignment must not be changed in the construction. Hence, the main points of the main span closure are to fix the geometric size and the morphology and ensure the easement connection of the local alignment.

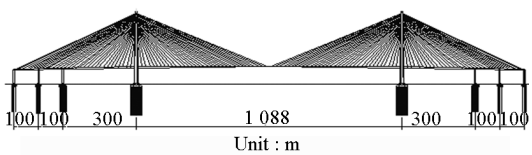

Fig. 1 The span layout of the main bridge of Sutong Bridge (unit: m)

2 Methods of the closure of the middle span at home and abroad

2.1 Methods of closure abroad[1,2]

Closure by incremental launching technology, which is manufacturing the closure segment according to design dimension, is usually used for the main span closure of the cable-stayed steel box girder bridge abroad. Hoisting jack must be sit at closure segment or cable tower before the closure to jack longitudinal or tense the girder to change the length of the closure. Then the bridge crane is utilized to lift the closure segment to match one side of the welding seam and the closure segment is moved back to the main girder. The next step is compulsory adjustment of the height difference on both sides of the cantilever roof and the width at the end of the seam using large-scale equipment and the last step is matching of welding seams. One of the most representative projects is Tatara Bridge in Japan whose process of cross-fold is as follows: push the main girder to the shore side→lift the closure, weld to matching one side of the main girder→push the main girder back→adjust the elevation and the width and the top end of the mouth, the next step is matching welding.

2.2 Domestic methods of closure[3,4]

Fit temperatures closure technology is usually used for the closure of the middle span of the cable-stayed steel box girder bridge in China, that is, the length of

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the closure segment is larger than the designed size, stiffening skeleton is used to limit the relative deformation of the both sides of the beam girder before the closure, then simulate the closure state after the lifting of the closure segment through added pressure, next, monitor the length of the closure segment continuously, and the length of closure segment is according to the measured temperature, which means that change the length of closure to accomplish the closure. In the construction process of the closure, the bridge crane lift the closure segment symmetrically, and the added pressure is removed synchronously, then close the closure segment into the gap of the closure when the temperature is lowest at night, weld the two seams synchronously to complete the closure of the main span. One of the most representative domestic projects is the No. 3 Nanjing Bridge, the process of cross-fold is as follows: push the main girder to the shore side→lift the closure, weld to matching one side of the main girder →push the main girder back→adjust the elevation and the width of the top end of the gap, the last step is matching welding.

2.3 The comparative study of the closure at home and abroad

The characteristics of fit temperatures closure technology and incremental launching technology both are distinct. The comparison of the two methods is shown in Table 1.

Table 1 The comparison of closure process of fit temperatures closure technology and incremental launching technology

Comparative item	Incremental launching technology	Fit temperatures closure technology
Advantages	1. Fix the dimension size of the closure segment to meet the constraints of the geometric control method; 2. Matching welding of two seams on both sides of the closure segment is asynchronous, the effects of the temperature are limited and there is enough time to complete the construction; 3. The simulation the structural morphology after closure due to the added pressure and the set of the stiffening skeleton are unnecessary, the construction link is few; 4. Monitoring of the length of the closure segment continuously is not required, the link of construction control is few.	1. Simulate the closure state after the lifting of the closure segment through added pressure, and the structural form may be adjust advanced , the difficulty and workload of adjustment is reduced after the lifting; 2. The length of the closure gap is not changed and the risks of releasing the provisional fixing are avoided; 3. Two seams of the closure should be welded simultaneously and the process of closure is short.
Risks	1. Main girder must be pushed the to the shore side to change the dimension size of the closure gap, and may bring about the reversion of the main girder; 2. The saddle fixing with tower temporarily must be released during pushing and the deformation of the structure after releasing may not revert; 3. With the increased span of the structure, the distance and the force of pushing become larger and the difficulty and risks of construction increase; 4. The closure segment is lift unilateral, and that increase the difference of deformation of the seams on the two sides of the girder, matching construction become more difficult.	1. The geometry size of the members and the stress-less alignment may be changed, that may affect the structure and the force; 2. Temperature affect the structure seriously, and it is possible that the closure segment can not be embedded into the closure gap after the cutting, or the width of the seams is too large to cause the quality problem; 3. The seams on the two sides of the girder must be welded simultaneously and increase the difficulty of the construction organization; 4. The lack of initiative adjustment for matching of two seams exists and influences the quality and safety.

3 Incremental launching and assisted closure method

3.1 Analysis of the incremental launching method and fit temperature closure technology

The risks of closure method at home and abroad are shown in Table 1. As for the closure of the Sutong Bridge, the risks and the influences to the structure increase with the span increasing:

1) According to the construction schedule, the middle span Sutong Bridge closure up at June or July, the highest ambient temperature is up to 30 ℃. In the light of experience, The maximum daytime temperature of steel structure is 20 ℃ greater than the ambient temperature, which means that the temperature will reach 50 ℃. Under such condition, if incremental launching method is used, the incremental launching distance of the main girder at one side is at least $540.8 \times 1.2 \times 30 \times 10^{-2} \approx 200$ mm, and due to the temperature difference, the incremental launching distance is greater than 240 mm. Analyses and computations show that safety factor of vertical cable fixing with tower temporarily is smaller than 2.0, which means the alignment of girder, cable-force and vertical cable fixing with tower

are influenced seriously, the most influential size of alignment is up to 65 mm, and the most influential force of cable reaches 110 kN.

2) By means of calculations and analyses, closure segment is lifted unilaterally by using incremental launching technology. Elevation difference of the seams on the two sides of the closure segment, width difference of the top end of the gap and the forced adjustment force for the matching are all shown in Table 2.

Table 2 Deformation difference of seams and the compulsory adjustment force

Item	Deformation difference of seams	Compulsory adjustment force
Elevation difference /mm	618 mm	628 kN
Width difference of the top end /mm	41 mm	47 000 kN· m

3) Using the fit temperature closure technology, in the temperature stable light, the temperature of steel box girder and the ambient temperature are approximately same and can reach 30 ℃. Under such condition, the length of the closure segment is about: $2 \times 540.8 \times 1.2 \times 10 \times 10^{-2} \approx 130$ mm. From the analysis result, the length of cutting for the closure is 130 mm, the influential size of alignment and influential force of cable are listed in Table 3.

Table 3 Influential size of alignment and influential force of cable due to the 130 mm cutting

The deformation of alignment of girder DZ /mm	Eccentric distance of the tower top (toward to main span) DX /mm	Influential force /kN
16	72	-30

4) Based on the continuous monitoring of the temperature for the girder of side span, even in the night when the temperature is stable, the average temperature of multiple days of the steel box girder has dramatic changes. As described and illustrated in Fig. 2, from 22:00 to 7:00 of the next day, temperature difference of the steel box girder will up to 5 ℃ within two days. Under such conditions, the variable quantity of the size of the closure gap will be about $2 \times 540.8 \times 1.2 \times 5 \times 10^{-2} \approx 65$ mm.

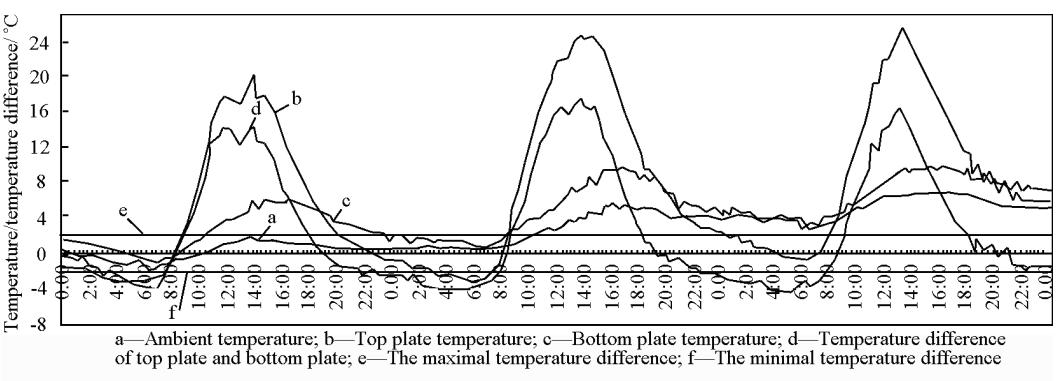

Fig. 2 Variation curve of temperature against time of steel box girder (day time)

Hence, if fit temperature closure method is applied, after the cutting size of closure is determined through the length of gap and the continuous monitoring of the alignment, the closure segment may be unable to embedded to the gap due to the vibration of temperature, or after the embedment, the joint dimension may be too large to bring about the quality problem of the seams.

3.2 Incremental launching and assisted closure method

Through the above analysis, it is can be found that for Sutong Bridge, if incremental launching method and fit temperature closure method are adopted, it will cause following major risks and problems.

1) If incremental launching method is adopted, the distance of pushing become larger for the girder, which will not only effect the structure alignment and the cable force, but also bring about problems that releasing the temporary fixed vertical cable force and the influence to the structure is unpredictable. Meanwhile, the closure segment is lifted unilaterally, and that can increase the elevation difference of the seams on the two sides of the closure segment and the width difference of the top end of the gap, and bring about a serious problem that the compulsory adjustment force for the matching is great, which brought difficulty to match the seams.

2) Applying fit temperature closure method, the length of the closure segment will become large, and possibilities of the eccentricity of completed bridge will

be created. Moreover, the cutting size of closure is changed because of the variation of temperature, the closure segment may be unable to embed to the gap due to the variation of temperature, or after the embedment, and the joint dimension size may be too large to cause the quality problem of the seams.

The analysis results of two methods reveal that avoidance of these problems and risks is impossible. Therefore, advantages and disadvantages of the above two methods are integrated to put forward a new method—incremental launching and assisted closure method, the construction process is as follows:

Step 1: Tense stay cables A34 and J34;

Step 2: Move back the bridge crane, demolish the tension platform and install the stiffening skeleton;

Step 3: Move forward the bridge crane to the location of closure segment;

Step 4: a. Tense stay cables A34 and J34 for the second time; b. emplace temporary substitute load; c. preliminarily adjust the local lineshape and axial line of girder and the width of the top end of closure gap; d. weld and assemble the stiffening skeleton at night, monitor the local alignment of girder from 12 to 24 h continuously; e. release the temporary fixed vertical cable force, move the girder segments on both sides toward the two banks, respectively;

Step 5: a. Adjust the length of closure segment; b. the bridge crane lift the closure segment and move temporary substitute load simultaneously;

Step 6: a. In the night, embed the closure segment into gap, and move the bilateral girder segments back and match the closure segment successively; b. move the welding flat forward and weld the bilateral joint seams at the same time, then release the temporary fixed vertical cable force before sunrise.

The advantages of incremental launching and assisted closure method are as follows:

1) Use the bridge crane lift the closure segment on both sides of closure gap, the structural deformation of both sides is small and consistent and quantity of closure joint gap is adjusted a little;

2) Embed the closure segment into gap in the night, that may reduce the incremental launching distance of the main girder, and the influence to the structure alignment and the cable force is little. Meanwhile, it is no need to release of the temporary fixed vertical cable force because of the short distance of incremental launching;

3) Simulate the closure state after the lifting of the closure segment through temporary added pressure, and adjust the local lineshape preliminarily, which may decrease adjustment quantity after the lifting of closure segment, compulsory adjustment using large-scale equipment is avoided;

4) Using stiffening skeleton to limit the relative displacement of the main girder, and that may reduce the vibration induced by wind and provide guidance for incremental launching, this work is also favorable to the measurement of the length of girder and local lineshape before the closure, then provide reliable data for the length adjustment of the girder and adjustment for the local lineshape;

5) Adopt incremental launch to adjust closure dimension size, this method make the technology have ability to overcome unfavorable influence of the temperature to structures actively. And there is enough time for embedment and matching;

6) The geometric size and the morphology are fixed, and the alignment and force of completed bridge the influence was unaffected.

3.3 Construction control conditions of incremental launching and assisted closure method

The main points of incremental launching and assisted closure method include three working procedures, which are embedment of closure segment into closure gap, matching of girder and welding works. The closure must be finished in one night. Hence, the construction control conditions of the every aided work procedure may be derived.

1) Welding time. Take into account the revision of the length of the closure segment, the top plate of one side is bolted by U ribs, and the plate of the other side is welded by inserting segment. The total time of welding seams is about 8 h according to the analysis of every welding procedure.

It can be seen in Fig. 2, after 8:00 am, the temperature of the steel box is greatly increased by the effects of sunshine, and it will induce temperature stress in the body of the girder, at this time, release the temporary fixed vertical cable force to ensure the quality of welding and force of the structure, when the welding of main steel girder should be basically completed. Hence, the welding of the seams should be started no later than 24:00.

2) Time of matching. According to the results of Fig. 2, from 20:00 in the evening to 8:00 the next day, the temperature of steel box is the same as the ambient temperature and temperature difference of top plates are smaller than 2 ℃, the time quantum is the best time for matching. Because the welding of the seams should be started no later than 24:00, the matching of girder segment must be accomplished in only 4 h, from 20:00 to 24:00.

3) Time of embedment of segment into closure gap. According to Fig. 2, after 18∶00 of clear day, temperature of steel box decrease significantly and close to the ambient temperature. The matching of joint seams must begin at 20∶00, so the best time for the embedment of segment into gap is 18∶00 at nigh, which means there is only 2 h for the embedment, and the Incremental launching distances due to the temperature of steel box at this time.

Hence, the construction control conditions of working procedures of incremental launching and assisted closure method are shown as follows (Table 4).

Table 4 Construction control conditions of working procedures

Working procedures	Time quantum	Duration time /h
Embedment of closure segment	18∶00 ~ 20∶00	2
Closure matching	20∶00 ~ 24∶00	4
Joint seams welding	0∶00 ~ 8∶00	8

3.4 Key construction parameters of incremental launching and assisted closure method

3.4.1 Incremental launching distance

The best time for the embedment of segment into gap is 18∶00 at night, under the conditions of clear days in June or July, the temperature conditions of steel box girder are shown in Table 5.

Table 5 Temperature conditions of girder for incremental launching ℃

Ambient temperature	Top plate temperature	Bottom plate temperature	Temperature difference of top and bottom plates
35	35	37.5	5

Distance of incremental launching consists of three parts: a. the impact of the rising of average temperature of steel box on the length of the closure segment; b. the influence of temperature difference of top plate and bottom plate to the width of the top plate and bottom plate; c. reserve working joint seams for the embedment (10 mm on each side).

Due to the above temperature conditions, the incremental launching distances obtained by using the overall computing model, which are shown in Table 6.

Table 6 Incremental launching distance mm

Influence quantity of rising temperature of the whole structure	Influence quantity of temperature difference to the width	Width of reserved working joint	Sum of distance
126	10	10	146

Namely, the incremental launching distance on both sides is 146 mm.

3.4.2 Incremental launching force

Incremental launching force composed of two parts:

1) Pedestal frictional forces. The forces consist of the frictional forces of vertical temporary support, the frictional forces of temporary support and permanent support in side span aided span. Experience has shown that friction coefficient of support taking value is 0.1 for safety. To reduce the reaction force of the temporary support of the tower anchor-range, the vertical force of the temporary fixed vertical cable force must release 50 %.

After analysis, if release 50 % of provisional vertical cable force, the reaction forces of temporary support and permanent support in side span aided span are listed in Table 7.

Table 7 Reaction forces and frictional forces of support

Pier number	Tower range	Pier 3	Pier 2	Pier 1
Reaction forces /kN	39 246	5 355	3 751	2 062
Frictional forces /kN	3 925	536	375	206

Total frictional force is 5 042 kN.

2) Provisional vertical cable force. Through theoretical calculation and analysis, we can see that in order to overcome the changes of temporary fixed vertical force, the needed incremental launching force is 10 399 kN.

Hence, the incremental launching force is 5 042 + 10 399 = 15 441 kN.

3.5 Key technological measures of incremental launching and assisted closure method

3.5.1 Adjustment measure of width difference of seams between the top plate and bottom plate

After the lifting of the closure segment, because of construction errors and the objective existence of temperature deviation, a certain deviation of the width difference of seams between the top plate and bottom plate is exist. The main causes are as follows:

1) The influence due to the setting of substitute pressure at the front-end of cantilever to the lineshape is different from the impact of load translate by closure segment through bridge crane, which can lead width difference of the roof and floor joints;

2) The temperature difference between the top and bottom plate of the steel girder is different at the time of closure as described in Fig. 2, which will cause width difference of the roof and floor joints;

3) The influence of static wind will cause the overall deformation of both sides of the main cantilever beams, and induce the width difference of the upper and lower joint seams.

In order to eliminate the width difference caused by the reasons mentioned above, and to ensure a

smooth matching of closure segment, it can take the following adjustment measures:

1) The influence to rotation angle of cantilever due to the substitute pressure of closure segment is different from the impact of reaction force of bridge crane. By calculating analysis, we can see that the resulting width difference between the top and bottom plate of gap is exceed 10 mm, the needed adjustment moment reaches 26 040 kN· m, and the adjustment force is more than 6 510 t after the installation of jack under the top and bottom plate of gap. As a result, this part of deviations may be overcomed by adjusting the stayed cable at front-end of cantilever.

2) Width difference of the top and bottom plate caused by the temperature difference: Set tension support for jacking on both sides of the top and bottom plate of seams, and produce moment to adjust the width difference through tension. Install 4 groups large-scale compulsory adjustment equipment on both sides of the top and bottom plate of seams, the 650 kN design load per group can meet the requirements of width difference adjustment quantity, which is 4 mm.

3) Width difference of the upper and lower joint seams induced by wind: Set tension support for jacking on the web of upper and lower plate, and use 200 t tension force to produce moment to adjust the width difference, which is 25 mm.

3.5.2 Measurements for overcoming the temperature variation

Even in the stable after midnight, the average temperature of steel box and the temperature difference between the top and bottom plate change continuously, as the temporary fixation between the girder and tower not release yet, the change of temperature inevitably induce the internal force in the structure, therefore, we must take measurements to over come the problem, and to ensure stability and quality of welding. The main measurements are as follows:

Use clamps to overcome temperature variation of clamp seams.

The clamp seams last a long time, and the temperature of the girder has changed, hence auxiliary measures are introduced as follows:

1) Weld to connect the beam on both sides of the plate beam using 4 steel plates at the top and bottom of the plate, before the installation of the clamps.

2) Set clamp seams and carry out welding base construction simultaneously. Implement situation of main span closure.

4 Implementing situation of middle span closure

4.1 Implementation time of main work procedures

Closurement of middle span closure started at 5 June and lifting of closure segment was carried out at 9 June, all seams welding work of closure segment completed at 12 June and the main process of closure lasted 50 h. It can be seen that from the adjustment of local linetype of girder to the release of temporary fixation between the girder and tower, the main process would complete in accordance with the basic theory and analysis of the complete plan, and it shown that theoretical analysis and the construction organization are reasonable.

4.2 Key construction parameters

4.2.1 Incremental launching distance

Due to the following factors, differences the actual amount of closure and theoretical calculation existed:

1) Temperature of girder at the time of embedment: two days before the closure, an analysis for temperature was carried out at 18:00, and the results show that the highest temperature of girder is 26 ℃, which is lower than theoretical calculation 37.5 ℃, but the temperature difference of the top and bottom plates is 5 ℃;

2) Deformation of tower at the time of closure: Before the lifting of closure segment, the vertical deformation of tower is −30 mm at the height of bridge deck.

Based on the above factors, the actual incremental launching distance is 70 mm, and the theoretical value is 146 mm.

4.2.2 Incremental launching force

There were 16 jacks for the north and south cable tower and incremental launching force of each jack was 650 t, when the girder was pushed to the shore side. In the process of pushing, the resultant measured force of the cable of north tower was 3 768 kN, and the resultant force of the shore side was 10 983 kN, both of them were less than the theoretical values.

The force of the cable of the shore side was 10 983 kN, which was greater than the theoretical values 10 399 kN when the pedestal frictional forces was not considered. The factors are as follows:

1) At the time of pushing, the relaxation length of longitudinal cable was 20 mm, but the actual extension length was less than 10 mm, that is, during relaxation, the longitudinal cable of the shore side was complete relaxed. Hence, theoretical incremental launching force should reduce the total cable force, which was 6 870 kN.

2) Due to the post-correction incremental launching force, the real pedestal frictional force was about

4 113 kN which shows that the bearing friction coefficient is smaller than 0.1 lied between 0.05 and 0.1.

4.3 Implementation of matching seams

Before the width adjustment of joint seams, the difference of top and bottom plate of SJ34 and JH were up to 5 mm, at this time, the matching was accomplished.

After adjustment, the width difference matched well and it was about 1 mm.

As for the width difference of the upper and lower joint seams of JH and SJ34, because of the effect of wind, before the width adjustment, the width difference of web of the upper plate was 8 mm greater than lower seams, and for the top plate was 5 mm. After tensioning adjustment of the upper plate using 100 t jack, the residual width difference of top plate was less than 1 mm.

5 Experience and realization

1) Incremental launching and assisted closure method colligated the advantages of fit temperatures closure technology and incremental launching technology, the geometric size and force of completed bridge was unaffected.

2) Key construction parameters and construction conditions of incremental launching and assisted closure method were determined by theoretical analysis, and the practice has showed it's reliable and rationality.

3) As for the risks in the construction, control measures was determined through detailed calculation, risks were effectively controlled and adverse effects were overcomed, which have been showed well during construction, the closure of mid-span was always under control.

6 Conclusion

This paper introduces incremental launching and assisted closure method which has been used in the closure of Sutong Bridge, and summarizes experience in conjunction with engineering practice for your reference.

There is an increasing tendency to extend the span of the bridge, the incremental launching and assisted closure method which has been successfully applied in the closure of Sutong Bridge, this paper has guidance and reference significance for main span closure of other long span bridges.

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Author

Chen Ming, male, was born in 1976. He graduated from Chongqing Jiaotong University in 1997, B.E., and now is a senior engineer, mainly engaged in bridge construction. He can be reached by E-mail: cmmc@vip.163.com

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