

Original research article

Research on the overall and local mechanical behaviors of steel box girder cable-stayed bridge via incremental launching construction

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Abstract: In this paper, a large-span cable-stayed bridge with double pylons and double cable planes is employed to study the overall and local mechanical behaviors. The steel box girder bridge is constructed by incremental launching with the maximum span of 50 m. Through the overall stress analysis, the most unfavorable stress position of the structure in the incremental launching construction is identified; the refined local stress analysis is carried out for the girder section at this position, and the local stress characteristics of the structure are studied. The mechanical performance and the applicability of incremental launching are determined by comparing four kinds of elastic cushion. This paper aims at improving the safety of incremental launching construction of steel box girder bridge, and can provide reference for similar projects.

Keywords: incremental launching construction; steel box girder bridge; overall stress analysis; local stress analysis; elastic cushion; safety

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1. Introduction

The launching construction is to set up a prefabrication yard behind the abutment along the axis direction of the bridge, and the girders are prefabricated in sections. After assembling the precast girder segments with the completed girder segment, the girder body is pushed forward out of the prefabrication site by horizontal jack, and then the next segment of girder is prefabricated in the prefabrication yard until the jacking is completed.

At present, the incremental launching construction technology has become mature, but the related research mainly focuses on the concrete continuous girder bridge. For steel box girder launching construction, due to its cross-section form, material characteristics, local stability, no-prestress and other issues^[1], the current incremental launching construction research of concrete box girder can not be directly applied to steel box girder bridge.

Xie carried out local stability analysis of steel box girders during the process of incremental launching on the basis of the elastic thin plate theory of small deflection^[2]. Liu and Fan presented the dynamic reliability prediction method of the existing steel box girder considering the time-variant nonlinear correlations among the performance functions for the failure modes at the multiple control monitoring points^[3]. Zhou et al. investigated the temperature-induced static responses of a long-span suspension bridge with steel box girder under real service environmental conditions using numerical simulations and field

measurements^[4]. Benmohammed et al. presented the homotopy perturbation method (HPM) to predict the preand post-buckling behaviour of simply supported steel box beams with rectangular hollow section^[5]. Wang and Xiang proposed that the geometric state transfer method could realize the precise control of the geometric state of a steel box girder with ectopic installation and multi-state transition^[6]. Wang and Zhu investigated the temperature distribution of the steel box girder systematically with the structural health monitoring system (SHIMS) of the Sutong Cable-stayed Bridge^[7].

As for the structural mechanical behavior in the process of incremental launching construction, Rosignoli, based on the error analysis of bridge boundary support construction, increased the bearing reaction force obtained from the overall analysis by 1.3 times^[8], so as to consider the stress of steel girder; Fontan et al.^[9] proposed an optimization design method of guide girder for the incremental launching construction of bridge; Granata et al.^[10] carried out relevant parameter analysis to study the influence of design parameters on the bridge structure in the construction process.

Jung et al. optimized the length of the steel launching nose, span-to-depth ratio, buckling shear stress of the corrugated steel webs to ensure the safety of the concrete box girder bridges with corrugated steel webs during the incremental launching construction^[11]. In response to the low stiffness of steel U-shaped girders, Wang et al. utilized a local stress control strategy to avoid local yielding of the bottom plate, which realized incremental launching construction of steel U-shaped girders^[12]. Considering the structural characteristics and construction conditions of the huge steel truss girder, Ding et al. proposed a technique of incremental launching method with suspension cable stiffening chords for incremental launching construction of the continuous steel truss girder bridge^[13]. Schmidt ameliorated the problem that the slender supports of the bridge were prone to vortex excitation during the incremental launching construction phase by using aerodynamic L-shaped spoilers^[14]. With the example of a long-span bridge whose main span is 180 m, Chai and Song analyzed the feasibility of the incremental launching construction method without supporting piers by finite element method^[15]. After analyzing different connections between steel webs and concrete bottom plates in pre-pressed concrete composite box girders with corrugated steel webs, Liang et al. proposed that local connections and complex U-shape configurations were necessary for meeting structure's stress state requirements during the incremental launching construction^[16].

Zhang^[17] combined numerical method and analytical method to study the expression and variation rule of pier reaction force and bending moment of steel box girder by analyzing the force of girder during jacking; Li et al.^[18] comprehensively used ANSYS and MATLAB software to carry out launching construction of a steel box girder. The simulation analysis and optimization were carried out, and the advantages of ANSYS and MATLAB software were fully used to effectively improve the safety of steel box girder incremental launching construction. Song^[19] carried out force analysis on the incremental steel box girder and temporary pier, studied the influence of horizontal friction force on pier in the process of pushing, and carried out corresponding optimization design; Qu^[20] established girder-shell mixed finite element and the local analysis model of steel box is used to analyze the stress of each plate of steel box under adverse working conditions in the process of pushing. A reliable solution is proposed for the case of excessive plate stress, and the stress distribution of different solutions is compared.

The previous research can enhance the understanding of structural stress characteristics in incremental launching construction and improve the accuracy of structural stress analysis. On this basis, the overall and local mechanical behavior of steel box girder in incremental launching construction of long-span cable-stayed bridge can be further studied, and the stress characteristics of steel box girder in the process of incremental launching can be analyzed precisely, and the applicability of each elastic cushion layer for

pushing can be clarified, so as to ensure the launching construction of large-span steel box girder cable-stayed bridge was carried out smoothly.

2. Project overview

In this paper, a large-span cable-stayed bridge with double pylons and double cable planes is employed. The total length of main bridge is 860 m, the main span is 430 m, and the steel box girder of the main bridge is 38 m wide and 3 m high. It is designed according to the two-way six lanes, and non-motorized vehicle lanes and sidewalks are set on both sides. The elevation and cross-section of the main girder are shown in **Figures 1 and 2**.

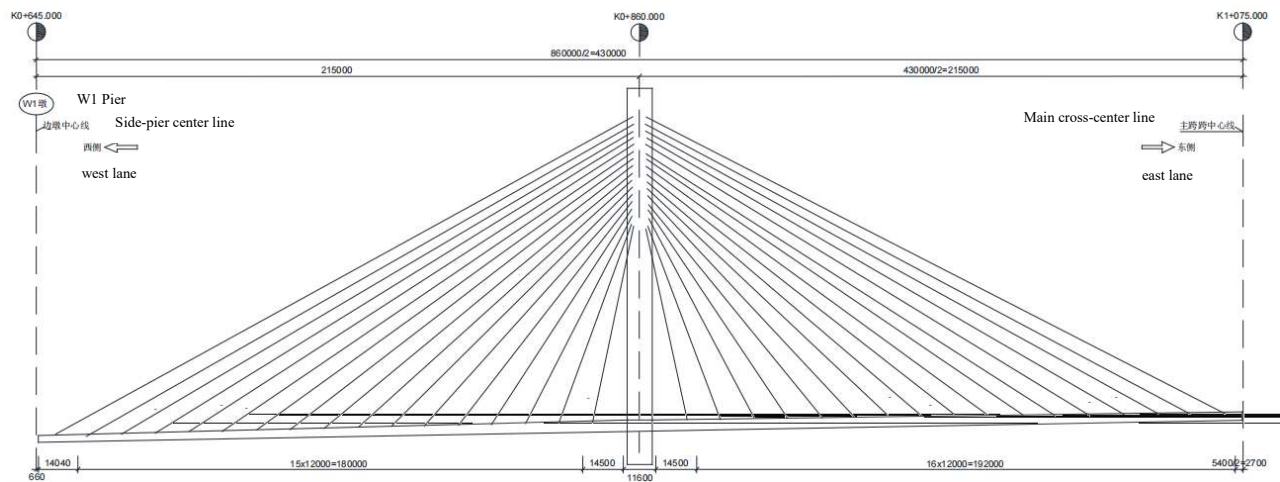


Figure 1. Elevation of main beam.

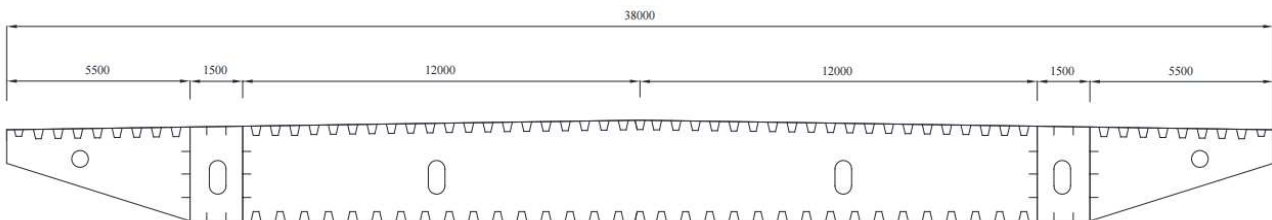


Figure 2. Section of main beam (unit: mm).

The steel box girder of the bridge is made of Q345qD material and adopts the incremental launching construction. Firstly, three segments are assembled on the assembly platform, and then the 36 m guide girder with Q345B material is installed. Then, the incremental launching construction is started, and a total of 9 temporary piers are set on the jacking path, with the maximum span of 50 m. The layout of temporary pier and launching platform is shown in **Figure 3**.

The thickness of top plate, bottom plate and web plate of the steel box girder is 20 mm. The thickness of U-shaped stiffening rib of top plate and bottom plate is 8–20 mm, and the thickness of diaphragm plate is 16 mm. The strength of steel plates with different thickness is different, as shown in **Table 1**^[21].

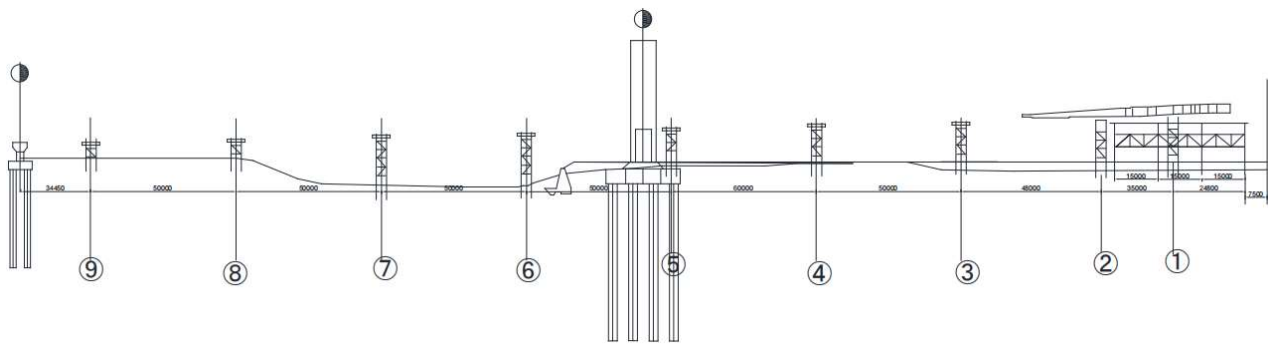


Figure 3. Elevation layout of incremental launching construction.

Table 1. Steel strength (unit: MPa).

Grade	Thickness t or diameter d (mm)	Tensile, compressive and flexural	Shear	End bearing (planed and pressed)
		f	f_v	f_{ce}
Q345	t (or d) ≤ 16	305	175	400
	$16 < t$ (or d) ≤ 40	295	170	
	$40 < t$ (or d) ≤ 63	290	165	
	$63 < t$ (or d) ≤ 80	280	160	
	$80 < t$ (or d) ≤ 100	270	155	

3. Overall stress analysis

3.1. Unfavorable working conditions of steel box girder

During the pushing process of steel box girder, the fulcrum and structural system are constantly changing. There are three kinds of unfavorable conditions for steel box girder: in front of the temporary pier on the steel guide girder, when the steel guide girder is on the temporary pier, and the steel guide beam is between the two temporary piers:

(1) Before the steel guide girder is upon the No. n # pier , the steel box girder is in the maximum cantilever state; at this time, the stress of the steel box girder at the top of the pier fulcrum is unfavorable;

(2) After the steel guide girder is upon the No. n # pier , the system transformation occurs, at this time, the reaction force of some pier supports is large, and the corresponding steel box girder on the top of pier is unfavorable;

(3) After the steel guide girder is installed on the No. n # pier, in the process of pushing to $(n + 1)$ # temporary pier direction, the guide girder and the steel box girder will continue to push. The internal force of steel box girder is constantly changing under the influence of self weight difference of girder and the change of cantilever length of guide beam; the internal force distribution of steel box girder is calculated every one meter after pushing No. n # on steel guide girder; And the continuous calculation and analysis show that when n # pier on steel guide beam is pushed backward to $(n + 1)$ # pier to 16 m of guide beam cantilever, steel box girder is more unfavorable. According to the above analysis, according to the most unfavorable control principle, the calculation conditions of steel box girder in the process of incremental launching are formulated. As shown in **Table 2**, the calculation and analysis are carried out according to the working conditions to clarify the stress law of steel box girder in the process of pushing.

Table 2. Jacking calculation conditions of steel box girder.

Calculation condition			
Serial number	Describe	Serial number	Describe
1	Assembly of initial three segments and guide beam	13	Continue pushing 16 m
2	Before upper temporary pier L3	14	Before L7 of upper temporary pier
3	After upper temporary pier L3	15	After L7 of upper temporary pier
4	Continue pushing 11 m and start to assemble lb13/lb12	16	Continue pushing 16 m
5	Before L4 of upper temporary pier	17	Before L8 of upper temporary pier
6	After L4 of upper temporary pier	18	After L8 of upper temporary pier
7	Continue pushing 16 m	19	Continue pushing 16 m
8	Before L5 of upper temporary pier	20	Before L9 of upper temporary pier
9	After L5 of upper temporary pier	21	After L9 of upper temporary pier
10	Continue pushing 16 m	22	Continue pushing 16 m
11	Before L6 of upper temporary pier	23	Steel beam reaches design position
12	After L6 of upper temporary pier	/	/

3.2. Calculation and analysis

The finite element model is established via the special software MIDAS Civil, and the steel box girder is simulated by beam element. According to the launching conditions of steel box girder in **Table 2**, the analysis is carried out one by one. With the launching, the longitudinal stress distribution of the steel box girder changes, but the maximum positive stress appears at the lower edge of the steel box girder section above the temporary pier under all working conditions, in other word, the safety state of the steel box girder is controlled by the negative bending moment at the top of the pier.

Table 3 shows the maximum stress of steel box girder under various launching conditions. From the table, during the construction process, when pushing 16 m steel guide girder on L8 and L9 piers, the stress of steel box girder is unfavorable, and the maximum stress of steel guide girder (condition 18) appears at L8 pier, $\sigma_{max} = 50.2 \text{ MPa} < f = 295 \text{ MPa}$, and the safety state of steel box girder meets the requirements.

Table 3. Maximum stress of steel box girder under different launching conditions (unit: MPa).

Pushing case	1	2	3	4	5	6	7	8	9	10	11	12
Stress	18.6	23.5	17.0	37.2	30.5	23	45.3	28.7	25.6	44	28.7	24.2
Pushing case	13	14	15	16	17	18	19	20	21	22	23	/
Stress	44.1	28.6	25.3	44.1	50.2	50.2	44.1	43.7	43.7	44.1	28.0	/

4. Local stress analysis

In this paper, the shell-solid mixed nonlinear finite element model is established via ABAQUS software to analyze the local nonlinear mechanical behavior of steel box girder during incremental launching construction. The shell element S4R (four node curved thin or thick shell, reduced integral, hourglass control, finite membrane strain) is adopted for steel box girder section, and solid element C3D8R (eight node linear hexahedron element, reduced integral and hourglass control) is adopted for elastic cushion. Two reference points are set up at shell-solid contact mixed nonlinear finite element model based on ABAQUS platform. The reference points are connected with the cross-sections of the girder by coupling constraint. The shear force and bending moment at both ends sections of the 13.2 m girder are applied to the reference points

at both ends of ABAQUS model to simulate the structural actual stress state.

On this basis, four kinds of elastic cushion are compared and analyzed: type I rubber cushion (elastic modulus 7.84 MPa), type II rubber cushion (elastic modulus 500 MPa), Teflon board plate (elastic modulus 1.42 GPa), steel plate (elastic modulus 2.06 GPa), and study the jacking applicability of each elastic cushion.

4.1. Local stress characteristics of steel box girder

The maximum Mises stress of each plate of steel box girder corresponding to each elastic cushion is shown in **Table 4**. According to Saint Venant’s principle, the influence of elastic cushion with different stiffness on the stress of steel box girder is limited to the supporting area. Therefore, the stress distribution of the steel box girder corresponding to each elastic cushion is approximately the same, and difference of the maximum stress is small.

Table 4. Maximum mises stress of each plate of steel box girder corresponding to each elastic cushion (unit: MPa).

Elastic cushion	Roof	Web	Floor	Diaphragm
Type I rubber pad	61.1	131.9	151.8	92.7
Type II rubber pad	63.8	145.3	156.4	106.6
PTEE plate	67.2	151.3	159.4	111.9
Steel plate	64.3	288.7	190.4	113.9

The maximum stress of web plate and bottom plate of steel box girder mainly occurs at the intersection area. For type I rubber pad and type II rubber pad, the stress in the joint area between web, bottom plate, and U-shaped stiffener near the bottom plate is relatively high, as shown in **Figures 4** and **5**, the geometric shape of these areas changes suddenly and there is stress concentration phenomenon. With the increasing of the stiffness of elastic cushion (PTFE plate, steel plate), the vertical load is more distributed to the web, and the load proportion of the bottom plate decreases, as shown in **Figures 6** and **7**. At this time, the stress of the bottom plate is relieved, but the stress of the web is more unfavorable.

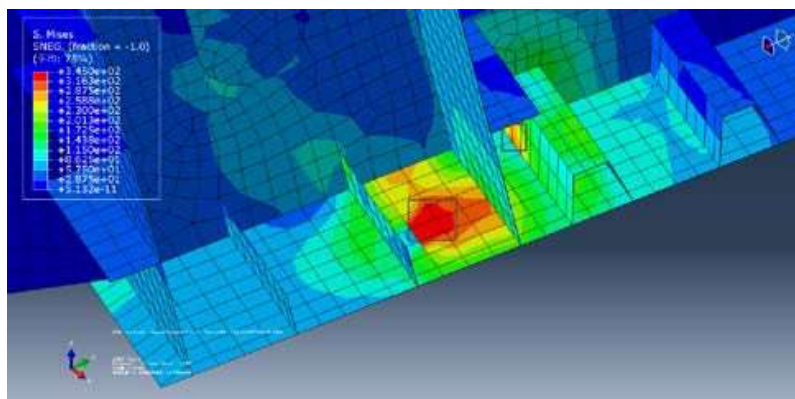


Figure 4. The most unfavorable area at bottom plate of steel box girder (type I rubber pad).

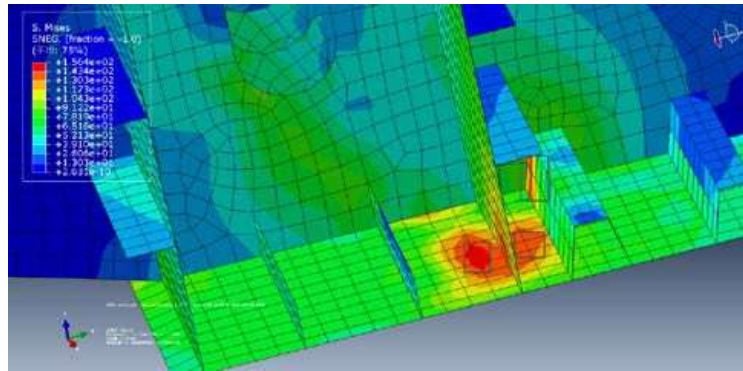


Figure 5. The most unfavorable area at bottom plate of steel box girder (type II rubber pad support).

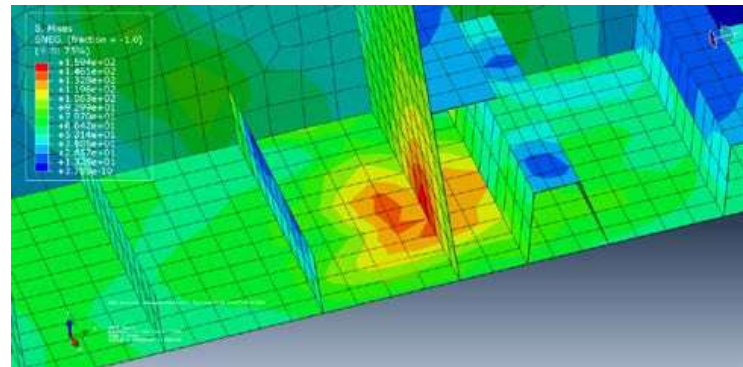


Figure 6. The most unfavorable area at bottom plate of steel box girder (PTEE plate).

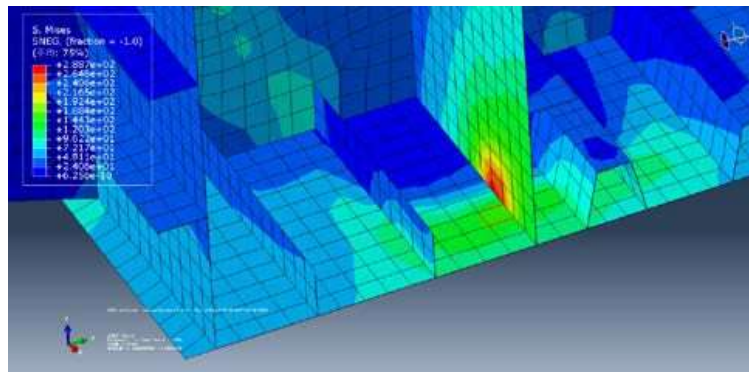


Figure 7. The most unfavorable area at bottom plate of steel box girder (steel plate support).

4.2. Elastic cushion analysis

The Mises stress of each elastic cushion of steel box girder during incremental launching is shown in Table 5.

Table 5. Mises stress range of elastic cushion.

Elastic cushion	Mises stress	
	Maximum	Minimum
Type I rubber pad	1.46	0.13
Type II rubber pad	8.88	0.12
PTEE plate	15.58	0.25
Steel plate	128.80	0.31

From the table, the larger the stiffness of elastic cushion is, the more uneven the Mises stress distribution is, and the more unfavorable the stress of material is.

Compared with the supporting reaction of elastic cushion, the uneven phenomenon of supporting reaction is more and more obvious with the increasing of stiffness of elastic cushion; among them, the steel plate has the highest stiffness, and the supporting reaction force near the section of diaphragm and web is very high, and the supporting reaction force of other parts is small, which is not conducive to the stress of steel box girder. In addition, the stiffness of type I rubber cushion is too low and the jacking force required is large, which makes the force of temporary pier more unfavorable. Therefore, type II rubber pad and PTFE plate are more suitable as elastic cushion to support steel box girder.

5. Conclusion

In this paper, a large-span steel box girder cable-stayed bridge constructed by incremental launching construction is taken as the research object, and the overall and local mechanical behavior analysis is carried out. The following conclusions are drawn:

(1) Under all working conditions, the maximum positive stress appears at the lower edge of the steel box girder section on the temporary pier, that is, the safety state of the steel box girder is controlled by the negative bending moment at the top of the pier.

(2) With the increasing of the stiffness of the elastic cushion, the vertical load is more distributed to the web, and the load proportion of the bottom plate decreases. At this time, the stress of the bottom plate is relieved, but the stress of the web is more unfavorable.

(3) According to the analysis of supporting reaction force of elastic cushion, with the increase of stiffness of elastic cushion, the uneven phenomenon of supporting reaction force becomes more and more obvious; type II rubber cushion and PTEE plate are more suitable for supporting steel box girder with elastic cushion.

Author contributions

Conceptualization, PZ and XJ; methodology, HG; software, PZ; validation, PZ, XJ and HG; formal analysis, XJ; investigation, PZ; resources, HG; data curation, XJ; writing—original draft preparation, PZ; writing—review and editing, PZ, XJ; visualization, HG; supervision, XJ; project administration, XJ; funding acquisition, PZ. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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