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RESEARCH ARTICLE

Experimental monitoring of the strengthening construction of a segmental box girder bridge and field testing of external prestressing tendons anchorage

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ABSTRACT Prestressed concrete segmental box girder bridges are composed of short concrete segments that are either precast or cast in situ and then joined together by longitudinally post-tensioning internal, external, or mixed tendons. The objectives of this study are to monitor the construction process of the external prestressing tendons to strengthen the bridge structure and perform a field load test to measure the strain and the deflection of the anchorage devices of the external prestressing tendons to determine the state of these devices after tension forces are applied. The monitoring process of the external prestressing tendons construction includes inspecting the cracks in the diaphragm anchorage and the deviation block devices before the tension forces are applied to the external tendons; measuring the deformation of the steel deviation cross beam during the tension process; measuring the deformation of the box girder after different levels of tension forces are applied; measuring the elongation of the external tendons in each level of the tension; and measuring the natural frequency of the external tendons after the tension process is complete. The results of the monitoring process show that the measured values of the deformation, the elongation, and the natural frequency meet the requirements. Therefore, there is no damage during the construction and the tensioning of the external prestressing tendons. A field load test is performed to the anchorage beam, the steel deviation block devices, and the steel deviation cross beam. The field load test results of the anchorage devices show that the values of the strains, the stresses, and the deflection are less than the respective allowable limit values in the requirements. Therefore, the anchorage devices have sufficient strength, and the working state is good after the tension forces are applied to the external prestressing tendons.

KEYWORDS prestressed concrete, box girder, monitoring, external tendons, strain, deflection

1 Introduction

Prestressed concrete segmental box girder bridges with externally post-tensioned tendons are one of the main new developments in bridge engineering construction in recent years. The many advantages of this type of structure include its fast and versatile construction, no disruption at the ground level, a highly controlled quality and its associated cost savings. Therefore, this type of structure is the preferred solution for many long, elevated highway bridges [1].

Prestressed concrete segmental box girder bridges are composed of short concrete segments that are either precast or cast in situ and then joined together by longitudinally post-tensioning internal, external, or mixed tendons. The cross-sectional geometry of the concrete segments has varied widely, ranging from single to multiple cells with straight or sloping webs. Prestressed box girder bridges typically exhibit small deflections during the first years of service and then continue to deflect excessively [2–4].

The concrete structure strengthening involves upgrading the strength and the stiffness of the structural members, and

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the repairing process involves re-establishing the strength and the function of the damaged members. The number of factors dictates which method is appropriate for the strengthening and the repairing of the bridge structural members. These factors include the type and the age of the structure, the importance of the structure, the magnitude of the strength (which increases) required, the type and the degree of the damage, the available materials, the cost, the feasibility, and the aesthetics. The strengthening and the repairing of the bridge structure can be both an effective and an economic solution in the appropriate situation [5–9].

External prestressing refers to a post-tensioning method in which the tendons are placed on the outside of a structural element to facilitate flexural resistance. It may be efficiently utilized in the construction of segmental box-girder bridges and the strengthening of existing concrete beams. External prestressing was first used in the late 1920s and has been widely used recently in bridges, both for new construction and the strengthening of existing structures to increase their load carrying capacity. The prestressing force is transferred to the member section through end anchorages, deviators saddles. The use of external post-tensioning became popular in the last two decades, after the corrosion protection of external tendons was improved by methods such as epoxy and grease coating [10–16].

External post-tensioning restores the serviceability of an existing bridge by relieving the dead load-bending effects and thus reducing deflections or eliminating cracking. The additional post-tensioning material will also increase the ultimate limit state capacity in bending and shear [17].

The main objectives of this study are to monitor the construction process of the external prestressing tendons used to strengthen a bridge structure and apply a field load test to measure the strain and the deflection of the anchorage devices of the external prestressing tendons to determine the state of these devices after the tension forces are applied to the external tendons.

2 Description of the bridge structure

The Sanguxian viaduct prestressed concrete bridge is a continuous segmental box girder T-shape rigid frame bridge that is located in the Mudanjiang-Harbin Highway within the Heilongjiang Province of north-east China. The bridge is 280-m long and 12-m wide. It has a slope of 2.2% along the length of the spans. The bridge was constructed using the cast-in-place cantilever method. There are two separate T-shaped cantilever beams. Each side of the T structure consists of 10 segments. The length of segment No. 0, which is on the top of the pier, is 7.0 m. Segment Nos. 1 and 2 are cast in situ. The 8 remaining cantilever segments are cast in place. The bridge was open to traffic in 1997. Figure 1 shows the longitudinal layout of the bridge structure, Fig. 2 shows the general view of the bridge, and Fig. 3 shows the pier and the span of the prestressed box girder.

3 Strengthening process of the bridge structure

The Sanguxian Bridge suffers from many damages, including serious cracks within the web, the top, and the bottom of the box girders, spalling and cracks in the bridge deck pavement, and damage of the expansion devices. Therefore, the damaged structural members of the bridge need to be strengthened to improve the stiffness of the bridge structure. The strengthening process of the bridge structure consists of six stages. In the first stage, the bridge structure spans are longitudinally strengthened by installing the external prestressing tendons, the diaphragm anchorage, and the deviation blocks devices. In the second stage, the grouting method is used to close the cracks in the web, the top, and the bottom of the box girders. In the third stage, the inclined webs of the box girders, which suffer from serious cracks that result from their sticking to the steel plates, are strengthened. In this stage, steel plates are pasted to the floor of the box girders in the middle and the side spans of the bridge to strengthen it. In the fourth stage, the connection rigidity of the closed end of the box girders is improved by attaching steel plates to the joints of that end's sides. In the fifth stage, the bridge deck pavement is reconstructed and the expansion devices are replaced. In the sixth stage, the box girder of pier No. 3 is repaired using epoxy concrete after the concrete surface, which has been frozen, is chiseled. This study investigates the strengthening process using external prestressing tendons. Figure 4 shows the external prestressing tendons that are located near pier box girder.

4 Monitoring of the external prestressing tendons construction

The monitoring process of the construction of external prestressing tendons consists of five stages. In the first stage, the cracks in diaphragm anchorage and the deviation block devices are inspected before the tension forces are applied to the external tendons. In the second stage, the deformation of the steel deviation cross beam is measured as the tension forces are applied to the external tendons. In the third stage, the deformation of the box girder is measured after different levels of tension forces are applied. In the fourth stage, the elongation of the external tendons is measured for each tension level. In the fifth stage, the natural frequency of the external tendons is measured after the tension process is completed. Four tension force levels, 30% σ_k, 60% σ_k, 80% σ_k, 100% σ_k, are applied to the external tendons. Figure 5 shows the steel deviation devices in the box girder.

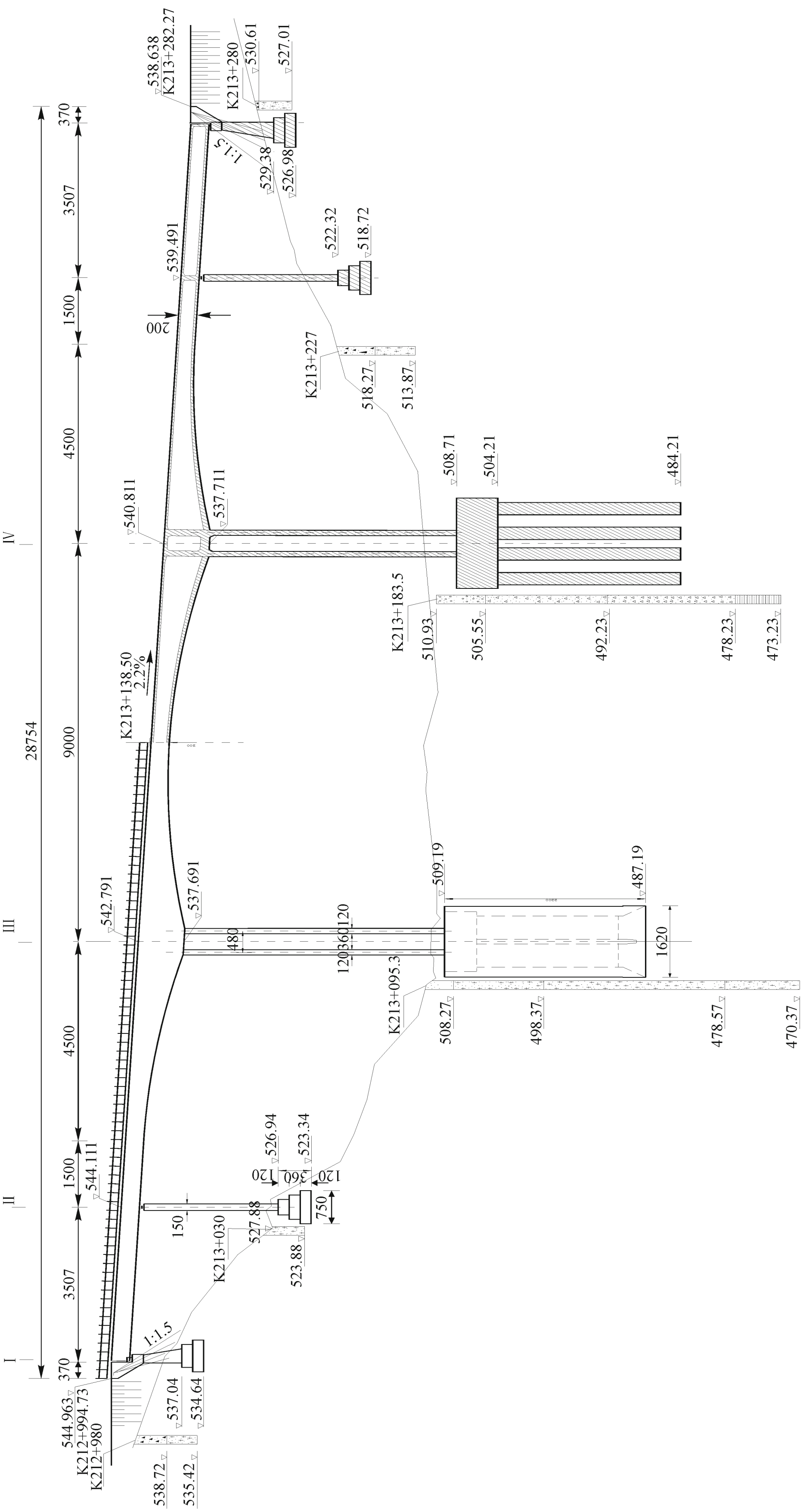

Fig. 1 Longitudinal layout of the Sanguxian Bridge/mm

Fig. 2 View of the Sanguxian Bridge

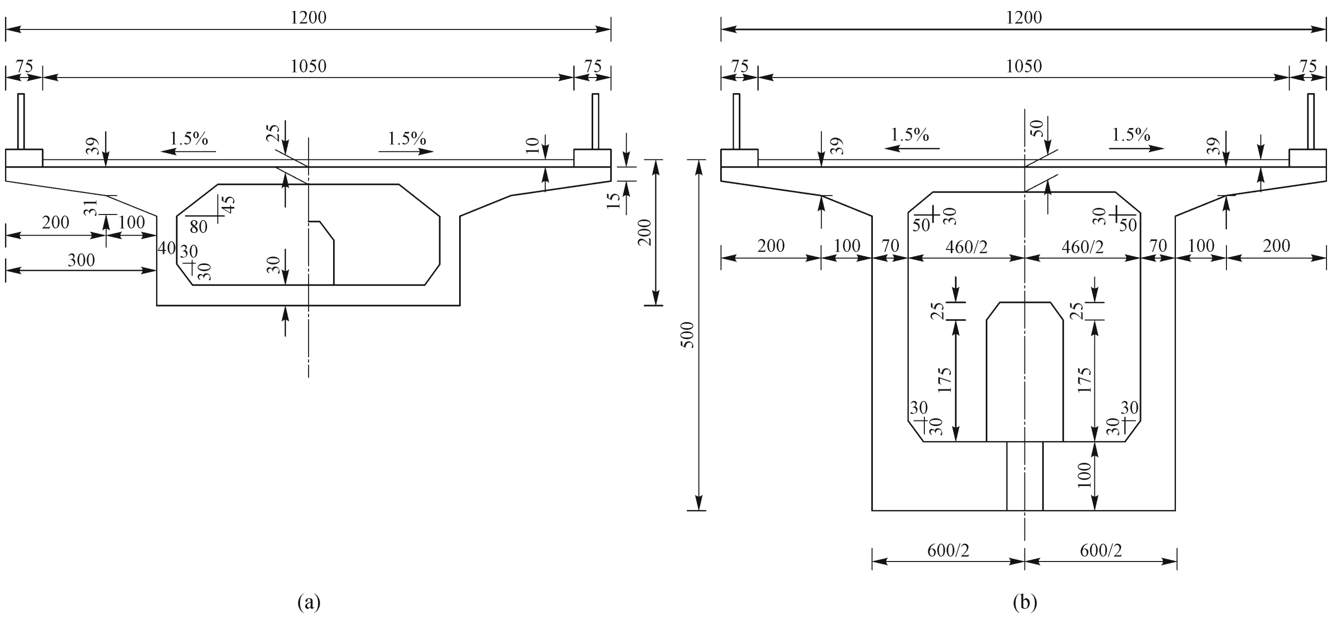

Fig. 3 Transverse section. (a) The span box girder; (b) the pier box girder/mm

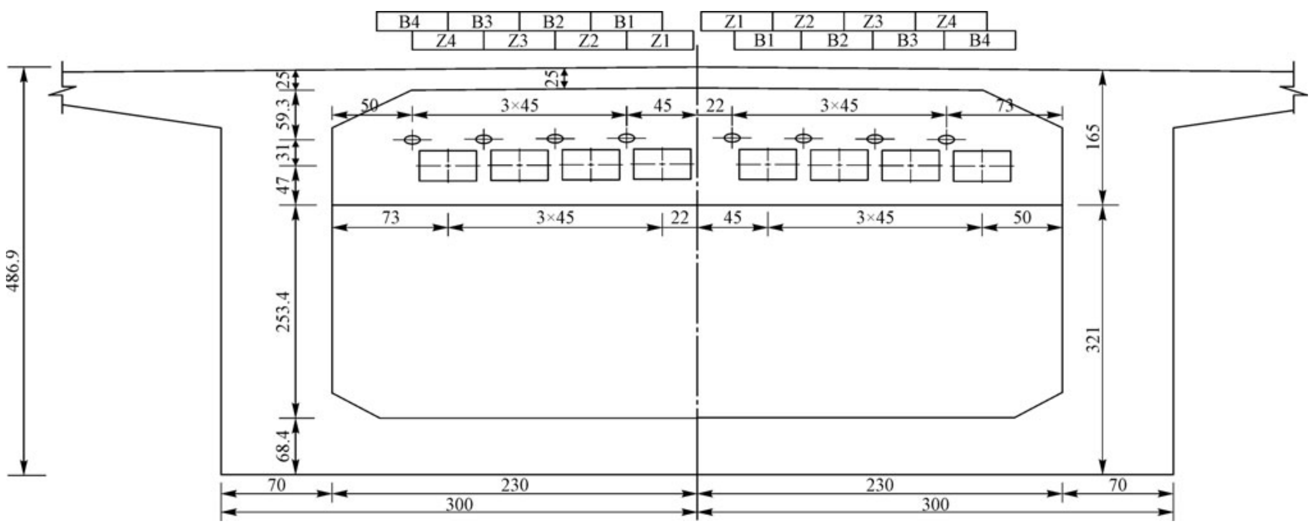

Fig. 4 External prestressing tendons near the pier box girder/mm

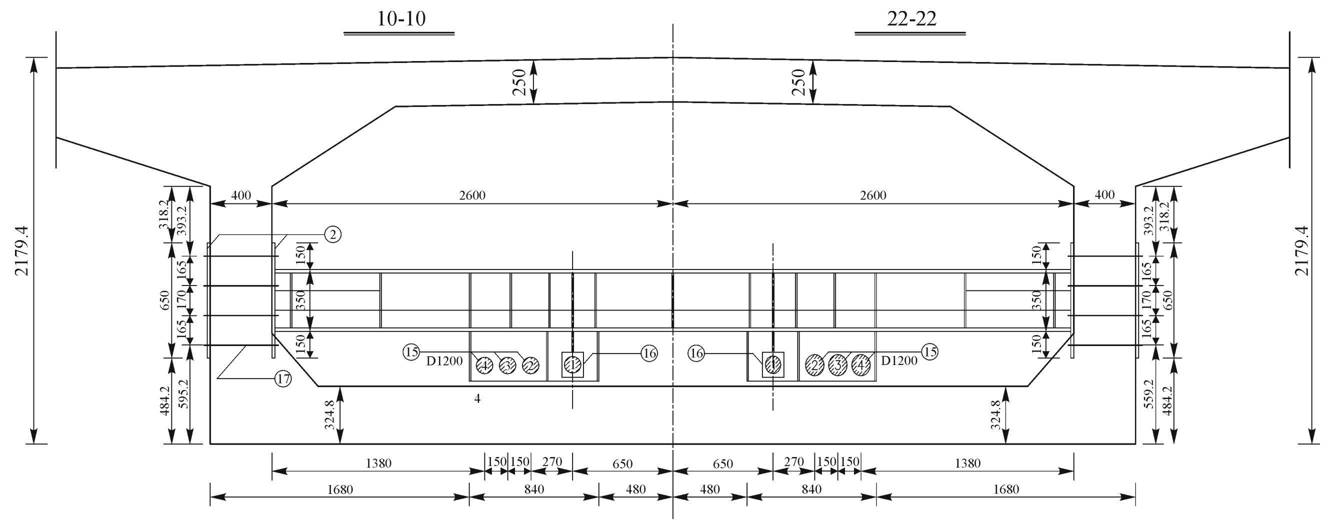

Fig. 5 Steel deviation devices in the box girder/mm

4.1 Inspection of the appearances of the diaphragm anchorage and the deviation block devices

The diaphragm anchorage and the deviation block devices are inspected before the tensions forces are applied to the external prestressing tendons. The results of this inspection show that there are no cracks or other damage in the diaphragm anchorage, the deviation block devices, or the surrounding area of these devices.

4.2 Measuring the deformation of the steel deviation cross beam

As different levels of tension forces are applied to the external prestressing tendons, the deformation of the steel deviation cross beam is measured at six points. As shown in Fig. 6, six dial gauges are installed at these locations, which have maximum vertical reactions. Table 1 lists the steel deviation cross beam deformations for the different levels of tension forces. As shown in the table, the maximum deformation is 2.18 mm at measuring point No. 4, which is located at the mid-span of the steel deviation cross beam. This value is less than the allowable limit value of 6.15 mm. Therefore, the safety factor is high, and the carrying capacity meets the requirements. The end anchorage of the steel deviation cross beam of the B4 and the Z4 tendons deforms when tension forces are applied to the B2 tendon. Figure 7 shows the deformation of the end anchorage of the steel deviation cross beam, and Table 2 provides the deformations of the end anchorage of the steel deviation cross beam. As shown in the table, the maximum and minimum vertical deformations, which occurred simultaneously, are 15 mm and 4 mm, respectively, and the deformation appears in the same time in the end anchorage.

4.3 Measuring the deformation of the box girder

The vertical deflection of the box girders needs to be measured along the length of the bridge to determine the

(a) (b)

Fig. 6 Locations of the deformation dial gauges on the cross beam. (a) At mid-span; (b) at end-span

Table 1 Measured deformations of the steel deviation cross beam/mm

location on cross beam	No.	30%–60%	60%–80%	80%–100%	total
left point	1	0.21	0.10	0.09	0.40
	2	0.28	0.10	0.11	0.49
span points	3	0.97	0.44	0.43	1.84
	4	1.04	0.57	0.57	2.18
right points	5	0.08	0.05	0.05	0.18
	6	−0.05	0.13	0.13	0.21

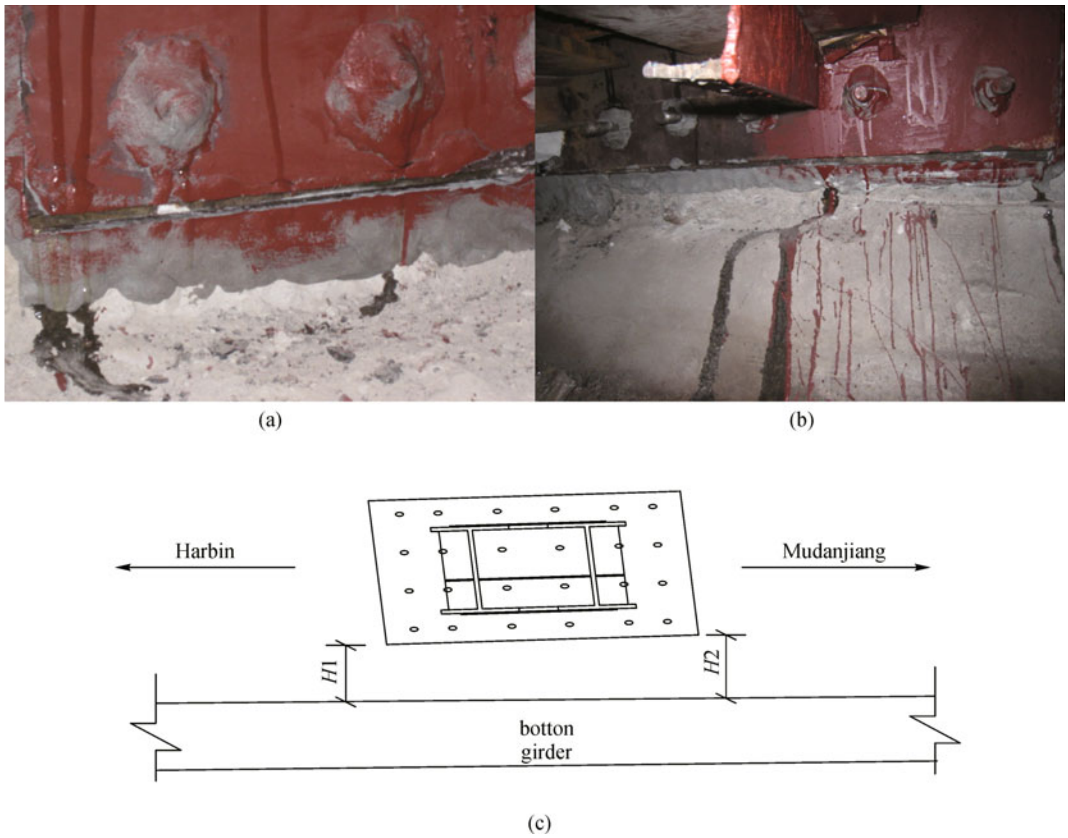

Fig. 7 Deformation of the end anchorage of the steel deviation cross beam. (a) Front view; (b) side view; (c) sketch of the end anchorage

deflection change due to the tension forces in the external prestressing tendons. Figure 8 shows the vertical deflections along the length of the bridge. As shown in the figure, there are different degrees of deflection at each mid-span after the external prestressing tendons are tensioned. The maximum vertical deflection is 12 mm on the Mudanjiang city side.

4.4 Measuring the elongation of the external prestressing tendons

As the tension forces are applied to the external prestressing tendons, the elongation of each external tendon is measured and compared with the designed elongation values. Tables 3 and 4 provide the measured and the designed elongation values, respectively. As shown in these tables, the measured elongation values are less than the designed elongation values, especially in the B3 and the B4 tendons. The difference between the measured and the designed elongation values is greater than 10%. Therefore, this difference meets the allowable limit value in the requirements (6%) [14].

4.5 Measuring the natural frequency of the external prestressing tendons

To measure the natural frequency of the external prestressing tendons, a DH5922 dynamic data collection system is

Table 2 Measured deformations of the end anchorage of the steel deviation cross beam/mm

measuring point	end-spans				mid-spans			
	Harbin left side	Harbin right side	Mudanjiang left side	Mudanjiang right side	Harbin left side	Harbin right side	Mudanjiang left side	Mudanjiang right side
H1	4	13	10	13	13	15	4	4
H2	4	13	7	4	4	4	10	13

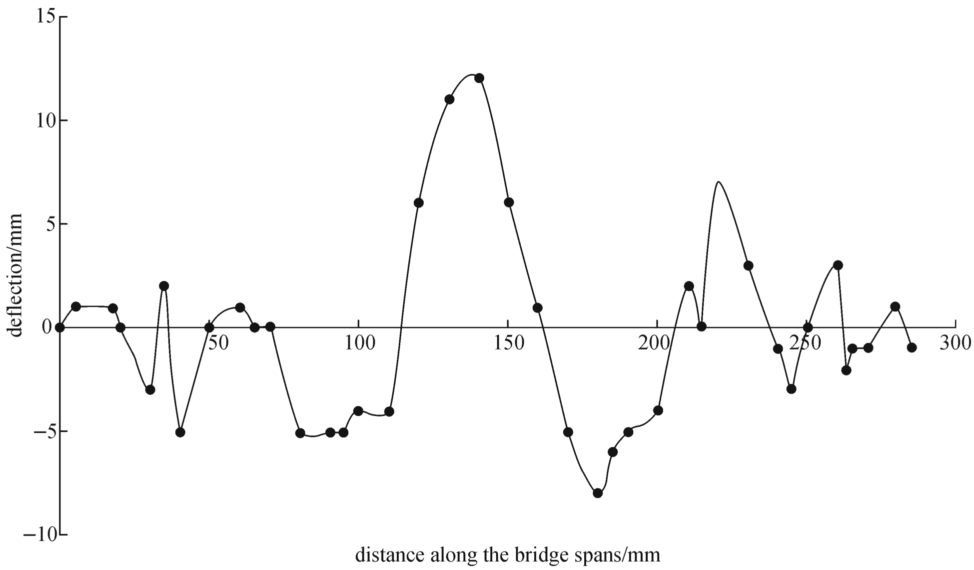

Fig. 8 Vertical deflections along the length of the bridge after the external prestressing tendons are tensioned

Table 3 Measured elongation values of the external tendons/mm

direction	external tendons			
	B1	B2	B3	B4
Harbin left	573	571	543	532
Harbin right	572	572	570	552
Mudanjiang left	570	573	545	565
Mudanjiang right	571	570	550	544
direction	Z1	Z2	Z3	Z4
left	585	578	581	594
right	574	584	581	601

Table 4 Designed elongation values of the external tendons

external tendons	B1	B2	B3	B4	Z1	Z2	Z3	Z4
tension force/kN	187.7	187.7	187.7	187.7	187.7	187.7	187.7	187.7
designed elongation/mm	603	604	604	604	598	600	600	600

installed. The relationship between the tension and the frequency of the external prestressing tendons is shown in Eq. (1) [9].

$$T = \frac{4wL^2}{n^2 g} f_n^2 = K \cdot f_n^2, \tag{1}$$

where T = the tension force, W = the unit weight of the external tendons, L = the length of the external tendons, n = the order vibration, g = the acceleration of gravity, f_n = the frequency, K = the proportional coefficient between the external tendon tension force and the frequency.

From Eq. (1), the theoretical frequency values can be calculated and compared with the measured natural frequency. Figure 9 shows the DH5922 dynamic data collection system, and Fig. 10 shows the measured frequency and the measured acceleration of the external tendons. Table 5 provides the theoretical frequency and the measured natural frequency of the external tendons. As shown in this Table, the measured frequency is 1.66 Hz for all of the external prestressing tendons. This value is less than the theoretical value, which ranges from 1.871 to 1.891 Hz. Therefore, the external prestressing tendons are in a good working state.

5 External prestressing anchorage device tests

To ensure that the strengthening process impacts the stability and the reliability of the anchorage beam and the deviation block devices, a field load test is performed on these elements. Three load tests are performed in this study, including the anchorage beam test, the deviation block test, and the deviation cross beam test.

5.1 Load test of the anchorage beam

The steel plate of the anchorage beam is type Q345, which is 20-mm thick; this steel plate is welded with an I-shaped steel section that is 500 mm high and 150 mm wide. Figure 11 shows the sketch of anchorage beam.

5.1.1 Test device

Two side I-shaped steel beams are used in opposing directions. The load is performed using two jacks, which apply an increasing force until it reaches 120% of the maximum tension force of the external tendon (187.5 $\times$ 1.2 = 225 T). Figure 12 shows the load test devices, including the strain and the deflection dial gauges. Figure 13 shows the dimensions of the I-shaped steel beam. In this test, the horizontal strain and the vertical deflection are measured under the applied load and compared with the respective allowable limit values. Two strain dial gauges are installed on the top plate of the steel beam at mid-span. Five deflection dial gages are supported at mid-span, the

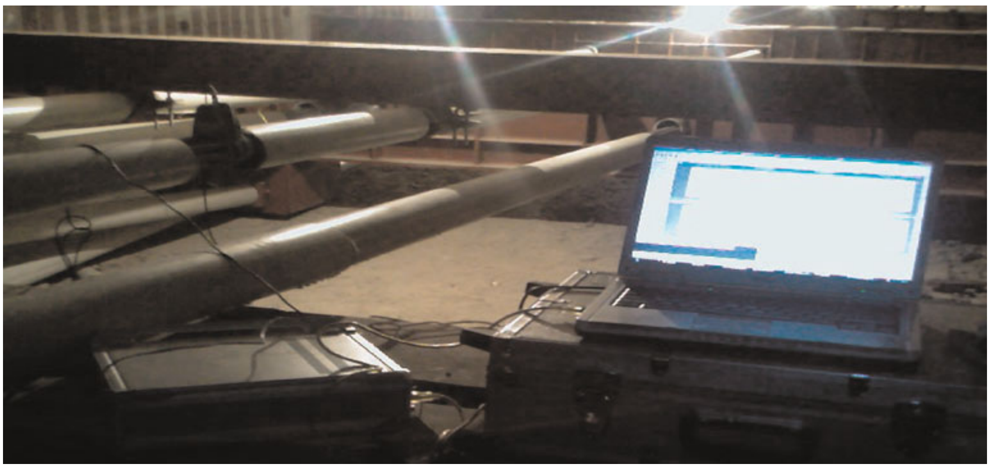

Fig. 9 DH5922 dynamic data collection system

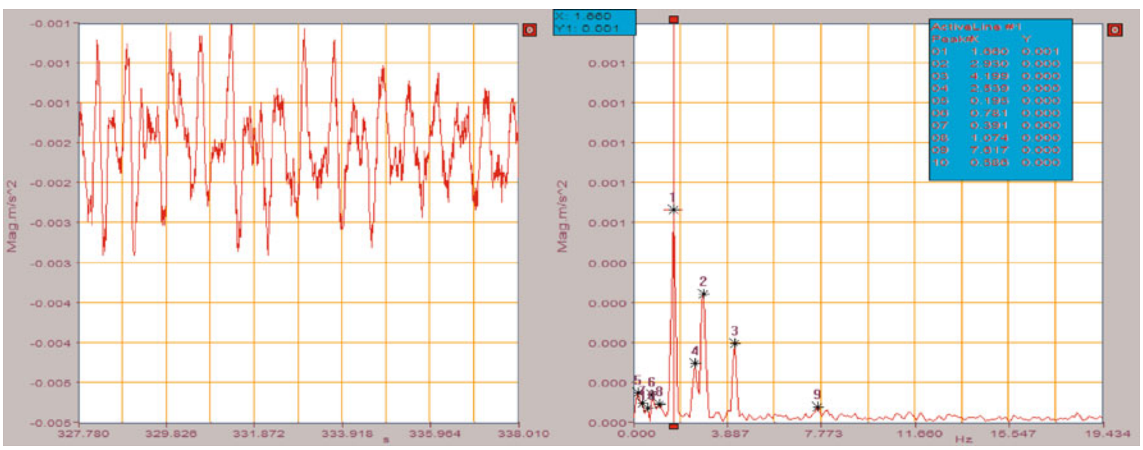

Fig. 10 Measured frequency and acceleration of the external tendons

Table 5 Theoretical and measured frequencies of the external tendons

external tendons	tension/kN	tendon length/m	theoretical frequency/Hz	measured frequency/Hz	measured/theoretical
B1	1877	100.592	1.874	1.660	0.89
B2	1877	100.614	1.873	1.660	0.89
B3	1877	100.656	1.872	1.660	0.89
B4	1877	100.746	1.871	1.660	0.89
Z1	1877	99.641	1.891	1.660	0.88
Z2	1877	99.684	1.891	1.660	0.88
Z3	1877	99.766	1.889	1.660	0.88
Z4	1877	99.943	1.886	1.660	0.88

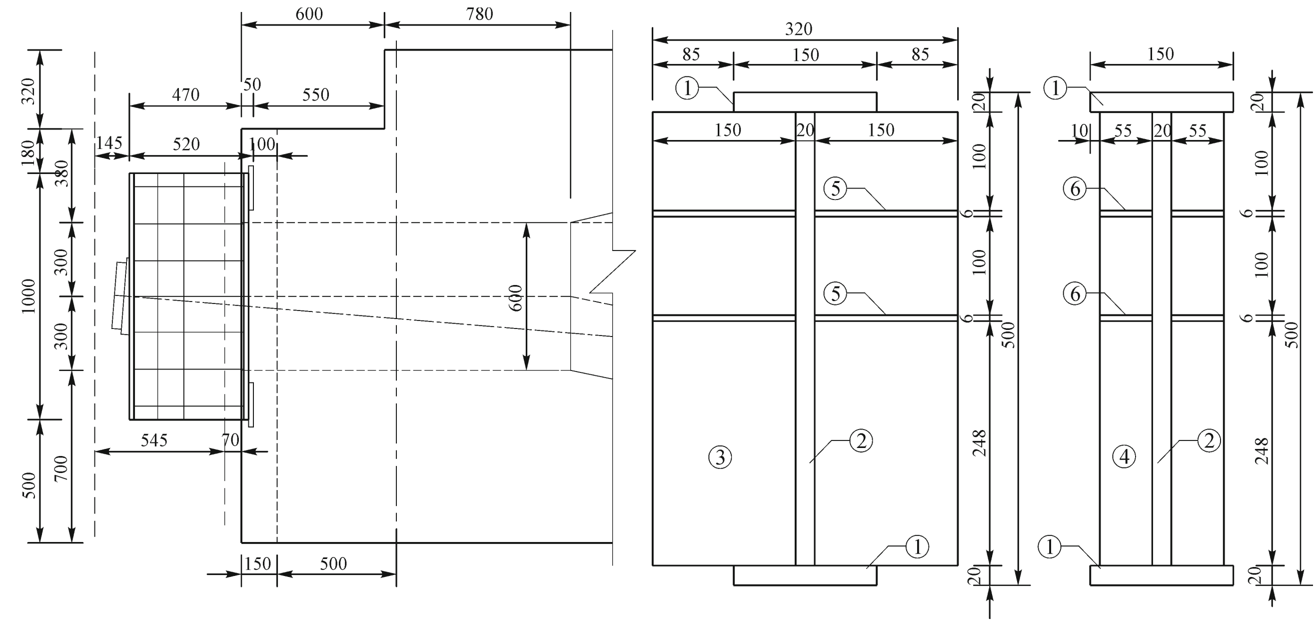

Fig. 11 Sketch of the anchorage beam

supports points, and along the height of the mid-span web plate.

5.1.2 Results of the test

Table 6 lists the strain values of the anchorage beam. As shown in the table, the maximum strain is 852 με at the mid-span of the anchorage beam under a 225-T load, and the stress is 170 MPa, which is less than the allowable stress of the steel plate Q345 (295 MPa). Therefore, the strength of the anchorage beam meets the requirements, and the anchorage beam is in a good elastic working state. Table 7 lists the vertical deflection of the anchorage beam. As shown in the table, the relative residual of the deflection ranges from -0.5% to 11.2%, which is less than the allowable limit value of 20%.

5.2 Load test of the steel deviation block

The steel deviation block is located at the mid-length of the external tendons and anchored to the bottom floor of the box girder using two steel plates. Figure 14 shows the steel deviation block structure. The load test is performed on the inside of the box girder.

5.2.1 Test devices

The load test system consists of main beam, two secondary beams, strengthening connections, and four jacks to apply the load. Figure 15 shows the sketch of the load test system. In this test, dial gauges that were installed on both sides of the steel deviation block measure the horizontal and the vertical deflections. Four measuring points are selected at the deviation block locations at which the

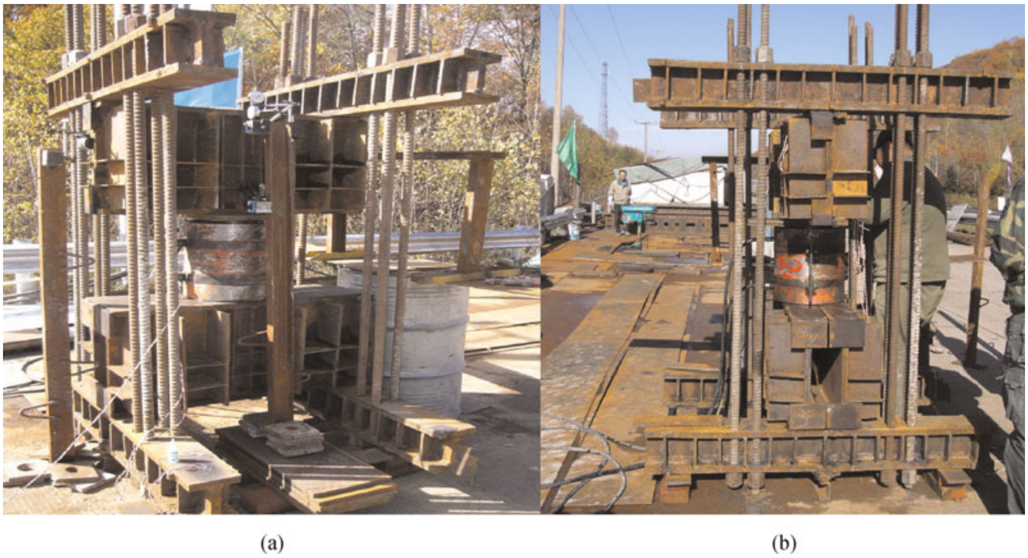

Fig. 12 Load test devices, including the strain and the deflection dial gauges. (a) Isometric view; (b) side view

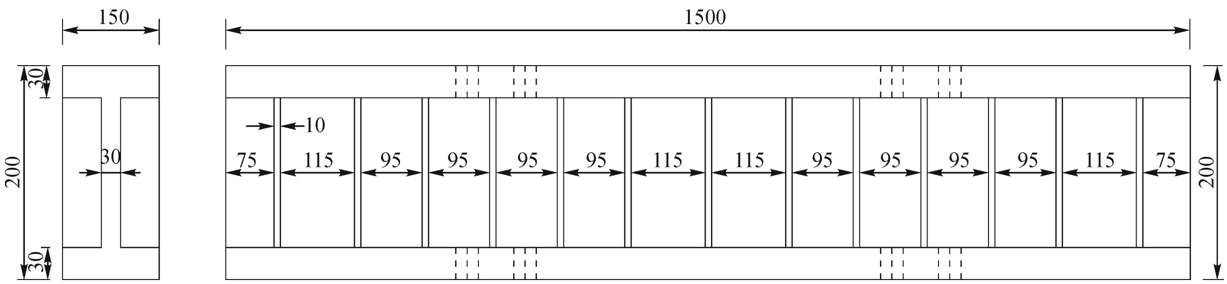

Fig. 13 Dimensions of the steel I-shaped beam/mm

Table 6 Strains of the anchorage beam/με

measuring point	loading						unloading				relative residual strain/%
	45T	90T	135T	180T	225T	total strain/με	135T	45T	0T	total strain/με	
1	151	177	168	180	176	852	–398	–256	–179	–833	2.2
2	135	174	161	177	175	822	–387	–243	–155	–785	4.5

Table 7 Vertical deflections of the anchorage beam/mm

measuring point	loading						unloading				relative residual deflection/%
	45T	90T	135T	180T	225T	deflection	135T	45T	0T	deflection	
F1	2.46	0.34	1.03	0.78	0.77	5.38	–1.63	–1.75	–1.40	–4.78	11.2
F2	0.81	0.70	0.53	0.51	0.50	3.05	–1.02	–0.91	–1.01	–2.94	3.6
D1	2.68	0.78	0.69	0.68	0.63	5.46	–1.31	–1.12	–2.95	–5.38	1.5
D2	2.75	1.01	0.86	0.85	0.85	6.32	–1.81	–1.42	–3.00	–6.23	1.4
D3	2.23	1.05	0.78	0.77	0.67	5.50	–1.57	–1.35	–2.61	–5.53	–0.5

highest stresses occur. Figure 16 shows the locations of dial gauges that were used to measure the strain and the deflection.

5.2.2 Results of the test

Table 8 lists the strain values of the steel deviation block

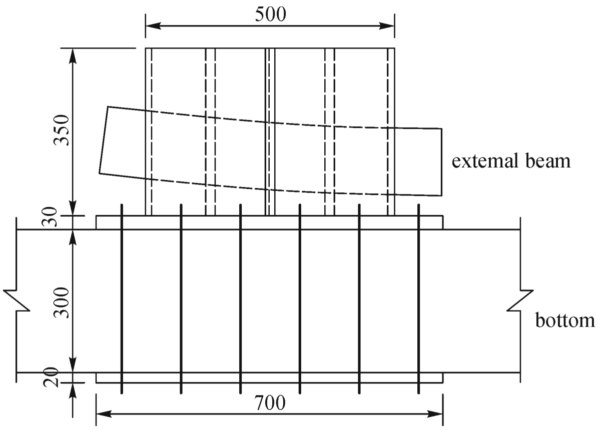

Fig. 14 Steel deviation block structure/mm

structure after the load is applied. As shown in the table, the maximum value of the strain is 24 με, and the maximum value of the stress is 4.8 MPa, which is less than the allowable limit value of the steel plate type Q345 (295 MPa). Therefore, the steel deviation block structure has sufficient strength to resist the loads and is in a good elastic state. Table 9 provides the vertical deflections of the steel deviation structure. The maximum deflection is 2.62 mm at the measuring point No. 4 at the mid-span of the structure; this value is less than the allowable limit value of 3.5 mm (1400/400 = 3.5 mm). Therefore, the carrying capacity and the reliability of the steel deviation block devices are acceptable.

5.3 Load test of the steel deviation cross beam

5.3.1 Test devices

The steel deviation cross beam is anchored to the web of the box girder using two steel plates. The load test is

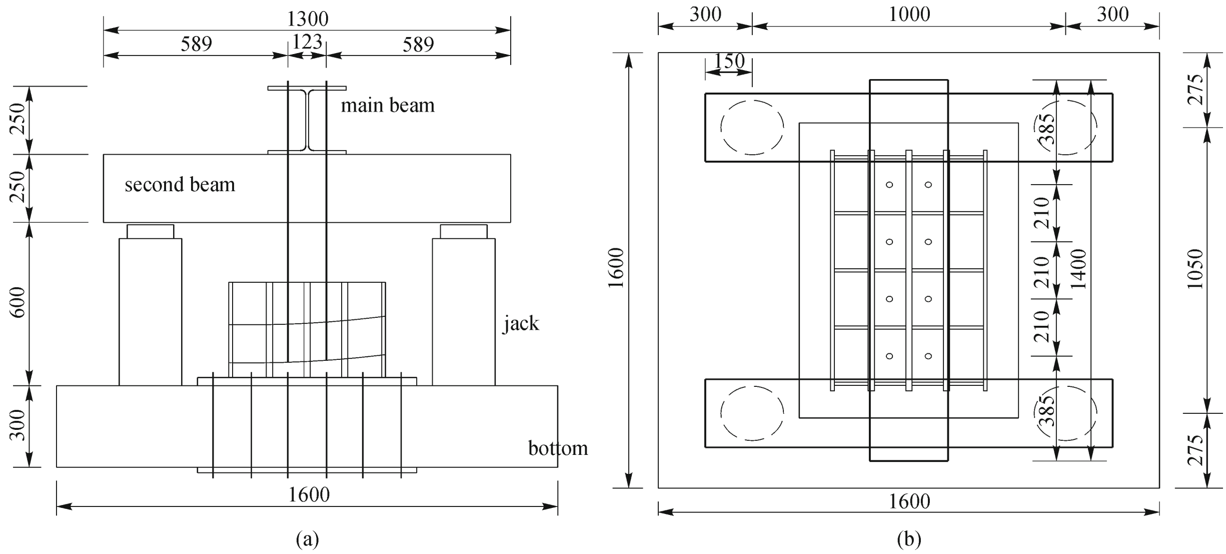

Fig. 15 Load test system. (a) Front view; (b) top view/mm

Fig. 16 Dial gauge location

Table 8 Strains of the steel deviation block structure

measuring point	1	2	3	4
strain/με	19	24	16	17

Table 9 Deflection values of steel deviation block structure

measuring point	first reading	final reading	difference in the deflections
1	1.00	1.01	0.01
2	0.65	0.64	−0.01
3	0.49	0.50	0.01
4	2.61	2.62	0.01

performed using two jacks, and the load is 70 T. The horizontal strain and the vertical deflection are measured using dial gauges. Figure 14 shows the load test system and the dial gauges.

5.3.2 Results of the test

Table 10 lists the strains of the steel deviation cross beam. As shown in the table, the maximum strain and the maximum stress are 696 με and 139.2 MPa, respectively. The maximum stress is less than the allowable limit value of the steel plate Q345 (295 MPa). Therefore, the stability and the reliability of the steel deviation cross beam are acceptable, and the strength meets the requirements. Table 11 lists the deflections of the steel deviation cross beam. As shown in the table, the maximum deflection is 6.56 mm at the mid-span of the steel deviation cross beam; this value is less than the allowable limit value of 12.25 mm ($L/400 = 4900/400 = 12.25$ mm). Therefore, the stiffness of the steel deviation cross beam structure is sufficient and meets the design requirements.

6 Conclusions

The main conclusions of this study are discussed below.

1) A strengthening process, including external prestressing tendons, a diaphragm anchorage, and deviation blocks devices, is used on a bridge structure. The construction process of the external tendons needs to be monitored to ensure that there is no damage during the construction and after the tension forces are applied. The monitoring process of the external prestressing tendons construction consists of five stages. In the first stage, the cracks in diaphragm anchorage and the deviation block devices are inspected before the tension forces are applied to the external tendons. In the second stage, the deformation of the steel deviation cross beam is measured as the tension forces are applied to the external tendons. In the third stage, the deformation of the box girder is measured after different levels of tension forces are applied. In the fourth stage, the elongation of the external tendons is measured for each tension level. In the fifth stage, the natural frequency of the external tendons is measured after the tension process is completed. The results of the monitoring process show that the measured deformations, elongations, and natural frequencies meet the respective allowable limit values.

Table 10 Strains of the steel deviation cross beam/με

measuring point	loading state						unloading state				relative residual strain/%
	20T	40T	50T	60T	70T	total strain	50T	20T	0	total strain	
top plate 1	136	127	99	99	80	541	−98	−253	−191	−542	0.0
top plate 2	135	186	133	126	116	696	−100	−280	−280	−660	5.2
top plate 3	153	197	134	115	89	688	−105	−285	−289	−679	1.3
top plate 1'	145	142	127	120	100	634	−112	−345	−181	−638	0.0
top plate 2'	110	136	130	90	106	572	−105	−259	−195	−559	2.3
top plate 3′	105	119	113	83	87	507	−101	−252	−158	−511	0.0
top plate 7	108	100	120	80	103	511	−82	−218	−207	−507	0.8
top plate 8	66	396	148	−48	303	865	−224	−300	−342	−866	−0.1
top plate 9	−1	−15	−17	−34	−20	−87	10	35	38	83	4.6
top plate 10	−42	−51	−55	−7	−39	−194	42	101	44	187	3.6
top plate 11	−79	−199	−94	−49	−94	−515	101	191	197	489	5.0
top plate 7'	95	108	92	42	86	423	−81	−183	−158	−422	0.2
top plate 8'	48	66	51	−26	25	164	−41	−68	−58	−167	0.0
top plate 9'	−6	−15	−7	−27	−15	−70	20	27	22	69	1.4
top plate 10'	−69	−56	−59	−71	−51	−306	45	101	154	300	2.0
top plate 11'	−71	−91	−74	−66	−65	−367	89	157	98	344	6.3

Table 11 Deflections of the steel deviation cross beam/mm

location	loading state						unloading state				relative residual deflection/%
	20T	40T	50T	60T	70T	total deflection	50T	20T	0T	total deflection	
left points	1.98	2.06	1.15	0.63	0.83	6.65	−0.28	−0.89	−5.44	−6.61	0.6
	2.84	1.87	1.03	0.57	0.76	7.07	−0.26	−0.84	−5.88	−6.98	1.3
mid-span points	0.07	4.00	2.70	1.37	2.05	10.19	−1.42	−3.51	−5.20	−10.13	0.6
	1.97	3.93	2.79	1.39	2.04	12.12	−1.46	−3.65	−4.42	−9.53	21.4
right points	1.82	3.13	1.96	0.74	1.09	8.74	−0.38	−1.25	−7.01	−8.64	1.1
	−1.78	2.05	2.03	0.70	1.06	4.06	−0.20	−2.23	−4.44	−6.87	−69.2
right fulcrum	0.10	—	0.34	—	0.21	0.65	−0.16	−0.27	−0.18	−0.61	6.2

Therefore, there is no damage during the construction and the tensioning of the external prestressing tendons.

2) A field load test is performed on the anchorage beam, the steel deviation block devices, and the steel deviation cross beam. The field load test results of the anchorage devices show that the strains, stresses, and deflections are less than respective allowable limit values in the requirements. Therefore, the anchorage devices are sufficiently strong and in a good working state after the tension forces are applied to the external prestressing tendons.

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