LIGHT WEIGHT DESIGN OF BENT CAPS IN MUNICIPAL BRIDGE ENGINEERING

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ABSTRACT

Prestressing concrete bent caps with long cantilevers are usually applied in municipal bridge engineering. However, large volume and heavy weight of bent caps put forward higher requests to transporting, handling, and assembling once precast elements are adopted instead of cast-in-place ones. To decrease the weight of bent caps, three structural schemes aimed at practical six-lane superstructures frequently used in China are proposed in this paper. Preliminary test results revealed that all the schemes are easy to construct and fairly effective in decreasing the weight of bent caps, which is very important for the development of precast segmental construction technology.

INTRODUCTION

The precast segmental construction technology has been widely adopted all over the world for the advantages such as improved construction speed, safety and quality, minimized traffic disruption and environmental impact (1). In municipal bridge engineering, the superstructures are usually wide enough to satisfy the increasing traffic quantity. Accordingly, prestressing concrete bent caps with long cantilevers are chosen as substructures to make full use of the space under the bridge. However, large volume and heavy weight of precast concrete bent caps usually make them difficult to transport, handle, and assemble.

Many creative schemes were proposed in order to decrease the weight of precast bent caps. Inverted T-type section was used for the bent cap by Billington (2). The web of the bent cap was made hollow to decrease weight except on the column tops and at the beam ends, where the prestressing tendons were anchored. Calculated results indicated that the maximum length of the bent cap could reach 13.1m and 27m for the single-column and dual-column pier, respectively. However, for the dual-column frame pier, the bent cap should be divided into two segments and connected by wet joints in the middle after being handled in position. Another precast system was developed by Washington State Department of Transportation (3), in which the bent cap was divided into two parts vertically and formed through two steps. The bottom part was precast in the first step and the top part was cast in place on site in the second step. The semi-precast bent cap was applied in the railway track project of Singapore. The outside shell was precast at first, while the internal concrete was cast in place on site using the precast shell as formwork.

In China, six-lane and eight-lane superstructures are extensively employed in municipal bridge engineering, and the corresponding bent caps are normally large in volume and heavy in weight. Obviously, a monolithic bent cap with solid section exhibiting better integrity and carrying capacity is desired. However, in this case, special transport and hoisting equipment were demanded for the bent cap weighting more than 300 tons, which could seriously affect the economic performance of the precast bent caps. Therefore, lightweight design is key to realizing the precast of bent caps. Currently, the common way is to divide the bent caps into two or three segments in the direction perpendicular to the bent cap central line, and then the segments are connected together on site by post-tensioning prestressing tendons (4). Temporary shoring and elevated formworks are needed when a certain width of wet joints was set in the middle, making it tedious to construct and time-consuming to cure. Epoxied joints could also be used to divide the bent cap into three segments, and the joints were then located on the cantilever. In this way, wet joints could be avoided, nevertheless, the joints should bear large bending moment and shear force.

Due to the disadvantages in the schemes mentioned above, new methods to decrease weight of precast bent caps are long desired, which to some extent can speed up the development of accelerated bridge construction in municipal engineering.

STRUCTURAL SCHEMES

All the schemes were proposed based on a practical project located in Zhejiang Province in China. In the prototype, the six-lane superstructure consisted of 6 small box girders, and the diamond-type section was adopted for the bent cap for better landscape effect. Each bent cap shown in Fig. 1 weights more than 300 tons, which is definitely too heavy to transport. Therefore, the bent cap was divided into two segments in the direction perpendicular to the bridge central line. The precast dual-column pier was connected with the bent cap by grouted splice sleeves (GSS) embedded in the bent cap. The bent cap was made of C60 concrete defined in the Chinese code (5), which had a cube compressive strength of 60 MPa. In the premise of similar carrying capacity, all the schemes were proposed to simplify the construction process and decrease the weight of bent caps as much as possible.

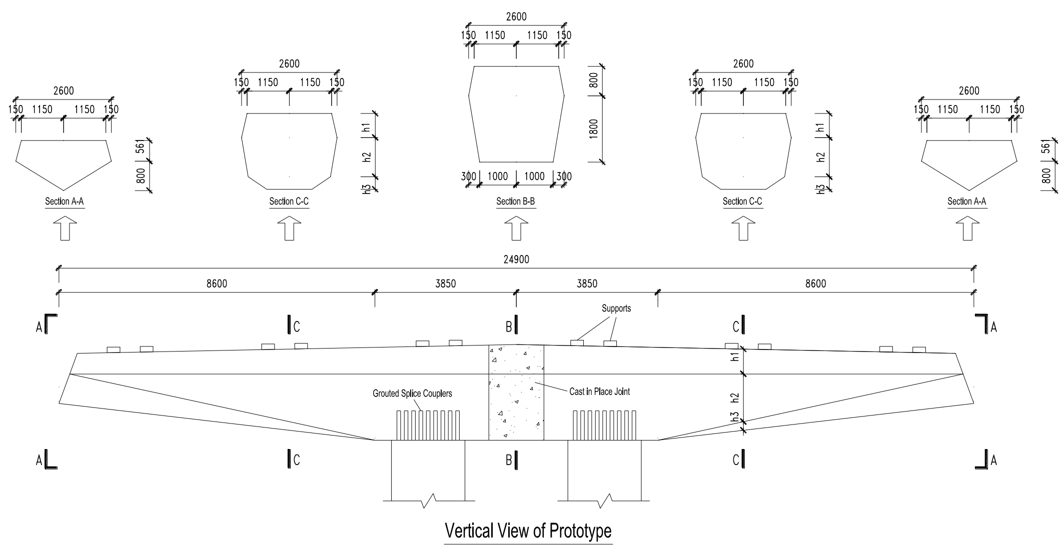


Fig. 1. Configurations for Prototype Bent Cap (millimeters)

Scheme 1

Diamond-type section was used in Scheme 1, which was the same as the prototype. However, the bent cap was divided into two equal segments in the direction parallel with the bent cap central line. The segments were precast separately and then transported to the construction site. As shown in Fig. 2, wet joints were placed longitudinally only near the supports and column tops, and the transverse U-type reinforcements were used to connect the two segments in these positions. The connection was able to ensure integrity of the two segments under external loads because the torsion effect in the bent cap is not obvious. The internal side surfaces of the segments near the bottom edge were filleted to avoid formworks when the wet joints were cast in place, and thus speeding up the construction process.

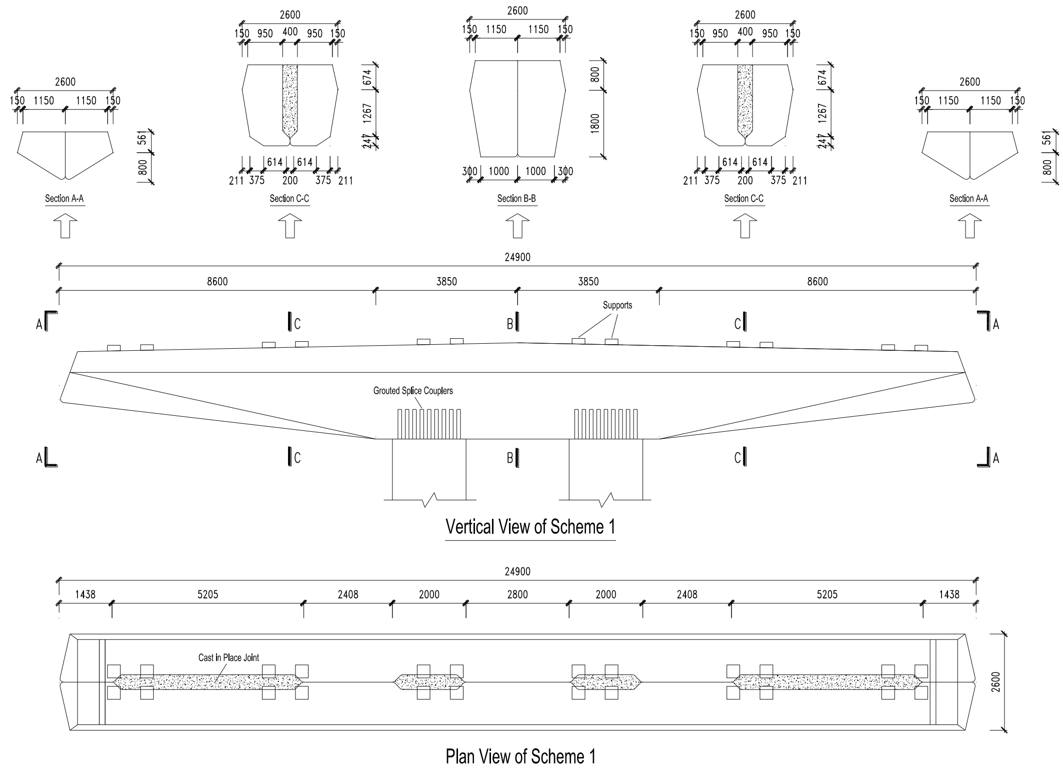


Fig. 2. Configurations for Scheme 1 (millimeters)

Scheme 2

As shown in Fig. 3, U-type section was used for the bent cap in Scheme 2. In this way, not only the weight was reduced, but also the internal steel formworks could be removed and reused after hardening of concrete. The section of the bent cap was solid on the column tops to facilitate the connection between bent cap and columns. The section under the supports was also solid to relieve stress concentration. At the beam ends, many post-tensioning prestressing tendons were anchored and the solid section was introduced again to resist localized compression. As a result, there were 5 internal cavities totally in the bent cap, and the size of the cavities was determined according to the calculation results specified on the Chinese code (5). In order to decrease the weight as much as possible, the C80 concrete defined in the Chinese code (5) was adopted. Compared with the prototype, Scheme 2 could reduce as much as 30% weight of the bent cap.

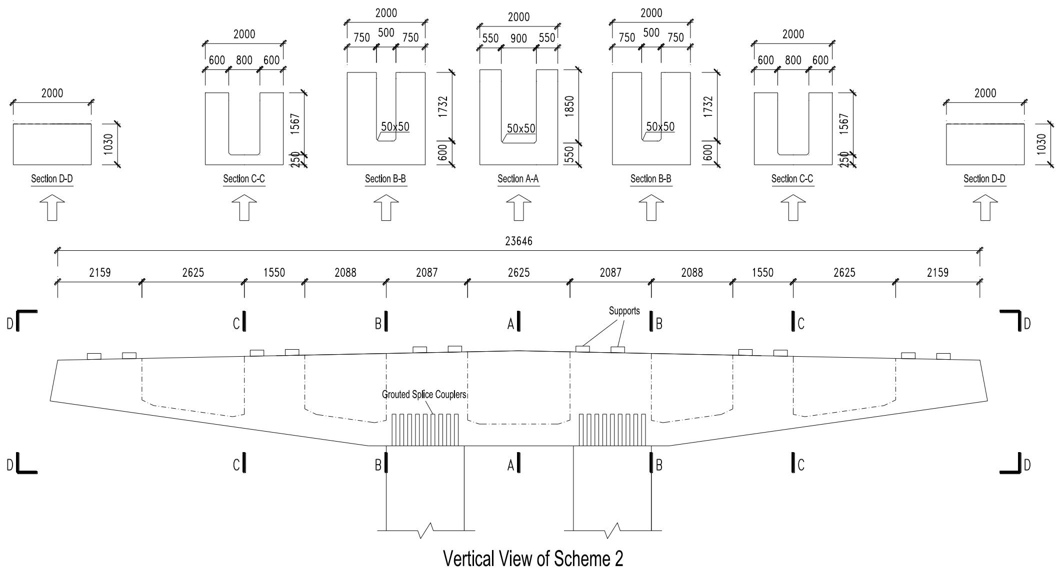


Fig. 3. Configurations for Scheme 2 (millimeters)

Scheme 3

As shown in Fig 4, inverted U-type section was used for the bent cap in Scheme 3. The internal steel formworks could also be removed and reused after hardening of concrete in this way. The section of the bent cap at the positions such as column tops, under the supports, and beam ends was solid due to similar reasons mentioned in Scheme 2. In order to decrease the weight as much as possible, the C80 concrete was adopted again. Compared with the prototype, Scheme 3 could reduce as much as 20% weight of the bent cap. The weight decreasing percentage in Scheme 3 is lower than that in Scheme 2 mainly because the bent cap with long cantilevers was under negative moment. Therefore, the U-type section was more reasonable than inverted U-type section from the aspect of mechanical analysis. However, compared with Scheme 2, the arrangement of supports in Scheme 3 could be more flexible. Besides, in the inverted U-type case, there is no need to worry about any unexpected foreign substances falling down into the boxes from the superstructures.

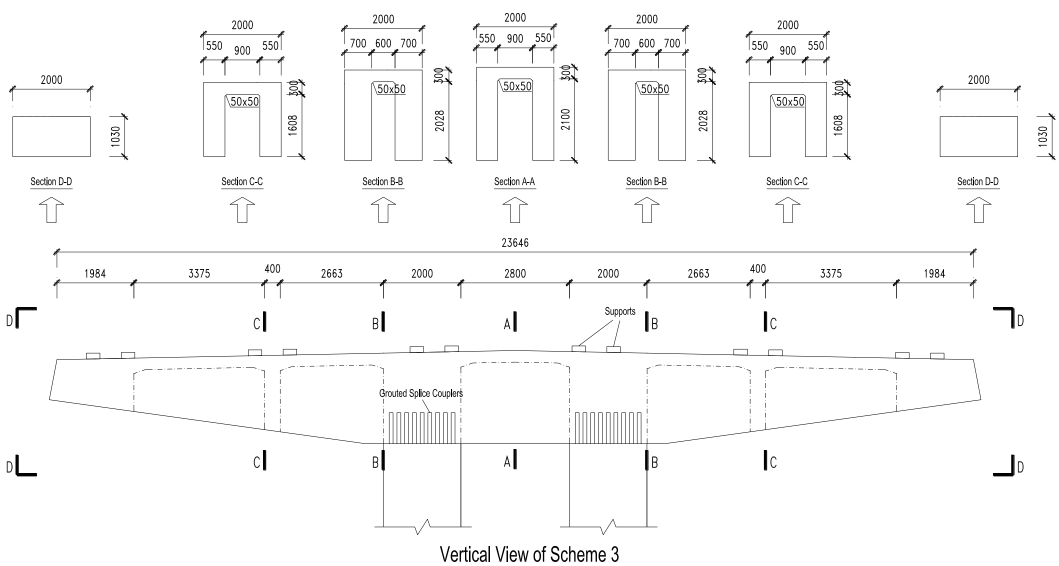


Fig. 4. Configurations for Scheme 3 (millimeters)

PRELIMINARY SUPPORTING TESTS

Design of Specimens

Five scaled specimens were designed as indicated in Table 1. Specimen 1 simulating the prototype bent cap was set as a comparison, and the other specimens were designed to simulate the schemes mentioned above. According to the loading features of the bent cap with long cantilevers, there are numerous prestressing tendons needed in order to resist the large negative moment that exists at the root of the cantilever. For each bent cap in this test, internal tendons consisting of $24\Phi_s15.2$ (each with a nominal diameter of 15.2 mm, a nominal section area of 140 mm^2, and consisting of $7\Phi5$ steel wires) were arranged in three rows vertically and placed symmetrically with the centerline of the bent cap. If all the prestressing tendons were tensioned at one-time directly in precast factory, it would cause large tensile stresses near the bottom surface of the bent cap at the root of cantilever, and the concrete would crack severely before the tests. In practical engineering project, the prestressing tendons are also tensioned in two batches. The first batch is finished in the precast factory and the second batch is done after the superstructures are hoisted in position on site. However, it is very inconvenient and time-consuming to tension the tendons in two batches in tests. In order to tension all the prestressing tendons at one-time, two thick steel plates were fixed at the bent cap ends so that $4\Phi_s15.2$ externally prestressing tendons could be arranged near the bottom surface of the bent cap. These external tendons were temporary, they were added to decrease the tensile stresses near the bottom surface of the bent cap at the root of cantilever, which was caused by the internal prestressing tendons. The external tendons were removed once a certain level of load was applied on the top surface of bent cap by hydraulic jacks in laboratory.

Table 1. Test Parameters

Specimen	Specimen Type	Section Type	Concrete Grade	Scale Ratio
1	Segmentally Precast—Prototype	Diamond-shaped	C60	1:3.08
2	Segmentally Precast—Scheme 1	Diamond-shaped	C60	1:3.08
3	Integrally Precast—Scheme 2	U-shaped	C60	1:3.24
4	Integrally Precast—Scheme 2	U-shaped	C80	1:3.24
5	Integrally Precast—Scheme 3	Inverted U-shaped	C80	1:2.92

Note: The strength grade of concrete in the table is defined in Chinese code. C60 concrete has a cube compressive strength of 60MPa, while C80 concrete has a cube compressive strength of 80MPa.

Fabrication of Specimens

All the specimens were fabricated in the precast factory. There were two supporting columns for each bent cap to simulate the commonly used precast substructures in municipal bridge engineering in China. The columns and the bent cap were precast separately. For Specimen 3-5, timber formworks were used to form the internal cavities in the bent caps and removed after hardening of concrete. For Specimen 2, the longitudinal joints between the two bent cap segments near the supports and column tops were filled with high-strength cementitious grout. To facilitate the assembly of the bent cap and the supporting columns, a 10 mm bedding layer was formed between the bent cap and the columns. High-strength cementitious grout with a compressive strength of 80 MPa was pumped into the bedding layer. Subsequently, they were jointed together by placing the bent cap on the top of the supporting columns with protruding bars being inserted into the GSS embedded in the bent cap. 24 hours later, after the hardening of the cementitious grout in the bedding layer, high-strength cementitious grout was pumped through the couplers using inlet ports at the bottom of the column until it flowed from the outlet ports at the top of couplers. Finally, the ports were plugged and the assembly process was completed. After tensioning of all the tendons to the designed stress level, they were anchored at the predetermined positions. Finally, all the embedded ducts were grouted.

The fabrication process of the specimens is shown in Fig. 5.

(a) (b) (c) (d) (e) (f)

Fig. 5. Fabrication of specimens: (a) steel cages; (b) PT ducts; (c) concreting; (d) assembling; (e) grouting; (f) prestressing

Test Setup and Loading Method

The specimens were loaded vertically in the similar manner as practical bent caps. As a result, six concentrated loads were provided by six hydraulic jacks at the positions corresponding to the supports of superstructures. In order to consider the adverse effect of torsion induced by vehicular load, all the concentrated loads were arranged eccentrically. The eccentric distance was also determined according to the maximum offset of the supports from the bent cap centerline in the prototype. Four load cases were considered as illustrated in Table 2 in this test. After that, all the specimens were loaded to final failure. After each load case, the machine was operated intermittently to maintain a constant load while the cracking of the specimen proceeded. The strain on the concrete, stirrups, reinforcements, prestressing tendons, and deflections were measured, and the crack patterns were noted during the test. The test setup is shown in Fig 6.

Table 2. Load Cases

Load Case	Load Type	Chinese code (5)	AASHOTO code (6)
1	1.0D	Construction stage load	
2	1.0D+0.7L	Frequent load combination	Service limit state
3	1.0D+1.0L	Standard load combination	—
4	1.2D+1.8L	Basic load combination	Strength limit state

Note: D denotes dead load from the superstructures, and L denotes the vehicular load.

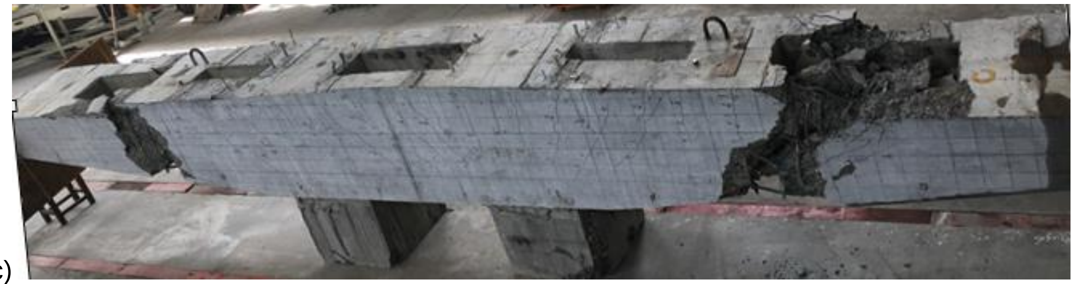
Fig. 6. Test setup.

Preliminary Test Results

The tests on Specimen 1-3 as list in Table 1 have been completed, while the tests on Specimen 4-5 were still underway. All the specimens were not cracked under Load Case 3 as illustrated in Table 2, which means the specimens satisfied the crack resistance requirements under service limit state as defined in the Chinese code (5). Finally, Specimen 1 and Specimen 2 failed in the similar way as shown in Fig 7(a) and Fig 7(b), respectively. The failure crack initiated from the top surface of the bent cap at the root of cantilever and propagated downward. Upon failure, the concrete near the bottom surface of the bent cap at the root of cantilever crushed and the failure was dominated by combined flexure and shear. Specimen 1 and Specimen 2 failed under the load that corresponds to 2.3 times and 1.8 times basic load combination, respectively. It means that dividing the bent cap into two segments along the bent cap centerline as indicated in Scheme 2 might decrease the carrying capacity of bent cap slightly. However, it still completely satisfied the carrying capacity requirements under strength limit state as defined in the Chinese code (5). For Specimen 3, the failure crack initiated from the top surface of the bent cap near the outermost loading point and extended obliquely downward at an angle of 40 degrees with the horizontal line. Finally, Specimen 3 failed under the load that corresponds to 1.5 times basic load combination, and the failure was dominated by combined shear and torsion. Because there was no enough space for all the prestressing tendons to anchor at the bent cap ends, the bottommost row of prestressing tendons had to be anchored on the bottom surface of the bent cap. The concrete there was removed to form the anchor block, which also caused localized damage. Therefore, the anchorage zone of the bottommost prestressing tendons should be strengthened in the further test. In general, the carrying capacity of Specimen 3 still satisfied the requirements of Chinese code (5).

(a)


(b)

(c)

Fig. 7. Failure modes of the specimens: (a) Specimen 1; (b) Specimen 2; (c) Specimen 3.

CONCLUSIONS

To decrease the weight of precast bent caps with long cantilevers utilized in municipal bridge engineering, three creative schemes were proposed in this paper and preliminary tests were also conducted. The following conclusions can be drawn:

1. Dividing the bent cap into two equal segments along the bent cap centerline could avoid elevated formworks and temporary shoring on site, thus saving time and cost. The segments could be connected by the longitudinal wet joints, which were placed longitudinally only near the supports and column tops.
2. By using U-type and inverted U-type section, internal cavities could be reserved in the cap beam and the internal formworks could be removed and reused. In order to maximum the size of the cavities as much as possible, high strength of concrete could be adopted. Consequently, 30% and 20% weight could be reduced for U-type section and inverted U-type section, respectively.
3. Preliminary test results revealed that Scheme 1 and Scheme 2 satisfied both the crack resistance requirements under service limit state and the carrying capacity requirements under strength limit state as defined in the Chinese code. However, the anchorage zone of the bottommost prestressing tendons in Scheme 2 should be strengthened to avoid localized damage.

ACKNOWLEGMENT

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