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A novel asynchronous-pouring-construction technology for prestressed concrete box girder bridges with corrugated steel webs

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ABSTRACT

Owing to the superior mechanical performance and material efficiency, the combination of prestressed concrete (PC) slabs and corrugated steel webs (CSW) as PC girder with CSWs (PCGCSW) is extensively applied to railway and highway bridges. To overcome the shortcomings of traditional balanced cantilever construction (TBCC) of PCGCSW, reduce environmental impact, and promote sustainable construction, a novel asynchronous-pouring-construction (APC) technology is introduced in this paper. This improved method makes full use of the excellent shear capacity of the corrugated steel webs (CSWs) to support the hanging basket, increases the construction platforms to accelerate the construction speed. Based on a practical project of a long-span composite box girder bridge with CSWs in China, the construction process of the APC method is systematically introduced, and the structural safety and environmental sustainability of such bridge using APC technology are evaluated and compared with that using TBCC. The comparison results indicate that APC method can reduce the compressive stress of top concrete slab, but slightly increase the shear stress and deflection during the cantilever construction stage because the hanging basket is directly supported by CSWs. Besides, the weight of the improved handing basket in APC technology is reduced up to half in comparison that in TBCC. Accordingly, the APC technology saves a lot of energy consumption, reduces huge CO_2 emissions for construction equipment, and shorts construction period. Therefore, the utilization of APRC technology can ensure the bridge's safety and reliability, effectively accelerate construction speed, reduce the construction load, decrease the environmental pollution, and save the engineering cost, which can be regarded as a sustainable and environmental-friendly construction method for composite bridges with CSWs.

1. Introduction

The governments of China and all over the world are more and more concern about urgent environmental and resources demands for sustainable development, such as the insufficiency of raw materials, overconsumption of limited non-renewable resources, finite space available for waste disposal and low efficiency of waste treatment [3]. The infrastructure sector is one of main sectors of circular economy, and plays a vital role to future sustainability, since it has significant effects on the environmental emission, resource consumption, and waste production [39]. However, the products of two main construction materials (i.e. concrete and steel) are widely applied in the infrastructure, taking account about 15% of the global anthropogenic CO_2 emissions [13]. In addition, the increment of material demands in the future requests more responsible consumption of natural resources. Thus, it's of great importance to make good use of the main construction materials (steel and concrete) considering both safety and sustainability in structures and infrastructures such as buildings, bridges, and so on.

Prestressed Concrete girders with corrugated steel webs (PCGCSWs), which consist of PC slabs, CSWs, external and/or internal tendons, as shown in Fig. 1, have been extensively utilized in the application of railway and highway bridges. Due to the replacement of the stiffened steel webs in steel bridges or the concrete webs in PC bridges with CSWs, composite bridges with CSWs provide the following advantages [19]:

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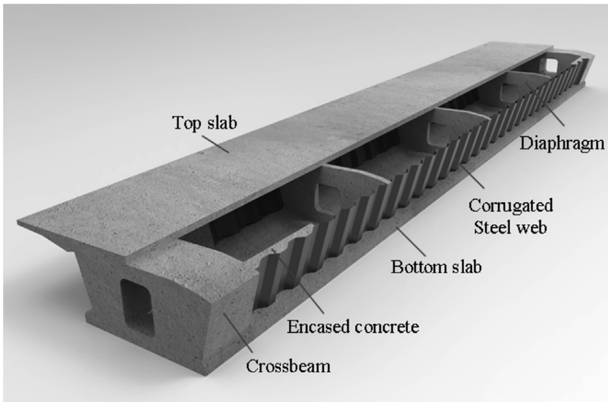


Fig. 1. Prestressed concrete girder with corrugated steel webs [19]

(1) In compassion with concrete girder having the same cross section, the self-weight of PCGCSW can be reduced about 20%∼ 30%, leading to the smaller substructures and lighter superstructures, thus saving the engineering budget.
(2) CSWs have high resistance to prevent shear bucking and outstanding out-of-plane flexural stiffness, therefore, no additional stiffeners are needed for CSWs.
(3) Thanks to the "accordion effect" of CSWs, prestressing forces are exerted to concrete slabs with high efficiency.
(4) CSWs can prevent inclined cracking of concrete web and remove stiffeners of flat steel web, thus, simplifying the assembly construction, reducing construction period and enhancing construction efficiency.
(5) When the external tendons are adopted in PCGCSW, they are convenient to install and replace, which are benefit for the maintenance and rehabilitation.
(6) PC slabs and CSWs resist bending moment and shear force respectively without interaction, which improve the material efficiency and definite the structural behavior.

Owing to the above advantages, e.g. light weight, high shear resistance, efficient prestressing force, and so on, PCGCSWs have been continuously constructed all over the world, especially in Japan and China [14,19;22,9]. Taken China as an example, over 100 composite bridges with CSWs have been built, including all kinds of bridge types, such as, simply supported girder bridges, rigid frame and continuous girder bridges, cable stayed bridges, in which more than 80% are rigid frame and continuous girder bridges whose main span are 50 ∼ 150 m, indicating those two types are the most applicable structural configurations. Generally, two cross-sections: box shape (trapezoid or triangle) and I-shape, are selected in composite bridges with CSWs. Similar to PC bridges, the composite bridges with CSWs can be constructed by conventional full framing construction, incremental launching construction, and balanced cantilever construction methods. In addition, incremental launching the CSWs as the nose beam was proposed to make full use of CSWs and save construction time [36,14]. Among these above-mentioned construction methods, the balanced cantilever construction is the most utilized method for medium and large span composite bridges with CSWs.

Since cantilever construction first appeared in Europe in the early 1950 s, it has been extensively applied in design and construction of concrete or steel bridges having constant or variable section height[24]. This method has been recognized as one of the most efficient ones without the need of scaffolding or falsework, and is recommended especially where scaffolding or falsework is difficult or impossible to erect over deep valleys, navigable waterways, and urban areas where temporary shoring would disrupt traffic and service below. The basic principle of balanced cantilever method is that a succession of segments (either cast-in-place by means of movable form carrier or prefabricated and lifted to place with appropriate equipment) is symmetrically cantilevered from the pier in both directions; a previously segment serves as the work basis for the next segment, each segment is anchored to the previous ones by post-tensioned tendons in top slab. However, some PC bridges constructed by balanced cantilever method were subjected to an increasing long-term deflection due to excessive creep and prestress losses, as well to extensive inclined cracking in concrete webs, resulting in those bridges must be closed to traffic (even collapse, e.g. Koror-Babeldaob bridge in Palau) or be repaired before the end of initially assumed service life[32,26]) . On the basis of previous studies of segmentally balanced cantilever PC bridges in term of the determination of reliability-based partial safety factors[5]), design moment variations [24–25], creep and time-dependent effects[31],construction stage analyses [1,2], to the authors' knowledge, accurate prediction of long-term deformation and stress state considering time-dependent effects through refined construction stages analyses and application of novel structural type such as PC girders with CSWs are effective ways to prevent inclined cracking in the webs and excessive deflection for PC bridges constructed by balanced cantilever method.

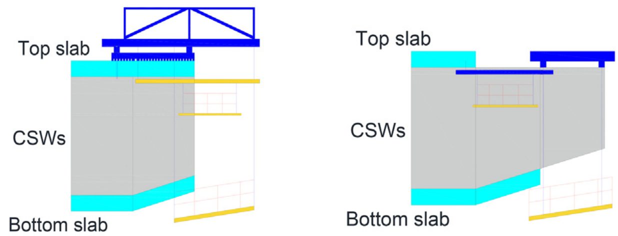
Recently, to improve the environmental sustainability and construction efficiency of PC girder bridges with CSWs, a novel construction technology called asynchronous pouring construction (APC) has been proposed on the basis of traditional cantilever construction and making full using of excellent shear capacity of the CSWs. The APC method can make up the shortcomings of traditional cantilever construction as follows: 1) heavy weight of the form traveler; 2) insufficient space for lifting CSWs; 3) limited construction area for casting top and bottom slab concurrently in one segment. Besides, in this method, CSWs can be used to support the movable form carrier and girder segments, the construction platforms of the bottom and top slabs, as well CSWs are separated, resulting in significantly improvement of construction efficiency. The APC method was first introduced at Altwipfergrund bridge in Germany [35], then adopted in many PCGCSWs in Japan, such as the Kinugawa Bridge, Tsukumi River Bridge, Akabuchigawa Bridge and Shigaraki Seventh Bridge. At present, such method has been extensively ultilized in China, e.g. the Toudao River Bridge [11] in Sichuan, Fenghua River Bridge [46] in Ningbo, and Yunbao Yellow River Bridge in Shanxi [40].

Previous studies have mostly paid attention to the main mechanical behaviors of prismatic and non-prismatic girders with CSWs, such as shear behavior[10,43;37;15–16,20,45,12,27], bending behavior [17,18,7];), torsional behavior[33,38], deformation characteristics [44,8], and so on. However, limited research involved in sustainable construction methods for PCGCSWs, although asynchronous pouring construction has been used in many PCGCSWs, a comprehensive analysis on APC method considering both safety and sustainability is insufficient, since this method not only enhances the construction efficiency but it also decreases the safety risk and environmental emissions. In the present study, based on a practical project in China, the construction process of the APC method is systematically introduced and analyzed in terms of structural safety and environmental sustainability.

2. Asynchronous pouring construction method

2.1. APC system composition

Similar to traditional balanced cantilever construction (TBCC), the APC system consists of the hanging basket system with a load-bearing truss system, a hanging lifting system, a construction platform, formworks for concrete casting, hanging basket moving and fixing equipment. But the hanging basket in APC is different from that in TBCC, as shown in Fig. 2, not only the structural configuration of hanging basket in APC is simplified, but also the support of hanging basket is changed from fixed at top concrete slab in TBCC to simply-supported at CSWs in APC. The hanging basket is directly supported by CSWs with the help of



(a) (b)

Fig. 2. The hanging basket system in (a) TBCC and (b) APC.

its high shear strength[21]), to overcome potential cracking on a bottom concrete slab near lifting position for TBCC. In order to prevent global and local bucking of CSWs in APC, temporary transversal bracings are arranged to improve the stability of CSWs, also twin-perfobond shear connectors (PBL) are suggested on top steel flange of CSWs not only to connect concrete slab but also to make hanging basket move safety and smoothly with good overall stability. Besides, there are three construction platforms for improved hanging basket system, thus the casting of the top concrete slab, bottom concrete slab, and the placing of CSWs can be performed simultaneously, which can solve the problems of limited lifting space of CSW segments and short curing time for bottom slab concrete before pouring the top slab concrete in TBCC[30,23].

2.2. Construction steps of APC

Fig. 3 illustrates the whole construction procedure of APC for PCGCSWs, which will be explained in the practical bridge case in the next section. The repeated construction steps for the standard segments of PCGCSWs using APC method begin from moving the hanging basket to the Seg. #*N*, then performing as follows (Fig. 4):

1. The steel components, i.e. the top and bottom flange, the perforated plates as shear connection, are welded, while CSWs of Seg. #*N* were connected to those of Seg. #*N*-1 using high strength bolts. And the hanging basket is fixed at CSWs of Seg. #*N*. Then, the formwork of bottom slab for Seg. #*N* and formwork of top slab for Seg. #*N*-1 are installed simultaneously.
2. The rebars of the top slab for Seg. #*N*-1 and bottom slab for Seg. #*N* are assembled simultaneously. Meanwhile, the CSWs for Seg. #*N* + 1 are hoisted in parallel.
3. The concrete of the top slab for Seg. #*N*-1 and bottom slab for Seg. #*N* is casting at the same time, and then curing for several days.
4. When concrete reaches sufficient strength, prestressed tendons of Seg. #*N*-1 can be stressed. Till now, a construction cycle of standard segment using APC method is completed; and
5. Moving forward the hanging basket to Seg. #*N* + 1, and proceeding to the next cycle.

3. Practical bridge project

3.1. Bridge outline

The case bridge is a three-span continuous box girder bridge with CSWs under construction, located in Guangdong province, China. The total length of the bridge is 352 m, and the length of each span is 90 m, 162 m, and 100 m respectively, as shown in Fig. 5 (a). The composite bridge adopts a single box girder with a variant height from 4.5 m at the middle-span section to 10 m at the pier section. The width of the top and bottom slab is 16.25 m and 8.5 m, respectively, as shown in Fig. 5 (b, c).

A typical type of corrugated steel web (CSW-1600), whose dimensions are shown in Fig. 5(d), is usually applied in long-span PC girder bridges with CSWs in China[29], also utilized in this bridge, the thickness of CSW changes from 16 mm at middle-span section to 30 mm at pier top section.

To restrict the torsional deflection, control the distortion and warping of box girder with CSWs, 6 transverse diaphragms in side-spans and 10 diaphragms in the main span are arranged, the thickness of those diaphragms is 0.5 m.

The connection between CSWs and concrete slabs is an important part that can effectively transfer longitudinal shear force and ensure all the parts of the cross-section undertake load integrally. Twin perforated plates (PBL) are welded on the top steel flange to connect the upper concrete slab, and channel connectors are proposed to connect the lower slab. Fig. 5 (e) and (f) shows the details of the connection between CSWs and upper / lower concrete slab respectively.

The arrangement of both external and internal tendons is adopted in this bridge, as shown in Fig. 5 (b), (c) and (g). Those tendons use steel strand of ASTM270 ϕ^j15.24 with a nominal diameter of 15.2 mm, a nominal area of 140.0 mm^2, and tensile strength of 1860 MPa.

3.2. Construction process

As for the construction of this bridge, cast-in-situ of pier head unit by scaffolding and balanced cantilever construction of cantilevering segments by moving hanging basket were adopted, in which most cantilevering segments used the APC technology during balanced cantilever construction.

During the cantilever construction period, the construction segments of box girders should be divided considering the longitudinal connection of the CSWs and the loading capacity of CSWs. Generally, the standard segment length is chosen as an integral multiple of the CSWs' wavelength (i.e. 2 or 3 times of wavelength). The segments division at the maximum cantilever are as shown in Fig. 5(g).

The construction process of box-girders with CSWs for this bridge is shown in Fig. 3, and illustrated as follows:

Step 1: Construction of Seg. #0

The Seg. #0 of concrete box girder was cast-in-situ on brackets, which were installed and supported by the already constructed pier. And Seg. #0 was anchored with the pier.

After the cast-in-situ Seg. #0 was completed, the CSWs of Seg. #1 were hoisted and connected to Seg. #0, followed by preparing construction Seg. #1 with the APC method.

Step 2: Asynchronous Construction of Nonstandard Seg. #1

After the finish of cast-in-situ Seg. #0, the CSWs of Seg. #1 were subsequently hoisted to support the hanging basket system. Followed the installation of hanging basket in place, the casting of Seg. #1 bottom concrete slab and installing Seg. #2 CSWs can be performed. Then, the hanging basket was moved forward to the next standard segment.

Step 3: Asynchronous Construction of Standard Segments #2–#17

During the construction of standard segments, to make sure the safety and stability of those cantilever segments, transverse brackets were temporally welded between the CSWs to prevent lateral buckling of CSWs when supporting and moving the hanging basket. Generally, the main construction works for a typic standard segment consists of moving the hanging baskets forward, placing the formworks, arranging steel bars, casting the top and bottom concrete slabs, and tensioning prestressed tendons.

As mention before, after the completion Segs #0 and #1 and the installation of the hanging basket at Seg. #2, the working platforms were increased to three for the construction of subsequent standard segments. The detailed steps of the APC method in a standard Segment #N are illustrated in section 2.2 and Fig. 4.

Step 4: Construction of Closure Segment

The construction of the side-span and mid-span closure segments are depicted in the following sub-steps:

1 Temporary supports were installed to construct cast-in-situ

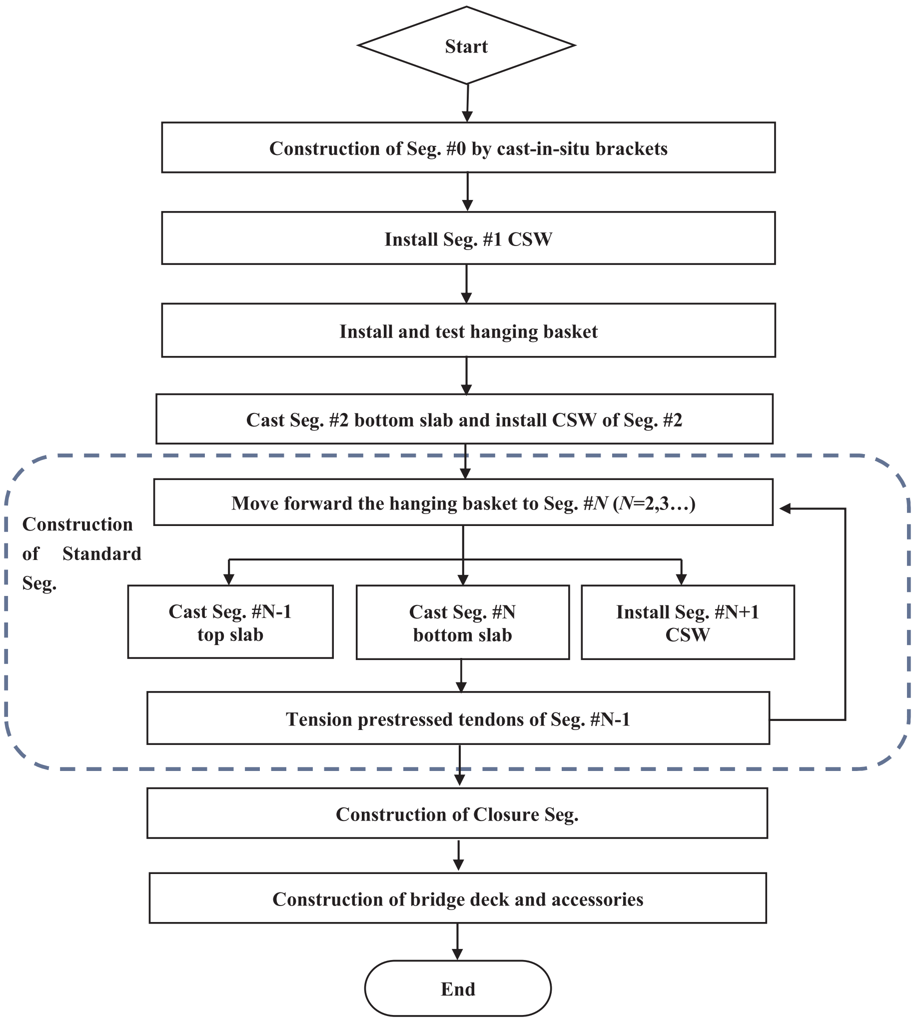


Fig. 3. Construction process of box girder bridges with CSWs using APC.

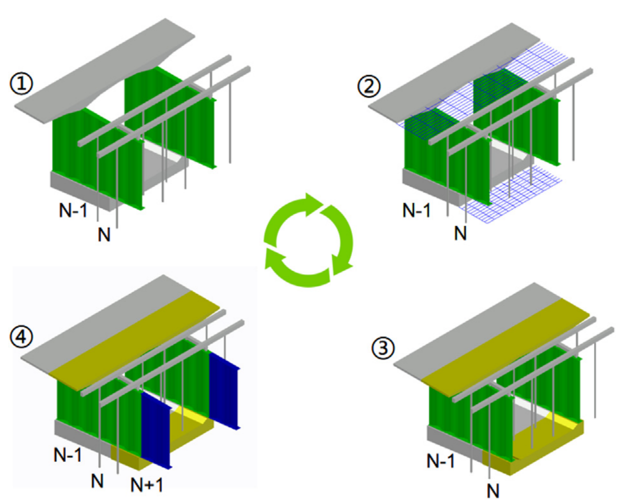


Fig. 4. Construction steps of standard segments using APC.

segments in-side span, then close the side span and tension prestressed tendons for side span closure.

2. For the mid-span closure, connect the CSWs at the beginning. Then, casting concrete of bottom and top slab in sequence after the placement of frameworks. Finally, the mid-span prestressed tendons are stressed after the concrete reach sufficient strength.

3. Remove the temporary brackets and tension the external prestressed tendons.

4. Complete the following works, such as construction of deck pavement, installation of auxiliary facilities, anticorrosion coating of CSWs, and so on, to finish the construction.

3.3. Structural analyses model

To analyze the structural behavior of the PC box girder bridge with CSWs, some assumptions are presented for simplification.

(1) The connections between concrete slabs and corrugated steel webs are stable. Slip and shear failures do not occur.

(2) CSWs have enough strength to prevent shear or lateral buckling.

(3) The internal tendon and concrete bond together completely. The external tendons fully connect with the structure at the anchorage and deviators without any slippage occurrence.

(4) The prestressing loss of internal and external tendons is not considered.

The box girders and piers are simulated as three-dimensional beam elements using FE software MIDAS Civil, considering the time-dependent effects using basic concrete creep and shrinkage prediction models recommended by Eurocode 2 standard [6]. It should be noted that there is a special beam element in MIDAS to consider the effect of corrugated steel web by using its equivalent stiffness [4], also this beam element can simulate PCGCSW with variable cross-sections at both ends. There are 1005 nodes and 554 elements for the bridge, each construction

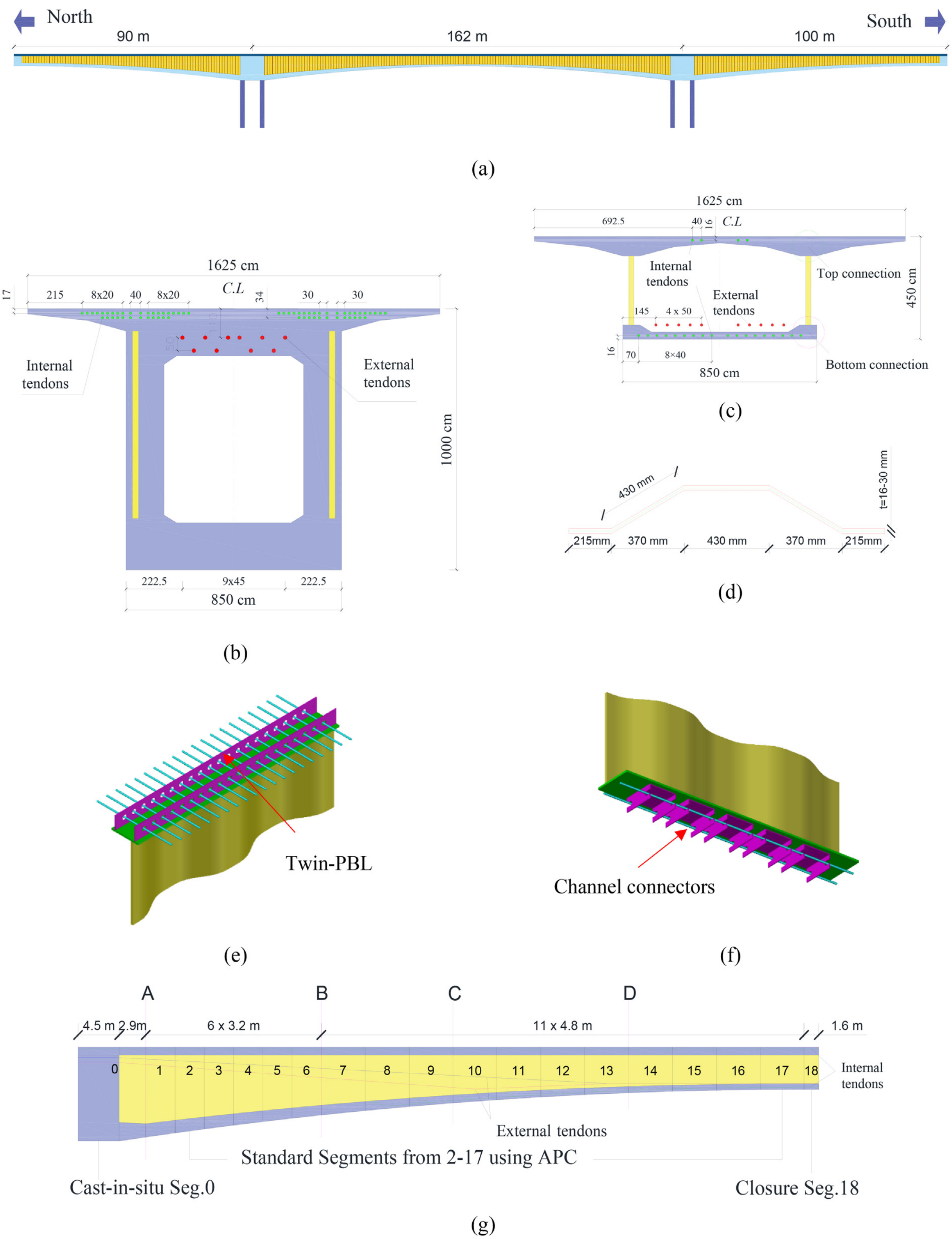


Fig. 5. Bridge outline: (a) Vertical view; (b) Cross section A; (c) Cross section D; (d) dimensions of the CSW-1600; (e) Connection between CSW and top slab; (f) Connection between CSW and bottom slab; and (g) segments division.

segment is divided into several elements, as shown in Fig. 6. The bottom of the piers is fixed, and the top of the piers are rigidly connected to the box girder, while the ends of side-spans are supported by the roller. The material for each bridge component is listed in Table 1. Loading on the bridge only considers the dead load, including the self-weight of structural components and hanging basket, the prestressing force of tendons. The self-weight of structural components and hanging basket are simulated as uniform distributed loading and concentrated loading respectively, and the prestressing force of each tendon is applied as the tensile stress (e.g. $0.65 \times 1860 = 1209$ MPa) multiply its cross-sectional area.

To accurately model the detailed steps of construction process using

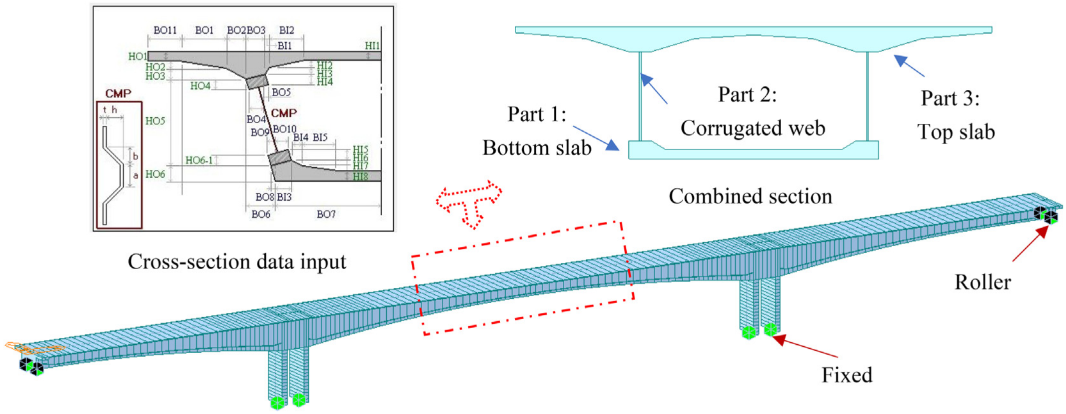


Fig. 6. Finite element model of the bridge.

Table 1
Material properties.

No.	Component	Material	Elastic modulus (MPa)	Density(kN/m^3)	Tensile strength (MPa)	Compressive strength(MPa)	Shear strength (MPa)
1	Pier	C50	34,500	25	23.1	1.89	–
2	Concrete slabs	C55	35,500	25	25.3	1.96	–
3	CSWs	Q345	206,000	78.5	310	310	180
4	Tendons	Φj15.24	195,000	78.5	1260	390	–

APC, a general incremental step-by-step method was applied, the combined section of box girder with CSWs is adopted, which is divided into three parts: CSWs, top and bottom slab, each part can be “activated” or “killed” to simulate its installation at a different time for the same cross-section.

4. Comparison of structural behaviors using APC and TBCC

The structural performance in terms of strength (stress state of concrete slabs and CSWs) and stiffness (the deflection) is evaluated by FE analysis during the whole construction process using APC, also compared with that using TBCC to clarify the difference of structural response between those two construction methods. All the construction segments are selected the same for both construction methods, the only difference is the structural type and dead load of the hanging basket, here different loading on hanging basket is applied, i.e. 460kN for APC while 1200kN for TBCC, besides, the loading points of hanging basket are at CSWs for APC and at concrete slab for TBCC. At complete state, the loading of hanging basket is removed, and only the self-weight is applied.

During the construction process, both the cantilever state and the complete state are considered. In cantilever state, four critical sections (A ~ D) are selected for comparison, i.e. at top pier, 1/4, 1/2, and 3/4 of the Max. cantilever segments (about half of the main span), as shown in Fig. 5 (g).

4.1. Cantilever state

4.1.1. Stress of concrete top slab

Fig. 7 shows the comparison of normal stress development at the top slab using APC and TBCC. The top slab of sections A ~ D is compressed, the maximum compressive stress using TBCC is 10.4, 4.86, 3.3, and 0.52 MPa for section A ~ D respectively, while it is 8.1, 3.9, 2.7, and 0.44 MPa using APC. The compressive stress of the top slab for sections A-C increased with the increasing of construction segments till Seg. #14, then slightly decreased for the followed construction segments, because the arrangement of prestressed tendons at top slab changed from Seg. #14. All the stress is less than the design value (25.3 MPa), indicating the strength of the top slab meets the requirement of the design code[34]. Besides, the stress of top concrete is reduced using APC in compression to that using TBCC, the reduction is about 20%.

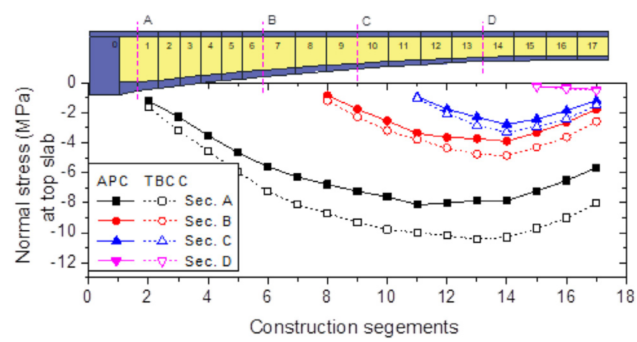


Fig. 7. Comparison of normal stress development at the top slab under cantilever states.

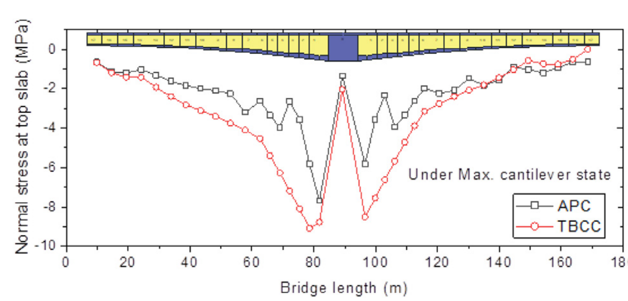


Fig. 8. Comparison of normal stress distribution at the top slab under Max. cantilever state.

Fig. 8 shows the comparison of normal stress distribution at top slab along the bridge length under maximum cantilever state using APC and TBCC. All the segments are compressed, and the compressive strength is less than the design value (25.3 MPa). The normal stress presents the same variation trend for both construction methods, the stress decreased from Seg. #0 to cantilever ends, but the stress at most segments using APC is less than that using TBCC, the difference between them is also decreased from Seg. #0 to cantilever ends.

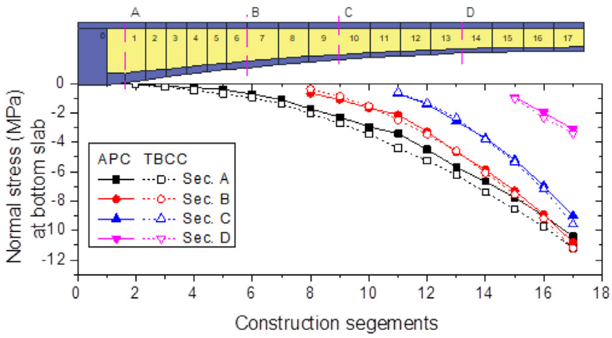


Fig. 9. Comparison of normal stress development at the bottom slab under cantilever states.

4.1.2. Stress of concrete bottom slab

Fig. 9 describes the comparison of normal stress development at the bottom slab using APC and TBCC. The bottom slab of sections A ~ D is compressed, the maximum compressive stress using TBCC is 11.2, 11.3, 9.6, and 3.4 MPa for section A ~ D respectively, and is 10.4, 10.8, 9.0, and 3.1 MPa using APC. The compressive stress of the bottom slab for sections A-D increased with the increasing of construction segments till Seg. #17 (before construction of closure segment). Also, All the stress is less than the design value (25.3 MPa), indicating the strength of the bottom slab meets the requirement of the design code[34]. The stress development trend and variation magnitude of the bottom slab using APC is almost the same as that using TBCC, indicating that those two construction methods do not affect the stress state of the bottom slab.

Fig. 10 shows the comparison of normal stress distribution at the bottom slab along the bridge length under maximum cantilever state using APC and TBCC. All the segments are compressed, and the compressive strength is less than the design value (25.3 MPa). The normal stress presents the same variation trend for both construction methods, the stress decreased from Seg. #0 to cantilever ends, also the stress at each segment using APC is almost the same as that using TBCC, proving again that those two construction methods do not affect the stress state of the bottom slab.

4.1.3. Shear stress of CSWs

Fig. 11 illustrates the comparison of shear stress development of CSWs using APC and TBCC. The maximum shear stress using TBCC is 24.9, 39.2, 53.8, and 35.7 MPa for section A ~ D respectively, and is 32.1, 41.7, 59.6, and 38.8 MPa using APC. The shear stress of CSWs for sections A ~ D increased with the increasing of construction segments till Seg. #17 (before construction of closure segment). Also, All the stress is much less than the design value (180 MPa), indicating the strength of CSWs meets the requirement of the design code[34]. Additionally, the stress of CSWs using APC is more than that using TBCC, the increment is 48% for section A and about 13% for sections B ~ D, the reason may be the hanging basket is supported directly by CSWs using APC while supported by the whole cross-section using TBCC.

Fig. 12 shows the comparison of shear stress distribution of CSWs along the bridge length under maximum cantilever state using APC and

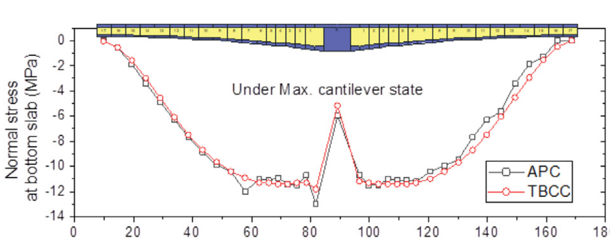


Fig. 10. Comparison of normal stress distribution at the bottom slab under Max. cantilever state.

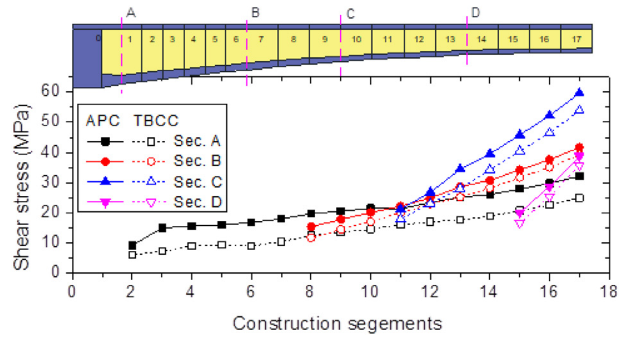


Fig. 11. Comparison of shear stress development at CSWs under cantilever states.

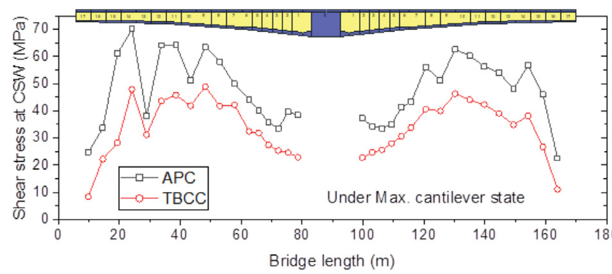


Fig. 12. Comparison of shear stress distribution at CSWs under Max. cantilever state.

TBCC. All the shear strength is less than the design value (180 MPa). The shear stress presents the same variation trend for both construction methods, the stress firstly increased from Seg. #0 to #14 then decreased to cantilever ends, due to the variation of the CSWs' thickness from 16 mm to 22 mm at Seg. #14, but the shear stress at each segment using APC is more than that using TBCC.

4.1.4. Defection

Fig. 13 presents the comparison of deflection development in each section using APC and TBCC. The maximum deflection using TBCC is 1.8, 12.3, 39.6, and 77.6 mm for section A ~ D respectively, and is 3.7, 16.3, 40.5, and 77.9 mm using APC. The deflection for sections A-D increased with the increasing of construction segments till Seg. #17 (before construction of closure segment). Also, all differences of deflection between those two construction methods decreased with the increasing of construction segments.

Fig. 14 shows the comparison of deflection distribution along the bridge length under maximum cantilever state using APC and TBCC. The deflection presents the same variation trend for both construction methods, the deflection almost coincides with each other for both construction methods except the segments near the closure section.

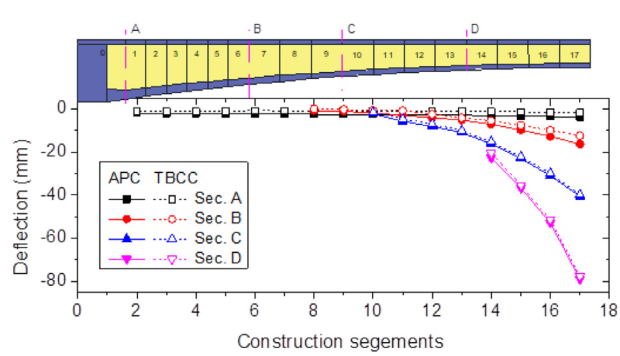


Fig. 13. Comparison of deflection development under cantilever states.

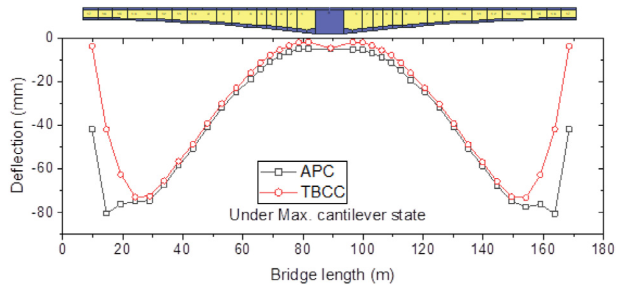


Fig. 14. Comparison of deflection along bridge length under Max. cantilever state.

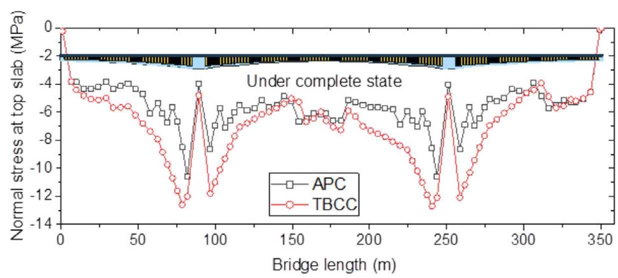


Fig. 15. Comparison of normal stress distribution at the top slab under complete state.

4.2. Complete state

4.2.1. Stress of concrete top slab

Fig. 15 shows the comparison of normal stress distribution at the top slab along the bridge length under a complete state using APC and TBCC. All the segments are compressed, the maximum stress is 12.7 and 10.6 MPa using TBCC and APC respectively, and the compressive strength is less than the design value (25.3 MPa). The normal stress presents the same variation trend for both construction methods, the stress decreased from Seg. #0 to mid-span (main span except for closure segment) or supports (side span), but the stress at each segment using APC is less than that using TBCC, the maximum difference is 18% and the difference between them is also decreased from seg. #0 to mid-span or supports.

4.2.2. Stress of concrete bottom slab

Fig. 16 describes the comparison of normal stress distribution at the bottom slab along the bridge length under a complete state using APC and TBCC. All the segments are compressed, the maximum stress is 16.6 and 15.7 MPa using TBCC and APC respectively, and the compressive strength is less than the design value (25.3 MPa). The normal stress presents the same variation trend for both construction methods, the stress decreased from the side span to the main span (except the support area). Besides, the stress at each segment using APC is almost the same as that using TBCC, illustrating that those two construction methods do not affect the stress state of the bottom slab under complete state, which is similar to that under cantilever states.

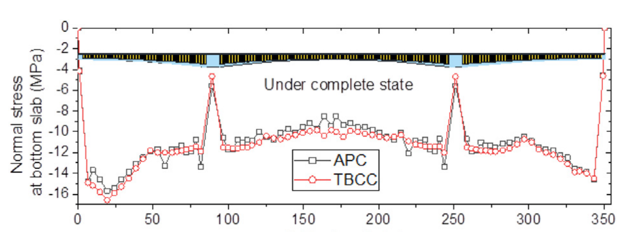


Fig. 16. Comparison of normal stress distribution at the bottom slab under complete state.

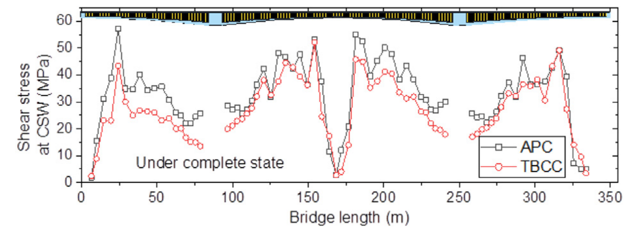


Fig. 17. Comparison of shear stress distribution at CSWs under complete state.

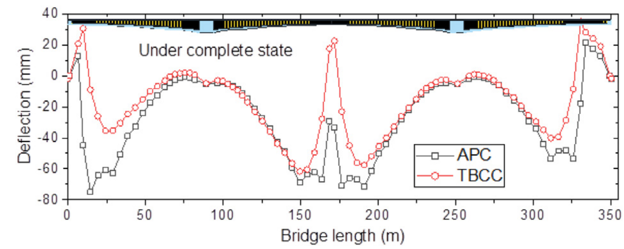


Fig. 18. Comparison of deflection along bridge length under complete state.

4.2.3. Shear stress of CSWs

Fig. 17 shows the comparison of shear stress distribution of CSWs along the bridge length under a complete state using APC and TBCC. All the shear strength is much less than the design value (180 MPa). The shear stress presents the same variation trend for both construction methods, the shear stress near Seg. #0, side-span supports, and closure segments is less than other sections, the shear stress at most segments using APC is larger than that using TBCC.

4.2.4. Defection

Fig. 18 shows the comparison of deflection distribution along the bridge length under a complete state using APC and TBCC. The deflection presents the same variation trend for both construction methods, the deflection almost coincides with each other for both construction methods except the segments near closure for the main span and near support ends for side span. The maximum deflection is 75.1 mm at Seg. #16 of side span using APC, and is 61.7 mm at Seg. #13 of main span using APC, the maximum deflection is less than the limit value $L/600$ (150 mm in side-span, L is the span length) provided in the design code [34].

5. Comparison of sustainable behaviors using APC and TBCC

5.1. Hanging basket system weight

Since the structural configuration of the PC box girder bridge with CSWs is almost the same using both APC and TBCC, the comparison is focused on the construction facilities especially the hanging basket system. In general, the ratio of the traditional hanging basket weight to a box girder segment weight is basically over 0.35 [28], this weight ratio is also adopted for PC box girder with CSWs using the TBCC method. However, the traditional hanging basket and framework system are redesigned and simplified when using APC, because hanging basket can be directly supported by CSWs and only the construction platform of the bottom slab is supported by hanging basket, therefore, the weight of the construction platform and the hanging basket is obviously decreased, the weight ratio for APC can be reduced about half (0.18) to that for TBCC, resulting in the reduction of steel consumption.

Fig. 19 depicts the comparison between the weights of new and traditional hanging baskets used in two PC bridges with CSWs having cross section of single-box and single-chamber (Toudao River Bridge and the case bridge), one bridge of single-box and three-chambers (Fenghua River Bridge). It can be found that the weight of new hanging

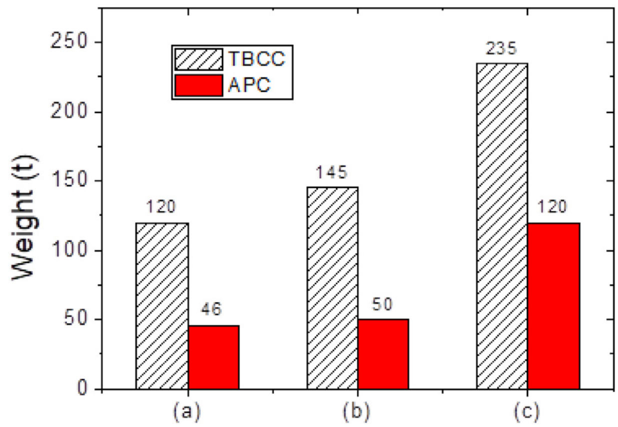


Fig. 19. Comparison between the weights of new and traditional hanging baskets used in three bridges with CSWs: (a) Case studied bridge; (b) Toudao river bridge in China; and (c) Fenghua river bridge in China.

baskets for APC in these three bridges is 46, 50, and 120 t, respectively, which is much less than the value (120, 145, and 235 t) of the traditional hanging baskets in corresponding bridge if using TBCC. Thus, for the same bridge, the weight of new hanging basket in the APC technology is reduced to 34%–52% accordingly of the traditional hanging basket.

5.2. Construction period

Generally, the construction of standard segments of PC box-girder bridges with CSWs using TBCC should be followed by the steps of CSWs' installation, casting bottom and top concrete slabs in the same segment, thus, results in a long construction period and limited space for the working platform. However, the APC technology expands the girder segmental working platform from the original single platform (#*N*) to three parallel and neighboring platforms (#*N*-1, #*N*, #*N* + 1), which are (1) top slab's working platform at Seg. #*N*-1, (2) bottom slab's working platform at Seg. #*N*, and (3) CSWs' working platform at Seg. #*N* + 1. Consequently, construction of top and bottom concrete slabs as well assemble of CSWs on three adjacent segments can be carried out simultaneously, leading to improved efficiency of equipment and workers, as well rapid construction time.

In addition, the girder segments is divided according to its weight and the loading capacity of the hanging basket, the segments length of box girder with CSWs constructed by the APC method can be extended properly in comparison to that constructed by TBCC, resulting in the reduced number of divided segments, since only the bottom formwork is supported by new handing basket system for APC while the whole section formwork is resisted by handing basket system for TBCC. So, APC technology shortens the construction period effectively.

Based on the available data of average construction period for standard segments from five PC bridges with CSWs, i.e. the case bridge, Toudao River Bridge, Yunbao Yellow River Bridge, Fenghua River Bridge in China, Akabuchigawa Bridge in Japan, as shown in Fig. 20, it can be revealed that the mean segmental construction time using APC technology is three days less than that by the TBCC. For example, the case bridge having a cross-section of a single-box and single-chamber, took an average of 6.5 days per segment using APC, in contrast, an average of 9.5 days per segment is obtained using TBCC, 3 days are shorten saving about 32% of the construction period, especially the casting period of the top and bottom concrete slabs are reduced. Therefore, the APC method can obviously accelerate the segmental construction progress, save the total construction time, and improve labor efficiency.

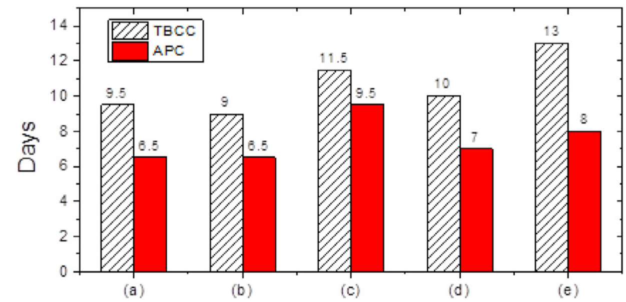


Fig. 20. Comparison of the segmental construction period with the APC and TBCC construction methods for the box girder bridges with CSWs: (a) Case studied bridge (b) Toudao river bridge in China; (c) Yunbao Yellow river bridge in China; (d) Fenghua river bridge in China; and (e) Akabuchigawa bridge in Japan. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.3. Environmental impact and construction cost

To evaluate the effect of the new APC technology on energy consumption, environmental impact (CO_2 emission), and the construction cost, the comparison of those aspects between both APC and TBCC is conducted. Since the structural materials of the bridge are all most the same using those two construction methods, only the consumption of the construction hanging basket system as well the indirect cost due to reduced time of box girder construction are considered.

Generally, produce a ton of steel needs 187 kW · h electrical power and 4.4 t water, as well releases about 3030 kg of carbon dioxide to the environment[42,46]. And the price of steel is supposed to be $584 per ton[41], the indirect cost due to reduced time of box girder segment construction is assumed to be $5860 per day.

As above mentioned, the weight of new hanging basket using the APC technology for case bridge is reduced by 74 t, and the construction time of the box-girder is decreased by 48 days. Thus, the APC method saves a lot of electrical power (13838 kW · h) and water (325.6 t), also decreases huge CO_2 emissions (224.22 t), resulting in enormous environmental benefits. Besides, the APC method reduces the direct cost of steel consumption ($43,216) and much indirect cost ($281,280). The effect of APC on environmental impact and construction cost in other bridges can also be easily envaulted by the same procedure and similar parameters as that in the case bridge.

Based on the above comparison of the case bridge constructed using APC and traditional technologies in terms of strength and stiffness, construction period and engineering cost, some main outcomes are summarized in Table 2 aiming to provide reference for the design and construction of PC bridges with CSWs. The comparison indicates that the application of the new hanging basket in the construction of PC bridges with CSWs using APRC technology can ensure the bridge's safety and reliability, effectively speed up construction speed, save the construction labor and the engineering cost, as well reduce the environmental pollution, which can be regarded as a sustainable and environmental-friendly construction method for PC box girder bridges with CSWs.

6. Conclusions

This paper presents an improved cantilever construction method (APC technology) for long-span PC girder bridges with CSWs to overcome the drawbacks of traditional cantilever construction, reduce environmental impact, and promote sustainable construction. Based on a practical project in China, the construction process using the APC method is systematically introduced and analyzed in terms of structural safety and environmental sustainability. The main conclusions and innovation points are summarized as follows:

Table 2
Comparison of the case bridge constructed using APC and TBCC.

Item			Construction method		
			TBCC	APC	APC/TBCC
Structural responses	Cantilever state	Max. deflection (mm)	72.8	80.4	1.10
		Max. stress at top slab (MPa)	−9.1	−7.7	0.85
		Max. stress at bottom slab (MPa)	−11.8	−13.0	1.10
		Max. shear stress at CSWs (MPa)	48.9	70.1	1.43
	complete state	Max. deflection (mm)	61.7	75.1	1.22
		Max. stress at top slab (MPa)	−12.7	−10.6	0.83
		Max. stress at bottom slab (MPa)	−16.6	−15.7	0.95
		Max. shear stress at CSWs (MPa)	49.0	57.1	1.17
Standard segmental construction period (d)			9.5	6.5	0.68
Engineering cost for hanging basket system ($)			70,080	26,864	0.38
Energy consumption for hanging basket system	Electrical power (kW · h)		22,440	8602	0.38
	Water (t)		528	202.4	0.38
CO_2 emissions for hanging basket system (t)			363.6	139.4	0.38

1. The improved APC method uses CSWs themselves as the main load-bearing members with excellent shear capacity to support the hanging basket and cantilever segments, increases construction platform number from single for TBCC to three for APC, thus casting of the top concrete slab and the bottom concrete slab, and the hoisting of the CSWs on three adjacent segments can be completed independently and simultaneously. Besides, asynchronously casting of the top and bottom concrete slabs in the same segment can be performed, so the concrete has sufficient time to reach the required strength.
2. The finite element structural analyses on PC box girder bridge with CSWs using both construction methods indicate that the strength and stiffness of such bridge during the whole construction process and at finish state meet the requirements of related design code, APC method can reduce the compressive strength of top concrete slab, but slightly increase the shear strength and deflection during the cantilever construction stage, since hanging basket is directly supported by the CSWs. The finite element analyses only consider the global structural response using beam elements, a refined finite element model with 3D solid or shell elements involving the local behaviors such as spatial stress distribution of concrete slabs, local buckling of CSWs, slip characteristic at interface between concrete slabs and CSWs, and so on should be further investigated.
3. APC technology significantly reduces the weight of the improved handing basket up to the half of traditional one, accordingly, saves a large amount of energy consumption and reduces huge CO_2 emissions for construction equipment. Also, the construction period of the standard segment is saved by an average of 3 days, construction efficiency and the economic benefit of the APRC method are significantly improved.

In short, the adoption of the new hanging basket using APRC technology can ensure the bridge's safety and reliability, effectively accelerate construction speed, save the construction labor and the engineering cost, decrease the environmental pollution emissions, which can be regarded as a sustainable and environmental-friendly construction method for PC box girder bridges with CSWs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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