A Variable Center of Gravity and Intelligent Walking Cantilever Casting Hanging Basket

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Abstract. A new type of concrete cantilever casting hanging basket that the gravity center is movable intelligently is presented. The gravity center of the hanging basket can be changed to the back of the equipment, which enhances the anti-anchoring ability under walking condition. The novel hanging basket also adopts hydraulic template, wheel-rail system and automatic control system, which could reduce lots of manual operations, improve the working efficiency. The working principle and the design of the critical components are presented, the sliding frame can support the weight of the bottom formwork and the side formwork, and can change the overall gravity center of the hanging basket by sliding on the top of the main beam, the automatic control system can control the continuous moving of the sliding frame, the continuous moving of the main beam and the intelligent adjustment of the formworks. Finite element analysis is performed to study the bearing capacity of all the components, which shows that all components of the hanging basket meet the requirements of the occupational standard and the anti-overturning ability of the intelligent hanging basket is sufficient. At last, the mechanical test and the kinematics test of full-scale hanging basket are carried out, and the tests results proved the feasibility and reliability of this new type of hanging basket.

Keywords: variable center of gravity, hanging basket, intelligent walking, cantilever casting, sliding frame system

1 INTRODUCTION

Due to good spanning capacity and economic advantages [1], prestressed continuous box girder bridges are widely used in mountainous area. Prestressed continuous box girder bridges are all constructed by cantilever casting technology. The hanging basket, as the main construction equipment, is mainly composed of the main truss system, bottom basket system, side formwork system, internal formwork system, suspension system and anchorage system[2][3]. Based on years of application, traditional hanging baskets have the following four shortcomings: (1) the gravity center of traditional hanging basket is front-overhanging continuously, which is anchored by its anchorage system, so overturning accidents sporadic outbreak as the failure of the anchorage system during walking condition[4]. (2) traditional hanging basket has two

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outer guide beams for the forward moving of the side formwork system, that manual demolition of the anchor bolts is needed after the moving of the basket, which is of high risk to the workers as weak protective measures. (3) the traditional hanging basket is moved forward by sliding on the anchorage beam under manual work, which is inefficient and the walking synchronization between two main trusses is difficult to be guaranteed, so the main trusses system often loses stability during walking condition. (4) the application of traditional hanging basket contains too many manual operations, which is of low level of automation and major of them belong to work at height. However, as a temporary construction measure, the innovation and development of traditional hanging baskets are extremely slow, and few researchers have conducted innovative research on them, in addition, the rare research is just focused on a customized study of hanging baskets for special bridges. As for the intelligent control system of hanging baskets, research has almost never been conducted in recent decades. Therefore, this article proposes a fire-new type of intelligent hanging basket, whose gravity center can be adjusted intelligently.

Compared to traditional hanging baskets, the intelligent hanging baskets mainly have the following characteristics: (1) the sliding frame drives the side formwork and bottom formwork to move back longitudinally along the main beam, so that the center of gravity of the hanging basket is retreated, which solves the problem of continuous forward leaning of gravity center of traditional hanging baskets and avoids the risk of walking overturning[5]; (2) The sliding frame system carries the side formwork and bottom formwork forward, which cancels the outer guide beam of the traditional hanging basket[6]; (3) The servo electrically controlled wheel rail running mode is adopted to replace the traditional hanging basket sliding running mode, which improves the walking efficiency and synergy of hanging basket running, and reduces the risk of unstable walking in the hanging basket; (4) The side formwork adopts hydraulic jack to complete the entire process of formwork erection, adjustment, and demolding, which eliminates the traditional formwork adjustment method by manual hand-pulled hoist, improves the construction accuracy and quality, and reduces the work at height. In summary, the new intelligent hanging basket is safer, more intelligent, and more convenient for construction.

2 INTELLIGENT HANGING BASKET DESIGN

2.1 Prototype Layout and Composition.

The new intelligent hanging basket structure proposed in this article mainly includes the following systems:

1) Cantilever beam: the main load-bearing component, composed of two welded box beams and transverse connection system, which are supported on the top of the concrete box beam.

2) Sliding frame: supported on the cantilever beam by two sliding blocks. It’s connected to the bottom formworks through four electric hoists, and to side formworks through twelve hydraulic cylinders, which can carry the bottom formworks and side

formworks forward/backward on the cantilever beam. It is the key structure to realize adjustment of gravity center.

3) Formworks system: including bottom formwork system, side formwork system, and internal formwork system. The bottom formwork and side formwork system are supported by cantilever beams during pouring conditions, and are changed to sliding frame system during walking conditions.

4) Suspension system: composed of upper crossbeam, suspension straps, suspension rods, etc.

5) Anchor system: composed of load distribution beams, anchor bars, etc.

6) Walking system: including walking wheels and rails, sliding frame walking hooks.

The new hanging basket structure is shown in Figure1.

2.2 Sliding Frame System Design

Compared to traditional hanging baskets, this intelligent hanging basket uses a C-shaped sliding frame that covers the entire width of the box girder as presented in Figure2. The sliding frame contacts with the top surface of the cantilever beam through a slider set on its bottom, and a polytetrafluoroethylene sliding plate is used as the sliding surface to reduce the sliding resistance. The sliding frame extends down to the position of the side formwork and directly above the bottom formwork, and sets four hanging points for each side formwork and bottom formwork. When the hanging basket moves, the sliding frame can change the overall center of gravity of the hanging basket backward and forward. The sliding frame slides on the top surface of the cantilever beam through a longitudinal hydraulic cylinder set next to the slider. Another slider is also set on the top surface of the cantilever beam, and a hanging claw mechanism is installed in it to hang on the reserved square hole on the top plate of the cantilever beam to provide the support force for the hydraulic cylinder to push and pull. The hydraulic cylinders on both sides are connected to the intelligent control system, and proportional hydraulic valves are used to get good synchronization of the cylinders during pushing and pulling.

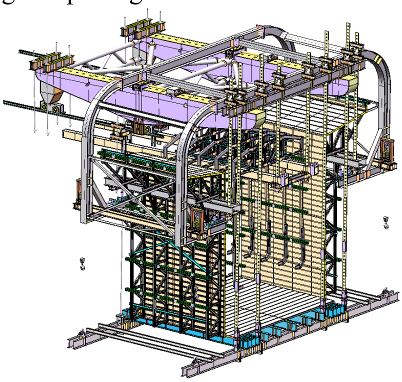


Fig. 1. Schematic diagram of hanging basket structure.

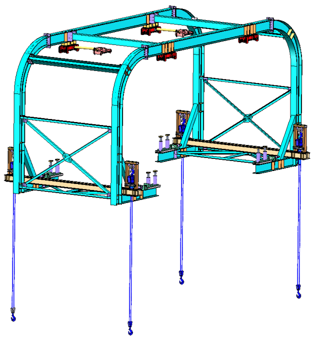


Fig. 2. Sliding Frame System Scheme.

The sliding frame is composed of shape-steel components, and its main function is to hang the bottom formwork system and support the side formwork system under hanging basket moving forward condition. The sliding frame needs to move forward and backward, so its width is designed to exceed the overall width of the bridge deck to avoid obstacles. The cross-sectional dimensions of the sliding frame must be able to bear the gravity of the side and bottom formwork systems safely. The needed thrust of the hydraulic cylinder, is determined by multiplying the sliding friction coefficient of the sliding surface and the gravity of the sliding frame, bottom mold, and side mold systems. If the bridge has a longitudinal slope, the longitudinal component of gravity is also needed to be considered into it. Taking the sliding frame discussed in following text as an example, the design width of the sliding frame is 13 meters, the cross-section is made of HM390 × 300 shaped-steel, and the thrust force of the hydraulic cylinder is 10 tons, considering a safety factor of approximately 1.5.

2.3 Wheel and Rail Walking System Design

As the continuous beam cantilever pouring process progresses, the hanging basket gradually moves towards the middle span of the bridge. The traditional way of moving the hanging basket forward is dragging it to slide on the bridge deck manually or by hydraulic cylinders, which is difficult to ensure the synchronization of the two main beams of the hanging basket. In the design of intelligent hanging basket, a wheel-and-rail walking system is adopted to get higher control accuracy and better synchronization. Two servo motors are installed at the front wheel boxes of the two cantilever beams, and the maximum allowable deviation value of the motor on both sides is set through the intelligent control system to guarantee the synchronization of the cantilever beams on both sides.

2.4 Technological Process of Intelligent Hanging Basket

The construction process of intelligent hanging basket is as follows:

1) Concrete the n# segments as anchored in Figure3a), and cure it to the specified strength;

2) Demould, and change the hanging point of the bottom formwork, side formwork, and inner formwork to the sliding frame, as shown in Figure3b), ensure the complete detachment of the formworks from the casted segment;

3) The sliding frame carries the bottom formwork and side formwork, and retreats to the tail of the cantilever beam through the sliding surface on the top surface of the cantilever beam, to complete the backward movement of the center of gravity of the hanging basket structure, as shown in Figure3c);

4) Extend the track, start the walking wheel to carry the entire hanging basket forward to the n+1# segment, as shown in Figure3d);

5) After anchoring the cantilever beam, the sliding frame carries the bottom formwork and side formwork and moves them to the casting position in front of the top surface of the cantilever beam as shown in Figure3e), and completes the formwork erection of the n+1# segment;

6) Change the hanging points of the side formwork, bottom formwork, and inner formwork to the cantilever beam and n # section as shown in Figure3f), and cast n+1# segment.

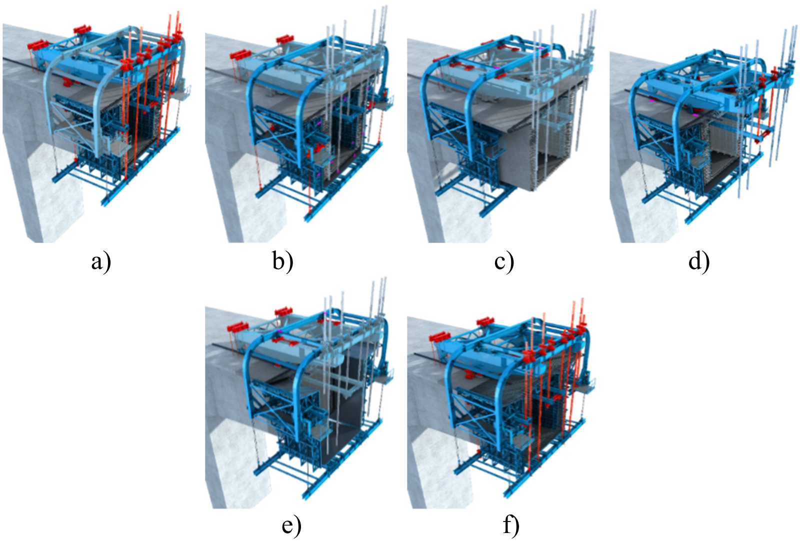


Fig. 3. Schematic diagram of hanging basket construction process.

2.5 Design Parameters.

Due to the addition of the sliding frame system, the weight of the intelligent hanging basket has increased compared to traditional hanging baskets. In order to control the weight of the intelligent hanging basket, Q345 steel is adopted in the main load-bearing components, while the auxiliary components are Q235 steel as the traditional hanging basket. The strength limits of the steels are shown in Table1 below.

Table 1. Material Mechanical Parameters.

Material	Elastic modulus (GPa)	Bending strength (MPa)	Shear strength (MPa)
Q235	206	215	125
Q345	206	295	170

3 MECHANICAL ANALYSIS OF INTELLIGENT HANGING BASKET

3.1 Load Cases

Based on the stress characteristics during the construction process of the hanging basket, two most unfavorable load conditions are determined.

Condition 1-Concrete casting condition: the intelligent hanging basket needs to bear the self-weight of the newly casted concrete beam, the weight of workers and machinery, wind load, etc;

Condition 2-Hanging basket moving forward condition: the intelligent hanging basket moves forward, and its gravity center has been retreated to the tail of the hanging basket, the hanging basket structure mainly bears inertia force during walking, so the strength and anti-overturning ability safety factor of the main components still needs to be checked.

3.2 Modeling

Based on the professional analysis software Midas Civil for bridges, two models were established to analyze the mechanical performance under two working conditions. The wet weight of concrete, the weight of workers and machinery are applied to the corresponding distribution beams of the hanging basket according to their projective coverage range for simulation[7][8]. The connection components of the sliding frame and the suspension straps, suspension rods, are simulated using truss elements, while other main structural components are simulated using beam elements. The boundary conditions of the front and rear support points of the cantilever beam are both simple support constraints, and the longitudinal constraints of rear support points are released[9].

3.3 Stress Analysis

The structural stress distribution of the hanging basket under the most unfavorable working conditions was analyzed. According to the stress result, the stress of the new hanging basket has the following patterns: (1) The most unfavorable working condition for the hanging basket cantilever beam is condition 1, and the maximum stress occurs at the front support section of the cantilever beam, which is 158MPa; (2) The most unfavorable working condition for the sliding frame structure is condition 2. Due to the horizontal inertial force, the main beam of the sliding frame is subjected to most unfavorable forces, with a maximum stress of 212MPa; (3) The front and rear crossbeams of the bottom formwork have different support systems under casting and walking conditions. The stress of the front and rear crossbeams is most severe under condition 1, and their vertical deformation is most severe under condition 2; (4) The most unfavorable working conditions for the bottom formwork longitudinal beam, inner formwork guide beam, and side formwork guide beam are in condition 1, which basically conform to the force mode of simply supported beams[10], and the maximum stress occurs at the mid span position.

The stress result of each main load-bearing component is shown in Table2.

Table 2. MISES stress results of main components.

components	MISES stress verification /MPa			
	Condition 1	Condition 2	[σ]	check result
Cantilever beam	158	-	295	√
Upper crossbeam	144	-	295	√
sliding frame	68	212	295	√
Bottom formwork crossbeam	152	82	295	√
Bottom formwork longitudinal beam	175	14	295	√
Side formwork distribution beam	168	38	295	√
Inner guide beam	152	-	295	√
Rear anchor rod	111	-	1080	√

3.4 Deformation Analysis

The maximum vertical deflection of the intelligent hanging basket under condition 1 is 19.7mm, which appears at the mid span position of the bottom formwork longitudinal beam. Under condition 2, the hanging basket bears its seif-weight and wind load, so the structural deformation is very small.

3.5 Analysis of Anti-Overturning Capacity

The intelligent hanging basket should have sufficient anti-overturning stability under various working conditions. Under condition 1, the rear anchor of the hanging basket is anchored to the casted segment with four finish-rolled screw-thread steel bars with a diameter of 40mm. that the anti-overturning stability factor reaches 2.5, larger than the limited value 2.0. Condition 2 poses a huge challenge to the anti-overturning stability of intelligent hanging basket, as the buckle wheels are cancelled, which are imperative in traditional hanging basket. The stability mechanical mode under condition 2 is shown in Figure4.

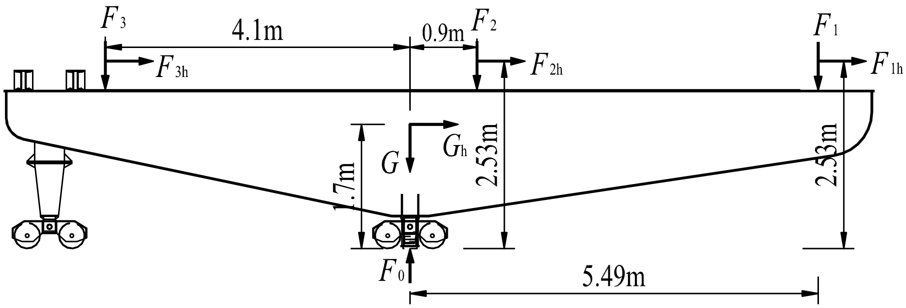


Fig. 4. Mechanical diagram of anti overturning calculation under working condition 2.

In condition 2, the rear anchor bars of the cantilever beam have been released, and the front and rear wheels are supported on the track, with no reverse buckle effect. Under this condition, the sliding frame has already carried the bottom formwork and side formwork backwards, and retreated the center of gravity to the tail. Therefore, the anti-overturning force is provided by the vertical force of the sliding frame, while the horizontal inertial force of the structure, the vertical gravity force of the suspension system and the front crossbeam, are all overturning forces. The stability coefficient against overturning under condition 2 is calculated as 2.17, which is larger than 2.0, the minimum requirements of the occupational standard. Due to the movable center of gravity, the intelligent hanging basket has reliable stability under the walking condition relying only on its self-weight.

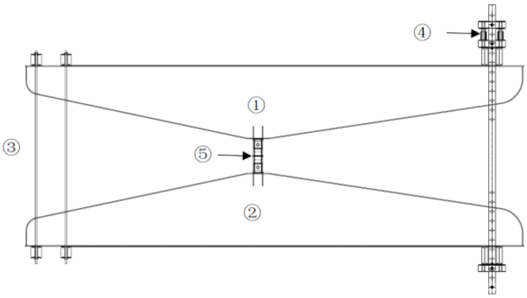
4 EXPERIMENT

4.1 Mechanical Test

4.1.1Experimental Scheme.

The intelligent hanging basket adopts a welded variable cross-section narrow box structure, which requires a lot of welding operation, instead of shaped-steel widely used in traditional hanging basket. In order to verify the reliability of the welded hanging beam, a mechanical performance test was designed. The experiment uses hydraulic jacks to load the cantilever beam in steps, to test the displacement and strain of the cantilever beam. The mechanical test plan and layout of the cantilever beam are shown in Figure5.

In the experiment, based on the actual working load, the test load is applied in four levels: 1) Level 1, 279kN, with a duration of 30 minutes. 2) Level 2, 534kN, with a duration of 30 minutes. 3) Level 3, 559.5kN, with a duration of 30 minutes. 4) Level 4, 636kN, with a duration of 30 minutes.



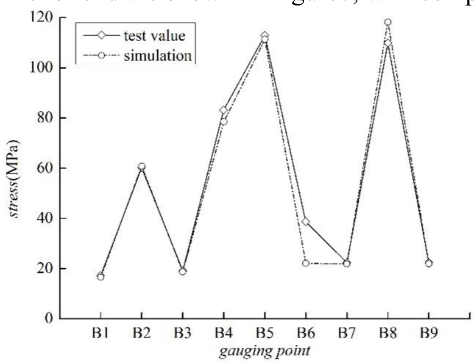
a)

b)

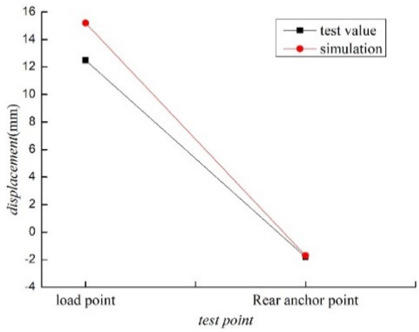
Fig. 5. Mechanical Test.

4.1.2Results.

The stress test results of the strain rosette and the maximum deformation at the rear anchor end are shown in Figure6, with comparison to the simulation.



a)



b)

Fig. 6. Comparison between measured stress & displacement and the simulation.

From the stress comparison results in Figure6a), it can be seen that the stress tested by the strain rosette has a high accuracy, which are in good agreement with the simulation. The comparison proves that the stress state of the cantilever beam is complex. In the test, under the maximum load of the casting condition, the maximum Mises stress of the cantilever beam is about 120MPa, which is less than the design strength of the steel of 295MPa, indicating that the safety of the cantilever beam is sufficient. According to the comparison in Figure6b), the measured displacement is slightly smaller than the theoretical displacement, which indicates that the real stiffness of the cantilever beam structure is slightly greater than designed.

4.2 Kinematics test

4.2.1Experimental Scheme.

The technological process and structural system of the intelligent hanging basket are quite different from those of the traditional hanging basket. The walking smoothness and safety are crucial to the application of the intelligent hanging basket. Therefore, the kinematics characteristics of the intelligent hanging basket in the walking condition are tested.

The dynamic test includes the speed test of the sliding frame and the speed test of the entire machine, with a focus on testing the dynamic response of the structure, the shaking amplitude of the structure, and the running smoothness of the wheel-rail system. In the sliding frame speed test, the hydraulic cylinder pushes and pulls the sliding frame at low speed (0.15 m/min), medium speed (0.25 m/min), and high speed (0.4 m/min) respectively. In the overall machine running speed test, the wheels are driven at three speeds: low speed (0.1m/min), medium speed (0.15m/min), and high speed (0.27m/min) respectively.

The kinematics test is equipped with inclination sensor, acceleration sensor and resistance strain gauge. During the walking process, both the bottom formwork and side formwork are suspended by sliding frames, so the stress of the sliding frames should be focused on. The bottom mold is suspended by four flexible electric hoists, with a suspension cable length of about 6m. During braking, due to inertia effect, the structure will shake forward and backward. Therefore, a triaxial acceleration sensor and a triaxial inclination sensor are installed at the central axis of the bottom mold. The field kinematics test is shown in Figure7.

Fig. 7. Kinematics Test of the Hanging Basket

4.2.2Results.

According to the experiment, the maximum acceleration and inclination statistics for the two speed tests are shown in Table3 and Table4. According to the measured results, the maximum starting and braking acceleration of the bottom mold is 0.16m/s² in the sliding frame speed test, and the maximum inclination angle of the bottom mold is 6.33°. In the overall machine speed experiment, the maximum starting and braking acceleration of the bottom mold is 0.0076m/s², and the maximum inclination angle of the bottom mold is 1.49°. Considering that the cable chain length of the sliding frame suspending the bottom mold is about 6m, it can be estimated that the swing amplitude of the bottom mold is about 661mm(6m×sin6.33°) under two operating conditions.

For the stress of all members of the sliding frame under kinematics test, according to the strain flower test result, the maximum stress is all below 100MPa, indicating that the strength of the sliding frame is very sufficient, and only the shaking range needs to be focused on in walking condition.

Table 3. Measured Acceleration of Accelerometer.

tests	X-direction (m/s^2)	Y-direction (m/s^2)	Z-direction (m/s^2)	XYZ-direction (m/s^2)
Sliding frame speed test	-0.105	-0.068	-0.099	0.160
Overall machine speed test	0.0045	0.0012	-0.0060	0.0076

Table 4. Amplitude of inclination measurement points in various directions.

tests	X-direction (°)	Y-direction (°)	Z-direction (°)	Maximum value (°)
Sliding frame speed test	0.12	0.03	6.33	6.33
Overall machine speed test	0.02	0.02	1.49	1.49

5 CONCLUSION

In this study, we present a novel concrete cantilever casting hanging basket that the gravity center of the equipment is adjustable intelligently, during moving from the casted segment to the next, this approach could change the mechanical state of the hanging basket under different working conditions, cancel the anti-anchoring devices of the track when walking forward. Moreover, hydraulic template, wheel-rail system and automatic control system are adopted in the novel hanging basket, this approach could reduce many manual operations, improve the working efficiency of hanging basket, enhance the structure instability and reduce the difficulty and risk of manual work at height.

The key components of the intelligent hanging basket include the sliding frame and the automatic control system. The sliding frame can support the weight of the bottom formwork and the side formwork, and can change the overall gravity center of the hanging basket by sliding on the top of the main beam. The automatic control system can control the continuous moving of the sliding frame, the continuous moving of the main beam and the intelligent adjustment of the formworks, just by sending several instructions to the hydraulic cylinder and the electric wheels.

The static simulation shows the stress of the components of the hanging basket all meet the requirements of the occupational standard, the most unfavorable working condition of the components are different, the anti-overturning ability of the intelligent hanging basket is sufficient.

The mechanical test and the kinematics test were carried out in Wuhan, China, to verify the strength of main beam, the walking smoothness of the sliding frame and the entire equipment, and the tests results proved the feasibility and reliability of the design.

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