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Research paper

Investigation on the influence of rotation speed on internal stresses in PC bridge built using rotation method

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Abstract: This paper investigates the impact of rotation speed on the internal stresses of prestressed concrete (PC) girder bridges constructed using swivel method. A numerical model is established to analyze the bridge's structural response under varying rotary speeds. The results reveal a positive correlation between the escalation of angular velocity and the magnification of concrete stresses, which are most pronounced at the top slab of the PC box girder near the pier. The stress of the PC girder at the selected cross-sections increases by 527% when the angular velocity goes from 0.02 rad/min to 0.05 rad/min. During the rotation acceleration phase, heightened stress concentrations are observed in the main girder and the underlying pier. Comparatively small stresses are achieved across the bridge under an angular velocity of 0.02 rad/min and rotational acceleration of 2.00×10^{-3} rad/min^2. The analytical framework employed in this study, which integrates stress monitoring data from the PC girder with advanced numerical simulations, confirms that the concrete stresses encountered during the rotation construction process remain within acceptable limits. The successful use of the rotation construction technique demonstrates its feasibility and effectiveness as a construction method for large-span asymmetric bridges overpass multi-line railways.

Keywords: asymmetric bridge, PC girder, rotary construction, rotational speed, structural response

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1. Introduction

According to authoritative governmental statistics, China's high-speed railway network has surpassed a noteworthy milestone of 38,000 kilometers by the end of 2022 [1], with numerous additional railway projects underway. This extensive expansion has complicated the country's intricate transportation networks [2]. In most occasions, integrating new traffic lines necessitates bridge intersections with existing highways and railways, presenting substantial challenges to traffic flow, operational efficiency, and economic stability when relying on conventional fabricating methodologies [3–5]. To address these limitations, an innovative approach, rotation construction, has emerged as a highly advantageous solution for bridge construction over operational lines [6–8]. This methodology involves constructing the bridge off-axis and rotating it into its final position. It offers numerous benefits, such as simplifying construction operations, minimizing disruptions to operational lines, and expediting the construction period. These advantages are particularly pronounced in long bridges that span operational railways and are constrained by limited site space [9].

The rotation construction technique represents a seminal advancement in bridge erection [10]. However, its implementation is complicated, posing challenges to rotary speed, structural weight, and span arrangement. Some studies have shown that improper adoption of rotation speed may result in large tensile stresses in the bridge, leading to cracking of the concrete [11]. Zeng et al. [12] conducted rotational testing on a scaled bridge at varying angular speeds, finding that accelerations below 0.24 rad/min^2 help mitigate stress impacts on the main girder. A rotary speed of 0.02 rad/min brings much lower stress variations than higher speeds (0.03, 0.04, and 0.06 rad/min). Yu [13], using numerical simulations and theoretical analyses, confirmed that while angular velocities marginally influence girder forces, angular accelerations have a more profound effect. Similarly, Han et al. [14] and Wang et al. [15] found that bridge deck tensile stresses are sensitive to rotary velocity, while bottom slab stresses vary notably with angular velocity. Thus, meticulous selection of rotary speed is crucial to ensure the structural safety of bridges during rotation construction.

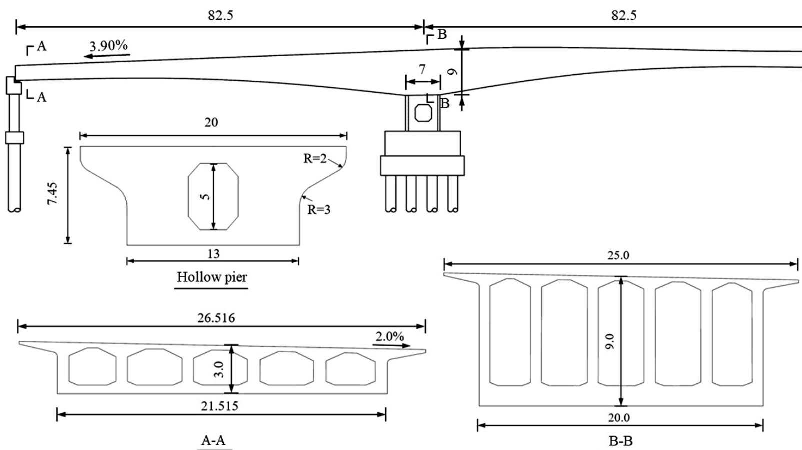
In recent years, bridge design has evolved to accommodate increased tonnage and extended spans, differing significantly from traditional, short, symmetric structures with modest tonnage. These monumental structures exhibit irregular weight distributions and dynamic inertia during rotational movements, posing unique challenges requiring careful execution. The additional stresses encountered during construction underscore the imperative for precise monitoring to avoid stress surges that could harm the safety and integrity of the bridge [16, 17]. Consequently, traditional construction methodologies must be reassessed and adapted to match modern bridge construction.

This study delves into the critical aspects of stress monitoring and the primary technologies utilized during the rotation construction of large-span asymmetric bridges overpass multiple-line railways. The paper encompasses extensive simulation analyses and real-time monitoring throughout the entire rotation construction process of an asymmetric large-span bridge in China. Based on the numerical model calculations and empirical data from practical projects, the rationality and effectiveness of the fabrication techniques by analyzing the stress development under different rotational parameters are examined, and a comprehensive evaluation of the suitability of the construction methodology for large-span asymmetric bridge rotations is conducted and presented. The findings of this research contribute invaluable insights to guide similar bridge rotation construction in the future.

2. Engineering background

2.1. Prototype bridge

This study is conducted on the complex rotation construction of a large-span asymmetric prestressed concrete (PC) girder bridge at Guangzhou Baiyun Station in Guangdong province, China. The bridge crosses over eleven railway tracks at an angle of 87° with the operational rail lines, presenting various design and construction challenges. Fig. 1 shows the schematic layout of this 165.0 m-long bridge, comprised of two spans of 82.5 m each, with a total weight of over 20,000 tons. The bridge has a bidirectional asymmetric design with vertical and horizontal plane differences. It showcases innovative engineering solutions in its construction. The PC box main girder utilizes C55 concrete designed to achieve a compressive strength of 55.0 MPa. It has a single-box, five-cell configuration with a straight web. The height of the girder varies from 3.0 m at the ends to 9.0 m at the middle pier. The top and bottom slabs have varying widths, contributing to the bridge's asymmetric shape. The main girder is inclined with a longitudinal slope of 3.9% and a lateral slope of 2.0%. The bridge also features rectangular hollow piers, with widths tapering from 20.0 m at the top to 13.0 m at the bottom and an overall thickness of 7.0 m. These components are firmly attached at the pier-to-girder joint to ensure structural integrity.



(a)

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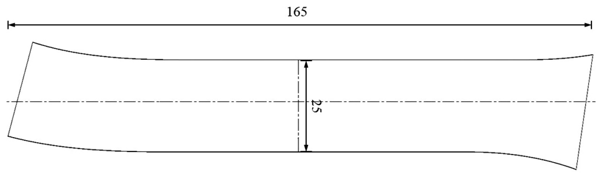


(b)

Fig. 1. Layout of background bridge (Unit: m): (a) Prototype bridge layout diagram; (b) Prototype bridge top view

The rotation process of the bridge encompasses three distinct phases: firstly, the accelerated rotation phase, wherein the rotary angular velocity gradually escalates from a standstill to the predetermined rotating speed; secondly, the uniform rotation phase, characterized by a consistent and constant angular velocity; and lastly, the decelerating rotation stage, during which the rotary angular velocity progressively decreases from the designated rotating speed back to zero. The bridge utilizes a rotation system with spherical hinges capable of bearing 26,000 tons. Fig. 2 displays the layout of the rotation system, including upper and lower turntables, spherical hinges, arm braces, a slide rail, a positioning framework, and two traction slopes. The spherical hinges support the rotational elements, while arm braces prevent overturning. The rotary torque is applied through hydraulic jacks. The 50 mm-thick spherical plate and reinforcing ribs are made from Q355C steel, complying with EC2 [18] standards for optimal chemical composition and mechanical properties. The pin shaft is constructed from 45 forged steel per EC2 [18]. With an 8.0 m spherical hinge radius, eight arm braces and slide rails encircle the upper turntable, enabling stable movement along the rails under rotational traction, achieving precise bridge rotation.

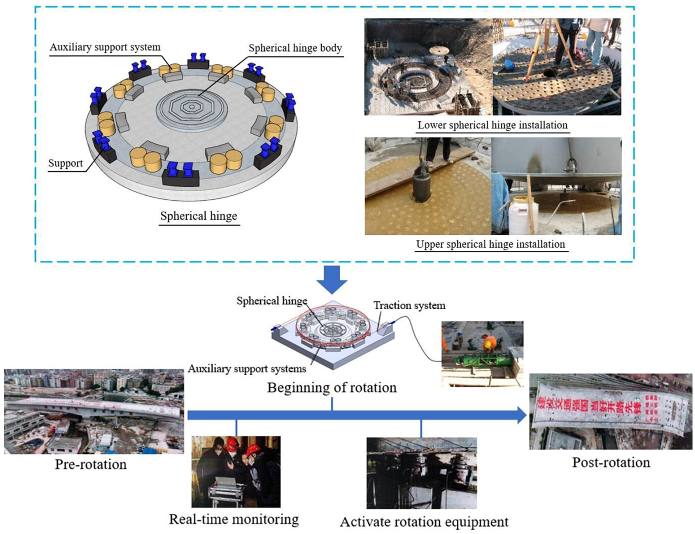
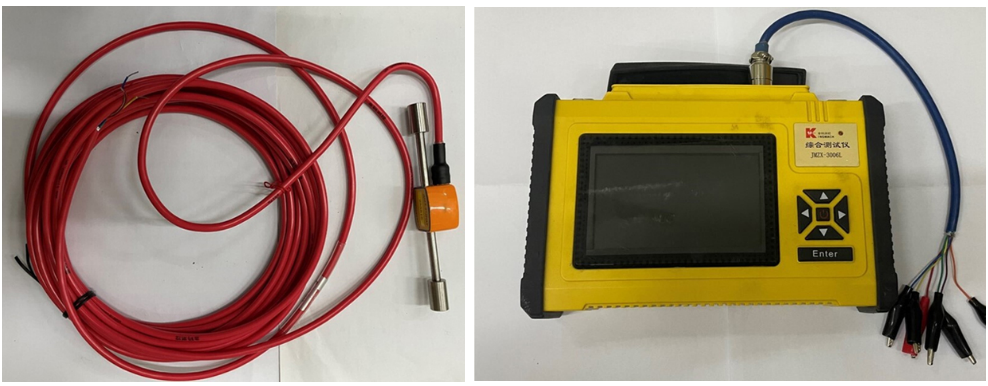


Fig. 2. Configuration of rotation system

The lower turntable, the foundation for the rotated structure, is made of C55 concrete and positioned beneath the 3.0 m-thick upper turntable. The arm braces incorporate a concrete-filled steel tubular design, utilizing Q355C steel tubes with 1.0 m outer diameter and 24 mm wall thickness, filled with concrete targeted at 55.0 MPa compressive strength. The traction system includes a pair of traction ropes, a reaction seat, and power equipment. During bridge rotation, the system overcomes friction at the upper and lower spherical hinge surfaces [19, 20], with an assumed static frictional coefficient of 0.08 based on literature [21], resulting in a calculated startup traction force of 2619 kN per side.

2.2. Monitoring scheme

Due to the prototype bridge's complex design and substantial weight, the PC girder encounters significant tensile stress from centrifugal forces generated by its rotational movements. Precise monitoring of the stress within the bridge components during rotation is necessary to prevent structural damage and ensure a smooth construction process. This monitoring requires employing sensing elements that are convenient, reliable, durable, and capable of tracking the structure's stress. Drawing from prior monitoring experience [22], as shown in Fig. 3, the steel chord sensor, standing out for its exceptional stability, strain accumulation capabilities, good anti-interference properties, and straightforward data acquisition procedures, has been chosen to monitor the investigated prototype bridge.



(a) (b)

Fig. 3. Monitoring equipment: (a) Strain sensor; (b) Portable comprehensive tester

Fig. 4 illustrates the location and arrangement of monitoring sensors. Six key sections within the PC girder have been identified, and each is outfitted with six strain sensors. These sensors are positioned at critical points to measure concrete strains by monitoring string vibrations of the chord sensors. The sensors embedded within the PC girder provide valuable insights to promptly identify potential deficiencies in structural elements. The strain value of the steel string can be obtained by testing the self-oscillation frequency of the sensor. As the tensile strain in the PC girder resulting from the bridge rotation construction is typically small, the compressive and tensile stress at the position of the steel string can be calculated using the following formula:

$$\sigma_c = E_c \varepsilon_g \tag{2.1}$$

where: σ_c – concrete stress; E_c – elasticity modulus of concrete, ε_g – strain measured by chord sensors.

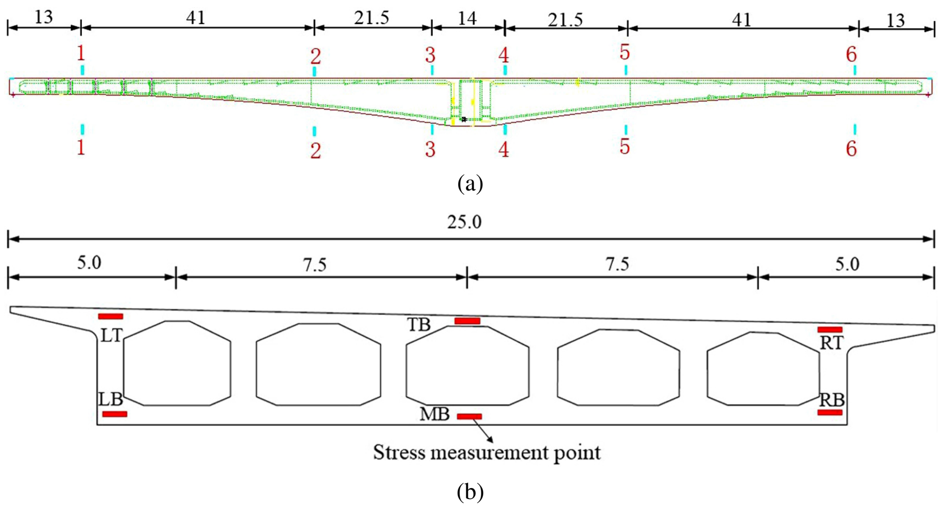


Fig. 4. Measurement arrangement (Unit: m): (a) Arrangement of critical sections; (b) Distribution of strain sensors

3. Numerical simulation and analyses

3.1. FE model establishment

Finite element (FE) model is established for the investigated bridge, facilitating a precise representation of its structural characteristics. The concrete box girder and the supporting piers are modeled utilizing solid elements, ensuring an accurate depiction of their material behavior and geometry. The constitutive model of the concrete is defined based on the stress-strain relationship provided in the Chinese code GB 50010-2010 [23]. The material properties of prestressing steel strands are set according to the standard tensile strength by the Chinese code JTG D64-2015 [24], as shown in Fig. 5. Link element is used to model the steel strand. In order to account for the influence of concrete cracking on the stresses, the element death function was activated when the stress or strain in the solid element reached its permitted values. The model's boundary conditions are consistent with the constraints of the real bridge, and at the pier-to-girder joint, all the nodes are coupled to form a fixed connection. The vertical displacement is limited by constraining the nodes at the bottom of the pier. According to the element sensitivity analysis results, the stress obtained from the models significantly varied with the element meshing size, and the stress became stable after the element size of the concrete approached 100 mm. Consequently, the concrete box girder has meshed using element sizes of 100 mm. The established FE model of the prototype bridge is shown in Fig. 5.

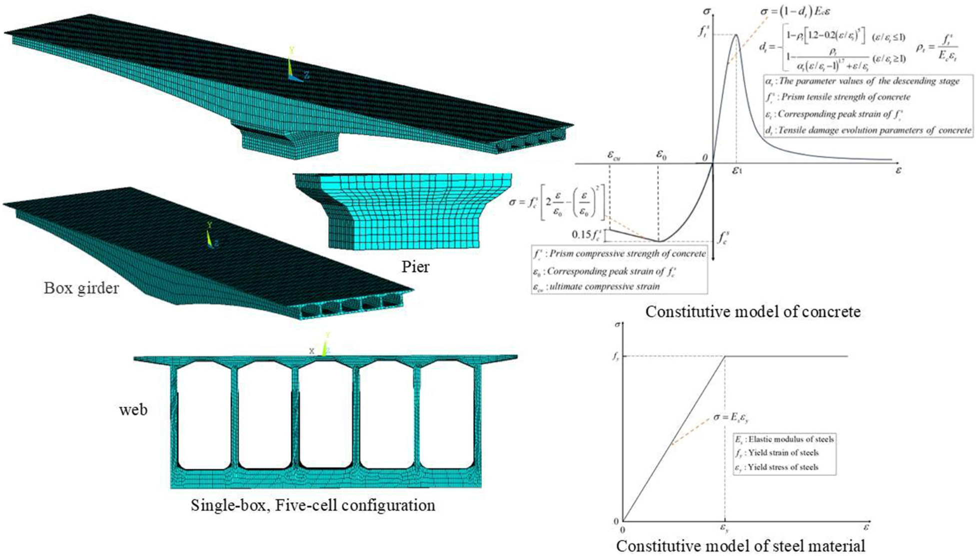


Fig. 5. Finite element model of Bridge

3.2. FE modelling results

3.2.1. Effect of rotary speed

The stress levels of the structural components in the bridge were evaluated under different rotary angular speeds: 0.01 rad/min, 0.015 rad/min, 0.02 rad/min, 0.05 rad/min, and 0.10 rad/min using FE models. The normal stresses from the box section of the PC girder at different angular speeds are shown in Fig. 6. The stress distribution during the rotation of the bridge is plotted in the figure, and the normal stresses are formed due to the centrifugal force during the rotation. As can be seen, the stress distribution along the main girder axis is symmetrical from the center to the ends. The highest stress is observed at the upper edge region of the PC girder's box section, while the stress at the lower-side edges is low. Stresses at the cantilever end are minimal during rotation. However, the stress at the top slab of the PC girder near the pier-to-girder connection is comparatively high, making it the most critical part of the bridge's superstructure during rotation. It is important to note that as the rotary angular speed increases, the maximum stress in the main girder also increases. The most critical stress of the bridge increases by 126%, 77%, 527%, and 299% sequentially as the angular velocity gradually increases from 0.01 rad/min to 0.015 rad/min, 0.02 rad/min, 0.05 rad/min, and 0.1 rad/min. Therefore, selecting a reasonable rotation speed is essential to ensure that the maximum stress of the bridge stays below the allowed material value.

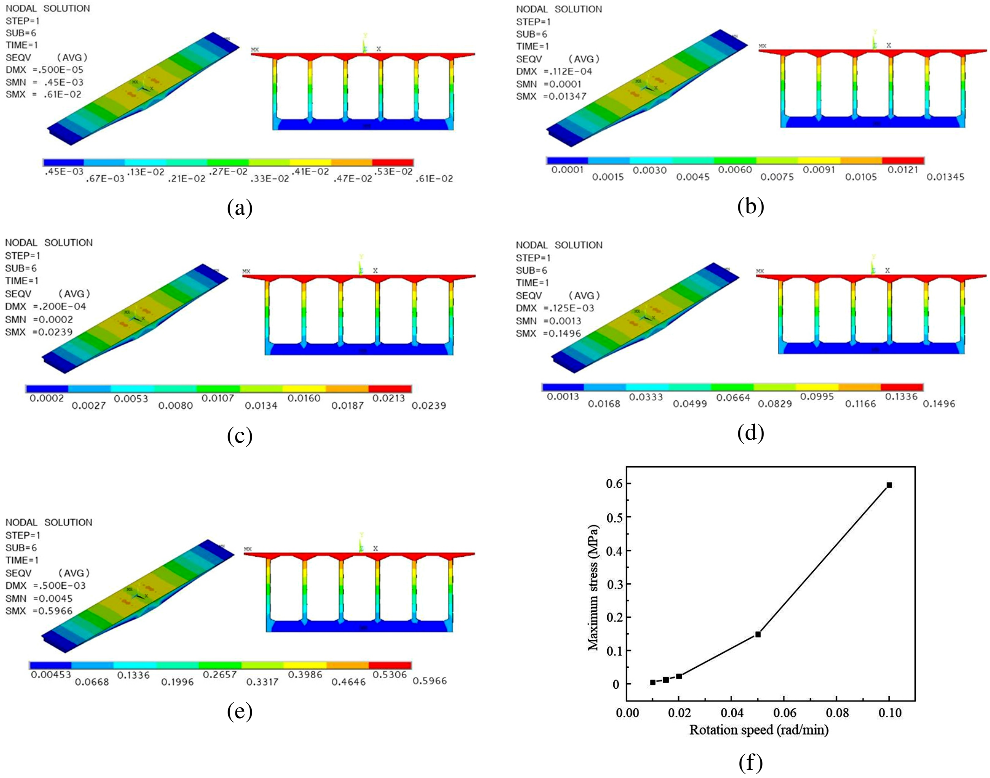


Fig. 6. Numerical prediction of bridge models with rotational angular velocities (Unit: MPa): (a) 0.01 rad/min; (b) 0.015 rad/min; (c) 0.02 rad/min; (d) 0.05 rad/min; (e) 0.10 rad/min; (f) Relationship between rotation speed and the maximum stress

As shown in Fig. 6(f), there is a non-linear correlation between the rotary angular velocity and the maximum stress endured by the PC girder. The maximum stress of the PC girder was enlarged by 527‰ as the rotary velocity increased from 0.02 rad/min to 0.05 rad/min. This finding implies that excessively high rotary angular velocity introduced dynamic stress to the bridge, potentially causing structural cracking. To reduce the risk of concrete cracking, it is essential to incorporate sufficient steel reinforcements in the girder's most critical region to align with the rotational construction requirements. To assess the bridge's safety under varied rotary angular speeds, the normal stress in the box section of the PC girder stemming from the combined effects of gravity and rotational centrifugal force is outlined in Fig. 7.

Fig. 7 shows that at a rotational speed of 0.02 rad/min, the predominant stress range on the structure is between 0.3 MPa and 1.25 MPa. This suggests that additional reinforcements are necessary to ensure the region's cracking resistance. However, at a rotary angular speed of 0.05 rad/min, the maximum stress shifts to a range between 1.0 MPa and 2.0 MPa, reaching a peak stress of 1.96 MPa. At this speed, the bridge's maximum stress nears the critical stress level, raising concerns about potential cracking and damage. Under the coupling effect of bridge self-weight and rotational speed, local tensile stress is prone to occur in the bridge roof, resulting in the risk of cracking in the bridge deck. Excessive acceleration will lead to a large inertial force on the bridge, which may cause deformation or even failure of the beam, which is not conducive to smooth rotation. According to the Chinese code JTG/T3650-2020 [25], the rotary angular speed should not exceed 0.01 to 0.02 rad/min during the bridge rotation. In order to ensure that the bridge's stress remains below the critical value during rotation, this study suggests a uniform rotation speed of 0.02 rad/min.

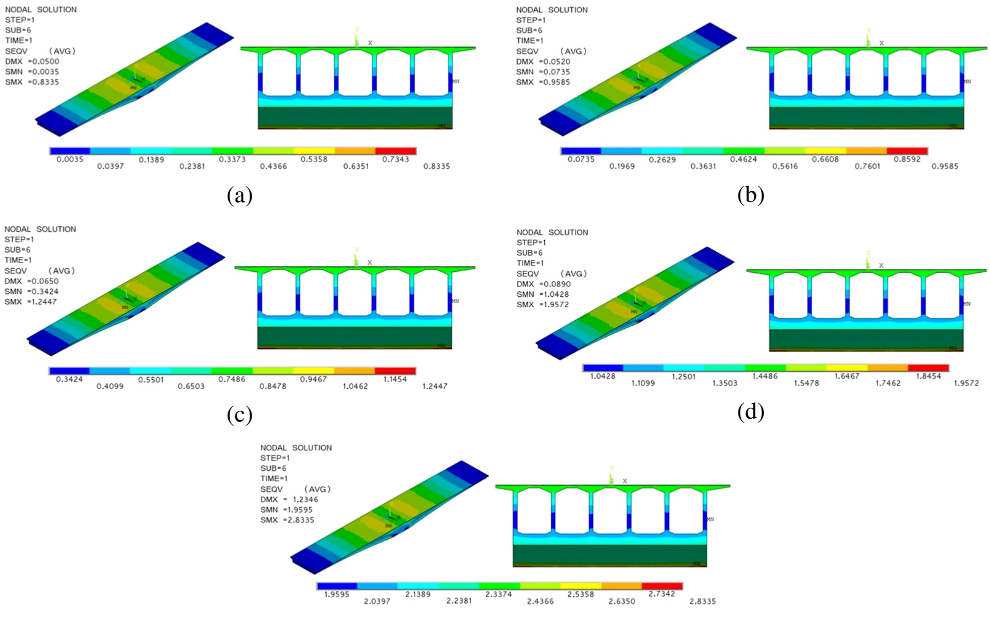
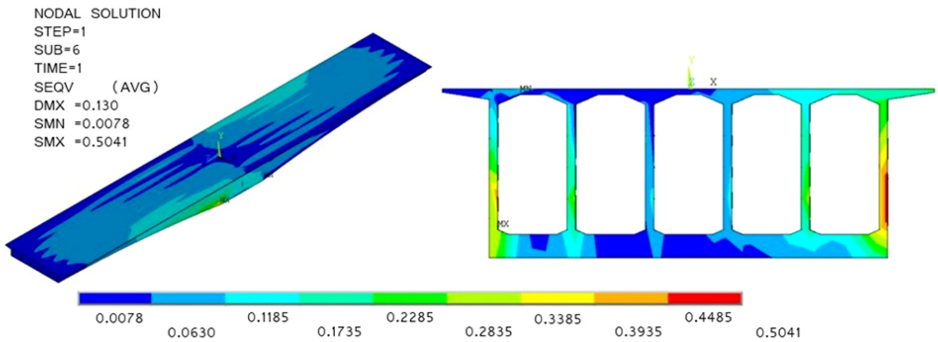


Fig. 7. Numerical prediction of bridge models with rotational angular velocities and gravity (Unit: MPa):): (a) 0.01 rad/min; (b) 0.015 rad/min; (c) 0.02 rad/min; (d) 0.05 rad/min; (e) 0.10 rad/min

3.2.2. Effect of rotary acceleration

The bridge's superstructure is affected by transverse moments during the acceleration and deceleration phases of rotation, and the superstructure risks concrete crushing when the PC girder is exposed to significant transverse moments. Choosing an appropriate rotational acceleration is crucial to ensure the bridge's safety during rotation. To ascertain the effect of rotary acceleration, the stress condition of the studied bridge is subjected to a more thorough assessment utilizing the established FE model, which incorporates the influence of gravity. In the simulations, rotary accelerations of 1.00×10^{-3} rad/min^2, 2.00×10^{-3} rad/min^2, and 3.00×10^{-3} rad/min^2 were selected for FE simulations. The results of normal stress obtained from the models are depicted in Fig. 8. The stress in the PC girder at the cantilever end is minimal. Conversely, significant stress is observed at the pier-to-girder joint, particularly in the side webs of the box girder. Inspection of the stresses in the box web reveals a pattern of initial increase from the cantilever end towards the middle between the end and the pier-to-girder connection, followed by a slight decrease towards the connection point. Obviously, reinforcing the concrete side webs is necessary to minimize the risk of concrete cracking.



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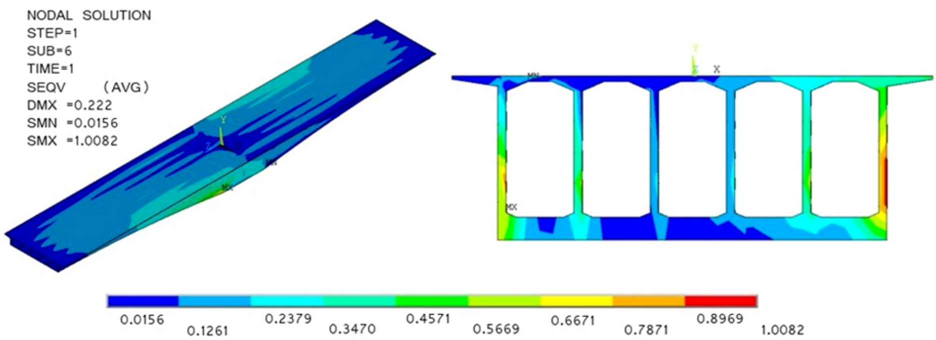

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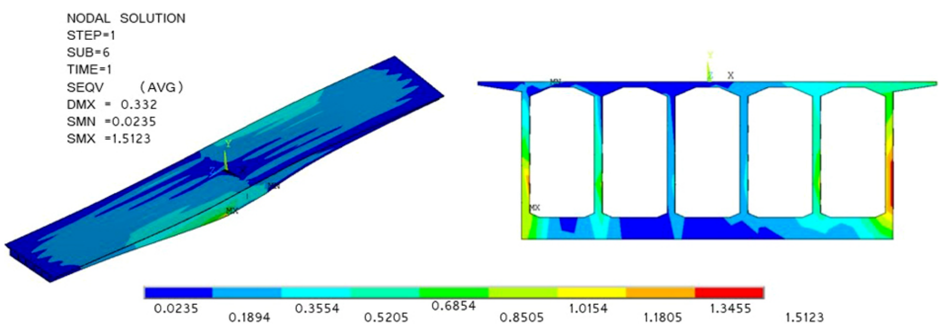

(c)

Fig. 8. Stress of PC girder under varying rotary acceleration (Unit: MPa): (a) 1.00×10^{-3} rad/min^2; (b) 2.00×10^{-3} rad/min^2; (c) 3.00×10^{-3} rad/min^2

Figure 8 depicts that when subjected to rotary accelerations of 1.00×10^{-3} rad/min^2, 2.00×10^{-3} rad/min^2, and 3.00×10^{-3} rad/min^2, the maximum stress in the bridge reaches 0.50 MPa, 1.01 MPa, and 1.51 MPa, respectively. A significant observation reveals that increasing the rotary acceleration from 1.00×10^{-3} rad/min^2 to 2.00×10^{-3} rad/min^2 and 3.00×10^{-3} rad/min^2 results in a 100% and 200% enlargement of the bridge's maximum stress, respectively. This finding aligns with Ma X.'s previous conclusion, indicating a strong linear relationship between rotary acceleration and the bridge's maximum stress [26]. The prescribed rotation angle for the prototype bridge is 102.25 degree. Considering the balance between construction time and structural safety, the recommended rotary angular acceleration for construction is 2.00×10^{-3} rad/min^2. This allows the full rotation to be achieved in 89 minutes plus 14 seconds, which aligns with project expectations. This method reduces construction and traffic control durations and minimizes overall construction costs.

4. Engineering verification

4.1. Optimized rotation construction scheme

The reliability and capability of the proposed rotating parameters are examined through the real-time tests of the prototype bridge. Fig. 9 shows the bridge's position of pre-rotation (marked in red) and the position of post-rotation (marked in green). The process for the bridge rotation consists of two main steps: preliminary rotation and final rotation. The preliminary rotation is carried out before the actual construction to determine the static frictional coefficient of the rotation system. During the preliminary rotation, the traction slopes are gradually tightened in opposite directions to create torque in the pier. When the pier starts to rotate, the amount of force achieved at that point represents the critical load of the rotating system. The stress on the bridge at specific key points is also monitored to ensure that the rotating equipment meets the requirements.

Final rotation is conducted 24 hours after the successful preliminary rotation. The angular velocity and acceleration for the rotation are set at 0.02 rad/min and 2.00×10^{-3} rad/min^2, respectively. During the final rotation, the sectional stresses of the bridge are continuously monitored to ensure that the structural parameters meet specific criteria and to provide timely data for the subsequent construction process. The final rotation procedure consists of two stages:

(i) Automatic rotation stage: The rotational equipment is started and runs in "automatic" mode. During this stage, the bridge stress is monitored based on the distance between the rotated objective's real-time location and the structure's expected final position. Initially, the stress is recorded at every movement of 5 degrees. The monitoring frequency is then increased to every 2 degrees when the distance is within 20 degrees. When the distance is within 10 degrees, the monitoring frequency switches to every 1 degree, and finally, it changes to every 0.5 degrees for the last distance of 5 degrees.

(ii) Manual rotation stage: After the automatic rotation is completed, the rotary system is switched to "manual" operation mode to rotate the bridge to the predetermined position accurately. Stress is continually recorded during this stage until the bridge is accurately seated.

Fig. 9. Arrangement of the rotation construction

4.2. Real-time tests and discussion

The construction of the bridge follows the rotation construction scheme proposed earlier. Fig. 10 summarizes the concrete stress results of the real bridge tests and the FE predictions. As shown in Fig. 10(a), the stresses in the top slab of the box section near the pier-to-girder connection under uniform rotation are comparatively higher than the other sections. This aligns well with the FE predictions. The small deviations between the test and the simulated results indicate that the established FE model can accurately simulate the stress status of the bridge under the rotation construction method. Referring to Fig. 10(b), one can see that the FE model produces similar stress results to the actual bridge-measured results. In the accelerated rotation stage, the stress at the middle web of the PC girder is much larger than that at the cantilever end, indicating that more attention should be paid to these regions to ensure structural safety.

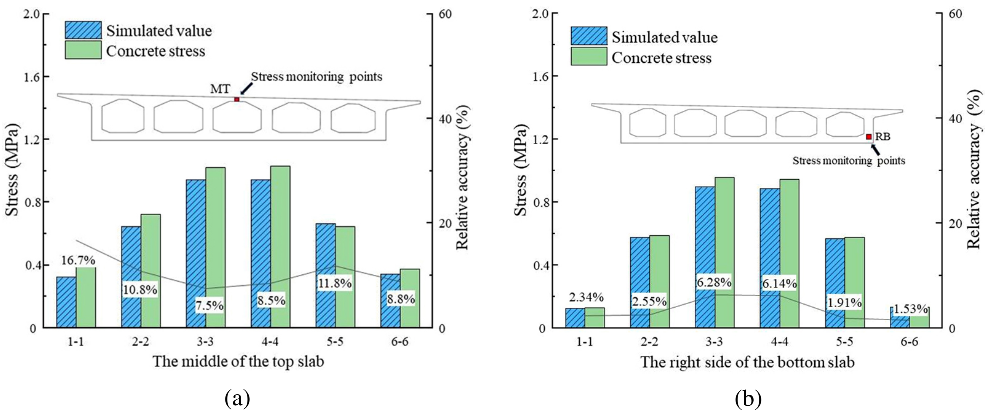

Fig. 10. Comparison of the measured value and simulated value: (a) Uniform rotating stage; (b) Acceleration rotating stage

Fig. 11 illustrates the distribution of longitudinal forces in the bridge during uniform rotation. The longitudinal force is greater in the middle and smaller on both sides. This explains why the stresses in the bridge are higher in the middle and lower at both ends during uniform rotation. It also indicates that the middle of the bridge is subjected to large centrifugal forces, which could lead to cracking of the deck slabs. Therefore, it’s important to focus on the design of the middle structure in the actual project. Overall, the relative error between the FE model and the actual real-time monitored results of the bridge is small, suggesting that the results of the FE simulation are reasonable and can be used to guide practical engineering applications.

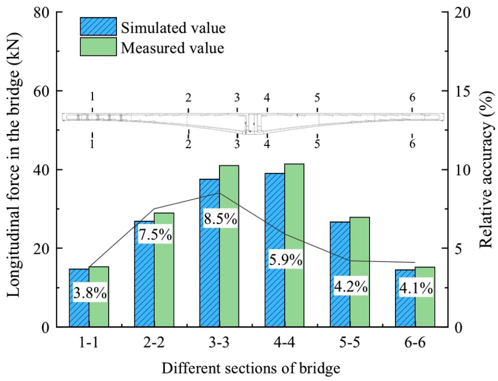

Fig. 11. Longitudinal force under uniform rotating

To understand the stress on the bridge during its rotation, Table 1 shows the stress results from key sections. It was found that there was significant stress in the girder section. Specifically, sections 3-3 and 4-4 showed increased stress on their top slabs during uniform rotation, with the highest stress occurring near the pier-to-girder interface. The concrete members remained intact throughout the rotation, indicating that the proposed parameters effectively prevented cracks in the areas under tensile stress. During accelerated rotation, stress patterns were changed, with higher stress levels recorded at the lateral edges of sections 3-3 and 4-4. The webs tended to have higher stresses near the bottom slab. Monitoring revealed that accelerated rotation due to transversal moments may subject the outer web of the box girder to tensile stresses. Ensuring compliance with safety standards, Table 1 confirms that all monitored stresses in the project strictly adhere to the specifications in the Chinese code [27], ensuring that the tensile stress at the cross-section remains within the permissible limit of $\sigma_{ct} \leq f_t' = 1.96$ MPa, thereby ensuring structural integrity and safety.

Table 1. Results of stress monitoring (MPa)

Section	Point	Acceleration rotating stage	Uniform rotating stage	Point	Acceleration rotating stage	Uniform rotating stage
1-1	LT	0.133	0.332	LB	0.218	0.211
	MT	0.111	0.388	MB	0.087	0.221
	RT	0.104	0.345	RB	0.128	0.232
2-2	LT	0.556	0.678	LB	0.623	0.334
	MT	0.466	0.723	MB	0.512	0.321
	RT	0.689	0.711	RB	0.589	0.333

Continued on next page

Table 1 – *Continued from previous page*

Section	Point	Acceleration rotating stage	Uniform rotating stage	Point	Acceleration rotating stage	Uniform rotating stage
3-3	LT	0.832	0.912	LB	0.977	0.478
	MT	0.533	1.021	MB	0.433	0.465
	RT	0.878	0.967	RB	0.956	0.488
4-4	LT	0.989	0.932	LB	0.913	0.454
	MT	0.487	1.032	MB	0.467	0.433
	RT	0.911	0.923	RB	0.945	0.472
5-5	LT	0.477	0.623	LB	0.498	0.366
	MT	0.366	0.645	MB	0.316	0.357
	RT	0.589	0.613	RB	0.577	0.373
6-6	LT	0.154	0.356	LB	0.098	0.177
	MT	0.087	0.376	MB	0.077	0.186
	RT	0.122	0.343	RB	0.131	0.223

Note: LT represents the left of the top slab, MT represents the middle of the top slab, and RT represents the right of the top slab. LB represents the left of the bottom slab, MT represents the middle of the bottom slab, and RT represents the right of the bottom slab.

The successful application of the rotation construction method demonstrates its effectiveness in executing large-span bi-directional asymmetric bridge rotation, which increases the possibility of large-span and large-tonnage rotary bridge construction [28, 29]. However, more simulation exercises and actual construction under different working conditions are necessary to further optimize the rotation construction technology and verify the method's feasibility.

5. Conclusions

Based on the rotation construction of large-span asymmetric prestressed concrete (PC) bridges overpass multi-line railways, effective methodology to optimize the erection of the bridge under different rotation speed is proposed. The following remarks can be concluded based on the analysis and experimentation:

1. During the uniform rotation stage, the rotational centrifugal force generates additional concrete stress in the bridge deck. In the accelerating and decelerating stages of rotation, the bridge's superstructure is subjected to transverse moments, resulting in significant stress on the side webs, making it crucial to incorporate adequate steel reinforcement at the regions to ensure the safety.
2. The maximum stresses of the bridge increase with the rotational velocity, and the most critical stress of the bridge increases by 126%, 77%, 527%, and 299% sequentially as the angular velocity gradually increases from 0.01 rad/min to 0.015 rad/min, 0.02 rad/min,

0.05 rad/min, and 0.1 rad/min. Adopting reasonable rotational speed and rotational acceleration can effectively reduce the bridge stress and lower the risk of bridge deck cracking.

3. The combination of simulation analysis and bridge monitoring can ensure the construction safety. The total time taken for successful rotation is 85 minutes, which is shorter than the scheduled time of 89 minutes plus 14 seconds. This construction technology can provide experience for the rotation construction of long-span asymmetric bridges, but more follow-up tests and engineering verification are needed.

In the research field of bridge rotation construction, it is important to study further the effects of wind load, girder stiffness, rotation devices, and bridge vibration. Additional experimental data from real bridge constructions is necessary to validate the conclusions drawn from this study.

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