

Mechanical Behavior Analysis of the Pier-Beam Joint Zone in a Continuous Rigid Frame Bridge with V-Shaped Piers and Corrugated Steel Webs

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Abstract: The main bridge of the Xinjiang Bridge is a corrugated steel web continuous rigid frame bridge with a span arrangement of 90 m + 165 m + 90 m. The connection area between Segment No. 0 and the V-shaped pier features a complex structure and prominent local mechanical issues. The main pier of the bridge adopts a rigid skeleton concrete structure, and approximately 2 m at both the top and bottom of the V-legs are equipped with UHPC reinforcement layers. To analyze the structural load transfer path of the pier-beam joint zone and prevent concrete cracking, a composite finite element model considering the influence of stress concentration was established based on Saint-Venant's principle. The V-shaped pier, pile cap and pile foundation, as well as Segments No. 0 to No. 6 of the main beam, were selected as the analysis scope. The concrete main structure, corrugated steel web, and prestressing tendons were simulated using solid elements, shell elements, and truss elements, respectively. The results indicate that the compressive stress near the web of Segment No. 0 is relatively high, exhibiting a significant spatial effect. As the thickness of the bottom slab increases from 60 cm to 90 cm, the normal compressive stress at the midspan of Segment No. 0 gradually decreases. When the bottom slab thickness is set to 90 cm, the maximum compressive stress is 18.8 MPa, satisfying the code requirements. Except for local stress concentration zones, both the principal compressive stress and principal tensile stress of the concrete in Segment No. 0 meet the code requirements. The mechanical behavior of the C50 concrete zone and the UHPC reinforcement zone of the pier is reasonable, and the longitudinal prestressed steel bars have a positive effect on the crack resistance of the pedestal area.

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Keywords: V-shaped pier; corrugated steel web; continuous rigid frame bridge; composite finite element model; UHPC

1 Introduction

With the continuous increase in bridge span and deck width, the structural mechanical state of continuous rigid frame bridges becomes more complex, imposing higher requirements on the rationality of load transfer paths. The V-shaped pier transmits the main beam loads to the pier shaft and foundation through its inclined legs, which can improve the structural mechanical behavior while enhancing the bridge's aesthetic effect; therefore, it is widely applied in long-span and wide continuous rigid frame bridges. However, compared with traditional straight-legged rigid frame bridges, the load transfer path in the pier-beam joint zone of V-shaped piers changes significantly: the pier top reaction force of a straight-legged rigid frame bridge is basically transmitted to the foundation along the pier axis, and the load transfer in the joint zone is primarily dominated by in-plane compression and bending, meaning that section verification using a bar system model can well capture its mechanical state. In contrast, the

V-shaped pier transmits forces obliquely through its inclined legs, where vertical loads are transformed into axial forces and bending moments within the inclined legs. The horizontal component force at the top of the inclined legs needs to be balanced by the Segment No. 0 between the two legs, subjecting Segment No. 0 to a spatial mechanical state superimposed by axial force, bending moment, shear force, and other effects. Meanwhile, geometric configuration mutations occur at the connections between the inclined legs, main beam, and pedestal. Structural factors such as manholes in the transverse diaphragms and web slope changes further disturb the load transfer path, resulting in shear lag and stress concentration at locations such as the beam-leg intersection corners and manhole edges. If verification is still conducted using the average section stress from a bar system model, the local peak stresses will be underestimated, posing a risk of concrete cracking. Since the pier-beam joint zone is located at a critical load-bearing part of the structure, post-construction maintenance and strengthening are difficult; once cracking occurs, it will directly affect the durability and service life of the structure.

For continuous rigid frame bridges using corrugated steel webs, attention must also be paid to the compatible deformation between the steel webs and the concrete top and bottom slabs. In box girders with corrugated steel webs, the concrete webs are replaced by corrugated steel webs. The folded plate surface minimizes the axial stiffness of the steel web along the bridge axis, leading to relative slip and local stress concentration in the connection area, which may cause fatigue damage to the connectors, local cracking of the concrete slabs, or stress overruns in the transition zone. The aforementioned spatial load transfer effect of the inclined legs and the steel-concrete composite deformation coordination issue are superimposed in the pier-beam joint zone, making it necessary to establish a refined model to analyze the stress state in this area.

Zhang et al. [1] targeted Segment No. 0 of a V-shaped pier continuous rigid frame bridge, established a spatial finite element model, and analyzed the stress distribution in the V-bracing consolidation zone. The results showed that stress concentration is prone to occur at the manholes of Segment No. 0 and the transition zone of the transverse diaphragm, and local structural optimization measures were proposed. Tai et al. [2] studied the influence of the inclined leg angle on the seismic response of V-shaped pier continuous rigid frame bridges, concluding that the inclined leg angle alters the structural internal force distribution and the pier's dynamic response. The aforementioned studies provide references for the local mechanical analysis of V-shaped piers, but further research is still needed for the pier-beam joint zone using corrugated steel webs and local strengthening structures. Peng et al. [3] studied the local deformation of corrugated steel web structures during asynchronous cantilever casting construction, pointing out that the construction process affects the deformation coordination between the steel webs and concrete panels. Zeng et al. [4] conducted dynamic characteristic and response spectrum analyses on a corrugated steel web high-pier, long-span continuous rigid frame bridge, and the results showed that structural stiffness and boundary conditions have a significant impact on the overall response. It is evident that the analysis of key areas in corrugated steel web continuous rigid frame bridges should take into account material composition, connection constraints, and spatial load

transfer effects. In recent years, domestic and foreign scholars have carried out extensive research on the local stability performance, additional stresses in the fulcrum area, and finite element modeling methods of corrugated steel web composite bridges [5-8].

The pier of the Xinjiang Bridge adopts a rigid skeleton concrete structure, with a UHPC reinforcement layer locally set at the V-legs, and longitudinal prestressed steel bars arranged at the pedestal. UHPC possesses high compressive strength, tensile properties, and durability, and its application in local strengthening of bridge key areas and composite structures is continuously increasing [9-11]. Its local application in key parts of the V-legs can ameliorate the stress concentration problem in the pier-beam joint zone. In this paper, a finite element model of the pier-beam joint zone for the composite beam of the V-shaped pier and corrugated steel web is established, taking into account strengthening structures such as the UHPC reinforcement layer of the V-legs and the longitudinal prestressed steel bars at the pedestal. Using the internal forces from the global model as the load boundary for the local model, a quantitative evaluation of the stress states of Segment No. 0, the transverse diaphragm, and the V-shaped pier is conducted, and a parameter analysis of the bottom slab thickness of Segment No. 0 is carried out, providing a reference for the design of key joints in similar bridges.

2 Engineering Background

The main bridge of the Xinjiang Bridge is a V-legged corrugated steel web continuous rigid frame bridge with a span arrangement of 90 m + 165 m + 90 m, as shown in Figure 1. The load class of the main bridge is Highway-I, the design speed is 100 km/h, and the deck is equipped with two-way 4 lanes and two-way non-motorized vehicle lanes. The main beam is a single-box single-room inclined web box section, with a web slope of 1/7, a midspan beam height of 3.8 m, and the beam height varies according to a quadratic parabola. The main beam concrete uses C60 concrete, and the webs adopt 1600-type corrugated steel webs. The upper part of the V-leg is connected to Segment No. 0, and the lower part is connected to the solid pier through the pedestal. The V-leg angle is 47.934°. The V-leg adopts a steel skeleton concrete, and its top and bottom local areas are reinforced with UHPC, while the remaining areas use C50 concrete. The UHPC reinforcement area is shown as the green area in Figure 2, and the UHPC performance indicators are shown in Table 1. The V-leg cross-section is a single-box single-room structure with a longitudinal width of 3 m. The transverse width varies from 8.7 m at the top to 6.0 m at the bottom, and the box chamber wall thickness is 50 cm. Longitudinal prestressed steel bars are arranged in the pedestal area to improve the transverse mechanical behavior at the pier-beam connection. The longitudinal prestressed steel bars for each bridge pier pedestal adopt seven $\Phi 32$ prestressed threaded steel bars, with a spacing of 75 cm and a tensioning control stress of 837 MPa.

Table 1 UHPC Performance Indicators

Item	Indicator
Compressive strength (MPa)	150.0
Elastic modulus (GPa)	54.0
Flexural tensile strength (MPa)	18.0
Specific gravity (kg/m ³)	2,650

According to Saint-Venant's principle, the local model needs to cover the main disturbance area. In this paper, the V-shaped pier, pile cap and pile foundation, as well as Segments No. 0 to No. 6 of the main beam, are selected as the analysis objects. This scope encompasses the pier-beam joint zone, transverse diaphragm, manholes, and corrugated steel web connection zone, which can reduce the impact of the outer boundaries on the calculation results of the core area.

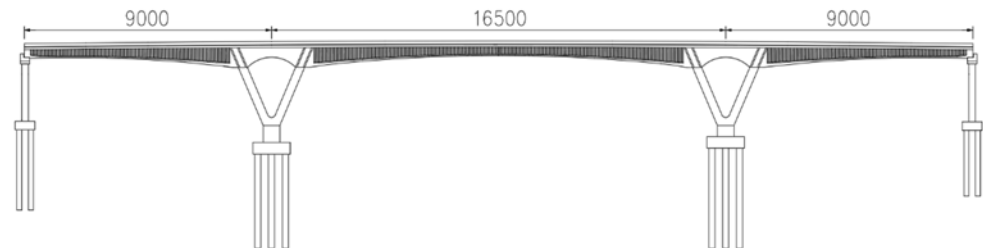


Figure 1 Elevation Layout of Bridge Type (unit: cm)

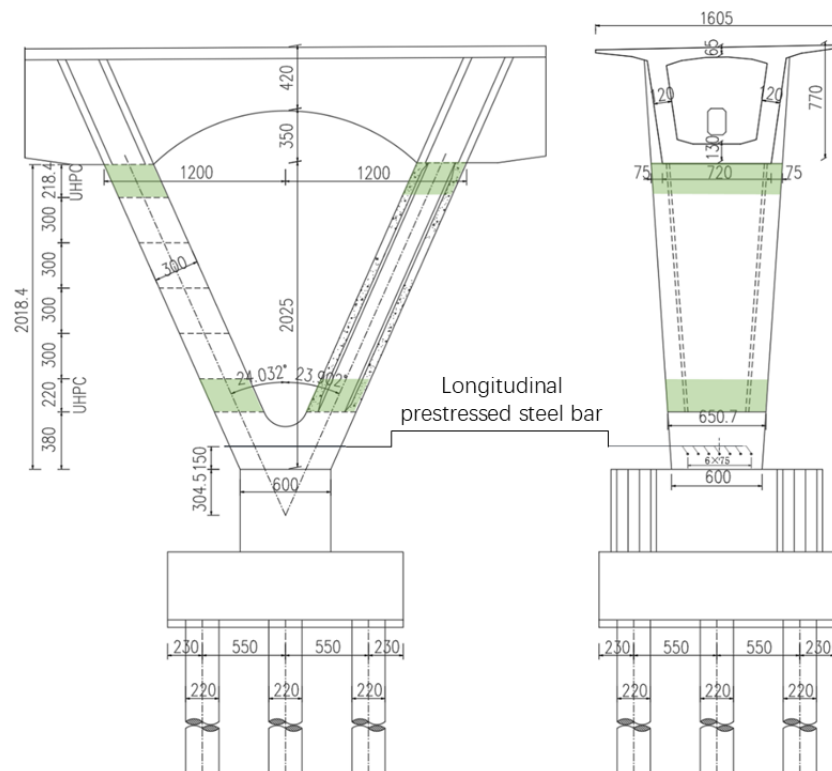


Figure 2 Elevation Layout of Bridge Pier (unit: cm)

3 Finite Element Model

3.1 Model Establishment

A local analysis model was established using ABAQUS 2021, consisting of Segments No. 0 to No. 6 of the main beam, the substructure, and prestressing tendons, as shown in Figure 3. Segments No. 0 to No. 6 of the main beam have a total length of 54.6 m, among which Segment No. 0 has a length of 33.8 m, Segments No. 1 to No. 5 are each 3.2 m long, and Segment No. 6 is 4.8 m long. The corrugated steel webs of the main beam and the concrete top and bottom slabs are connected using shell-to-solid coupling constraints. The superstructure and substructure are connected by binding constraints. The internal prestressing tendons, as shown in Figure 4, are constrained with the embedded region to act

compositely with the concrete. The global coordinate system of the local model is defined as the x-axis along the longitudinal direction of the bridge, the y-axis vertically upwards, and the z-axis along the transverse direction of the bridge.

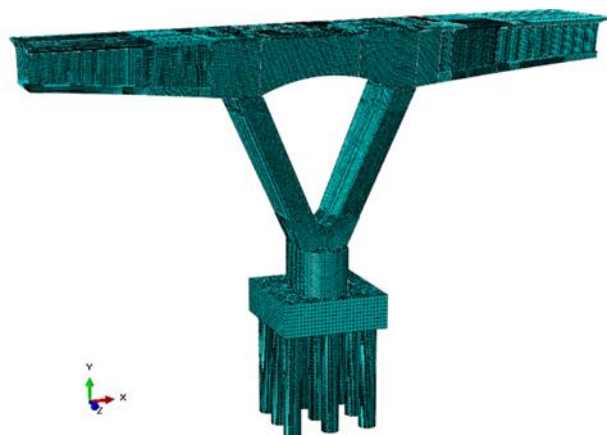


Figure 3 Composite finite element model of the pier-beam joint zone



Figure 4 Prestressing model

3.2 Element Types

The concrete main structure is modeled using 8-node linear hexahedral reduced-integration elements (C3D8R). The corrugated steel webs are modeled using 8-node shell elements (S8R). The prestressing tendons are modeled using 2-node linear 3D truss elements (T3D2). The model is divided into a total of 793,572 elements, and the specific quantities of each element type are shown in Table 2.

Table 2 Element Types and Quantities

Component/Material	Element type	Number of elements
Concrete part	C3D8R	705,611
Corrugated steel web	S8R	62,044
Prestressing tendon	T3D2	25,917

3.3 Prestressing Simulation

Referring to the prestressing simulation method by Lu et al. [12], the prestressing tendons are embedded into the concrete solid elements, and the prestressing effect is simulated by applying initial strain. The prestressing system in this paper includes internal prestressing, external prestressing, and longitudinal prestressed steel bars at the pedestal. The external prestressing is simulated using the equivalent load method; the internal prestressing and the longitudinal prestressed steel bars at the pedestal are modeled as one-dimensional tendon elements according to their actual line shape and are embedded into the C3D8R concrete solid elements using the Embedded Region function in Abaqus. The

prestressing is applied by means of initial strain, in which a 20% prestressing loss is considered for the longitudinal internal tendons.

The concentrated equivalent forces generated by the external prestressing at the turning points and anchorage ends can be expressed as:

$$F_i = -P_{e,i}(t_i^+ + t_i^-) \quad (1)$$

$$F_a = -P_{e,a}t_a \quad (2)$$

where F_i and F_a are the concentrated equivalent forces at the turning points and anchorage ends, respectively; $P_{e,i}$ and $P_{e,a}$ are the effective prestressing forces at the corresponding positions; t_i^+ , t_i^- , and t_a are the tangential unit vectors of the tendon.

The solid tendon method realizes the displacement compatibility between the tendon and the concrete through embedded constraints, and its interpolation relationship is:

$$u_a = N_1u_1 + N_2u_2 + \cdots + N_8u_8 \quad (3)$$

where u_a is the nodal displacement of the tendon; N_i is the shape function of the host element; u_i is the nodal displacement of the host element.

The initial strain of the prestressing is back-calculated based on the effective prestressing:

$$\varepsilon_{p0,j} = \sigma_{pe,j}/E_p = P_{e,j}/(A_{p,j}E_p) \quad (4)$$

where $\varepsilon_{p0,j}$ is the initial strain of the j -th prestressing tendon; $\sigma_{pe,j}$ is the effective prestressing stress; E_p is the elastic modulus of the prestressing tendon; $A_{p,j}$ is the cross-sectional area; $P_{e,j}$ is the effective tensioning force.

3.4 Boundary Conditions

The model boundary conditions include the actual structural constraints and the boundary conditions at the outer end section of Segment No. 6 of the main beam. In the actual structure, the V-shaped pier is connected to the pier shaft through the pedestal, and the pier shaft is fixed to the pile cap. To consider the adverse effects of water flow scouring, a group of piles with a length of 5 times the diameter below the scour line is established at the bottom of the pile cap in the model, and all degrees of freedom at the pile bottom are constrained.

The outer end section of Segment No. 6 of the main beam uses a load boundary. First, the internal forces at the outer end section of Segment No. 6 under the most unfavorable combination of actions are extracted from the global bridge model. The load combination selects the maximum bending moment combination at the pier root, mainly including dead load, vehicle load, pedestrian load, overall temperature drop, gradient temperature drop, and bearing settlement; subsequently, in the local model, a reference point is set at the centroid of the end section, and the reference point is coupled with the outer end section; finally, the extracted internal forces are applied to the reference point. The values of the extracted internal forces in the global coordinate system of the local model are shown in Table 3.

Table 3 Load boundary at the outer end section

Loading position	Fx (N)	Fy (N)	Fz (N)	Mx (N·mm)	My (N·mm)	Mz (N·mm)
Left end	1.51×10^8	-6.53×10^6	-4.48×10^4	1.28×10^8	9.23×10^8	1.57×10^{11}
Right end	-1.46×10^8	-6.00×10^6	2.00×10^4	9.80×10^7	5.92×10^8	6.56×10^{10}

4 Stress Verification Criteria

In this paper, according to Clauses 7.1.1, 7.1.5, and 7.1.6 of the *Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts* (JTG 3362—2018), the stress states of the local regions of the main beam and the V-shaped pier at the service stage of the persistent situation are evaluated [13]. The verification contents include the normal compressive stress of concrete in normal sections, the principal compressive stress, and the principal tensile stress of concrete in oblique sections; the effect of actions adopts the characteristic value combination, and the vehicular load includes the impact effect.

For C60 fully prestressed concrete flexural members, the control limit value of the maximum compressive stress of concrete in normal sections is:

$$\sigma_{kc} + \sigma_{pt} \leq 0.5f_{ck} = 19.25 \text{ MPa} \quad (5)$$

The control limit value of the principal compressive stress of concrete in oblique sections is:

$$\sigma_{cp} \leq 0.6f_{ck} = 23.10 \text{ MPa} \quad (6)$$

The principal tensile stress is mainly used to determine the requirements for stirrup reinforcement. When $\sigma_{tp} \leq 0.5f_{tk} = 1.43 \text{ MPa}$, the stirrups can be arranged according to structural requirements; when $\sigma_{tp} > 0.5f_{tk} = 1.43 \text{ MPa}$, further calculation for stirrup reinforcement should be conducted.

where σ_{kc} is the normal compressive stress of concrete; σ_{pt} is the normal tensile stress of concrete generated by the prestressing force; σ_{cp} and σ_{tp} are the principal compressive stress and principal tensile stress of concrete under the combined action of the characteristic values of actions and the prestressing force, respectively; f_{ck} and f_{tk} are the characteristic values of axial compressive strength and axial tensile strength of concrete, respectively, which are taken as 38.5 MPa and 2.85 MPa for C60 concrete.

5 Results and Analysis

5.1 Normal Stress of Segment No. 0

As shown in Figure 5, except for the prestressing anchorage zones, transverse diaphragms, and the connections between the corrugated steel webs and the main beam, the stresses in all other parts of the main beam are compressive stresses. The maximum compressive stress is 18.8 MPa, located near the web at the midspan bottom slab of Segment No. 0. As can be seen from Figure 6, there is a significant spatial effect in the normal stress of the section at this location, where the compressive stress near the web at the bottom slab is higher than that far away from the web.

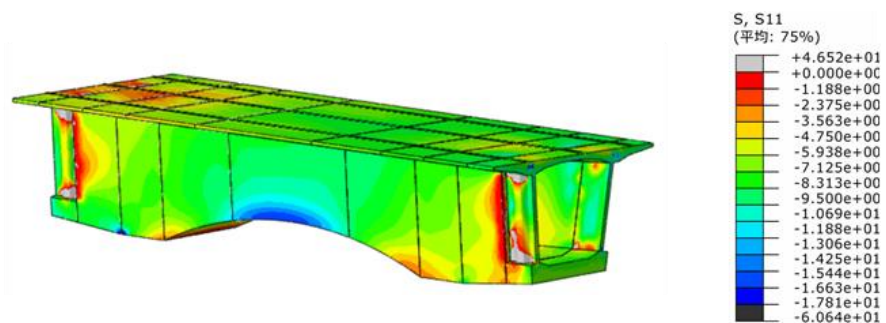


Figure 5 Normal stress contour of Segment No. 0 (unit: MPa)

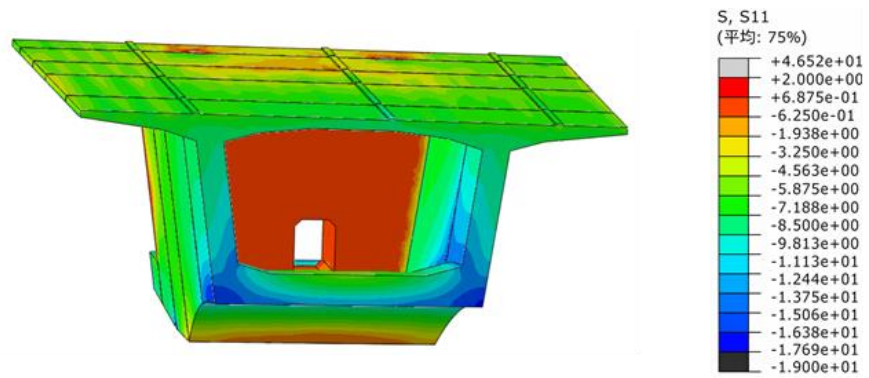


Figure 6 Normal stress contour of the midspan profile of Segment No. 0 (unit: MPa)

To verify the rationality of the current bottom slab thickness, a parametric analysis was conducted on the bottom slab thickness. Figure 7 shows the variation in the maximum normal stress at the midspan of Segment No. 0 when the thickness of the bottom slab ranges from 60 cm to 90 cm. An increase in bottom slab thickness enlarges the compressed area and stiffness of the midspan section of Segment No. 0, thereby dispersing the normal compressive stress generated by the longitudinal prestressing force. The maximum compressive stress at midspan decreases from 21.7 MPa at a thickness of 60 cm to 18.8 MPa at a thickness of 90 cm, representing a reduction of approximately 13.3%. Continuing to increase the thickness will lead to increments in self-weight and construction volume. Considering the stress level, structural self-weight, and economic efficiency comprehensively, the bottom slab thickness can be set to 90 cm, which satisfies the code requirement that the normal compressive stress under the elastic combination shall be less than $0.5f_{ck} = 19.25$ MPa.

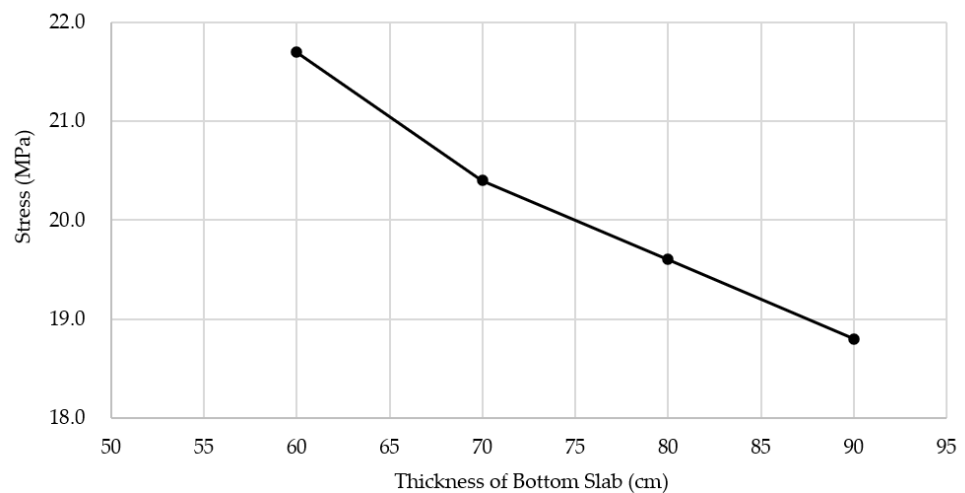


Figure 7 Variation curve of the maximum normal stress at the midspan of Segment No. 0 with the bottom slab thickness

5.2 Transverse Diaphragm Stress

Figure 8 shows the longitudinal normal stress contour of the transverse diaphragm, indicating the presence of local tensile stress near the manhole. This is primarily related to the section weakening and the variation of the local load transfer path. The tensile stress around the manhole is generally within 0.05 MPa, and the local maximum tensile stress above the manhole is approximately 0.7 MPa. Overall, the tensile stress level of the transverse diaphragm is relatively low and does not govern the structural safety.

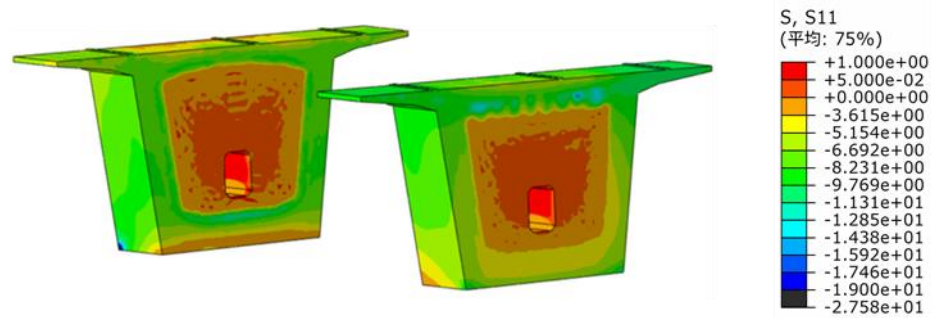


Figure 8 Normal stress contour of the transverse diaphragm in Segment No. 0 (unit: MPa)

5.3 Principal Stress of Segment No. 0

As can be seen from Figure 9, the principal compressive stress of Segment No. 0 exhibits local concentration at the pier-beam interface and the corrugated steel web connection. Excluding the stress concentration zones, the principal compressive stress is less than $0.6f_{ck} = 23.10$ MPa, satisfying the code requirements for the principal compressive stress of concrete in prestressed concrete flexural members at the service stage. According to the actual reinforcement and code calculation formulas, excluding the lined concrete, the allowable principal tensile stress at this location is:

$$\sigma_{tp} = \frac{f_{sk}A_{sv}}{s_v b} = \frac{400 \times 5 \times \pi \times 100}{100 \times 1200} = 5.23 \text{ MPa} \quad (7)$$

As shown in Figure 10, the regions with larger principal tensile stress are mainly located near the beam end and the transverse diaphragm. Except for the prestressing anchorage zones and the pier-beam interface, the principal tensile stress of Segment No. 0 satisfies the allowable requirements under the current reinforcement conditions.

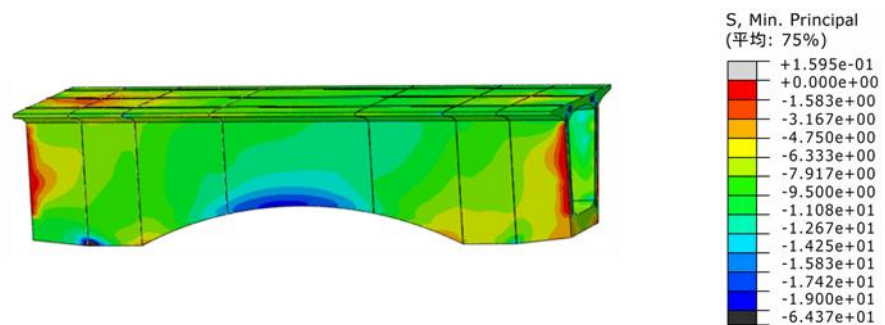


Figure 9 Principal compressive stress contour of Segment No. 0 (unit: MPa)

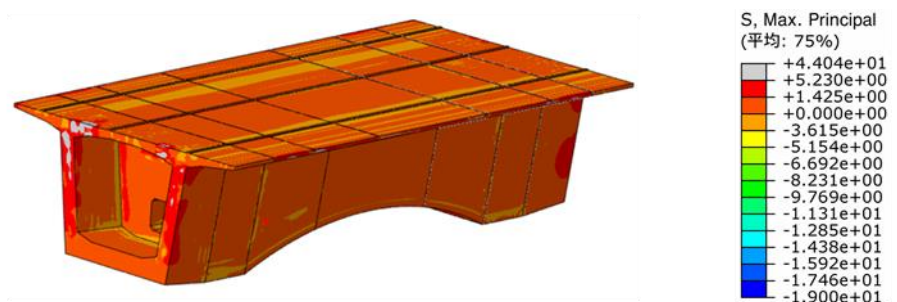


Figure 10 Principal tensile stress contour of Segment No. 0 (unit: MPa)

5.4 V-Shaped Pier Stress

As shown in Figure 11, the maximum normal compressive stress in the C50 concrete zone of the V-shaped pier is 15.7 MPa, satisfying the code requirements for the maximum compressive stress of concrete in normal sections of prestressed concrete flexural members at the service stage. The local compressive stress on the outer side of the V-leg top is relatively large, with a maximum value of 41.8 MPa. This region is reinforced with UHPC, which can meet the compressive requirements. The tensile stress of the V-leg mainly occurs at the inner top. The maximum tensile stress of the left V-leg is 1.1 MPa, and that of the right V-leg is 0.3 MPa. Both locations are within the UHPC reinforcement range and are less than the tensile strength of UHPC. As can be seen from Figure 12, the normal stress at the bottom of the V-shaped pier is entirely compressive, with a maximum compressive stress of 6.5 MPa and a minimum compressive stress of 0.02 MPa in the intersection area of the V-legs. This indicates that the overall mechanical state of the V-shaped pier is reasonable.

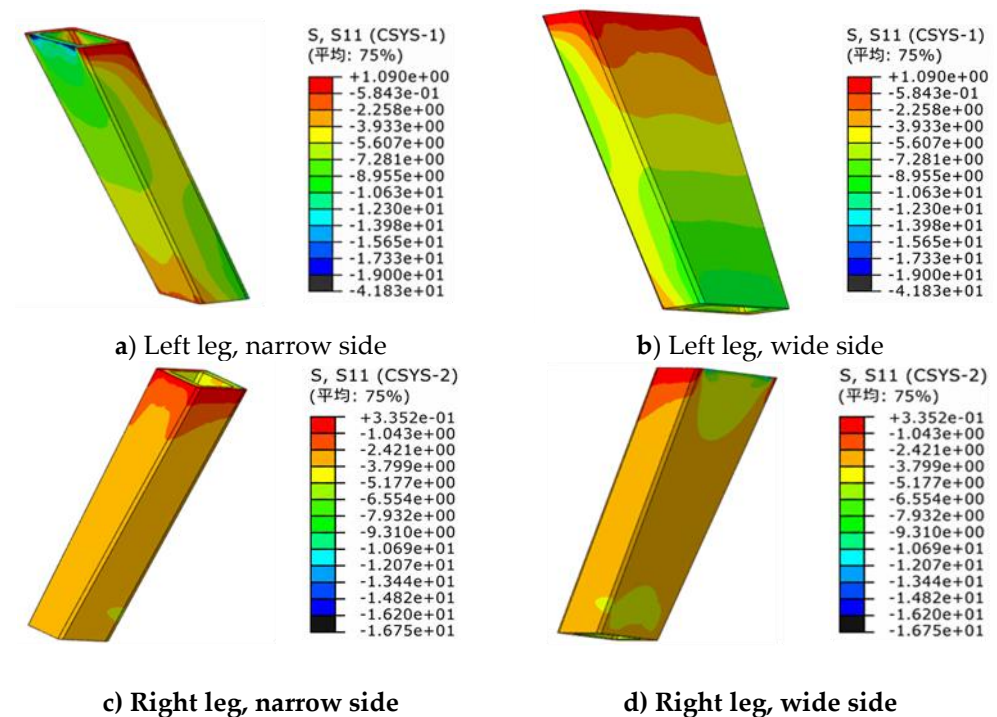


Figure 11 Normal stress contour of the V-shaped pier (unit: MPa)

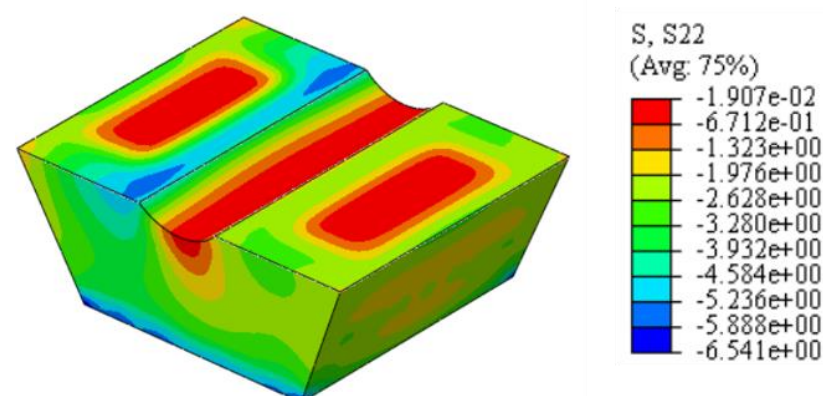


Figure 12 Normal stress contour at the bottom of the V-shaped pier (unit: MPa)

6 Conclusions

Based on the local composite finite element model of the V-shaped pier of the Xinjiang Bridge, the mechanical states of the pier-beam joint zone and the key parts of the V-legs were analyzed. The results indicate that the overall mechanical state of the structure is reasonable, and the local strengthening measures can improve the stress state in key areas. The main conclusions are as follows:

- (1) The area near the web at the midspan bottom slab of Segment No. 0 is the controlling position for normal compressive stress, where the compressive stress is higher than that far from the web. Therefore, the spatial stress effect of the main beam between the V-legs should be considered in design verification, and it is not appropriate to substitute the section average stress for the local spatial stress verification. As the thickness of the bottom slab increases, the normal compressive stress in this region gradually decreases; when the bottom slab thickness is set to 90 cm, the structural mechanical state satisfies the code requirements.
- (2) Excluding the local stress concentration zones, both the principal compressive stress and the principal tensile stress of the concrete in Segment No. 0 are within the allowable range, indicating that the current reinforcement conditions can meet the local crack resistance and bearing capacity requirements.
- (3) The manhole in the transverse diaphragm is the local crack resistance control point for the perforated member, but its influence range is small, the overall stress level is low, and it does not govern the structural safety.
- (4) The C50 concrete zone and the UHPC reinforcement zone of the V-shaped pier exhibit a good mechanical state, and the local tensile stress at the inner top of the V-leg is located within the UHPC reinforcement range. The local UHPC reinforcement and the longitudinal prestressed steel bars at the pedestal adopted in this paper can effectively improve the mechanical behavior of the V-shaped pier, which can provide a reference for the design of similar V-shaped piers.

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Conflict of Interest Statement: The authors declare that there is no conflict of interest regarding the publication of this paper.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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