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Research Article

Analysis of Mechanical Performance of Steel-Concrete Composite Girder Bridge with V-Shaped Piers

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The steel-concrete composite girder bridge with V-shaped piers is a new type of bridge structure. It has both the unique mechanical performance of a combined continuous girder and that of a V-shaped pier bridge. At present, studies on the mechanical properties of steel main girders combined with concrete deck slabs are mainly focused on the substructure for vertical piers, but piers and girders are not solidified. However, if the V-shaped piers are cemented to the main girder, the performance of the V-shaped piers will directly affect the performance of the total superstructure. The steel main girder and concrete deck slab of a steel-composite girder are considered to be different parts of the same section. The joint section is used to simulate the changes in section stiffness of each section during the different stages of construction. In this paper, the first steel-concrete composite girder bridge with V-shaped piers is studied in detail. The effects of different influencing factors on the structural forces are investigated using finite element analysis. The results show that the force performance of this bridge type is strongly influenced by the structure. These can provide guidance for the design and construction of this bridge type, which is of great significance.

1. Introduction

The steel-concrete composite girder bridge with V-shaped piers is a new structure formed by the solidification of V-shaped piers and combined continuous piers. It has both the force characteristics of a combined continuous girder and the force characteristics of a V-shaped pier bridge. The steel-concrete composite continuous girder bridge can be continuous across many spans or even the whole bridge, which can ensure the smoothness of the traffic and can save the cost of setting up expansion joints. Studies have shown that the V-shaped pier continuous rigid bridge shortens the span of the main girders and has the advantages of light weight, good aesthetics, and high dynamic stability. This structure allows the bridge to have a large span capacity without excessive girder height, especially to meet the needs of the span development of steel-concrete composite girders. A number of studies have investigated on the structural stability and seismic performance of completed bridges with V-shaped piers, proving that the structural system of bridges with V-shaped piers has good seismic performance. The force characteristics and influencing factors of steel-concrete composite girder bridge with V-shaped piers are different from those of conventional continuous girders or V-pier bridges.

In 1955, La Voulte-sur-Rhone Bridge was built in France, and it is a prestressed structure in the upper part with a main span of 56 m and a total bridge length of 300 m. The Saint-Michel Bridge in the UK was completed in 1963, which has a main span of 65.2 m and a total length of 326 m. Since then, a number of bridges with V-shaped pier girder have been built in the world, such as Germany, Netherlands, and Japan [1]. In recent years, the main girders of bridges with V-shaped piers have rarely been built using the prestressed concrete. V-shaped pier bridges built with steel structures are more common as they can effectively increase the span and reduce the weight of the structure.

Since the turn of the 21th century, V-shaped pier bridges have developed in the direction of large spans and multiple spans, but they are still predominantly concrete V-shaped pier bridges, and steel V-shaped pier bridges have only been used to a less extent in recent years in the great development of combined structure bridges. A lot of research studies have been done on the mechanical properties of combined steel main girders and concrete deck slabs and on construction methods to improve the forces in the negative moment zone of combined continuous girder bridges [2–9]. However, most of the research studies are based on the focus where the substructure is a vertical pier and the pier and girder are not cemented or where the structure is of a single form and the main girder is not a composite girder structure.

The first steel-concrete composite girder bridge with V-shaped piers in the world is studied in the paper. The important factors affecting the mechanical performance of a steel-concrete composite girder bridge with V-shaped piers, such as removal time of the V-shaped pier supports, V-shaped pier's angles, influence of counterweights, are analyzed.

2. Bridge Description

A new steel-concrete composite girder bridge with V-shaped piers is built in China, with a span of 20 m + 24 m + 34 m + 56 m + 34 m. The main beam section is a typical π-shaped (double main beam) steel-concrete composite section. The bridge is the first steel-concrete composite girder bridge with V-shaped piers in the world. The main girder of the bridge is continuous, and only the abutment has expansion joints. In the substructure, P1 and P2 piers are column piers, and hinge supports are set between pier beams. P3 and P4 piers are V-shaped piers, which are consolidated with the main beam with high-strength bolts. An elevation view of the bridge is shown in Figure 1.

The deck of the bridge is constructed of reinforced concrete. The thickness of the slab is about 0.3 m at the center line and 0.35 m at the joint with the stud. The transverse direction of single precast slab is a whole block with four shear nail group holes. The transverse length of precast slab is 8.9 m and the longitudinal width is 3 m. The transverse wet joint reinforcement is welded as a whole to connect the precast slabs. The precast slab and the steel main beam form a composite system by shear studs. The standard height of I-shaped steel girder is 1 m. Near the top of the V-shaped piers, the girder becomes higher to 1.6 m, and the width of lower flange of steel girder is from 0.6 m to 0.8 m. The bridge section is shown in Figure 2.

P1 and P2 piers are vertical piers, and P3 and P4 piers are V-shaped piers. They are mainly I-shaped sections with outer sealing plates. The concrete deck in the negative bending moment area of the bridge is constructed with C40 microexpansion concrete and is constructed with the method of compaction. When the midspan bridge deck is erected, the concrete in the negative moment area is poured after the load is applied in the midspan area. When the concrete strength in the negative moment area reaches 90% of the design strength, the load in the midspan area is unloaded. The structural diagrams of V-shaped piers are shown in Figure 3.

3. Finite Element Model of the Bridge

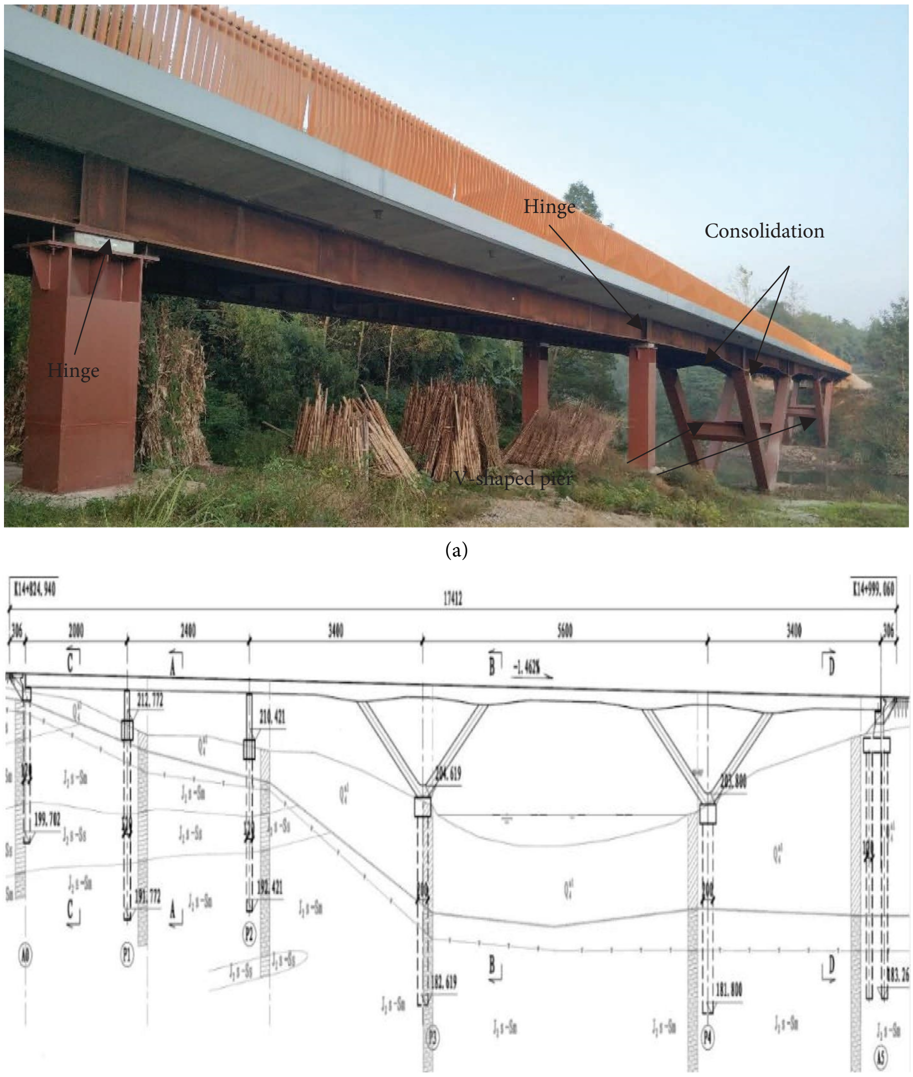
3.1. Modelling Methods of Composite Section. The joint section at the construction phase is a special type of section for combined sections in finite element calculation, the definition of which relies on the simulation of the construction processes. The steel main girder and concrete deck slab of a steel-composite girder are considered to be different parts of the same section. The joint section at the construction phase requires an accurate understanding of the change in section stiffness of each section during the different stages of construction, using a sequential activation of the different components to simulate the changes in section stiffness of the steel and concrete girder during the actual construction processes. The advantage of the joint section in the construction phase is that the modelling approach uses superposition to calculate the various load effects and can be better adapted to the calculation of a combined girder bridge considering phased construction, which is shown in Figure 4. The theoretical basis of the joint section is that the section satisfies Euler–Bernoulli beam theory, which is the assumption of flat section and the assumption of elastic deformation. This method distributes the internal forces and stresses of the members according to the principle of strain coordination at the interface of the two members and enables accurate calculation of time-varying effects. In practical engineering, concrete deck slabs are usually of variable thickness in the transverse direction, and it is necessary to firstly simplify the original section when modelling the rod system using the joint section equivalently.

3.2. Model Description. For the purpose of description, the structures are numbered. Starting from platform A0, the girder sections are named k1 and k2~k7 along the longitudinal direction of the bridge, and the girder sections in the negative moment zone after casting concrete are named d1 and d2~d6, respectively.

The deck is made of C40 concrete with a unit weight of 25 kN/m^3. The steel girder is made of Q345qDNH steel with a unit weight of 76.98 kN/m^3. The secondary load of the deck is calculated according to the design drawings, and the result is 22.8 kN/m.

According to the design drawings, the precast deck of the bridge adopts the precast concrete slab which has been placed for at least 6 months. Therefore, the initial age of precast concrete is 180 days. The initial age of cast-in-place concrete is still 0 days, and the relative humidity is 70%. There are the obvious influence of shrinkage and creep effects on the internal force and stress of the girder section. The concrete compressive strength is required to reach 90% of the standard compressive strength when unloading the load, so the construction period of cast-in-place construction section is 14 days.

The bridge position is in good condition and the effect of foundation displacement is not considered at the base of the



(a)

(b)

Figure 1: Elevation of the bridge: (a) in situ photo of bridge; (b) elevation of the bridge.

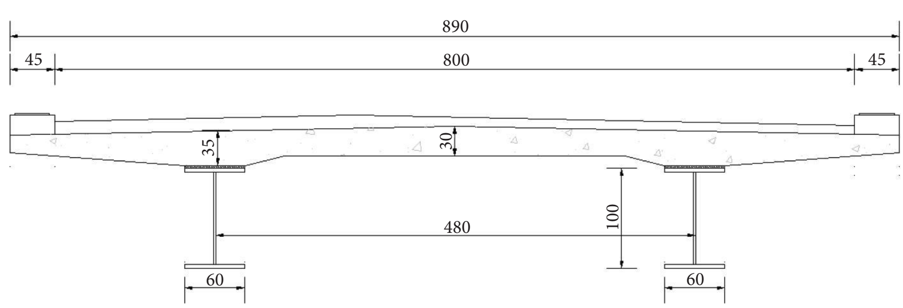


Figure 2: The key section of the girder (cm).

piers. The tops of the vertical piers are restrained according to the actual supports of the bridge according to the design drawings. The actual bridge has V-shaped piers, and steel main girders with high-strength bolted connections and rigid connections are modelled.

The method of joint section in construction stages is used in FEM (finite element method) simulation, and the effective width of deck, the influence of cross slope, and longitudinal slope of deck are considered. The FEM model of the bridge is built by MIDAS/Civil software, shown in Figure 5. The steel

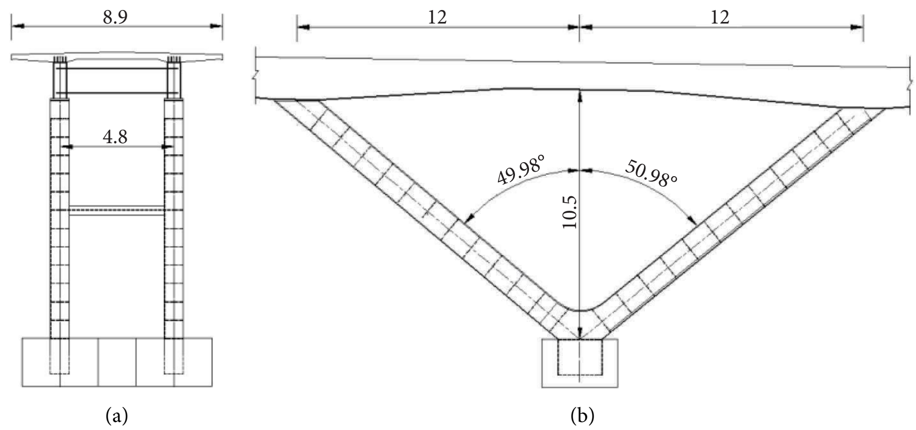


FIGURE 3: V-shaped pier: (a) sectional view; (b) elevation view.

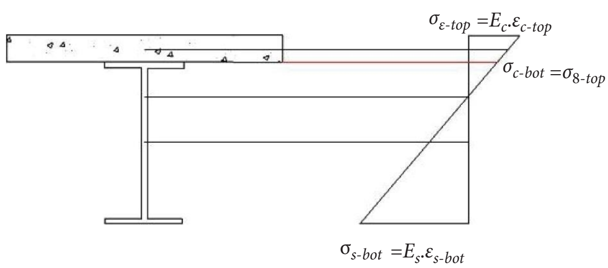


FIGURE 4: Joint section stress-strain calculation.

components are simulated by beam element, and concrete decks are simulated by plate element. The FEM model of the bridge shown in Figure 5 is compared and updated according the results of the static test.

4. Effects of Removal Time of the V-Shaped Pier Supports on the Bridge

4.1. Removal Time of V-Shaped Piers' Temporary Supports. The dismantling of the V-shaped piers' temporary supports has an impact on the load bearing performance of the girders. The vertical stiffness of the V-shaped pier affects the preload weight during the construction. The timing of the removal of the temporary supports for the steel V-shaped piers of this structure is discussed below.

For the convenience of comparative verification, the first construction stage of the modelling was predetermined to be when the steel V-shaped pier and the steel main beam had been dropped in one go (construction completed). However, in the actual construction process, the steel V-shaped pier is generally set up with temporary supports and then welded, and the steel main beam is also welded section by section. In the finite element calculations, the temporary supports are simulated in compression-only units.

In the construction phase of the simulation, an additional construction phase for the erection of the steel V-shaped pier was set up before the CS1 phase, making it CS0. The V-shaped pier unit was split from CS1 to CS0, and the temporary support of the V-shaped pier was simulated with the elastic support of the compression-only node. For the removal time of the V-shaped pier temporary supports, the 3 key cases are listed as follows:

(1) CS1 dismantling: the temporary supports are removed as soon as the steel V-shaped pier forms an integral part with the steel main beam
(2) CS2 dismantling: the removal of the temporary supports after the erection of the prefabricated deck slabs is completed
(3) CS8 dismantling: removal of temporary supports after completion of construction of the cast-in-place section at the top of the full piers is finished

4.2. Deflection Analysis. The maximum deflection was found at CS2 when the temporary supports were removed, with a maximum deflection of 33.36 mm and a minimum deflection of 31.75 mm. The results of the deflection analysis are shown in Figure 6. The calculations of the girder's deflection for the two different simulation methods are almost identical, and the deflection curves are very similar.

4.3. Stress Analysis. For the compression weight method of construction, the vertical piers produce a better effect of compressive stress reserve than that of the V-shaped piers. It is because the vertical stiffness of the V-shaped piers and the vertical piers are different. The discussion of the removal timing of the V-shaped pier supports also is suitable for that of the stiffness of the V-shaped pier. When the V-shaped pier support is not removed, the V-shaped pier vertical stiffness is very large.

A comparison of the stresses in the upper flange of the steel main girder is shown in Figure 7. It can be seen that the choice of removing the temporary supports before the concrete slab is cast, between CS1 and CS2, has little effect on the stresses in the upper flange of the steel girder. The stress levels in the V-shaped pier and steel main girder at one time are comparable to the stress levels in the upper flange of the main girder when the V-shaped pier construction process is considered. The choice of the removal of the temporary supports of the V-shaped pier will be the main factor

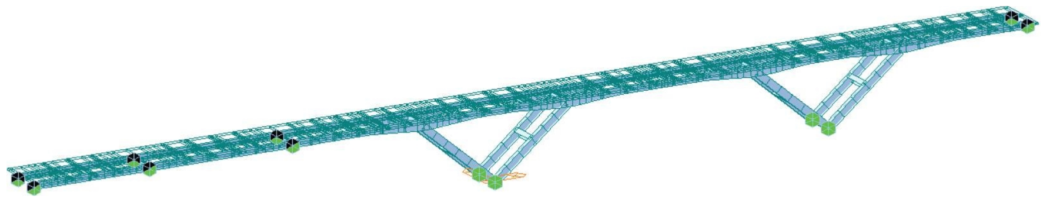


Figure 5: FEM model of the bridge.

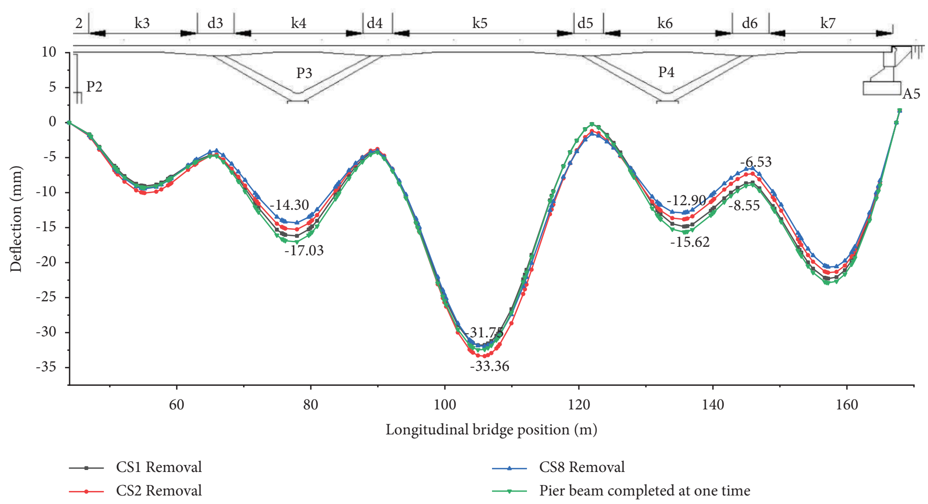


Figure 6: Different deflections for the removal of temporary supports at different stages.

affecting the stress level of the upper flange of the steel main girders. The choice of the removal timing of the temporary supports can produce a maximum tensile stress difference of 20.5 MPa at the top of pier d5, and the choice of removing the temporary supports at the CS1 stage can produce a compressive stress of 5.8 MPa in the k5 span.

The stresses in the lower flange of the steel main girder are shown in Figure 8. Overall, the calculation results of the simplified V-shaped pier construction are consistent with those of the CS1 dismantling condition. For the magnitude of tensile stresses in the lower flange of the span at these three dismantling times, the earlier the temporary support of the V-shaped pier is removed, the greater the tensile stresses in the span of the main span is. The maximum tensile stress difference in the lower flange of the main span can reach approximately 8.4 MPa when the temporary supports are removed at different times, and the maximum compressive stress difference at the top of pier d5 is 3.9 MPa. From the perspective of the upper and lower flanges of the main girder, the timing of the removal of the V-shaped pier temporary supports has an obvious effect on the stress levels in the upper flange of the pier top and the lower flange of the span.

The different dismantling times of the V-shaped pier supports have a significant effect on the stress level of the upper flange of the concrete slab at the time of bridge formation. Analysis of the maximum tensile stress under different demolition conditions shows that the earlier the demolition is, the lower the tensile stress at the upper edge of the concrete is. The maximum tensile stress at the upper edge of the concrete in the bridge state is 0.7 MPa under the CS1 demolition condition, with a maximum difference of 0.5 MPa between the CS1 demolition and the CS8 demolition. The choice of removing the temporary support for the V-shaped pier before and after the cast-in-place concrete construction is the main factor affecting the stress levels in the cast-in-place section of the bridge. A comparison of the stresses at the top edge of the deck slab is shown in Figure 9.

There is also a very strong correlation between the magnitude of the compressive stresses on the lower edge of the deck slab and the removal timing of the temporary supports for the V-shaped piers. Overall, the earlier the V-shaped pier brackets are removed, the more favorable the concrete stress level at the lower edge of the deck slab is. In the longitudinal view of the whole bridge, the unfavorable location of the lower edge of the deck slab is at the top girder end of the V-shaped pier. A different removal timing can cause a maximum tensile stress difference of 0.33 MPa to the deck slab here. It can be seen that the stress levels in the deck slab under CS1 demolition conditions are significantly better than those in the other two conditions. A comparison of the stresses at the lower edge of the deck slab is shown in Figure 10.

The relationship between the maximum compressive stress of the V-shaped pier and the demolition time in the bridge state is obvious. The earlier the demolition time is, the greater the maximum compressive stress of the V-shaped pier is. However, the later the demolition time is, the smaller

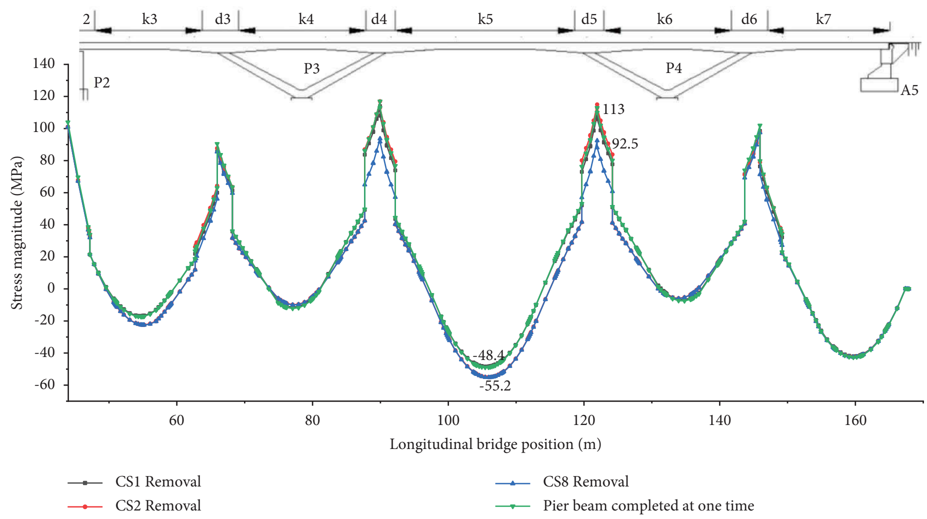


Figure 7: Stresses in upper flanges of steel beams.

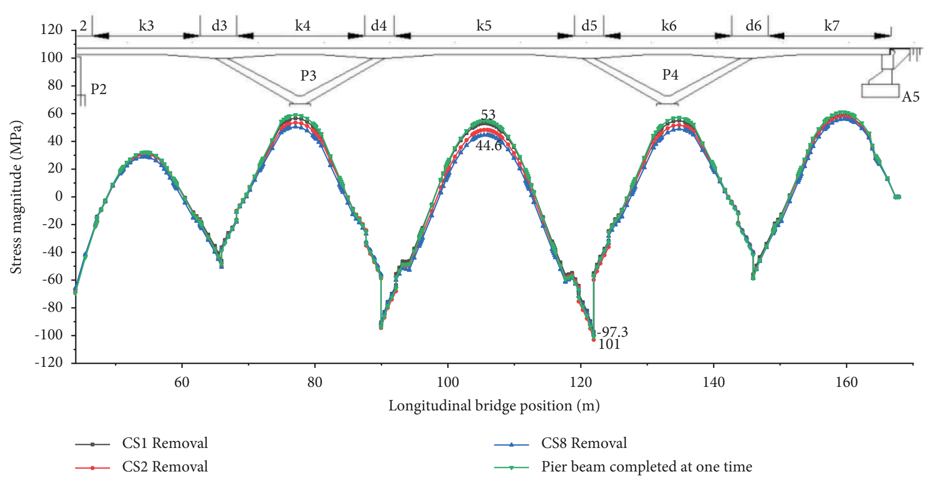


Figure 8: Stresses in lower flanges of steel beams.

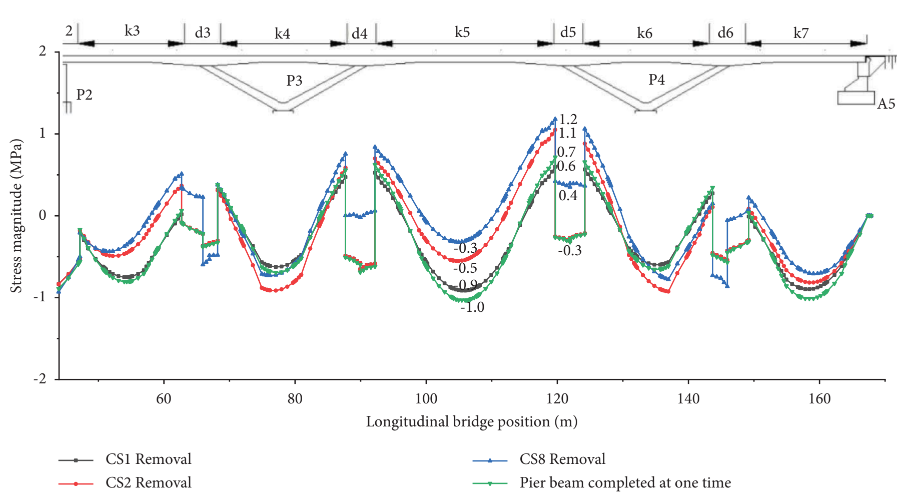


Figure 9: Stresses at the upper edges of the bridge deck slabs.

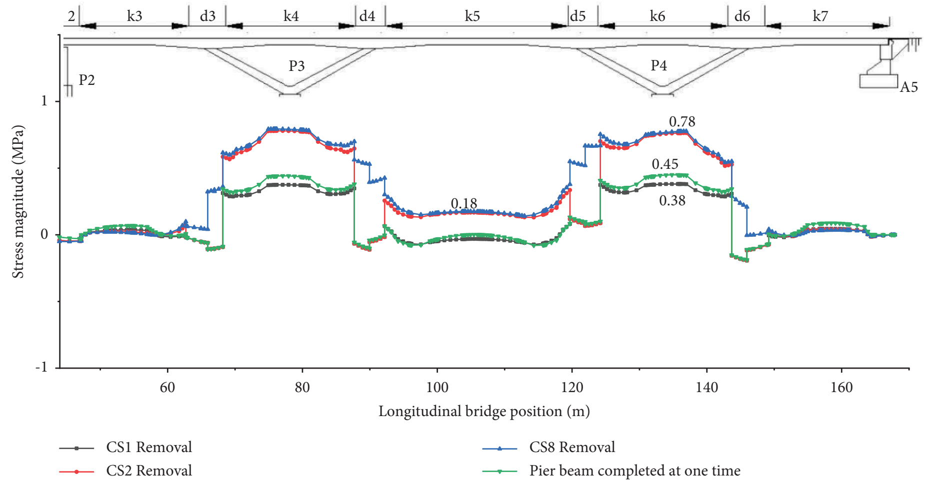


FIGURE 10: Stresses at lower edges of bridge deck slabs.

the maximum compressive stress of the V-shaped pier is. However, the stresses in the V-shaped pier are small in general. Different from the concrete V-shaped piers, the mechanical properties of the materials used in the steel V-shaped pier are outstanding, but the static properties of the material are not the main factors to be considered in the design view.

The characteristics of the steel girder stresses and deck slab stresses in the V-shaped pier temporary supports under different dismantling conditions show that the removal of the V-shaped pier supports will have a significant effect on the bridge stresses in the main girders. Overall, the early removal of the temporary supports increases the spanwise tensile stresses in the upper flange of the main girder and the compressive stresses in the V-shaped piers but induces the reduction of the deck slab stresses. For composite structures, the stress level of the concrete has a greater influence on the stiffness of the section.

5. Effects of V-Shaped Pier's Angles on the Stress State of the Completed Bridge

When the cross section of the main beam is the same, different angles of the V-shaped pier will produce different vertical stiffness and bending moments of the main girder. On the basis of the original finite element model, the V-shaped pier section is kept unchanged, and the construction method is not changed, but only the angles of the V-shaped piers is used as a parameter to build several FEM models with the central line of the V-shaped piers and the plumb line at 40°, 45°, 55°, and 60°. For the differences between these models at the final stage of bridge's formation, the effects of different angles of the V-shaped piers on the stress state of the bridge are analyzed.

5.1. Deflection Analysis. The final bridge deflections for different V-shaped pier's angles are shown in Figure 11. As can be seen from Figure 11, the different angles of the V-shaped pier have almost no effect on the deflection of span K1 and K2. The larger the angle of the V-shaped pier in d3 to d6 is, the larger the deflection at the pier and beam solidification is, and the smaller the vertical stiffness of the V-shaped pier is. The greater the deflection in the span of K4 and K6 is the larger the angle of the V-shaped pier becomes. The larger the angle of the V-shaped pier is, the smaller the difference between the maximum deflection of K6 and K7 is. It indicates that when the vertical stiffness of the V-shaped pier is small, the uneven deflection of the main beam between the two adjacent spans will be improved accordingly.

5.2. Stress Analysis. The stresses on both sides of the top of pier d5 have differently opposed patterns of changes. The flange's stress on the left main beam at the top of pier d5 decreases as the angle of the V-shaped pier increases, and the flange stress on the left main beam at the top of pier d5 increases as the angle of the V-shaped pier increases. When the angle of the V-shaped pier is 50 degrees, the sudden change in the stresses on the left and right sides of the main beam is minimal. When the angle of the V-shaped pier starts to increase or decrease gradually, the sudden change in the stresses on the left and right sides of the main beam increases gradually. When the angle of the V-shaped pier starts to increase or decrease gradually, the sudden change in stress in the upper flange of the left and right sides of the main girder will gradually increase. A comparison of the upper flange's stresses in the steel main beam is shown in Figure 12.

The obvious changes in stresses in the lower flange of the steel main beam are the same as the sudden changes in stresses in the upper flanges. It indicates that the angle of the V-shaped pier has a significant effect on the stresses in the main girder near the consolidation position of the piers and girder, and that there is an "optimal solution" for the V-shaped pier angles. When a suitable V-shaped pier angle is used, the stress levels in the main girder on both sides of the top of the V-shaped pier are comparable, which can improve the stresses in the main girder on both sides of the negative moment zone to a certain extent. A comparison of the

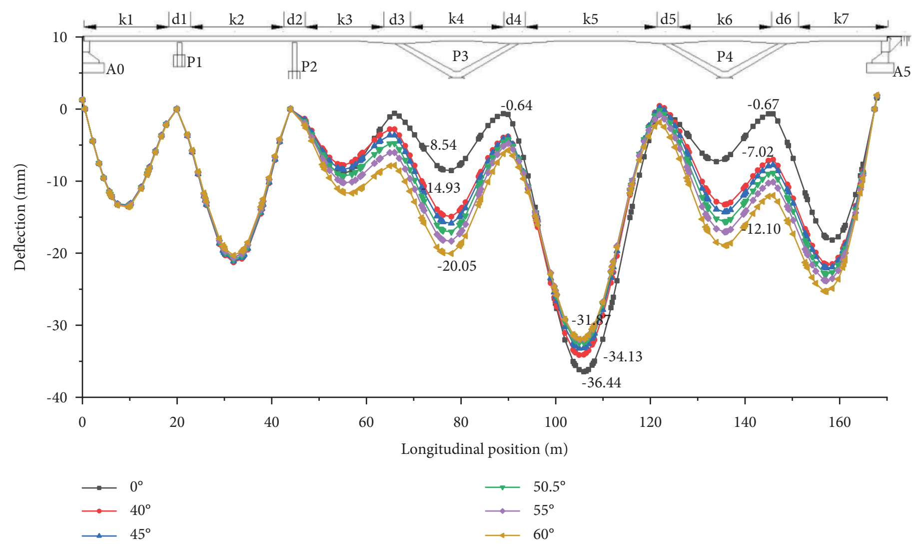


Figure 11: The girder's deflection for different V-shaped pier's angles.

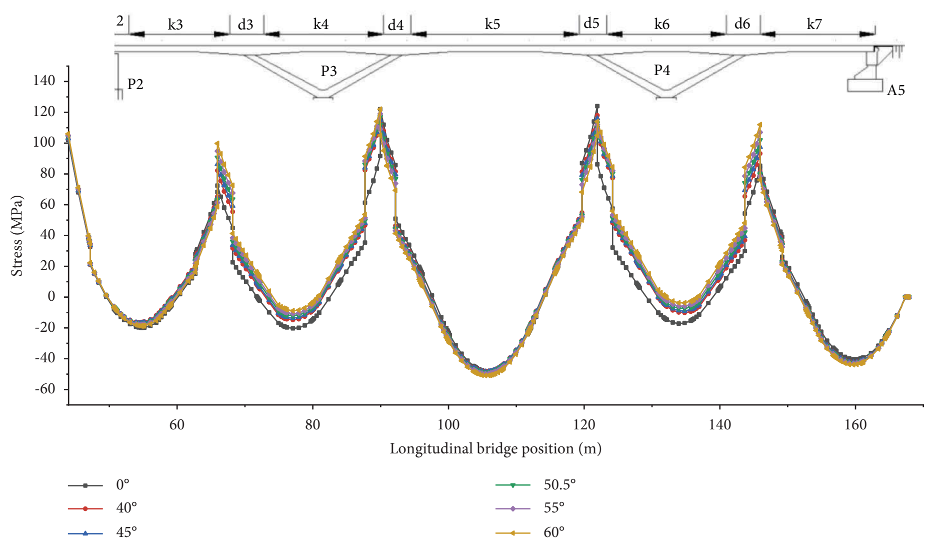


Figure 12: Comparison of stresses in the upper flange of a steel main beam.

stresses in the lower flange of the steel main girder is shown in Figure 13.

The upper and lower edges' stresses of deck plates at the top of pier d5 indicate that if the V-shaped pier angle is smaller in general, the pre-pressure effects using the pressure weight construction method is better. A comparison of the stresses at the top edge of the deck slabs is shown in Figures 14 and 15. The main reason is that the larger the angle of the V-shaped pier is, the smaller its vertical stiffness is. At the construction phases of the compression weights, V-shaped pier top will have a certain degree of deflection; at this time, this deflection of the main girder can be approximated as a reverse jacking of the top of the pier because the effects of the top of the pier induce a positive bending moment. When the compression weight is restored, the reverse jacking (deflection at the pier and girder consolidation) is restored, generating additional negative bending moments, and this downward deflection of the pier top is not conducive to the construction of the compression weight method. The maximum stresses in the V-shaped pier in the bridge state have a great relationship with the angles of the V-shaped pier. The maximum compressive stress of the V-shaped pier increases almost linearly with the increase of the angle.

6. Influence of Counterweights on the Stress States of the Completed Bridge State

6.1. Deflection Analysis. The deflection at the top of pier d3 has the positive relationship with the compression weight, indicating that the compression weight will have some effects on the forces in the negative moment zone of the bridge. However, in general, the final bridge's deflection

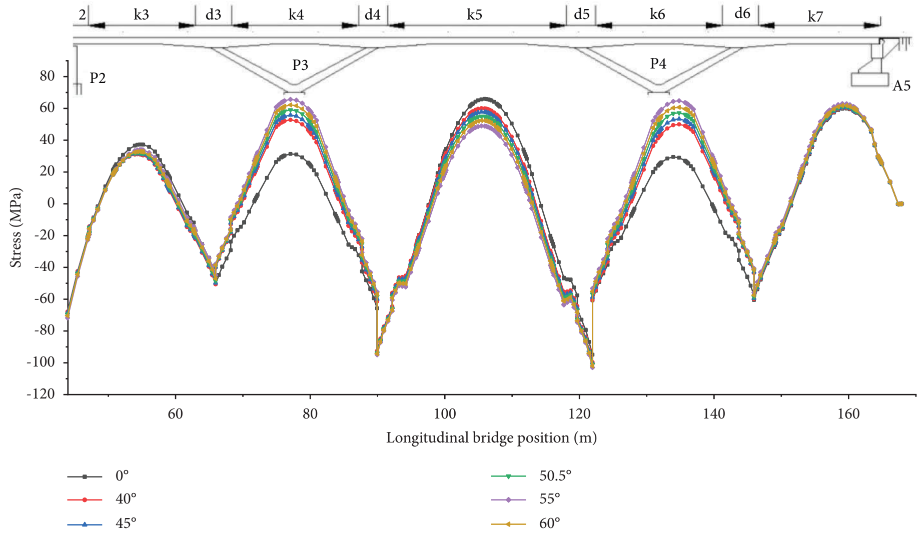


FIGURE 13: Comparison of stresses in the lower flange of a steel main beam.

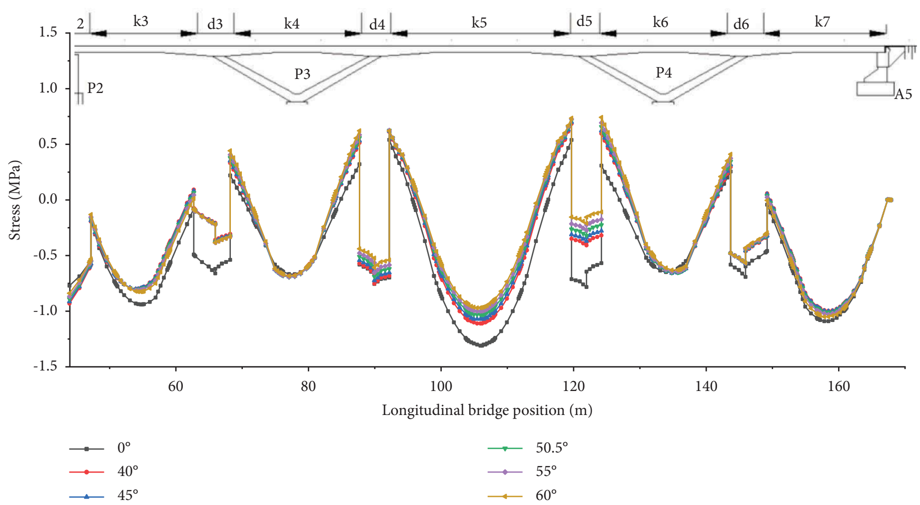


FIGURE 14: Comparison of stresses at the top edge of the deck slab.

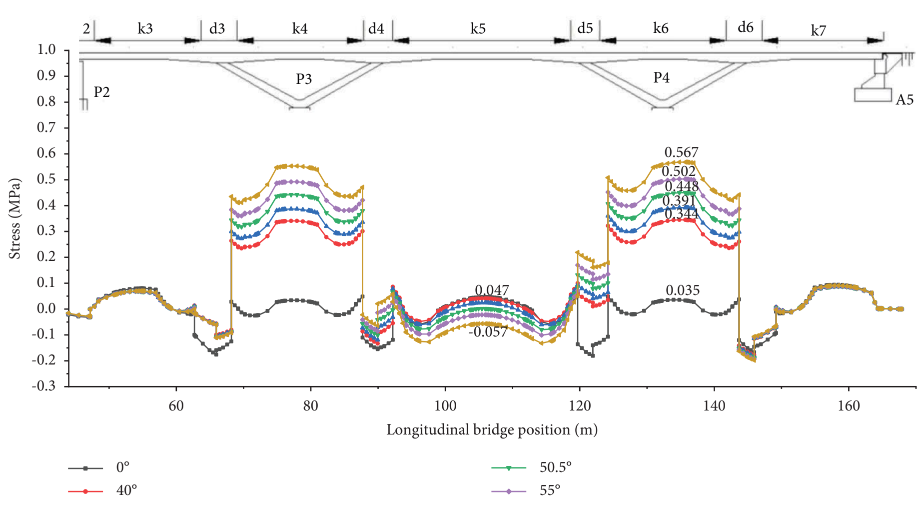


FIGURE 15: Comparison of stresses at the lower edge of the deck slab.

increases with compression weight when the compression weight in the span is different, but the actual structural deflection is not much, and the influence of compression weight on the maximum deflection of the bridge state is not significant.

6.2. Stress Analysis. Under the same compression weight construction method, the final main girders do not have the same compressive stress reserve in the negative moment zones of the vertical and V-shaped piers, so the stresses in the main girders near the top of the d1, d5, and d6 parts of the piers were taken for comparative stress analysis.

In the completed bridge condition, the use of different midspan compression weights has almost no effect on the upper flange stresses of the steel girder sections where precast deck slabs have been laid, while there is a significant effect on the upper flange stresses of the steel girders in the post-cast concrete sections. If the compression weight increases, the upper flange stresses in the post-cast concrete section will increase. The maximum upper flange stress in the steel main girder is still found at the end of d5 for all compression conditions. The stress at the end of d6 can still be seen in all conditions where the upper flange of the steel girder on the left side is subjected to tensile stresses caused by the deformation of the V-shaped pier due to the steel main girder restraining the V-shaped pier on top of the V-shaped pier.

When different compression weights are used in the construction stage, the construction process does not have a significant effect on the stresses in the lower flange of the steel main girders in the bridge-forming condition. The common weak variation rule is that as the preload weight increases, the slope of the stress change curve in the lower flange of the main girder gradually increases. The compressive stress in the lower flange of the main girder decreases more rapidly in the direction away from the top of the pier.

Even if no additional precompression weight is applied and only the deck slab is constructed in stages, the tensile stresses at the top of the pier can be reduced to some extent. As the precompression weight increases, the maximum tensile stress in each negative moment section gradually becomes smaller. The higher the compressive stress is, the better the precompression effect applied to the concrete slab at the top of the pier is. Overall, the precompression weight in the span has little effect on the deflection of the completed bridge, while it has a significant effect on the tensile stresses in the steel main girders and concrete deck slabs near the top of the piers. The most unfavorable location for the concrete slab is still in the negative moment zone at the top of pier V (d5 and d6 girder ends).

7. Conclusion

A steel-concrete composite girder bridge with V-shaped piers is taken as the background, and the main factors affecting the stress state of the steel-composite continuous rigid bridge with V-shaped piers are investigated in the paper. The main conclusions are drawn in the following:

(1) According to the construction characteristics of the compression weight method for bridges with V-shaped piers, the effects caused by different removal times of the temporary supports of V-shaped piers were studied. The earlier the temporary supports of the V-shaped pier are removed, the better the stress level of the bridge deck is. Therefore, the temporary supports should be removed after the V-pier and steel main girders are formed as a whole structure immediately or at the latest before the concrete is poured in the negative moment zone.

(2) The angles of V-shaped pier affect the stresses in the main girders. When the appropriate V-pier angle is used, the stresses in the main girders on both sides of the top of the V-pier are equal and can improve the stresses in the main girders to some extent. Outside of this optimum V-pier angle, either increasing or decreasing the angle will result in increased stresses in the main beam on one side. If the change in the vertical stiffness is not taken into account, the angle of the V-shaped pier has little effect on the stresses in the concrete slab.

(3) Although the final deflection increases with increasing preload weight, the effect of preload weight on the maximum deflection in the finished condition is not significant. The effects of construction at different preload weights on the stresses in the lower flange of the steel main girders in the finished condition of the bridge were not significant. The midspan preload weight had little effect on the deflection of the girder in the finished condition, while it had a significant effect on the tensile stresses in the steel main girders and concrete deck slabs near the top of the piers.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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