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Quantitative Study on the Effect of Shrinkage and creep and Foundation Settlement on the Widened T-Beam Bridge

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--***ABSTRACT***--
With the rapid development of society and economy, existing highway bridges need to be widened to meet the dramatically increasing traffic volume. Fisrtly, this study compares and analyses bridge widening methods and splicing techniques for old and new bridges. Secondly,taking a T-beam bridge-the Hualong Bridge after being widened as an example, the effects of shrinkage and creep and foundation settlement on its mechanical characteristics was analysed based on finite element method. Research has shown that the bridge structure generated a stress increment of 5.5 MPa under the influence of shrinkage and creep, at a distance of one-fifth of the span from the end of the bridge. The end position of the widening bridge and the adjacent main longitudial beam of the old bridge are the most affected locations, with a maximum stress increment of 3.0 MPa under the 15 mm settlement. Therefore, the influence of shrinkage and creep and foundation settlement should be considered in the design. It provides some references for the difficult and heavy design of bridge widening.
KEYWORDS;- *Bridge widening; Splicing technology; Shrinkage and creep; Foundation settlement*

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I. INTRODUCTION

With the increase in traffic volume, a large number of highway bridges can no longer meet the current demand for traffic[1-3]. In order to solve the traffic pressure of highway bridges, it is necessary to widen the bridges[4-5]. However, the process of bridge widening is complicated. If the problem of connecting the old and new bridge interfaces cannot be properly handled during the widening process of the bridge, cracks will appear in the later operation of the bridge, which will ultimately affect driving safety[6,7]. There are many factors that can cause cracks to appear after widening bridges, including the shrinkage and creep and the foundation settlement. Before the bridge is widened, the shrinkage and creep and foundation settlement of the old bridge have been basically completed. After the bridge is widened, the widened part is in the initial stage of shrinkage and creep, and the shrinkage and creep will have a greater effect on the widened part compared with the old bridge [8-11]. Simultaneously, during bridge operation period, the new bridge foundation will produce a relatively larger settlement under the bridge self weight and the vehicle load, and inconsistent deformation will occur between widened part and old bridges, causing cracks due to the additional internal forces in the bridge structure, which eventually affects the safety of the bridge operation[12-15]. A large number of scholars have conducted research on the impact of shrinkage and creep and foundation settlement on bridges[16-19]. As known from existing lieteratures, most scholars analyse the effect of shrinkage and creep and foundation settlement on bridges from a qualitative perspective, and there is less quantitative analysis of the shrinkage and creep and foundation settlement at the widened bridges, the the mechanism of crack formation in beam bridges has not been thoroughly analyzed, the mechanical characteristic of the widened bridge structure is unclear.

Therefore, it is necessary to conduct a quantitative analysis of the effect of shrinkage and creep and foundation settlement on the widened T-beam bridge, and analyse the mechanism of bridge structural cracks due to the difference in concrete shrinkage and creep and foundation settlement of the old and new bridge. Based on the actual engineering of the Dayuan Reservoir Bridge, a refined three-dimensional solid finite element model of the widened T-beam bridge is established. By comparing and analyzing the bridge structural mechanical behavior under different working conditions, the stress and displacement variation laws are obtained and the most unfavorable position of the bridge structure is clarify. The research results of this paper can provide valuable reference for similar projects in the future.

II. SUMMARY OF BRIDGE WIDENING TECHNOLOGIES

The Principles of Bridge Widening

In the process of widening bridges, it is often necessary to follow four principles[20]:

① During the construction process of bridge widening, efforts should be made to minimize the impact on the original traffic, as widening retrofitting is aimed at alleviating a series of adverse effects caused by the excessive traffic volume of the original bridge. Even if there is too much interference to the original road traffic during the short period of bridge widening construction, it is not a wise decision, as it may bring dual losses to the economy and society. For traffic restrictions or closures on old bridges, comprehensive consideration should be given to all aspects and careful choices should be made.

② The structural form of the upper and lower parts of the widened bridge should be as similar or identical to the original bridge as possible, so that the widened bridge has consistent stress, coordinates with each other, and forms a whole.

③ Widening the bridge deck is an effective way to solve the insufficient width of the original bridge deck, but the lateral connection problem between new and old bridges should be effectively handled.

④ Due to the operation of the old bridge for many years, the concrete has fully shrunk and the creep under self-weight has also been basically completed. When designing and calculating, full consideration should be given to the concrete self-weight, shrinkage, and creep of the widened new bridge to avoid cracking or significant deformation differences in the concrete joints at the connection between the new and old bridges.

The Methods of Bridge Widening

Early researches on the bridges widening began with the retrofitting of reinforced concrete simply supported girder and plate girder bridges. In the bridge retrofitting project, the requirement to improve the original bridge capacity and to increase the width of the bridge at the same time must be meet. In order to meet the above requirements, increasing the main girder method is adopted to widen the original bridge, the additional main girder (T-beam or plate girder) can be the same cross-section size with the original superstructure, or can be a larger cross-section size main girder. The use of new main girders and the original girders together to improve the bearing capacity of the bridge. Some normal widening methods are concluded as follow:

① Addition of reinforced concrete cantilevered beams

This is the easiest way to widen the bridge structure. when the original box beam pier, abutment and foundation is intact, which can meet the widening or even load lifting requirements, the main load-bearing structure of the superstructure can be reasonable retrofitted. Meanwhile, both sides of the railing and pavement plate are removed, the original deck pavement layer are chiseled away. By the re-pouring of strengthened reinforced concrete deck pavement layer or the addition of the pavement cantilever beams and lane cantilever plate on the piers and abutment accordingly, and re-installation of pavement plate and railing, the purpose of widening the bridge deck can be achieved. The schematic diagram adopting the above widening method is shown as Figure 1.

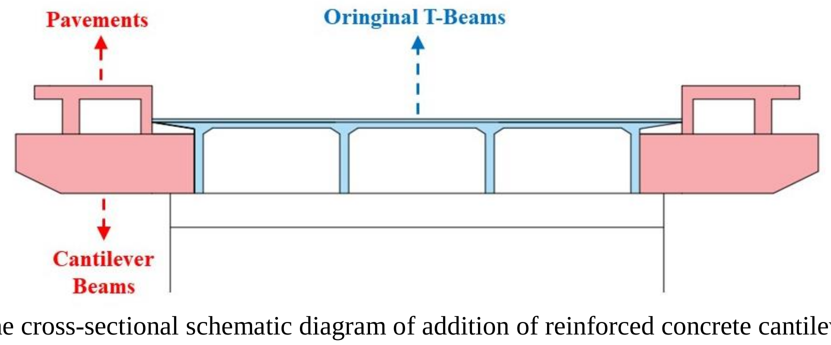

Figure 1 The cross-sectional schematic diagram of addition of reinforced concrete cantilevered beams

② Addition of main longitudinal beams

This method is generally used in situations where bridges need to be widened and the bearing capacity of old box girders needs to be improved. The bridge deck has been widened by adding main beams or arch ribs, and due to the participation of new main beams in load distribution, the original main beams or arch ribs are unloaded, achieving the goal of improving bearing capacity. This widening method requires simultaneously widening the bridge piers, abutments, and foundations, or constructing new bridge piers and abutments separately near the existing bridge.

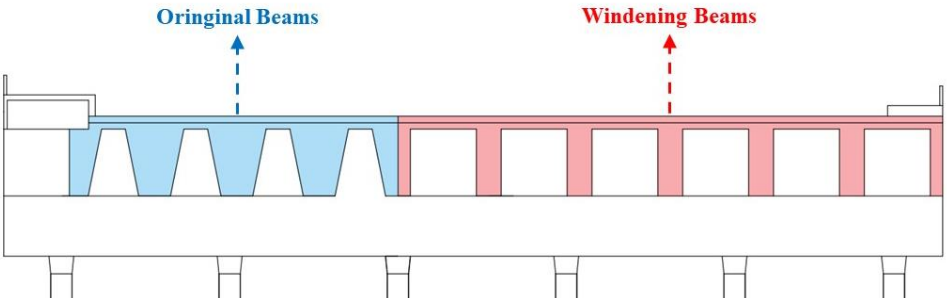

Figure 2 The cross-sectional schematic diagram of addition of main longitudinal beams

The Lateral Connection of Bridge Widening

At present, literature [21] summarizes three typical lateral connecting forms:

① The upper and lower structures are not connected

In this widening connection form, the forces acting on the new bridge and the old bridge are independent of each other, and the difficulty of bridge widening construction is reduced. Moreover, it can be constructed without affecting the original road traffic. However, when vehicles are running on the bridge, there is a significant deflection difference between the main beams of the new and old bridges, which causes damage to the bridge deck pavement layer at the connection between the new and old bridges, affecting driving safety and road appearance, and making maintenance more difficult.

② Both the upper and lower structures are connected

In this widening connection form, due to the integration of the new and old bridges, the deformation difference at the connection between the new and old bridges under various loads such as traffic loads, uneven settlement of the foundation, shrinkage and creep, and temperature loads is reduced. Its bridge deck is smooth, and its driving safety and comfort are better than other connection forms. However, due to the inconsistent deformation of the concrete beams in the upper structure of the new and old bridges, significant additional internal forces may be generated inside the structure, resulting in cracks at the connection points of the lower structure's cap beams, piers and abutment, affecting the service life of the bridge. In addition, when planting reinforcement technology is used for the connection of the lower structure, the original bridge main beam needs to be removed, which is a cumbersome construction process and has a significant impact on the traffic of the original expressway (generally requiring complete closure of traffic). This poses significant limitations to this connection form as the traffic volume is already high for bridge deck widening, and unless there are special conditions, completely closing traffic does not seem to be a reasonable choice.

③ Upper structure are connected, while lower structure are not connected

In this widening connection form, the upper structure of the new and old bridges forms a whole, which is conducive to reducing the deformation difference between the new and old bridges, making the bridge deck smooth and driving comfortable and safe. The lower structures of the new and old bridges are not connected and are subjected to separate forces, which can reduce the additional internal forces caused by the inconsistent deformation of the upper structures of the new and old bridges. In this widening connection form, the bridge deck generally does not have a dividing strip. After the removal of the sidewalk and railing, the old side beams are connected together by planting reinforcement between the new and old main beams, pouring transverse beams, and other methods. However, the difficulty of this connection form is how to ensure the construction quality of the longitudinal joints connecting the upper structure of the new and old bridges without interruption in high traffic volume, ensure continuous deformation between the new and old bridge decks, and reduce the adverse effects of traffic loads during concrete joint pouring.

The above three connection methods have their own advantages and disadvantages. Different bridge widening projects should adopt suitable lateral connection forms according to their specific situations. The choice of lateral connection form will directly affect the performance of widening bridges. At present, for most widening bridges, the third approach seems more reasonable and applicable.

III. THE CASE OF BRIDGE WIDENING

The Overview of Original Bridge

The Hualong bridge, located in Yiyang city, Hunan Province, is applied as the case. Widening of both sides of the Hualong bridge is required to cater for the rapidly increasing traffic volume. This bridge is twin-separate bridge. The left part of the bridge is arranged as 4 × 25 m, and the total length of the bridge is 100 m; The right part of the bridge is 5 × 25 m, with a total bridge length of 125 m. The main beam of the bridge adopts the form of a T type section which consists of 7 longitudinal beams with the height of 1.7 m and the deck width of 16.75 m. The remaining dimensions of the bridge are shown in Figure 3.

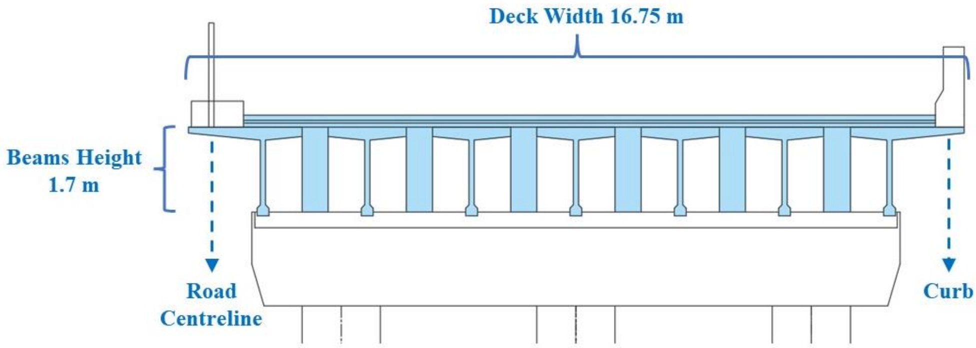

Figure 3 Design scheme for the Hualong bridge

The Design Scheme of Bridge Widening

The lateral connection of the Hualong bridge widening adopts the third forms, namely Upper structure are connected rigidly, while lower structure are not connected. In the premilary programme, the connectiong form of the superstructure of the widening bridge with the original bridge is by rigid connection. Cast-in-place prestressed concrete (post-tensioning) T beam is used to widen the bridge, which adopts the simply supported-continuous system. The bearing piles and abutments are used as the lower structure. The specific construction process for widening this bridge is as follows: 1) The existing structure of the bridge deck 1 m wide range of guardrail and pavement are demolited, and the old bridge side panels 33cm flange are chiseled away. 2) The planted reinforcement technology is used in the existing diaphragm and transverse beams to weld to form a whole with the new bridge beams rebar. 3) The new and old bridge wet joints are poured, so that the formation of a whole. The design scheme of widening the Hualong bridge as shown in Figure 4.

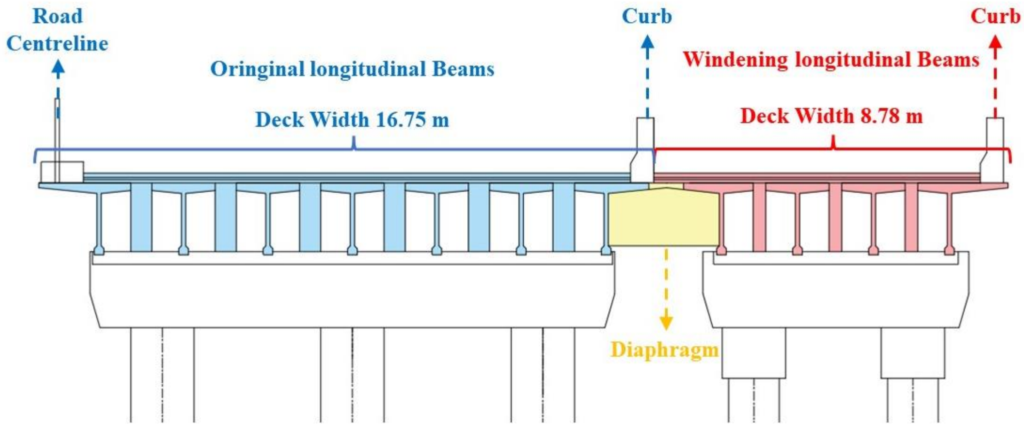

Figure 4 Design scheme for widening the Hualong bridge

The Influence of Shrinkage and creep on the bridge

The three-dimensional solid model of the entire new and old bridge was established by using the MIDAS/FEA software to finely simulate the effects caused by shrinkage and creep of the new and old concrete, and the finite element model is as shown in Figure 5. During the widening process of the old bridge, the rigid connection boundary conditions between the new and old bridges are simulated using node coupling method. In references [22-24], the construction process of bridge widening is simulated as follows: the old bridge is completed in one time, and it is considered that the shrinkage and creep have been completed, while the duration of the shrinkage and creep of the widening part is considered ten years.

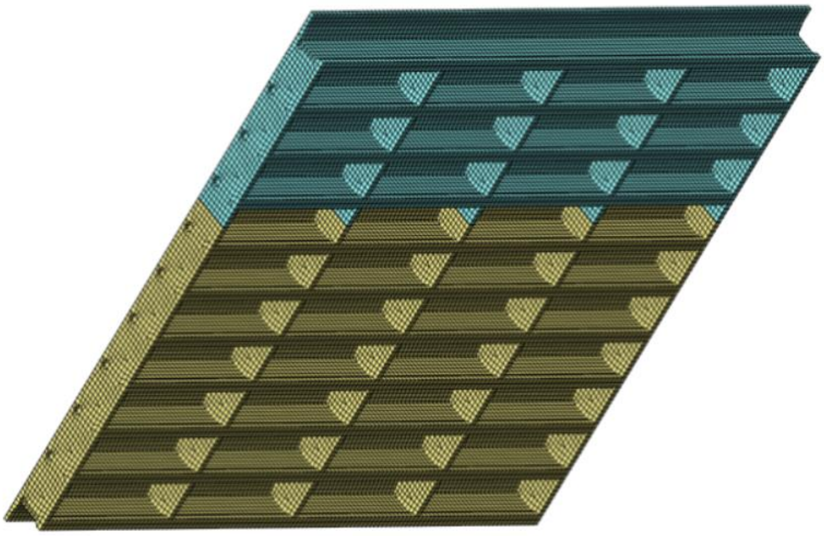

Figure 5 Finite element model of widened T-beam bridge

After the old bridge widening due to the difference in shrinkage and creep between the old and new main beams, the shrinkage and creep of the new bridge is constrained by the old bridge, which will produce additional internal forces in the connecting interface of the old and new bridges. Therefore, in the design of concrete bridge structure, shrinkage and creep is an important influence factor that cannot be ignored, according to the JTG 3362-2018 specification [25], the concrete creep coefficient can be calculated according to the following formula, and the creep function is shown in Figure 6.

$$\phi\left(t,t_0\right)=\phi_0\cdot\beta_c\left(t-t_0\right) \tag{1}$$

$$\phi_0=\phi_{RH}\cdot\beta\left(f_{cm}\right)\cdot\beta\left(t_0\right) \tag{2}$$

$$\phi_{RH}=1+\frac{1-RH/RH_0}{0.46\left(h/h_0\right)^{1/3}} \tag{3}$$

$$\beta\left(f_{cm}\right)=\frac{5.3}{\left(f_{cm}/f_{cm0}\right)^{0.5}} \tag{4}$$

$$\beta\left(t_0\right)=\frac{1}{0.1+\left(t_0/t_1\right)^{0.2}} \tag{5}$$

$$\beta_c\left(t-t_0\right)=\left[\frac{\left(t-t_0\right)/t_1}{\beta_H+\left(t-t_0\right)/t_1}\right]^{0.3} \tag{6}$$

$$\beta_H=150\left[1+\left(1.2\frac{RH}{RH_0}\right)^{18}\right]\frac{h}{h_0}+250\leq 1500 \tag{7}$$

In the formula:

t_0 —Age of concrete at the time of loading (d);

t —Calculation of the age of concrete at the moment of consideration (d);

$\phi\left(t,t_0\right)$ —The age of loading is t_0, calculate the coefficient of creep of concrete when the t is considered;

ϕ_0 —Nominal creep coefficient;

β_c —Coefficient of development of creep with time after loading;

f_{cm} —Strength grade C20~C50, The average cubic compressive strength of concrete at 28 days of age, $f_{cm}=0.8f_{cu,k}+8\text{MPa}$ (MPa);

$f_{\mathrm{cu,k}}$ —Standard value of compressive strength of concrete cubes with a 95% guarantee rate and an age of 28 days (MPa);

β_{RH} —The coefficient related to the annual average relative humidity, formula (4) applies to 40%≤ RH <90%;

RH —Annual average relative humidity of the environment (%);

β_{sc} —A coefficient determined by the type of cement, for general Portland cement or rapid hardening cement, β_{sc} =5.0;

h —Theoretical thickness of components (mm), $h = 2A/\mu$, A is the cross-sectional area of the component, μ is the peripheral length of the component in contact with the atmosphere.

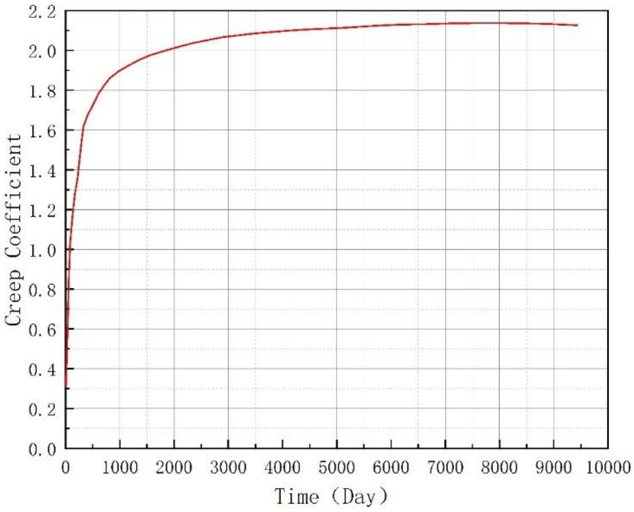

Figure 6 Creep function

The stress state at the completion of bridge widening construction is shown as in Figure 7, and the effect of prestressed steel strands is't considered in the finite element model. Therefore, the stress state obtained from the model calculation results is only a basic reference state, and we just focus on the stress increment after considering shrinkage and creep. The principal tensile stress nephogram of the flange inferface and the top position under ten years of shrinkage and creep is shown as Figure 8 and Figure 9 seperately.

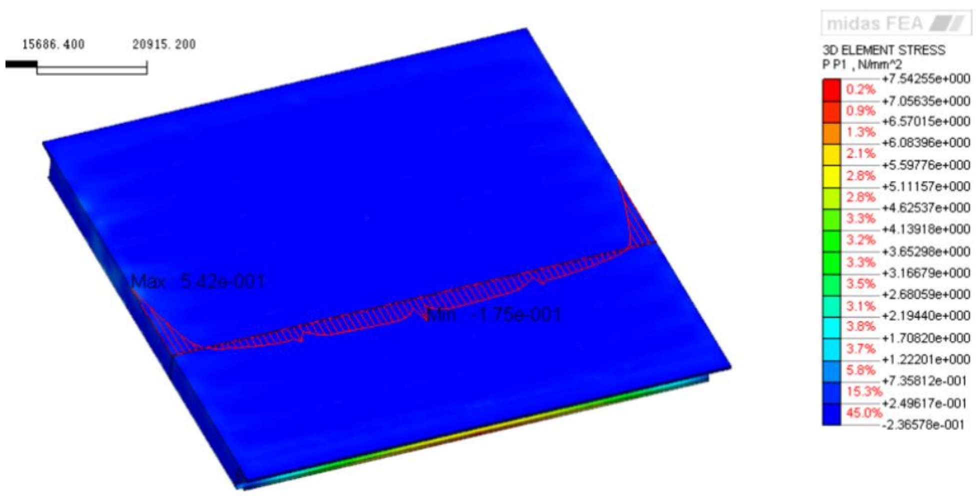

Figure 7 Principal tensile stress nephogram at the interface of flange plates under self weight (MPa)

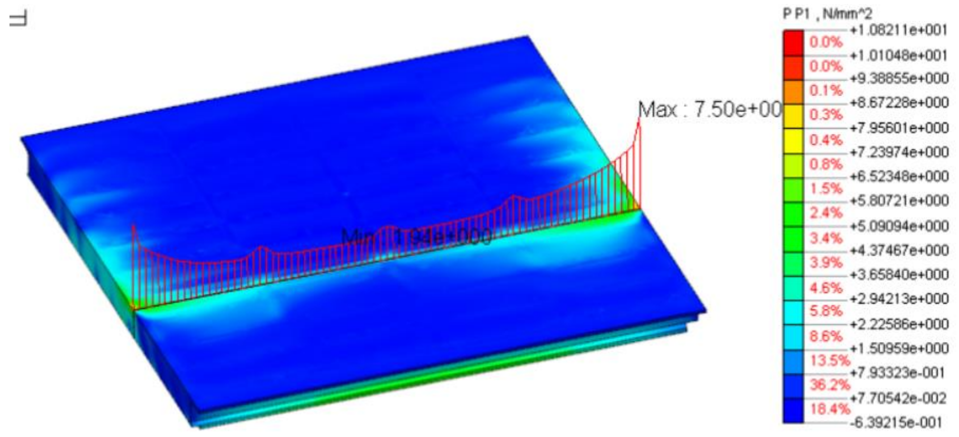

Figure 8 Principal tensile stress nephogram at the flange inferface under ten-year shrinkage and creep (MPa)

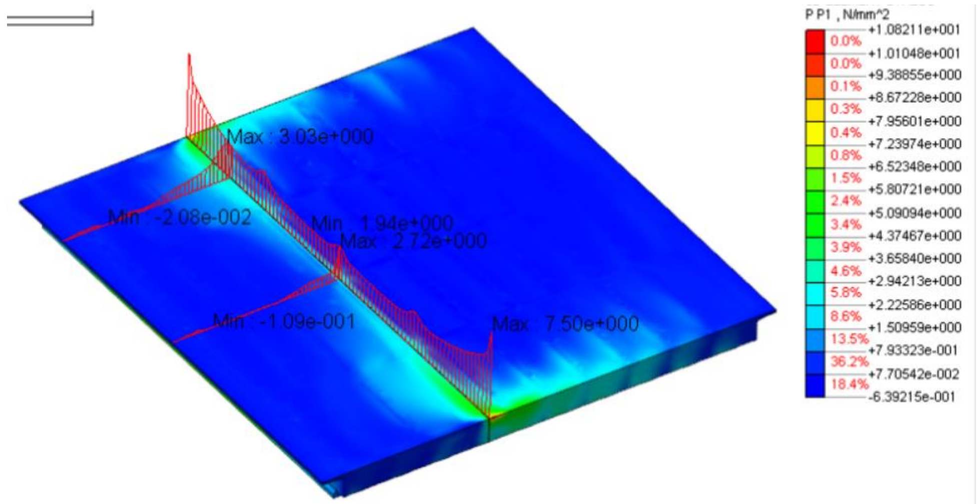

Figure 9 Principal tensile stress nephogram at the top position under ten-year shrinkage and creep (MPa)

According to Figure 7-9, after the completion of ten years of shrinkage and creep, the stress state of the top plate of the T-beam structure has undergone significant changes compared to the stress state before shrinkage and creep. The main changes are listed as followed:

(1) The old bridge generated a large tensile stress area near the end of the new bridge side, which is due to the overall contraction of the new bridge, and the force flow is transmitted to the end of the old bridge.

(2) The new bridge is located near the interface, where a significant tensile stress is generated on the top plate of the first beam of the new bridge, which is due to the constraints of the old bridge.

(3) At a distance of one-fifth of the span from the end of the bridge, the structure generated a stress increment of 5.5 MPa under the influence of shrinkage and creep. Therefore, its influence cannot be ignored in design calculations.

The influence of Uniform Settlement of the Foundation on the Bridge

In the simulation analysis process, we first assume that the detachment of the support is caused by excessive settlement, that is, no support boundary conditions are applied to the widened part in the model. The deformation mode is shown in Figure 10, with a maximum deformation of 25 mm. In actual situations, due to unreasonable treatment of the widened bridge foundation, when the settlement reaches 25 mm, the lower structure will detach from the upper structure, and the lower structure cannot play a supporting role.

The actual foundation settlement cannot reach such a large amount. Based on the observed settlement values of the existing bridge foundation, we took 15 mm for analysis of the influence of uneven settlement, as shown in Figure 11. The principal tensile stress nephogram under the 15 mm settlement is shown as Figure 12.

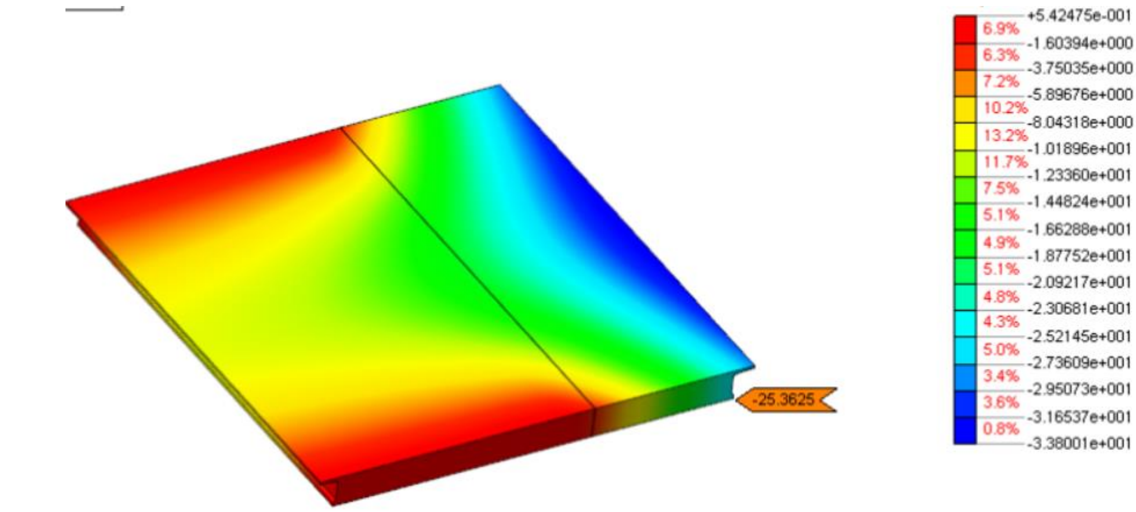

Figure 10 Maximum displacement nephogram of the widened part without support (mm)

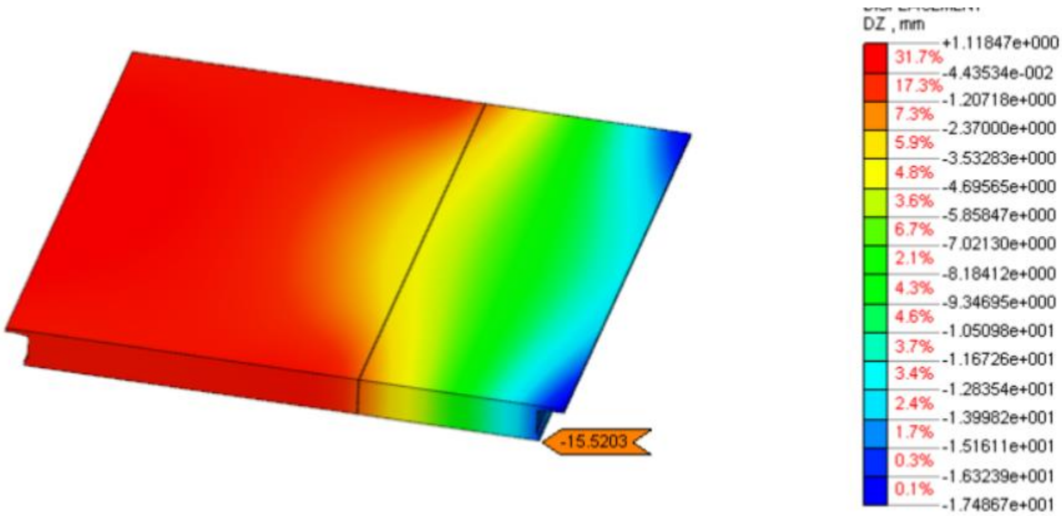

Figure 11 Vertical displacement nephogram of the widened part with a settlement of 15 mm (mm)

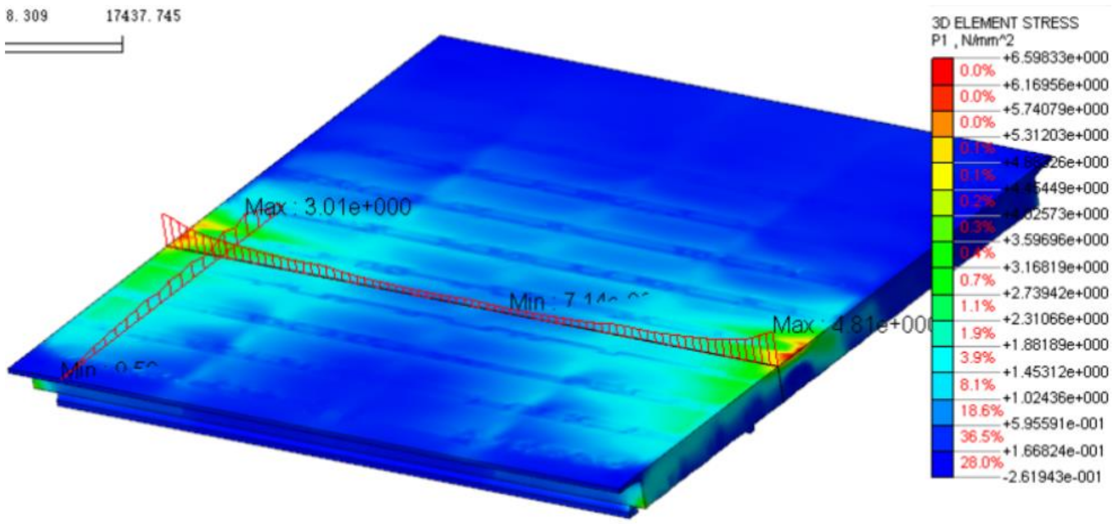

Figure 12 Principal tensile stress nephogram under the 15 mm settlement (MPa)

As seen from the Figure 12, the area affected by the settlement is mainly located at the end position of the widening bridge, and the affected area extends to the adjacent main longitudial beam of the old bridge, with a maximum stress increment of 3.0 MPa.

IV. CONCLUSION

The effect of shrinkage and creep and foundation settlement on the widened T-beam bridge is analyzed based on the three-dimensional solid finite model, and the affected range caused by shrinkage and creep, as well as the law of force flow transmission are obtained, which provides valueable references for bridge widening design. The main conclusions are listed as follows:

(1) The old bridge generated a large tensile stress area near the end of the new bridge side, and the force flow is transmitted to the end of the old bridge. The new bridge is located near the interface, where a significant tensile stress is generated on the top plate of the first beam of the new bridge, which is due to the constraints of the old bridge.

(2) At a distance of one-fifth of the span from the end of the bridge, the structure generated a stress increment of 5.5 MPa under the influence of shrinkage and creep. Therefore, its influence cannot be ignored in design calculations.

(3) Under the 15 mm settlement, the area affected by the settlement is mainly located at the end position of the widening bridge, and the adjacent main longitudial beam of the old bridge, with a maximum stress increment of 3 MPa.

(4) Although specific stress values are quantitatively provided in this paper, there is still some deviation between the model and actual bridge structure. For example, the contribution of ordinary steel bars aren't considered in this paper, and due to the limitation of calculation scale, the element size has a significant impact on the calculation results, especially the problem of stress concentration. In the following research, we will focus on considering the influence of the above factors on the structural stress performance.

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