Study on stud performance of steel UHPC composite structure based on temperature

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Abstract—The stress and deformation of the specimen under static load and temperature load coupling are deduced by simulation. With the help of finite element software ABAQUS, the user subroutines DFLUX and FILM are called to introduce the temperature field, so as to realize the analysis and research on the stress, displacement, PEEQ, arrangement and load slip curve of the stud under different action conditions. The results show that based on the existence of temperature stress, the service performance of studs under coupling action is significantly lower than that under static action alone, and the proportion of shear performance of studs in different rows is different. Through the research and analysis of the above phenomena, it can provide reference value for the research of temperature on the performance of studs in composite bridge deck and prolong the service life of bridge deck.

1. Introduction
At present, flexible pavement is mostly used for steel bridge deck pavement in China. Usually, under the action of large vehicle load and high temperature environment, pavement damage and fatigue cracking of steel bridge deck are easy to occur [1, 2]. In order to better solve the disease problem in steel deck pavement, many scientific researchers start with the stiffness of pavement materials [3], and introduce super performance concrete with high strength and good durability as the main material for steel deck pavement. Many practical results show that the introduction of materials with large stiffness can reduce the dead weight of the bridge. It can well solve the disease problem in steel deck pavement and form composite deck. However, what kind of connector is used to make the thinner UHPC layer and steel bridge deck work together effectively will become the key problem for the successful popularization and application of composite steel bridge deck. At present, for steel-concrete composite structures, channel steel, PBL connectors and studs are usually used as shear connectors [4]. The selection, layout and optimization of shear connectors are the key factors for the cooperative work of steel plate and concrete and giving full play to their respective advantages. In actual work, the steel bridge deck pavement is always exposed to natural climate conditions. Natural factors such as climate conditions, solar radiation and wind speed will cause periodic changes in the working temperature of the pavement. Temperature changes will cause pavement deformation. When this deformation is constrained and cannot be carried out freely, temperature stress will be generated in the pavement [5]. According to the experimental research and theoretical analysis of several typical bridge decks conducted by Kennedy et al., the distribution law of pavement temperature along the thickness is found, and the temperature stress caused by temperature of pavement is estimated according to the temperature distribution law. The results show that the temperature stress of steel-concrete composite beam bridge is of great significance compared with vehicle static load and dynamic load stress [5,6]. Temperature load is a factor that can not be
ignored in structural design. For UHPC steel composite pavement structure, when the ambient temperature changes, due to the large difference in expansion coefficient between UHPC and steel, the deformation of the two materials will be different, resulting in additional stress at the interface between UHPC and steel [5, 8 ~ 11], which has a certain impact on the bearing capacity of studs.

However, the stress of stud under temperature and the synergy between UHPC and steel plate have not been studied. Therefore, it is of great significance to study the mechanical properties of stud in UHPC under ambient temperature. In this paper, the stud is selected as the connector, and the simulation of the launch test is carried out with the help of the finite element software ABAQUS. The force field and temperature field under the action of load and temperature are analyzed and studied, so as to make the steel-concrete composite structure work better and prolong the service life of the composite bridge deck.

2. Mechanism study
Due to the effect of solar radiation, the atmospheric temperature has obvious differences between day and night, and presents the characteristics of daily periodic variation. The influence of this periodic variation law of solar radiation on the temperature field of pavement structure can be approximately described by periodic boundary conditions [7]. When the bridge deck structure (thickness, thermal characteristics, etc.) is determined, the main environmental factors affecting its temperature field are daily maximum temperature $T_{a_{\text{max}}}$, daily minimum temperature $T_{a_{\text{min}}}$, daily total solar radiation $Q$, effective sunshine time $c$ and daily average wind speed $V_w$ [8].

2.1 solar radiation
According to the research results of Barber and Yan Zuoren, the daily variation process of solar radiation $q(t)$ is approximately expressed by the following function formula (1):
\[
q(t) = a_0 + \frac{c}{2} \sum_{k=1}^{\infty} a_k \cos \frac{k\pi(t-12)}{12}
\]

Where $a_0 = 2q_0/\pi$, the $q_0$ is the maximum radiation at noon, and $m = 12/c$ ($c$ is the actual effective sunshine hours), the $a_k$ calculation formula is as follows:
\[
a_k = \begin{cases} 
\frac{q_0}{\pi} \frac{1}{m+k} \sin(m+k) \frac{\pi}{2m} \frac{\pi}{2m} & k = m \\
\frac{q_0}{\pi} \frac{1}{m+k} \sin(m+k) \frac{\pi}{2m} \frac{1}{m-k} \sin(m-k) \frac{\pi}{2m} & k \neq m
\end{cases}
\]

2.2 Temperature and convective heat exchange
Due to the influence of solar radiation, the atmospheric temperature presents periodic variation characteristics. Therefore, the linear combination of two sinusoidal functions (equation (2)) can be used to simulate the daily variation process of air temperature, and the results are in good agreement with the actual situation.
\[
T_a = T_{a_{\text{max}}} + T_{a_{\text{min}}} \left[0.96 \sin \omega(t - t_0) + 0.14 \sin 2\omega(t - t_0)\right]
\]

The heat exchange coefficient $h_c$ of heat exchange between the pavement surface and the atmosphere is mainly affected by the wind speed $u_w$, and there is a linear relationship between them, as shown in formula (3):
\[
h_c = 3.7u_w + 9.4
\]

2.3 Pavement effective radiation
The effective radiation of pavement is mainly related to many factors, such as ground temperature, air temperature, cloud cover, air humidity and transparency. Equation (4) can be used to directly realize the boundary conditions of effective ground radiation:
\[ q_F = \varepsilon \sigma \left[ (T_1|_{z=0} - T_Z)^4 - (T_a - T_Z)^4 \right] \]  \hspace{1cm} (4)

Where:
- \( q_F \) is the effective ground radiation;
- \( \varepsilon \) is the emissivity (blackness) of the pavement, taken as 0.81 in this paper;
- \( \sigma \) is blackbody radiation coefficient;
- \( T_1|_{z=0} \) is the road surface temperature;
- \( T_a \) is the atmospheric temperature;
- \( T_Z \) is absolute zero - 273 °C.

### 3. Establish finite element model

In this paper, the finite element model of temperature field under the condition of continuous variable temperature will be simulated, and then the results of temperature field will be assigned to the load stage as the initial condition through the restart step of ABAQUS to analyze the mechanical state of shear studs under the coupling action of temperature and load.

#### 3.1 Finite element simulation of temperature field

##### 3.1.1 Model size

As shown in Figure 1, the test piece is composed of an I-beam, two UHPC plates and studs. According to eurocode-4 and references [12, 13 and 14], the size of the test piece is designed as follows: UHPC layer is 80mm thick, 250mm wide and 300mm high; The diameter of transverse and longitudinal reinforcement is 8mm. Four studs are welded on the steel interface, with a diameter of 14mm and a total height of 56mm. The specific dimensions are shown in Figure 1. Since the model is completely symmetrical, a 1/2 model is used for modeling to simplify the calculation.

![Fig.1 model dimensions](image)

##### 3.1.2 Constitutive relation

The constitutive model of material is a mathematical description of its stress-strain relationship, which can directly affect the calculation accuracy and even the calculation process of finite element. According to the existing literature and research [4], in the push out experiment of UHPC steel...
composite structure, the steel plate is not damaged, and the stud is only damaged at the edge of the root. Therefore, during modeling, the steel plate, stud and reinforcement used are regarded as ideal elastic-plastic models; In the actual test, UHPC material will be squeezed by the moving stud and damaged, so the damage plastic constitutive model of concrete is used for modeling. Q345 steel is used for steel plate, Q275 steel is used for stud, and Q235 steel is used for stirrup and longitudinal reinforcement. The establishment of temperature field also requires the expansion rate, thermal conductivity and specific heat capacity of corresponding materials. The specific parameters are shown in Table 1:

| Material | E/(GPa) | $\mu$ | Expansion rate | Heat transfer rate (W/(m$^2$k$^{-1}$)) | Specific heat capacity/(mJ/(t$^\circ$C)) |
|----------|--------|------|---------------|----------------------------------|-------------------------------------|
| I-beam   | 206    | 0.28 | 1.3e-005      | 44                               | 46e7                                |
| stirrup  | 210    | 0.27 | 1.3e-005      | 43                               | 44e7                                |
| Stud     | 210    | 0.27 | 1.3e-005      | 43                               | 44e7                                |
| UHPC     | 53     | 0.19 | 9e-006        | 1.28                             | 97e7                                |

### 3.1.3 Call of ambient temperature

In the interaction module, by calling the user subroutine film and specifying the wind speed, daily maximum temperature, daily minimum temperature and temperature change time difference, in fact, the user subroutine film realizes the temperature corresponding to the formula and heat flow exchange. The ambient temperature is input by amplitude curve. Here, the day and night temperature in Lanzhou is used, as shown in Table 2 below:

| Time/h | Temperature $^\circ$C | Time/h | Temperature $^\circ$C | Time/h | Temperature $^\circ$C | Time/h | Temperature $^\circ$C |
|--------|-----------------------|--------|-----------------------|--------|-----------------------|--------|-----------------------|
| 0      | 25.6                  | 6      | 23.5                  | 12     | 36.6                  | 18     | 36                    |
| 1      | 25.1                  | 7      | 24                    | 13     | 37.7                  | 19     | 32.7                  |
| 2      | 25.2                  | 8      | 25.1                  | 14     | 41.1                  | 20     | 30.1                  |
| 3      | 24.9                  | 9      | 29.8                  | 15     | 40.2                  | 21     | 29.2                  |
| 4      | 24.3                  | 10     | 34                    | 16     | 39                    | 22     | 28.8                  |
| 5      | 25.2                  | 11     | 37.2                  | 17     | 37.2                  | 23     | 27.5                  |

### 3.1.4 Contact properties and temperature loads

According to reference [5], the interface adhesion between steel plate and UHPC has no significant effect on the shear bearing capacity of the specimen and is not the main factor providing shear resistance. Therefore, in the finite element analysis, the normal hard contact is adopted for the contact between UHPC and steel interface in this paper; Binding contact is adopted for the contact between stud and steel plate; The contact between stud and UHPC adopts surface to surface contact; Reinforcement is defined in contact with UHPC by built-in embedding.

The realization of temperature load mainly realizes solar radiation by calling the user subroutine DFIUX. The effective radiation of the test piece is mainly related to ground temperature, air temperature, cloud cover, air humidity, etc. In the user subroutine DFIUX, the first kind of boundary conditions of heat flow varying with time are defined, and the relevant heat transfer parameters such as total solar radiation and sunshine time are imported.

### 3.2 Temperature load coupled finite element simulation

Reimport the results of temperature field in the way of restart and establish a new model. In the contact module, the contact between steel plate and UHPC, stud and UHPC should be fully considered, and the contact mode is surface to surface contact; The reinforcement adopts built-in contact,
embedded in ultra-high performance concrete, and the binding contact is adopted between the bolt and the steel plate.

The load module is applied by forced displacement and loaded according to sinusoidal cyclic mode. During finite element simulation analysis, the displacement is applied to the top of the steel plate through coupling motion, and the simulation is pushed out of the experiment.

As shown in Figure 2 below, it is the component stress nephogram under three conditions, from which it can be clearly seen that the component in the coupling stage is subjected to the maximum stress, followed by the static load.

![Fig.2 stress nephogram of components](image)

4. Result analysis

For the evaluation of stud performance, various indexes of the specimen are derived from three states (temperature field, static action and temperature load coupling action) for analysis and comparison. The main judgment indexes are stress, displacement, stud arrangement, damage and load slip curve.

4.1 Stress and displacement analysis of stud

Figure 3 and Figure 4 respectively show the stress nephogram of the stud under the separate action of static load and the coupling action of temperature and load, and select the stud at the left of the bottom row for analysis.

![Fig.3 static action](image) ![Fig.4 coupling action](image)

It can be seen from Figure 5 that under the action of static load, the stress on the root of the stud is the largest, there is a sudden increase, and finally tends to a stable value, that is, the root of the stud is the main part providing shear resistance and bears a large load; The stress in the middle of the stud increases first and then decreases, which is related to the yield of the stud in the process of displacement; The stress at the head of the stud increases as a whole, which is mainly caused by the local reaction force and accumulates with the change of time. It can be seen from Figure 6 that the root displacement of the stud suddenly changes at 0.2S, and the maximum displacement is 0.6mm. With the passage of time, the root is gradually damaged; The displacement change of head and neck is not obvious and can be ignored.
Fig.5 stud stress under static action
Fig.6 stud displacement under static action

Figures 7 and 8 show the stud stress and displacement under coupling. It can be seen from Fig. 7 that compared with the static force alone, the stress increase of the middle and head of the stud under the temperature load coupling effect is obvious and has large fluctuation, which is directly related to the temperature stress under the temperature effect; In Figure 8, the maximum displacement of the root of the stud reaches 1.4mm, which is between the existence of temperature stress, making the overall deformation of other parts of the stud more significant than that of the load alone.

Fig.7 stud stress under coupling action  Fig.8 stud displacement under coupling action

It can be seen from the above analysis that the root and middle of the stud are the main parts to provide shear resistance, which should be paid more attention. Through the comparative analysis of the stress and displacement of the stud under different conditions in Figures 9 and 10, we can more specifically understand the influence of temperature on the bearing capacity of the stud.

Fig.9 Comparison of stud stress  Fig.10 comparison of stud displacement

It can be seen from Figure 9 that temperature has a significant effect on the middle part of the stud, which is related to the thickness and heat transfer coefficient of UHPC, while the root of the stud only
plays a significant role in the initial stage due to material yield. Through calculation, the maximum stress in the middle of the stud under the influence of temperature load is 20% higher than that under static load alone; From the comparison of stud displacement in Figure 10, it can be found that in the initial stage, the stud has slight expansion due to the existence of temperature stress, and then slip and damage gradually occur under the passage of external force. The displacement is more obvious than the static force alone, and the maximum displacement reaches 1.3 times of the static force. Under the action of coupled load, the stress and displacement of the shear nail are obviously greater than those under the separate action of static force, which shows that the temperature has a non negligible influence on the bearing capacity of the shear nail. In practical engineering, the influence of temperature on the shear resistance of the shear nail should be fully considered.

4.2 stud layout analysis

In the process of pushing out, the stress state of the stud at different positions shall be considered and its contribution to the shear resistance of the composite member shall be analyzed. As shown in Figure 11, the stress comparison of the stud in the upper and lower rows under the separate action of static load is shown. It can be seen that in the initial stage, the stress value in the middle of the lower row of stud is greater than that of the upper row of stud, which changes with the action time, The upper row of bolts gradually play a role and provide the main anti sliding force; It can be seen from Figure 12 that the displacement of the lower row of studs is significantly greater than the displacement of the upper row. Combined with figure 11, it can be seen that in the pushing process, the main shear resistance is increased by the lower row of studs first, and then gradually increased by the upper row of studs with the yield of the lower row of studs, and the upper row of studs will bend in the middle.

4.3 stud damage analysis

The damage of stud in the pushing process is analyzed by observing the equivalent plastic strain PEEQ. PEEQ is an important parameter reflecting the plastic state of the structure. When the PEEQ value of
an element is greater than 0, it indicates that the element begins to yield [13]. Figure 13 shows the equivalent plastic strain values of the roots of the upper and lower rows of studs under static action (from the tensile side to the compression side), and Figure 14 shows the equivalent plastic strain values of studs under coupling action. It can be seen from the figure that the plastic strain of the lower row of studs in the whole process is greater than that of the upper row of studs, which shows that in the pushing process, the lower row of studs provide the main shear resistance and yield first; At the same time, the PEEQ value of the stud under the coupling action is greater than the equivalent plastic strain under the static action alone, and the PEEQ value is increased by 31%.

5. Load displacement curve

Figure 15 shows the load slip curve of the member. The load slip curve generally shows the elastic stage and yield stage. In the elastic stage, the slip value increases linearly with the increase of load, and the slip value is generally small in the elastic stage, while in the yield stage, the growth rate of slip is much faster than the load, which indicates that the stud has yielded. An obvious turning point can be seen from the load slip curve, which can be regarded as the beginning of the yield stage. In the static stage, the steel plate begins to yield when it drops by 0.22mm, and the maximum force is 139.57kN. In the coupling stage, the steel plate begins to yield when it drops by 0.14mm, and the maximum force is 139.57kN.

6. Conclusion

In this paper, the three-dimensional finite element model of the push out specimen is established, the mechanical states of the stud in the composite bridge deck under different conditions are compared, and the influence degree of ambient temperature on the bearing capacity of the stud is obtained. Based on the current research, the following conclusions can be drawn:

(1) According to the finite element model, under the influence of temperature, the bearing capacity of the stud is significantly lower than that of the load alone, and its displacement increases significantly, and the maximum displacement is 1.3 times of the static action.

(2) For different rows of studs, the proportion of shear resistance provided is different. The lower the studs share the greater the shear ratio, and the first yield occurs. With the yield of the lower row of studs, the shear resistance is gradually increased by the upper row of studs, and the upper row of studs will bend in the middle.

(3) The plastic strain of the lower row of pegs is greater than that of the upper row of pegs, and the peek value of the pegs in the coupling stage is greater than the equivalent plastic strain under static force alone, and the peek value is increased by about 31%.

(4) For the load slip curve in the coupling stage, when the steel plate decreases by 0.14mm, the stress reaches the maximum and yields, while in the static stage, it yields only after it decreases by 0.22mm.
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