Shear properties of studs in alkali-activated ultra-high performance concrete

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Abstract: With the wide application of ultra-high performance concrete in strengthening orthotropic steel bridge deck, the fatigue damage of steel bridge deck and the cracking of pavement layer are effectively solved. More green and environmentally friendly alkali-activated ultra-high performance concrete is also proposed. The finite element analysis method was used to study the shear performance of different diameter and length of the stud in alkali-activated UHPC. The results show that the diameter of the stud has the greatest influence on the shear bearing capacity of the stud, and the length-diameter ratio has a certain influence on the slip.

1. Introduction

Ultra-high performance concrete (UHPC) has excellent performance in strengthening orthotropic steel bridge deck [1], but the consumption of a large number of silicate cement increases CO2 emissions and brings a burden to the environment, which runs counter to the mode of green development, environmental protection, energy conservation and emission reduction [2]. To solve this problem, some researchers proposed to optimize the design of UHPC mixture to make it more environmentally friendly, but none of them completely abandoned the cement component [3, 4]. Aydin et al. [5] made alkali-activated UHPC by completely replacing cement with slag. The compressive strength of alkali-activated UHPC was similar to that of UHPC, but the cost of alkali-activated UHPC was slightly lower, and it was more environmentally friendly. Compared with ordinary silicate concrete, alkali-activated concrete has the advantages of low carbon emission, fast setting and hardening, and saving aggregate resources.

The connector plays a very important role in strengthening orthotropic steel bridge deck by alkali-activated UHPC. If the shear performance of the connector is insufficient, the concrete layer and the steel bridge deck cannot be cooperatively stressed, and the stiffness of the steel bridge deck cannot be improved. Therefore, it is very important to study the shear performance of the connector in alkali-activated UHPC. Kruszewski et al. [6] selected different diameter, arrangement and different concrete compressive strength as parameters to study the performance of studs in UHPC. Cao et al. [7] studied the stud embedded in thin UHPC by finite element simulation, established a finite element model with the diameter and height of the stud and the compressive strength of concrete as parameters, and carried out experimental verification. Liu et al. [8] studied the static and fatigue properties of studs in high performance fiber reinforced concrete. A large number of studies have shown that different concrete types and strength have an impact on the shear performance of studs. The shear bearing capacity of studs in high performance concrete is higher but the ductility is poor. However, the existing
research on the shear performance of alkali-activated UHPC studs is rarely involved. In this chapter, the shear performance of alkali-activated UHPC studs by referring to the research experience of some researchers on the shear performance of studs in high performance concrete.

2. Finite element analysis
ABAQUS was used to simulate the shear test of studs in alkali-activated UHPC. Compared with the finite element analysis of experimental analysis, it has the advantage of low cost. The influence of the length and diameter of studs on the shear bearing capacity of studs was discussed in ABAQUS.

| Specimen | Diameter (mm) | Length (mm) | L/D |
|----------|---------------|-------------|-----|
| NS13-35  | 13            | 35          | 2.7 |
| NS13-55  | 13            | 55          | 4.2 |
| NS13-75  | 13            | 75          | 5.8 |
| NS13-95  | 13            | 95          | 7.3 |
| NS16-55  | 16            | 55          | 3.4 |
| NS16-75  | 16            | 75          | 4.7 |

2.1 Finite element modeling
The steel plate, alkali-activated UHPC plate and stud are simulated by C3D8R solid element, and the steel bar is simulated by T3D2 two-node three-dimensional truss element and embedded into the alkali-activated UHPC plate. In order to save the calculation cost, a quarter of the specimen is selected for modeling. The constitutive relationship of steel is a two-line model, and alkali-activated UHPC is simulated by concrete damage plasticity model. The loading mode of the vertical displacement simulation test is selected in ABAQUS. Because the maximum slip of the stud in the test is about 2 mm, the vertical displacement is 3 mm. The top surface of the H-beam is coupled to the reference point, and the vertical displacement is applied at the reference point. The root of the stud is bound to the steel plate, and the alkali-activated UHPC plate drills out the hole of the stud size. The contact relationship between the surface of the stud and the corresponding alkali-activated UHPC surface is defined. The contact is divided into hard contact and penalty function contact, and the friction coefficient is defined as 0.2. The contact between steel plate and alkali-activated UHPC is also divided into hard contact and penalty function contact friction coefficient defined as 0. When meshing in ABAQUS, the calculation cost and accuracy are considered at the same time. The global fine grid of 2 mm is adopted for the stud, and the grid of 2 mm is distributed in the contact area between the steel plate and the stud, and then the global grid of 15 mm is used. The contact part of the alkali-activated UHPC plate and the stud is distributed in 2 mm fine grid, and the rest of the less relevant parts are distributed in 17 mm global grid, as shown in Fig. 1.

![Fig. 1 Push-out test grid division and assembly](image-url)
3. Finite element results and analysis

3.1 Finite element results

The ultimate bearing capacity and slip value of each specimen in finite element simulation are arranged and shown in Table 2.

| Specimen  | Load-carrying capacity per rivet (kN) | Slippage (mm) | L/D |
|-----------|---------------------------------------|---------------|-----|
| NS13-35   | 46.4                                  | 0.55          | 2.7 |
| NS13-55   | 49.3                                  | 0.56          | 4.2 |
| NS13-75   | 47.93                                 | 0.76          | 5.8 |
| NS13-95   | 47                                    | 0.74          | 7.3 |
| NS16-55   | 79                                    | 1             | 3.4 |
| NS16-75   | 76.5                                  | 1             | 4.7 |

As shown in the table, diameter has the greatest influence on the bearing capacity and slip of single nail, while length has less influence on the bearing capacity and slip of single nail.

3.2 Stress and strain

As shown in Fig. 2, the maximum stress of the stud appears in the root of the stud and the binding part of the steel plate and the bottom of the stud rod indirectly under the load, so the failure mode of the stud is that the bottom of the stud is cut, and the farther away from the root of the stud, the smaller the contribution to the shear bearing capacity. For the concrete part, as shown in Fig. 3, the maximum plastic strain is located in a small part of the lower part of the stud rod (away from the loading position), which is consistent with the failure mode of the stud in high performance concrete.

3.3 Load slip curve

As shown in Fig. 4, the load slip curve of each specimen shows a similar trend, indicating that the load-carrying capacity of the nail decreases with increasing slip.
As shown in Fig. 4, the bearing capacity of the stud with diameter of 16 mm was significantly higher than that of the stud with diameter of 13 mm. The bearing capacity of the single nail was about 80 kN, and the initial elastic stiffness was also greater than that of the stud with diameter of 13 mm. The slip of the stud in alkali-activated UHPC did not reach 6 mm. The ultimate bearing capacity of each model appeared when the slip reached about 0.6 mm. It may be that the ultra-high compressive strength of alkali-activated UHPC hindered the continuous development of the ductility of the stud, and the accumulated energy led to the sudden shear of the stud. The bearing capacity of the single stud with diameter of 13 mm is about 50 kN. It can be seen from the figure that when the aspect ratio is less than 4, the shear capacity of the stud increases slightly but not obviously with the increase of the length of the stud. The length of the stud has no effect on the slip. When the ratio of length to diameter is greater than 4, the slip of the stud increases, and the shear bearing capacity of the stud decreases with the increase of the length of the stud. It can be seen from the figure that the initial elastic stiffness of the stud with the same diameter is basically the same, and the difference begins at the yield stage. The figure shows that increasing the diameter of the stud is the most direct way to improve the bearing capacity of the stud. The diameter increases by 3mm from 13mm to 16mm and the bearing capacity of the single nail increases by about 50%.

4. Conclusions

Alkali-activated UHPC is a more environmentally friendly alternative cementitious material for UHPC. At present, there are few studies on its structural mechanical properties. In order to better guide engineering practice, it is necessary to study the mechanical properties of bolts in alkali-activated UHPC. In this paper, six groups of bolts in alkali-activated UHPC were simulated by finite element method, and the effects of length and diameter of bolts on shear properties of bolts were studied. According to the results, the following conclusions can be drawn:

1. The diameter of the stud has the greatest impact on the shear capacity of the stud. In the finite element simulation, the bearing capacity of the two groups of specimens increases by about 50% from 13 mm to 16 mm. The length of the stud has a certain influence on the bearing capacity of the stud, but it has little effect.

2. Length-diameter ratio has a certain influence on slip and bearing capacity, and there is a critical value of about 4. The increase of length-diameter ratio has the opposite effect on slip and bearing capacity when it is greater than or less than the critical value.

3. The slip value of studs in alkali-activated UHPC is generally small, and the alkali-activated plate is only damaged in a small range near the studs. The farther the stud is away from the root, the smaller the contribution of shear capacity is.

4. Limited to personal time and energy, only several aspect ratios of studs are discussed, and a large number of experimental verification and finite element analysis are needed to further explore the shear properties of studs in alkali-activated UHPC.

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