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FINITE ELEMENT ANALYSIS OF MECHANICAL PROPERTIES OF SPECIMEN WITH UHPC AND STUD CONNECTOR

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ABSTRACT

UHPC is different from ordinary concrete for mechanical properties. To study the stress state of stud connector when UHPC is used to strengthen RC beam and its influence on bearing capacity of the strengthened beam, in this paper, ABAQUS was adopted first to simulate the push-out test of stud to verify accuracy of the finite element model. The nonlinearity of materials and contact conditions was considered in the model, and then three parameters including concrete strength, stud length and stud diameter were studied. Results showed the finite element model established by surface to surface contact method was possible to simulate the force and failure of the stud connector. UHPC could improve the bearing capacity of the stud specimens obviously, and the length of stud had little effect on bearing capacity of stud while failure of the stud may occur if length of the stud was too small. The increase of stud diameter could improve bearing capacity of elastic working stage.

KEYWORDS

Push out test, UHPC, Stud connector, Finite element, Reinforcement

INTRODUCTION

Ultra high performance concrete (UHPC) is considered as one of the most important innovative cement-based engineering materials in last 30 years. Compared with ordinary concrete, UHPC has better mechanical properties, its compressive strength is for three to six times and tensile properties for five to eight times that of the ordinary concrete. Since UHPC was put forward for the first time in 1990s, UHPC has developed rapidly, its components and performance has been improved, and its price has been gradually reduced, making it more and more widely used [1]. In recent years, researches on UHPC is mainly focused on how to make full use of its performance characteristics to achieve purpose of structural form innovation and provide basis for the large-scale promotion and application of UHPC [2]. Because of its ultra high tensile and compressive strength, as well as good ductility and durability, UHPC has unique advantages in all kinds of civil engineering structures, especially in bridge engineering, the way UHPC repairs and strengthens ordinary reinforced concrete beams has been recognized by more and more civil engineers and scholars [3]. Figure 1 is a new reinforced concrete beam strengthened by UHPC and CFRP proposed by the author. UHPC and oncrete beam are connected by a peg at the top, and traditional CFRP rod is glued to concrete beam at the bottom.

Stud is the most researched and applied shear connector currently, which can well bear the shear force on the connecting surface in UHPC reinforcement of existing Bridges. Stud connectors are suitable for industrial production because of their simple manufacturing and low cost [4]. However, stud is an isotropic material with the same strength and stiffness along the intended direction, with large deformation, good ductility and little impact on reinforcement placement in concrete slabs, which is widely used as shear connectors in bridge reinforcement [5].

Many research has been carried out on mechanical properties of stud connectors at home and abroad. Qing-hua han et al introduced the extended finite element method into calculation and analysis of composite beam, established the analysis model and simulated whole process of shear stud from crack beginning to fracture failure [6].Tian Qixian et al. studied the use of UHPC for bridge deck pavement, analyzed different length and diameter ratios of shear studs by push-out test and finite element analysis, and focused on the static performance of short studs[7].

Aiming at the new structure that UHPC is used for reinforcement, this paper adopts method of simulating studs in ABAQUS to carry out finite element analysis on push-out test of stud. By nonlinear finite element analysis model verified by push-out test results, three parameters of different concrete strength, stud length and stud diameter were studied to find out influence of three parameters on load-bearing capacity, failure and slip amount of push-out specimen, providing a theoretical basis for wide application of UHPC in beam reinforcement.

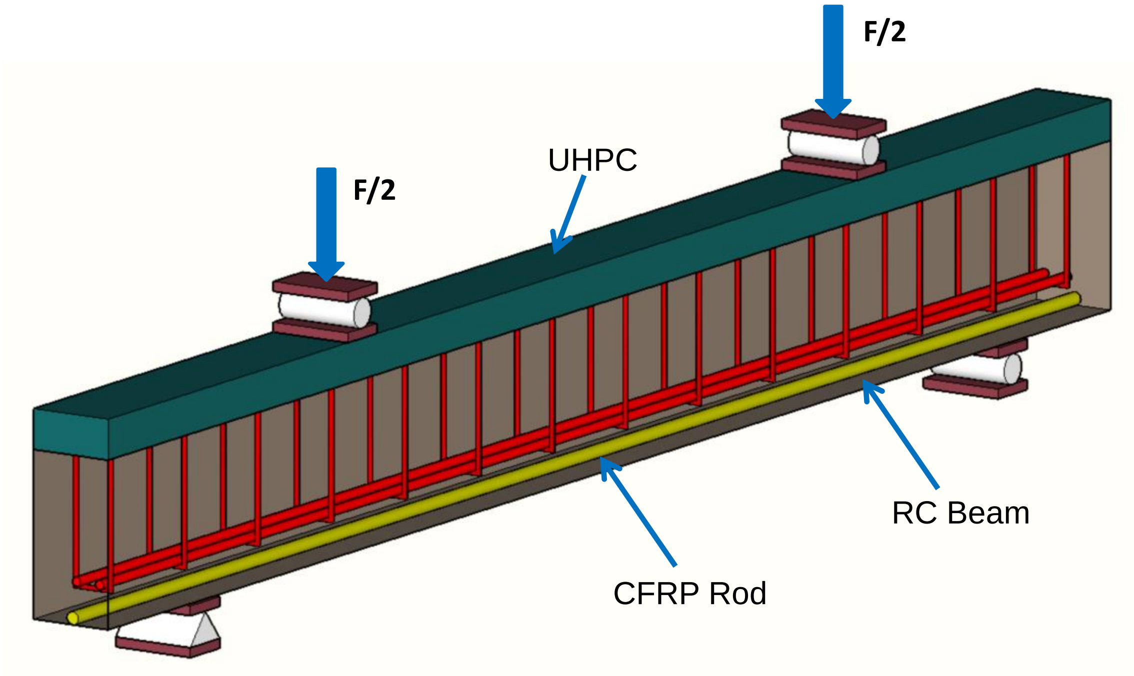

Fig. 1 - RC beam strengthened by UHPC and CFRP Rod

Verification of Finite element model

The reliability of finite element simulation analysis is effected by many factors, such as material constitutive relationship, contact action quality, load boundary condition, element type, mesh technique, loading, etc. [8]. Improper analysis modeling or assumptions may even lead to errors in analysis results. Therefore, to ensure the reliability of following parameter studies, the model verification of push-out test of the stud in literature [9] was carried out to ensure the reliability of the finite element model.

(1) Test overview

In reference [9], length, width and height of concrete of SS-1 were 460mm, 400mm and 460mm respectively. Two studs were welded horizontally on the outside I-shaped steel flange plate, arranged symmetrically on both sides. The studs were 22mm in diameter, 200mm in length and 150mm in spacing. Specific size of the specimen was shown in Figure 2.

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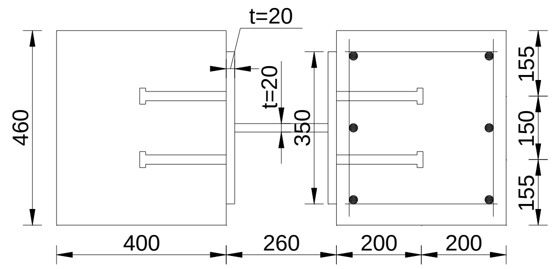
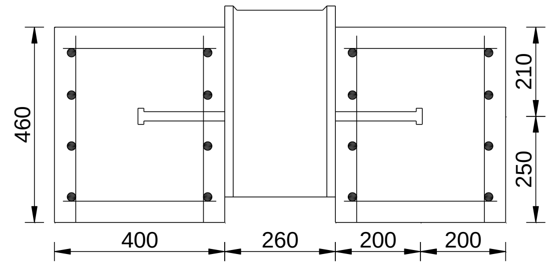


(a) Plan



(b) Elevation

Fig. 2 - Structure diagram of the ejector specimen (mm)

(1) The constitutive relationship

The compressive strength of the high-strength concrete cube (150mm×150mm×150mm) used in the specimen was 72MPa, and the constitutive relationship was based on the curve recommended in the Code for Design of Concrete Structures (GB50010-2015) [10]. Stress-strain curve under uniaxial compression could be determined according to formula (1) and formula (2):

$$\sigma = (1-d_c)E_c\varepsilon \tag{1}$$

$$d_c = \begin{cases} 1-\dfrac{\rho_c n}{n-1+x^n} & x \le 1 \\ 1-\dfrac{\rho_c}{\alpha_c (x-1)^2 + x} & x > 1 \end{cases} \tag{2}$$

Where, $\rho_c = \dfrac{f_c^*}{E_c\varepsilon_c}$, $n = \dfrac{E_c\varepsilon_c}{E_c\varepsilon_c - f_c^*}$, $x = \dfrac{\varepsilon}{\varepsilon_c}$, E_c is elastic modulus of concrete; α_c is reference value of the descending section of stress-strain curve under uniaxial compression of concrete ; f_c^* is the uniaxial compressive strength of concrete ; ε_c is the peak compressive strain of concrete corresponding to uniaxial compressive strength f_c^* ; d_c is the damage evolution parameter of concrete under uniaxial compression.

$$\sigma = (1-d_t)E_c\varepsilon \tag{3}$$

$$d_t = \begin{cases} 1-\rho_t(1.2-0.2x^5) & x \le 1 \\ 1-\dfrac{\rho_t}{\alpha_t (x-1)^{1.7} + x} & x > 1 \end{cases} \tag{4}$$

Where, $\rho_t = \dfrac{f_t^*}{E_c\varepsilon_t}$, $x = \dfrac{\varepsilon}{\varepsilon_t}$, α_t is reference value of the descending section of the uniaxial tensile stress-strain curve of concrete ; f_t^* is the uniaxial tensile strength of concrete ; ε_t is the peak tensile strain of concrete corresponding to uniaxial tensile strength f_t^* ; d_t is evolution parameter of uniaxial tensile damage of concrete.

Diameter of the welded nails was 22mm, the yield strength was 367MPa, the tensile strength was 480 MPa, and the elastic modulus was 210000MPa. The material properties of stud had an important influence on the results of push-out test. In this paper, a three fold line model was adopted [11], which was first elastic, then entered yield stage and finally failure stage. Stress-strain curve of stud is shown in Figure 3.

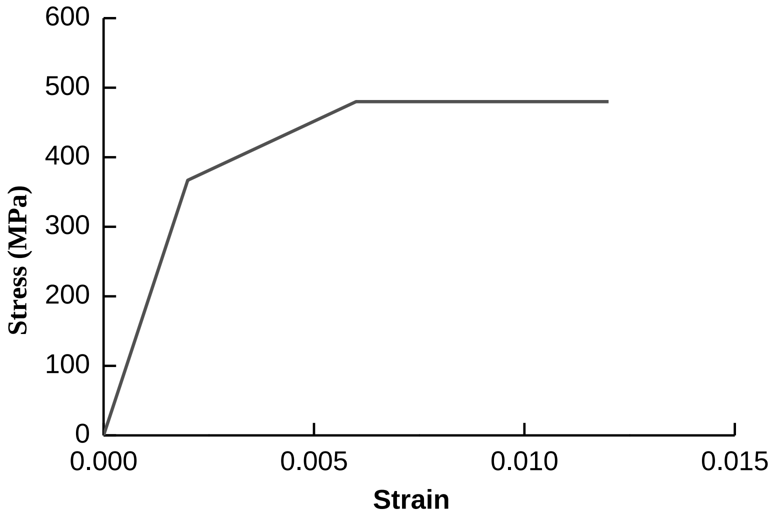


Fig. 3. - Stress - strain curve of stud

(3) Model establishment

According to the geometric symmetry, boundary symmetry and load symmetry of the extruded sample, a quarter part of the extruded sample was modeled. Studs and I-shaped steel members were created in the same part, while concrete and steel bars were created separately. In the model, concrete, stud and I-shaped steel were simulated by C3D8R three-dimensional eight-node reduction integral element, and steel bar was simulated by T3D2 three-dimensional two-node truss element. When assembling each member, reinforcement was placed inside concrete as a built-in unit to ensure reinforcement member nodes were bound to relevant nodes of the concrete member. The contact friction was simulated by creating contact unit pairs between concrete and stud, and rigid contact was simulated by creating contact unit pairs between concrete and I-shape. 1/4 finite element model of the extruded specimen is shown in Figure 4.

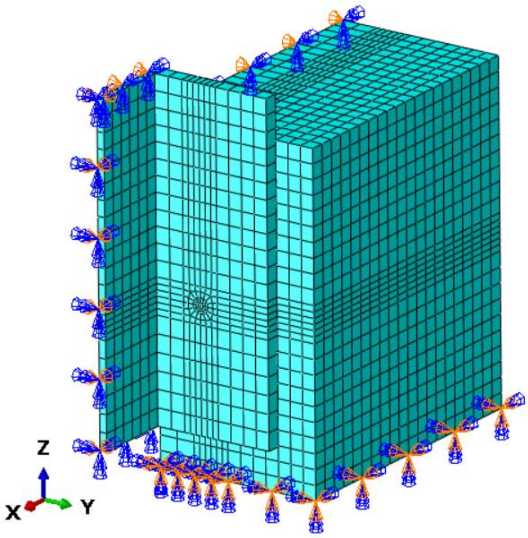


Fig. 4.- Finite element model of 1/4 of the specimen

(4) Boundary conditions

Boundary conditions of the model were set by mechanical symmetry adjustment. The bottom concrete surface was restricted in all three directions with a fully fixed boundary. Concrete and I-shaped steel adopt symmetrical boundary conditions on the symmetry plane of the X-axis and Y axis, which meant that points in the plane could not move along normal direction of the plane of symmetry, but could rotate in the plane.

(5) Contact relationship

In the finite element model, surface to surface contact method was used to simulate contact between concrete and I-shaped steel and between concrete and studs. Compared with common nodes or built-in elements, this simulation method could simulate relative slip between concrete and studs more accurately, and the contact stress was more consistent with the load [12]. It was assumed the contact properties of the two contact surfaces of concrete and I-shaped steel, concrete and studs were the same. The normal behavior adopted the default hard contact to ensure no penetration of component nodes. The tangential behavior adopted penalty friction, assumed the friction coefficient of the contact surface was 0.3, surface of I-shaped steel and studs was selected as the main contact surface, and the surface of concrete was taken as the secondary contact surface.

Finite element model result

Figure 5 shows load-slip curves gained from the finite element analysis results and test results of the test specimens. Finite element analysis results are consistent with the test results. The load-slip curves are mainly divided into elastic and plastic working stages, and the elastic working stage accounts for about 50% of the ultimate bearing capacity of the studs. In elastic working stage, slip of stud is small and load-slip curve is almost straight. Slip of stud in the test curve and finite element curve is about 0.3mm. In plastic working stage, slip amount of studs increases rapidly, shear stiffness of stud gradually degrades. When slip amount is about 7.5mm, the test specimen and finite element model reach the maximum load of 786.87kN and 783.20kN respectively. Then it enters failure stage, and shear stiffness of stud degrades rapidly. The test load value decreases to about half of the maximum value, and the finite element load value decreases to about 75% of the maximum value. Because the introduction of contact nonlinearity makes the calculation convergence difficult, but it does not affect bearing capacity of the model.

The results show both the test results and the finite element analysis results end with shear failure of studs, and the deviation between the experimental values and the calculated values is less than 10%, showing the finite element model with the face-to-face contact method is reliable for parameter study of bolt push-out test.

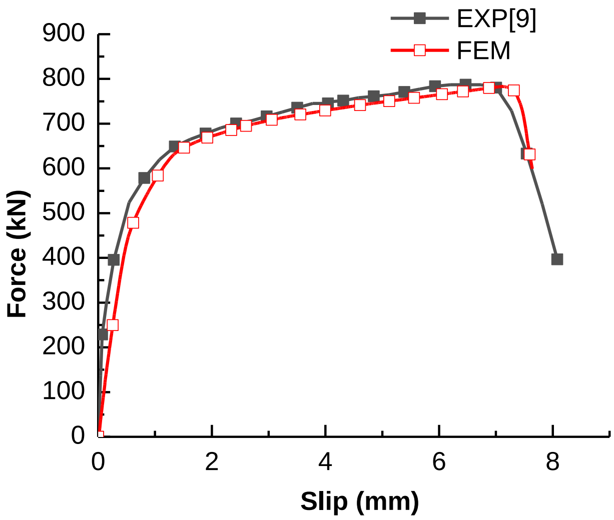


Fig. 5 - Comparison of load-slip curves between finite element calculation and test results

Parameter study

Based on the experimental verification of the material constitutive relationship and contact algorithm in the finite element model, finite element model of concrete and stud used for parameter study were established. The contact action, boundary conditions and element types were used in the same way as the finite element verification model. 11 finite element studies of stud connectors, numbered ST-1 to ST-11, were carried out. Sizes of each specimen were the same as those of the finite element verification model, and the main variation parameters were concrete strength, stud diameter and stud length. Specimens and their main parameters are shown in Table 1. In Table 1, d is diameter of stud, l is length of stud, f_{cu} is axial compressive strength of concrete, and f_s is yield strength of stud.

Tab. 1 - Main parameters of specimens

Specimen No.	*d*/mm	*l*/mm	Concrete	f_{cu}/MPa	f_s/MPa
ST-1	16	200	UHPC	140.3	367
ST-2	19	200	UHPC	140.3	367
ST-3	22	200	UHPC	140.3	367
ST-4	25	200	UHPC	140.3	367
ST-5	22	50	UHPC	140.3	367
ST-6	22	100	UHPC	140.3	367
ST-7	22	150	UHPC	140.3	367
ST-8	22	250	UHPC	140.3	367
ST-9	22	200	C40	36.8	367
ST-10	22	200	C60	38.5	367
ST-11	22	200	C80	50.2	367

(1) Concrete strength

Existing studies have shown concrete strength directly affects bearing capacity and failure of composite members [13]. When concrete strength grade is low, bearing capacity depends on concrete strength, and the failure form is mainly compression failure of concrete. As concrete strength increases to a certain level, bearing capacity depends on ultimate tensile strength of stud. To study load-slip between UHPC and ordinary concrete in the push-out test, C40, C60 and C80 ordinary concrete were selected for comparative analysis with UHPC.

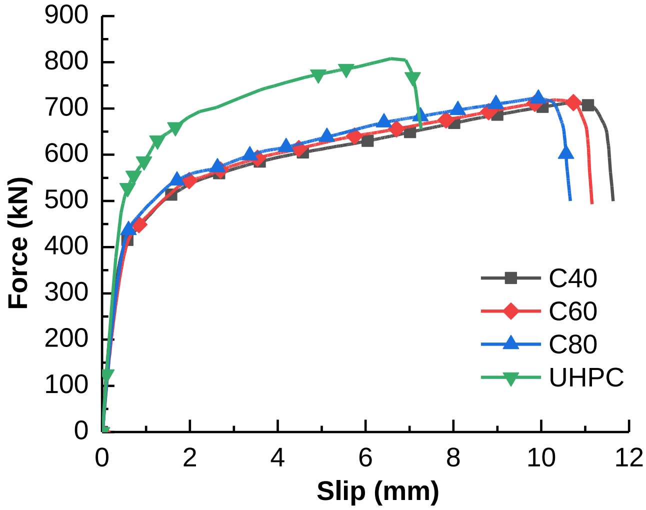


Fig. 6 - Load-slip curves of concrete with different strengths

Figure 6 shows load-slip curves of specimens pushed out with four different strengths of concrete. As can be seen from Figure 6, load-slip curves of three kinds of ordinary concrete are close to each other. With improvement of concrete grades, bearing capacity of specimens remains unchanged, and the maximum loads of ST-9, ST-10 and ST-11 are 712.2kN, 718.5kN and 721.8kN respectively. Stiffness of ST-3 of UHPC specimen is obviously greater than that of ordinary concrete specimens. In elastic working stage, maximum load of ST-3 is about 450 kN, which is about 20% higher than that of ordinary concrete. Slip amount of each specimen is the same. In plastic working stage, the maximum load of UHPC specimen can reach 807.8kN, about 1.13 times of ultimate bearing capacity of ordinary concrete specimen, and slip amount is obviously less than that of ordinary concrete specimen, only about 60% of it.

(2) Stud length

The length of stud connectors should not be too short, studs may be damaged when pulled out. In Design Standard of Steel Structure (GB50017-2017) [14], it is clearly stipulated the ratio of stud length L to stud diameter D must be greater than 4. In this paper, stud specimens with lengths of 50mm, 100mm, 150mm, 200mm and 250mm were selected to calculate the influence of length of stud on its bearing capacity and slippage. Figure 6 shows bearing capacity of composite members with the same diameter and different stud length.

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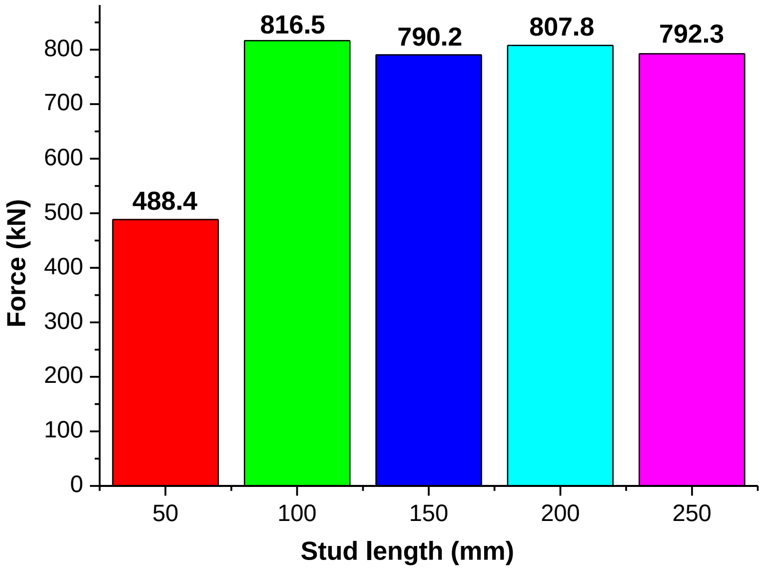

Fig. 7 - Influence of different stud lengths on load capacity

As shown in Figure 7, when length of stud is 50 mm, bearing capacity of composite components is only 188.4 kN, at this time, concrete around stud has reached ultimate compressive strain. Studs are pulled out and damaged, while other composite members with different lengths of studs have the same load-bearing capacity, and the small range of numerical changes is caused by different local meshing of the finite element model. Results of finite element numerical analysis show the design is reasonable to prevent failure of stud pulling out in composite members under requirement the ratio of stud length l to stud diameter d in code [14] is greater than 4.

(3) Stud diameter

Parameters that have important influence on the shear bearing capacity between UHPC and the stud combination members are cross-sectional area and tensile strength of stud. When tensile strength of bolt was kept unchanged, four studs diameters of 16mm, 19mm, 22mm and 25mm were selected to carry out parameter study. The calculation results are shown in Figure 8. Influence of different stud diameters on bearing capacity in elastic working stage is shown in Figure 9.

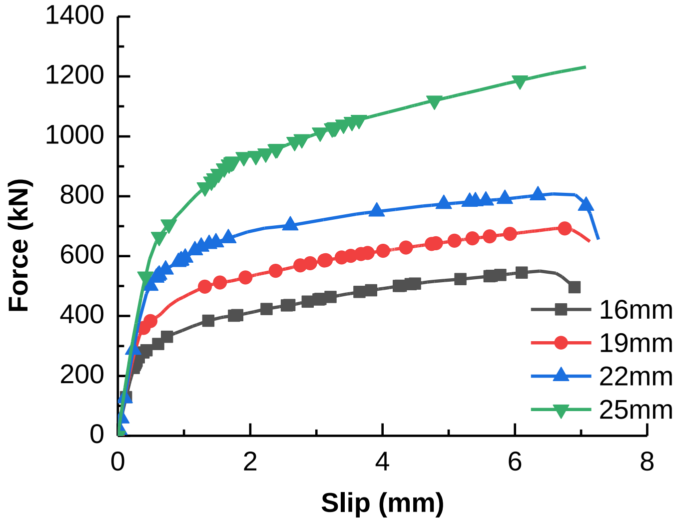

Figure 8 Load-slip curves of different stud diameters

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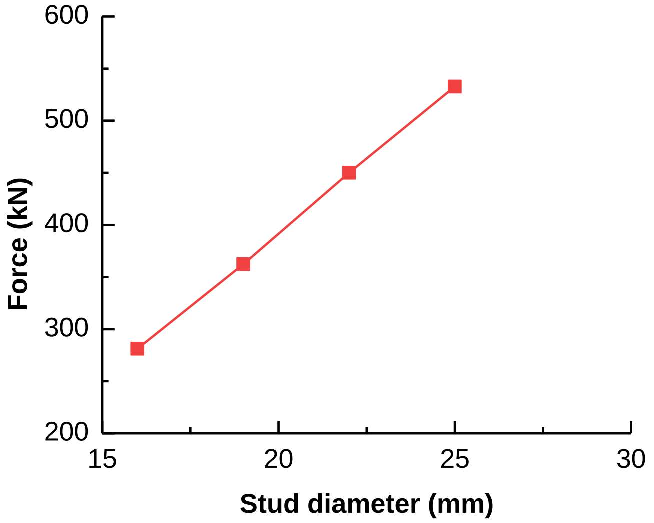

Fig 9 - Influence of different stud diameters on bearing capacity in elastic working stage

Diameter of stud has a great influence on elastic working stage of the load-slip curve. Compared with specimen with diameter of 16mm, the maximum load of the specimen with diameter of 19mm, 22mm and 25mm increases by 30%, 60% and 90% respectively in the elastic working stage, which shows an linear increase, but slip amount remains the same. Diameter of stud has little effect on the slope of load-slip curve in elastic working stage. From comparison of plastic development stages of load-slip curves of different diameter specimens, it can be seen the larger the stud diameter is, the higher the ultimate load will be. Except the slope of load-slip curve is slightly larger when stud diameter is 25mm, four curves remained parallel in plastic development stage, which is mainly because UHPC does not fail in plastic development stage, and load-slip is mainly affected by ultimate tensile strength of stud.

CONCLUSION

Through verification of push-out test of ABAQUS simulated stud connectors, variation rule of bearing capacity between UHPC and stud connector was further studied, and the following conclusions were drawn:

(1) The calculated results fit well with measured values by using surface-to-surface contact method to simulate contact between stud and concrete, and the deviation between calculated values and tested values is less than 10%, which shows the finite element simulation of the force and failure of stud connectors by using the surface-to-surface contact method is feasible.

(2) The adoption of UHPC with higher compressive strength can significantly improve bearing capacity of composite members. The maximum load is about 1.13 times of bearing capacity of ordinary concrete composite members, and slippage is less than that of ordinary concrete composite members obviously, which is only about 60%.

(3) Length of stud has little influence on bearing capacity of the composite components. However, if stud length is too small, it will lead to stud pulling out failure. It is reasonable to adopt stud as UHPC shear connectors according to requirement, and ratio of stud length to diameter should be greater than 4.

(4) With increase of stud diameter, the maximum load in elastic working stage increases obviously, but slippage remains unchanged. Stud diameter has little influence on development of load and slip amount in plastic development stage.

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