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Study on the Mechanical Properties of Oblique Shear of UHPC-NC Composite Components

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Abstract

UHPC is widely used to reinforce all kinds of dilapidated bridges because of its super high strength and superior performance. However, due to the different shrinkage properties of UHPC, the interface strength of NC is different. Therefore, proper UHPC- CNC interface treatment method and stress state are an important prerequisite to ensure the performance of steel bars. In this paper, a finite element model of UHPC-NC composite members is established. By changing the bonding, damage, friction coefficient and interface angle, different interface treatment methods and different shear angles are simulated, so that the failure characteristics and mechanical response of UHPC-NC interface can be obtained. Through the test results, we found that the surface roughness of NC can greatly improve the bearing capacity of UHPC-NC. For example, the bearing capacity of the "chiseled" interface is 20% higher than that of "smooth" interface. At the same time, the smaller interface shear angle has less influence on the bearing capacity of the specimen. When the shear angle exceeds 30, the bearing capacity will decrease greatly. Finally, the reliability of the model is verified by comparing the simulation test results of two articles with the actual test data.

Keywords

UHPC; NC; Oblique Shear Test; Interface Processing; Contact-separation Model; Finite Element Method.

1. Background

Reinforced concrete (Normal Concrete, NC) structure is widely used in contemporary bridge engineering, however, over time, in the external environment, load, material degradation, construction quality defects, a large number of NC structure mechanical properties and durability have different degrees of decline, a threat to bridge and other infrastructure safety operation[1]. Once the safety accident occurs in the NC structure with bad performance status, it will cause a major and bad international impact.In recent years, there have been many tragedies about NC Bridges around the world, which have seriously affected the normal performance of traffic functions, caused heavy losses to people's lives and property, and sounded the alarm to the construction and maintenance personnel[2]. On August 14,2018, an NC cable-stayed bridge (Polcevera Viaduct) suddenly collapsed on the A10 highway in the northern Italian city of Genoa.The bridge is an important bridge connecting Milan, Italy and France. It is the main artery of commercial transportation between the two countries and the main passage for people to the mountain area and Mediterranean beaches.The 1,200 m bridge, built in 1967, was 52 years in service when the accident happened, and dozens of cars collapsed together on the bridge, killing 43 people.The Italian government had just signed a 20 million euro

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maintenance contract for the bridge in April 2018, but it collapsed before the maintenance work was started.

The traditional bridge reinforcement technology is based on conventional materials, which has a certain effect on improving the performance of NC structure, but the disadvantages mainly focus on the insufficient durability of the reinforcement materials and the thickness of the reinforcement layer.The emergence of new cement-based concrete (ultra-high performance concrete of Ultra High Performance Concrete, UHPC) provides a new idea for NC structure reinforcement.At present, UHPC is used in the test and engineering applications at home and abroad[9-12], Steel bridge panel[13, 14]And so on, have achieved a more obvious effect.However, there are few studies on the bonding performance of UHPC and the existing NC structures, and there are many gaps in the mechanism, design and calculation compared with the traditional reinforcement methods[15].

The shear resistance of the interface of cast-in-place UHPC and the existing bridge is the key to the success of the reinforcement project with the new material. The reinforcement layer must be reliably combined with the original structure to achieve the purpose of common force and overall work.Through the text research, the interface bonding performance can be clarified, and its strength directly determines the safety and durability of the reinforced structure.In the actual construction, it is difficult to control the surface treatment of the existing structure, and the workers chisel hair treatment is more random.Therefore, it is an important prerequisite to propose the bonding between UHPC and existing bridge.

In view of this, the NC interface of UHPC reinforcement is urgent, but the essence involved in the interface bonding problem has not been solved, this paper plans to carry out the UHPC-NC interface shear performance test, put forward the quantitative interface surface disposal, based on the composite structure shear test results, obtain the interface damage characteristics and mechanical response, analyze the impact of various factors on the interface shear bearing capacity, research results can provide guidance for UHPC-NC calculation and treatment, has important theoretical and practical significance.

2. Objective

The aim of this paper is to develop a finite element model of UHPC-NC composite components, which can accurately represent the interfacial shear resistance of UHPC-NC composite components, so as to further investigate the mechanical behavior of UHPC-NC.In this paper, three different interfaces and four different angles of comparative test groups are set up to verify the influence of the interface processing mode and the interface angle on the UHPC-NC oblique shear strength.In ABAQUS, cohesive behavior was used for the UHPC-NC composite component interface setting and set the damage parameters for friction with the tangential interface to establish a contact —— separation model.General static analysis of one-end consolidation, one-end consolidation and 2-displacement loading was used.Control variables, analyze the results of two groups of trials, and pass with Liao Zhaoqian mm[16], Song Hengxiang[17]Experimental data were compared to verify the reliability of the model.

3. Test Scheme

First, we obtain elastic plasticity parameters during model building in NC and UHPC.According to GB50081-2019 Standard for C40 concrete, including cube compressive strength test, elastic modulus test and axial compressive strength test.According to the compressive strength and elastic modulus test specified in the standard are $150mm \times 150mm \times 150mm$ and $150mm \times 150mm \times 150mm$ respectively, and the loading rate is $0.5MPa/s \sim 0.8MPa/s$. The test device uses 200 ton microcomputer to control the electrohydraulic servo pressure test machine, as shown in Fig. 1 and 2.

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Figure 1. NC cube compressive strength test **Figure 2.** NC axial core strong pressure strength test

The resulting basic mechanical properties of the C40 are shown in Table 1.

Table 1. C 40 Basic mechanical properties

material	age	compression strength MPa	axial compressive strength MPa	modulus of elasticity MPa
C40	28d	53	41.3	32600

According to the test method introduced in GB / T31387-2015 "Active powder Concrete", the corresponding material test for UHPC, similar to the material test of ordinary concrete, mainly including compressive strength test, elasticmodulus test and axial compressive test.Cube block of $100mm \times 100mm \times 100mm$ and $100mm \times 100mm \times 100mm$ prism block were used for compressive strength test and elastic modulus test specified in the standard, with a loading rate of $1.2MP/s \sim 1.4MPa/s$. The test device uses a 200-ton microcomputer to control the electrohydraulic servo pressure test machine, as shown in Figure 3 and 4.

Figure 3. UHPC cube compressive strength test **Figure 4.** UHPC axial core compressive strength test

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The basic mechanical properties of the obtained UHPC are shown in Table 2.

Table 2. Basic mechanical properties of U H P C

UHPC	parameter	compression strength MPa	axial compressive strength MPa	modulus of elasticity MPa
age	3d	78.63	59.78	40162
	7d	102.30	78.23	41438
	28d	125.60	96.41	45774
temperature	60℃	133.29	103.97	46320
	90℃	161.14	126.47	48815

$mm\ mm\ mm$ The specimen size of the simulation test is $100mm \times 100mm \times 100mm$, as shown in Figure 5.The oblique shear test was conducted to study the influence of different interface angles and interface treatment methods on the oblique shear bearing capacity of UHPC-NC specimens.Interface tilt angles are divided into 0,15,30, and 45°, indicated by "0", "15", "30" and "45", respectively.The interface processing method is divided into "smooth", "steel brush" and "chisel hair", as indicated by "GH", "GS" and "ZM" respectively.(Test using 60° interface).

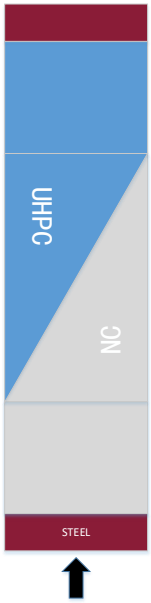

Figure 5. oblique shear test

4. Finite Element Model

In this paper, we perform a finite element simulation using ABAQUS.ABAQUS mainly includes two analysis modules, Standard and Explict, both of which can solve nonlinear problems, but with different priorities. Standard module is mainly suitable for static analysis and dynamic analysis, while Explict module is suitable for nonlinear dynamics and quasi-static problem analysis[18]. According to the data structure, the influence of some materials and interface parameters on the stress performance of UHPC-NC combined column is analyzed.

4.1 Model Selection

ABAQUS software has three different concrete constitutive models: brittle cracking model, plastic damage model and diffusion cracking model[19]. The simulation process in this paper adopts one-way displacement loading, that is, two-dimensional pull pressure simulation, and the surrounding pressure is low, so it is suitable for the plastic damage model.

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4.2 Unit Selection

ABAQUS has a rich unit library, and appropriate units should be selected according to the actual requirements and stress characteristics.The model includes the UHPC short column, the C40 short column, and the steel pads.The UHPC short column, C40 short column and steel pad are simulated by the C3D8R unit (eight-node hexahedral linear reduction integral unit) in the continuum unit.

4.3 Interaction Simulation

There are two different interactions between UHPC and NC, and support and compression short column in the model.To prevent relative slip between contact surfaces, the upper and lower support pads and concrete are bound (tie).Since UHPC and NC are both cement-based materials with better binding properties, it was considered to establish a contact -- separation model for the binding interface.The contact -- separation model is defined in two main ways in ABAQUS[20]: One is to define the cohesion unit (Cohesive element), which can be defined as zero thickness and mostly used for damage simulation between multilayer composite materials, mainly COH3D8 and COH3D6; the other is surface-based cohesion contact behavior (Cohesive behavior), which is a contact attribute, whose theoretical basis is very similar to the cohesive unit, but simpler than the cohesive unit.The typical contact -- separation model response is shown in Figure 6.

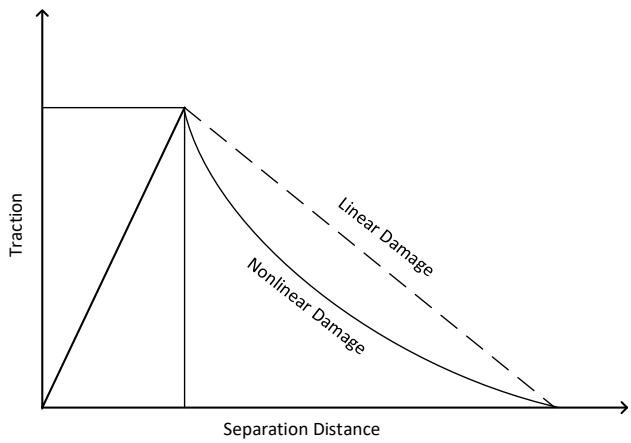

Figure 6. contact - a separation model

$t_n^0(t_s^0, t_t^0)$ is the maximum separation stress in the directions of three coordinate axes, and $\delta_n^0(t_s^0, t_t^0)$ is the corresponding displacement. $\delta_n^f(t_s^f, t_t^f)$ is the maximum separation distance. The elastic stage of the contact-separation model can be expressed as:

$$t = \begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{bmatrix} \begin{Bmatrix} \delta_n \\ \delta_s \\ \delta_t \end{Bmatrix} = K\delta$$

Where k is the contact stiffness matrix in the elastic stage, which also contains three directions. When the cohesive force reaches the peak point (i.e. t^0 in Figure 4.7), damage begins to occur.

The definition of contact damage criterion in ABAQUS is divided into four kinds: maximum stress criterion, maximum separation criterion, secondary stress criterion and secondary separation criterion, and the relatively simple maximum stress criterion is adopted in this paper.

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$$\max\left\{\frac{t_n}{t_n^0},\frac{t_s}{t_s^0},\frac{t_t}{t_t^0}\right\}=1$$

That is, when the cohesion force in any direction reaches the set maximum stress, the damage begins to occur.

It can be seen from the above that when defining the contact-separation model, it is mainly necessary to define the initial separation stress t^0 in three directions, the bonding stiffness K in the linear elastic stage, the initial separation distance δ^0 and the maximum separation distance δ^{max}. At the same time, for better convergence of the whole simulation process, it is necessary to define the dimensionless parameter-viscosity coefficient α, which is generally 0.005.

4.4 Constitutive Model

In the finite element analysis, it is very important to choose the correct material constitutive relationship.There are three main materials of the model: UHPC, NC and steel pad.

The UHPC material in this simulation test is mixed with steel fiber with end hook, length of 13mm, diameter of 0.2mm, diameter ratio of 65, volume mixing of 2.5%, citing Zhang Zhe, Shao Xudong of Hunan University[21]Experimental constitutive data, as shown in Figure 7.

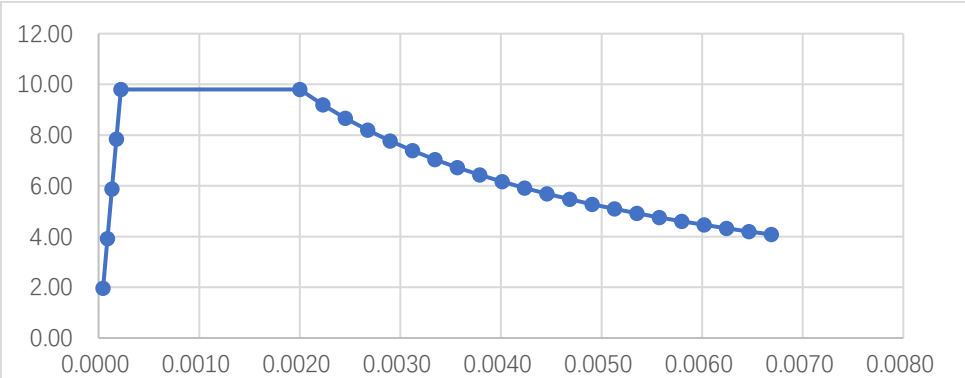

Figure 7. UHPC is subject to ated

Yang Jian and local Chronicles[22]In uniaxial compression test of UHPC with 1.5% steel fiber volume, UHPC compression constitutive relationship presents the experimental results of monotonic loading stress -- strain curve.

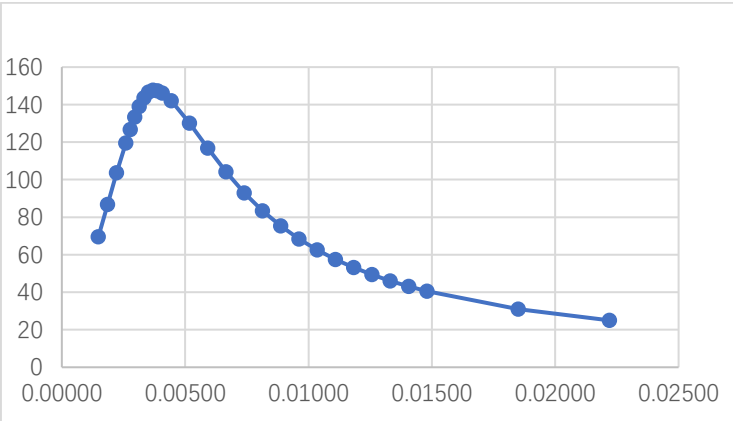

Figure 8. UHPC compression constitutive

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The Code for Design of Concrete Structure shows the compression constitutive relation of axial axis as follows.

$$\sigma = \begin{cases} f_{c,r} \dfrac{nx}{n-1+x^n} & x \le 1 \\ f_{c,r} \dfrac{x}{\alpha_c (x-1)^2 + x} & x > 1 \end{cases}$$

$$n = \frac{E_c \varepsilon_{c,r}}{E_c \varepsilon_{c,r} - f_{c,r}}$$

Formula: $f_{c,r}$ -- Axial compressive strength is calculated according to formula $f_{c,r} = 0.76 f_{cm}$ specified in Code for Design of Concrete, $f_{c,r} = 40.4MPa$.

x -- The strain ratio $x = \varepsilon / \varepsilon_{c,r}$, $\varepsilon_{c,r}$ is the peak tensile strain of concrete corresponding to $f_{c,r}$, and $\varepsilon_{c,r} = (700 + 172 f_{c,r}^{0.5}) \times 10^{-6}$ can be calculated according to the formula h specified in the code $\varepsilon_{c,r} = 1793 \times 10^{-6}$.

α_c -- The parameter values of the descending section of uniaxial compressive stress-strain curve are formulated according to the specification $\alpha_c = 0.157 f_{c,r}^{0.785} - 0.905$, $\alpha_c = 1.96$.

The constitutive relationship of ordinary concrete is as follows:

$$\sigma = \begin{cases} f_{t,r} \left(1.2x - 0.2x^6\right) & x \le 1 \\ f_{t,r} \dfrac{x}{\alpha_t (x-1)^{1.7} + x} & x > 1 \end{cases}$$

$f_{t,r}$ -- uniaxial tensile strength, according to the specification specified formula $f_{t,r} = 0.395 f_{tm}^{0.55}$, can be obtained; $f_{t,r} = 3.51MPa$.

x -- sThe strain ratio $x = \varepsilon / \varepsilon_{c,r}$, $\varepsilon_{c,r}$ is the peak compressive strain of concrete corresponding to $f_{c,r}$, and $\varepsilon_{t,r} = f_{t,r}^{0.54} \times 65 \times 10^{-6}$ can be calculated according to the formula h specified in the code $\varepsilon_{t,r} = 128.1 \times 10^{-6}$.

α_c --The parameter values of the descending section of uniaxial compressive stress-strain curve are formulated according to the specification $\alpha_t = 0.312 f_{t,r}^2$ $\alpha_t = 3.85$.

4.5 Determination of Concrete Plastic Damage Model Parameters

The elasticity parameters and plasticity parameters of the concrete material shall be entered in the ABAQUS.The elastic parameters include elastic modulus and Poisson ratio; the plasticity part definition uses the concrete damage plasticity model (CDP).

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Table 3. The elastic parameters of the concrete

material	Density(kg/m^3)	modulus of elasticity (MPa)	Poisson ratio
UHPC	2700	46400	0.2
C40	2500	32600	0.2

In the damage plastic model of concrete, besides defining the material constitutive relation, it is also necessary to determine the parameters related to the plastic criterion, such as expansion angle of 30, eccentricity coefficient of 0.1, ratio of biaxial compressive strength to uniaxial compressive strength of 1.16, k of 0.667 and viscosity coefficient of 1E-5.

Concrete compressive stress-inelastic strain relationship and tensile stress-cracking strain relationship shall be input in ABAQUS.Therefore, the elastic limit point in the pressure state needs to be determined.By reviewing the literature, the tensile parameters used in the simulation are shown in Table 4 and 5.

Table 4. NC

compression stress MPa	inelastic strain 10^{-6}	harm MPa	inelastic strain 10^{-6}	tensile stress MPa	inelastic strain 10^{-6}	harm MPa	inelastic strain 10^{-6}
18.9452	0.0000	0.0000	0.0000	2.7250	0.0000	0.0000	0.0000
23.3639	0.0001	0.0321	0.0001	2.4219	0.0000	0.2396	0.0000
24.3481	0.0001	0.0364	0.0001	2.0207	0.0001	0.4442	0.0001
25.8739	0.0001	0.0441	0.0001	1.6951	0.0001	0.5859	0.0001
28.4844	0.0002	0.0617	0.0002	1.4489	0.0001	0.6822	0.0001
32.9175	0.0005	0.1303	0.0005	1.2625	0.0001	0.7490	0.0001
33.5568	0.0007	0.1826	0.0007	1.1188	0.0001	0.7968	0.0001
33.0911	0.0009	0.2210	0.0009	1.0054	0.0002	0.8320	0.0002
31.9018	0.0011	0.2650	0.0011	0.9141	0.0002	0.8587	0.0002
30.2879	0.0013	0.3120	0.0013	0.8391	0.0002	0.8793	0.0002
28.4791	0.0015	0.3602	0.0015	0.7765	0.0002	0.8955	0.0002
26.6300	0.0018	0.4079	0.0018	0.5738	0.0003	0.9418	0.0003

Table 5. UHPC

compression stress MPa	inelastic strain 10^{-6}	harm MPa	inelastic strain 10^{-6}	tensile stress MPa	inelastic strain 10^{-6}	harm MPa	inelastic strain 10^{-6}
133.3343	0.0000	0.0000	0.0000	9.8000	0.0000	0.0000	0.0000
139.0372	0.0002	0.0393	0.0002	9.8000	0.0018	0.6802	0.0018
143.5682	0.0003	0.0513	0.0003	9.1914	0.0020	0.7066	0.0020
146.5905	0.0005	0.0669	0.0005	8.6659	0.0023	0.7284	0.0023
147.7000	0.0006	0.0871	0.0006	8.1954	0.0025	0.7471	0.0025
147.2872	0.0008	0.1103	0.0008	7.7717	0.0027	0.7634	0.0027
146.1363	0.0010	0.1342	0.0010	7.3882	0.0030	0.7777	0.0030
142.1240	0.0015	0.1825	0.0015	7.0396	0.0032	0.7904	0.0032
130.1879	0.0025	0.2756	0.0025	6.7214	0.0034	0.8017	0.0034
116.7750	0.0035	0.3583	0.0035	6.4297	0.0037	0.8118	0.0037
104.1249	0.0045	0.4287	0.0045	6.1615	0.0039	0.8210	0.0039
92.9808	0.0055	0.4878	0.0055	5.9140	0.0041	0.8293	0.0041

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4.6 Finite Element Analysis Model

According to the finite element parameters determined above, the nonlinear finite element model of pressure shear test is established, as shown in the figure below, the pad grid is divided according to hexahedral, the concrete structure is divided according to tetrahedral rules, and the load loading mode adopts displacement loading mode.(NU -0, NU -15, NU -30, NU -45, NU -60).

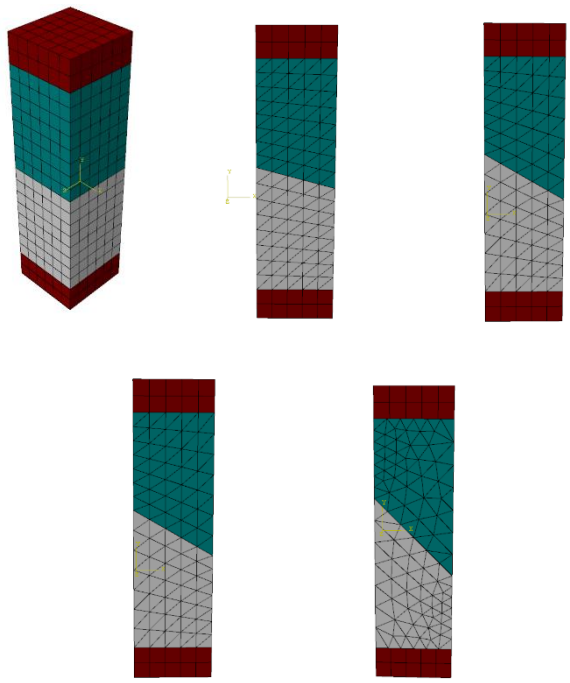

Figure 9. UHPC stretch constitutive

5. Results of Finite Element Analysis

5.1 NU-60-Compress Simulations

The interface parameters of shear members also refer to the experimental contents in the above literature. The model needs to define the tangential friction (penalty) between interfaces in addition to the cohesive behavior parameters. According to the test in reference [16], the peak loads of three interfaces are 208.68kN, 231.79kN and 248.71kN respectively. The fitting parameters and results of the three interfaces are shown in Table 6. This parameter is suitable for the interface of components mainly subjected to oblique shear.

Table 6. The interface fitting parameters of inclined shear components

Interface processing	$K_{nn} / K_{ss} / K_{tt}$	$t_n^0 / t_s^0 / t_t^0$	δ_p	μ	end of test
GH	2884/79/79	6.97/12.07/12.07	0.2	1.42	208.68
GS	2884/79/79	9.29/16.09/16.09	0.2	1.46	231.79
ZM	2884/79/79	12.32/21.33/21.33	0.256	1.49	248.71

As shown in Figure 10~12, the results of stress and sliding cloud map of NU-60-Compress-GH, GS and ZM groups.

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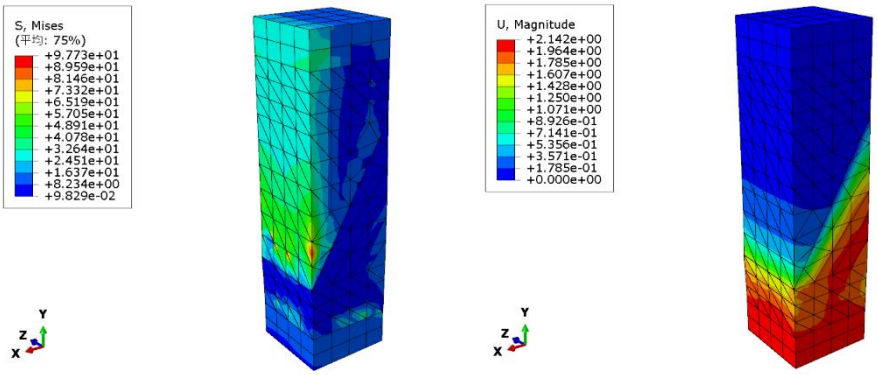

Figure 10. G H group stress shift

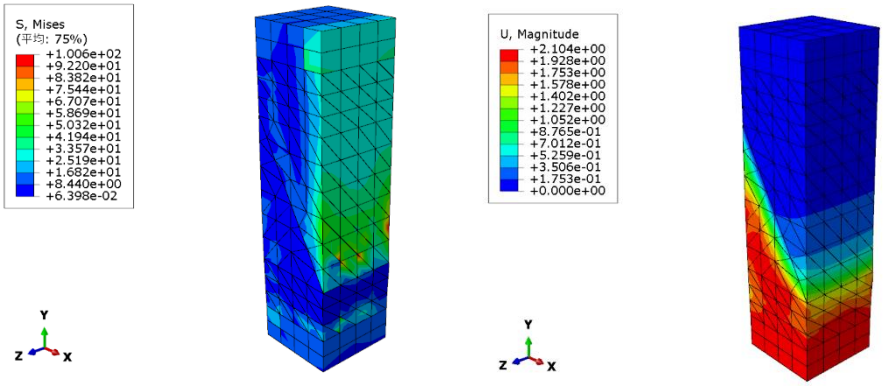

Figure 11. Stress shift in the G S group

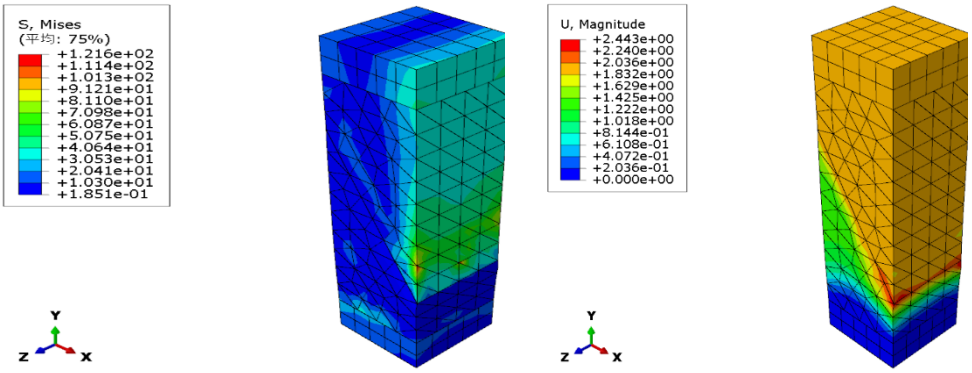

Figure 12. Stress displacement of the Z M group

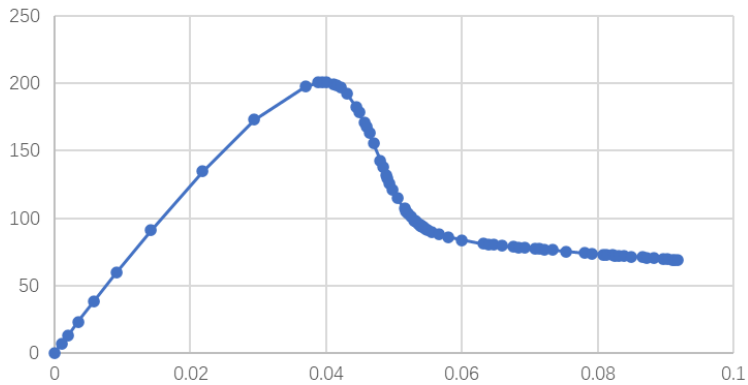

Figure 13. GS group load -- slip curve

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The Load -- slide curve is drawn according to the reverse force and the binding surface, as shown in Figure 13~15.

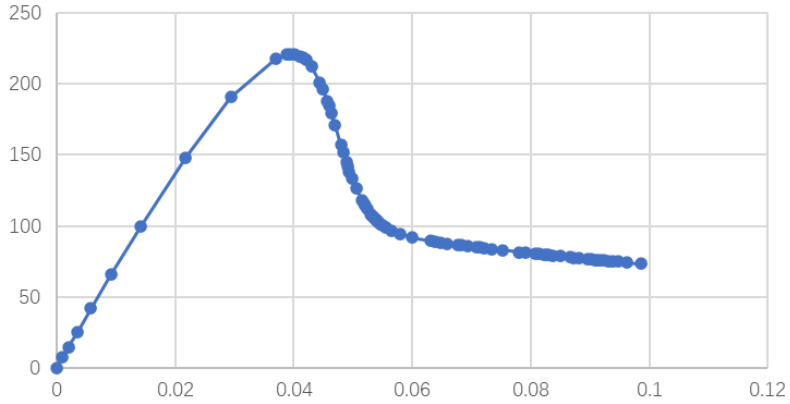

Figure 14. GS group load -- slip curve

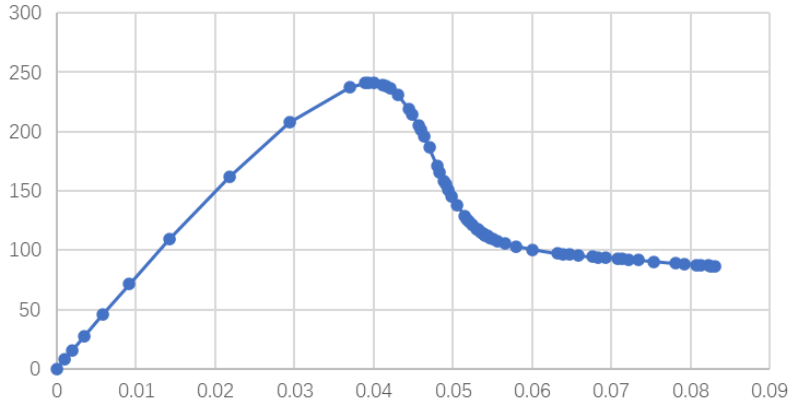

Figure 15. -- sliding curve of Z M group load

The peak loads obtained by three interface treatments are 201kN, 221.3kN and 241.4kN respectively, which are close to the experimental results, so the fitting effect is good. The above tests verify the influence of different interface treatments on the oblique shear strength of UHPC-NC composite members.

5.2 NU-Compress Different Shear Angles

The oblique shear test was conducted to study the bonding properties of UHPC with different interface angles to U H P C-NC specimens.Interface tilt angles are divided into 0°,15°,30°and 45°, indicated by "0", "15", "30" and "45", respectively.Here, in order to control the variables, the interface treatment method is unified according to the "chisel hair" treatment, NC chooses C65 concrete, and UHPC chooses steel fiber 2% mixture of concrete.

As shown in Figure 16, the stress cloud map results and load -- slip curves for groups NU-0, NU-15, NU-30, and NU-45.

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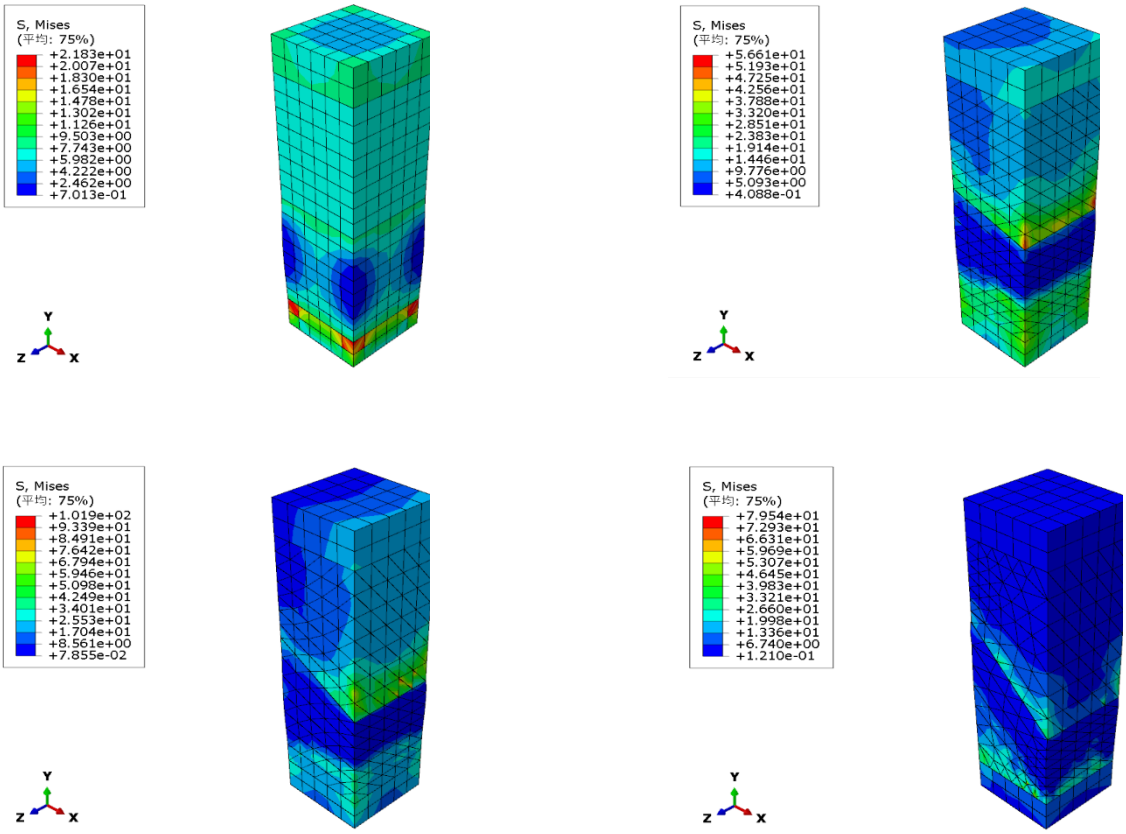

Figure 16. Stress cloud map (N U-0 upper left, N U-15 upper right, NU-30 bottom left, N U-45 lower right)

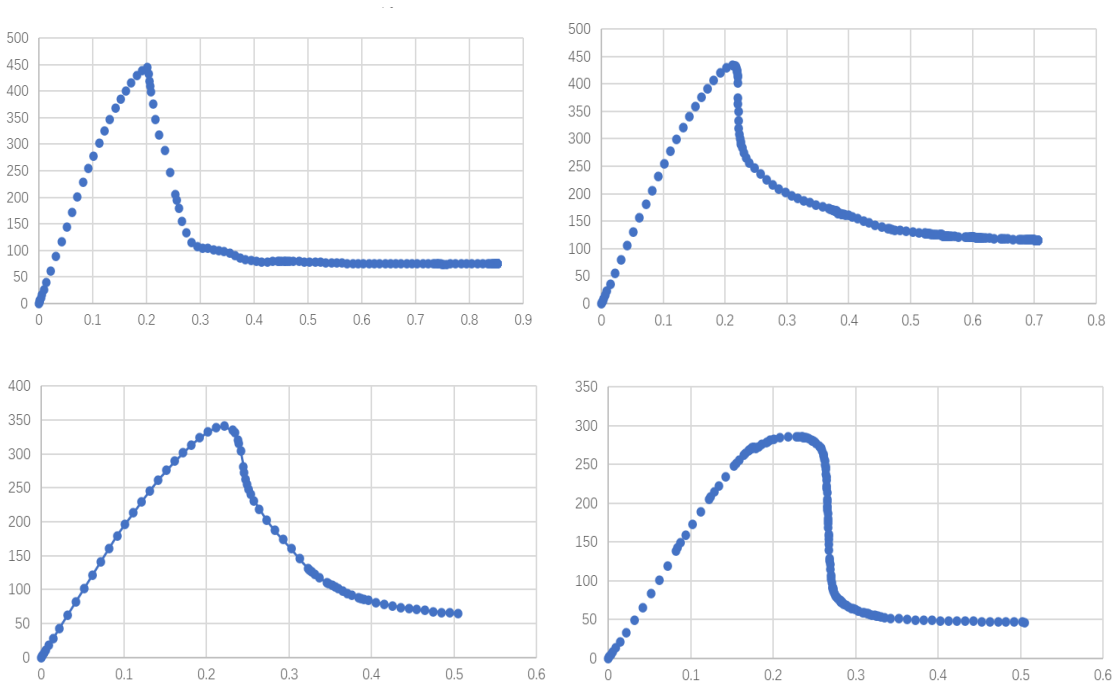

Figure 17. Load -- sliding curve (NU-0 upper left, NU-15 upper right, NU-30 lower left, NU-45 bottom right)

The peak loads at different interface shear angles are summarized in Table 7.

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Table 7. Peak loads at different interface angles

Test number	Peak load / kN	interfacial area / mm^2
NU -0	445.641	10000
NU -15	433.792	10352.76
NU -30	335.052	11547
NU -45	285.877	14142.14

The nominal bond strength is used to measure the oblique shear strength of UHPC-NC specimen. calculation formula:

$$f_n = \frac{P}{A}$$

Where: f_n is oblique shear strength; P is the peak load; A is the bonding area.

According to the calculation, the oblique shear strength of UHPC-NC is 44.5641MPa, 41.90MPa, 29.16MPa and 20.21MPa, respectively.

6. Analysis and Outlook

6.1 Conclusion

In this paper, combined with extensive literature research on basic materials, the interface mechanical behavior analysis of UHPC-NC components with three different interface processing methods and four interface Angle methods was conducted. Based on the "separated -- contact" model, the 3D finite element calculation model was established and fitted to the data, and the following conclusions were mainly obtained:

1) There is a strong bonding effect between NC and UHPC.The roughness of the NC surface is the main factor affecting the strength of the UHPC-NC interface, and the rougher the NC surface, the stronger the interface is.Among the three interface processing methods, the smooth interface has the lowest strength, and the test results of the steel brush processing interface are less than the chisel interface.It is mainly because the chisel hair expands the contact area between the new and old concrete, and at the same time, the uneven interface increases the mechanical bite force between the interface.

2) In the oblique shear test, three different interface forms were compared. The chisel interface made the bond strength obtained by UHPC-NC and the smooth interface was the worst.

3) For UHPC-NC components with different interface angles, when the interface angle of the composite specimen is 0° and 15°, the failure mode of the specimen is close to the traditional concrete being "crushed", and its peak load and interface strength are similar; when the interface Angle reaches more than 30°, the interface strength is rapidly reduced.Therefore, the larger the bond angle, the more difficult the composite specimen to exert its stress properties, and the bond performance.

6.2 Outlook

1) This study only analyzed the influence of different interface processing methods and angles on the bond strength of composite specimens, but the bonding interface between UHPC and actual bridge engineering is complex, and affected by various factors, including temperature, humidity, age, reinforcement rate, and various factors can be analyzed later.

2) In the ABAQUS model established in this paper, for UHPC and NC, only simple parameters, different longitudinal tendons and stirrups, and detailed modeling of the actual engineering text.

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3) When establishing the ABAQUS nonlinear finite element model, the cohesive contact behavior (cohesive behavior) between UHPC and cast-in-place ordinary concrete is simulated by considering various factors, which has certain accuracy, but there are still some errors.For example, a cohesive unit (cohesive element (of 0 thickness) can be established for comparative study.

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