Numerical Investigation of Bond Interface Morphology between Normal Strength Concrete and Ultra-High-Performance Concrete under Shear Loading

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Abstract. In order to address the challenge of accurately quantifying the roughness of the bond interface morphology between Normal Strength Concrete (NSC) and Ultra-High-Performance Concrete (UHPC), this study employed the spatial frequency content method to characterize randomly rough surfaces. The roughness was quantified using the sand filling method, and subsequently, a "Z"-shaped direct shear finite element model with rough bonding surfaces was established. The results indicate that the rough surfaces generated by the spatial frequency content method can be applied to the bonding interfaces of both types of concrete. This approach facilitates the three-dimensional characterization of the bond interface morphology and roughness, yielding reliable simulation results. The failure mode obtained from the finite element model corresponds precisely to the actual observed behavior. Through analysis, it was determined that shear loading is primarily borne by the effective bonded area and mechanical interlocking forces.

Keywords: Ultra-High-Performance Concrete; Surface Morphology; Shear Action; Modeling; Restoration.

1 Introduction

In recent years, the aging issues of concrete structures have become increasingly prominent, necessitating the maintenance and strengthening of concrete structures[1,2]. Through years of practical application, Ultra-High-Performance Concrete (UHPC) has emerged as a crucial choice for concrete reinforcement and repair materials, owing to its exceptional strength, bond performance, durability, ductility, and environmentally sustainable properties[3-5]. However, the repaired bond interface often becomes a weak point for load transfer between concrete elements[3]. To enhance the strength of the repaired bond interface, it is essential to roughen the bonding surface[6]. This is because a rough bonding surface encapsulates the micro-mechanisms and fundamental information of the bond interface, providing a comprehensive reflection of the concrete's microstructure and other influencing factors[7]. It serves as a critical factor in evaluating bonding performance, reinforcement effects, and predicting bond strength

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between interfaces. The specific parameters of the bond interface require representation through interfacial roughness. To address the limitations of purely qualitative assessments of interfacial roughness, it becomes imperative to quantitatively describe the roughness of the bond interface[8]. Additionally, existing research on quantifying bond interface roughness is confined to cases where concrete surfaces exhibit smooth morphology[9]. Attention to bond interface roughness has mainly focused on relatively regular interfaces, leaving limited understanding of the bonding performance for rough interfaces closer to real-world conditions. Therefore, quantifying and evaluating roughness as a parameter for studying changes in interfacial bonding capabilities is essential. Faced with these challenges, it becomes crucial to integrate rough bonding surfaces with both types of concrete seamlessly, and quantify the roughness of the bond interface accurately. An effective approach to achieve this is through numerical research. In this study, we adopt the spatial frequency content method to characterize randomly rough surfaces, and then quantitatively assess surface roughness through simulated sand casting. Based on these findings, the rough surface model is applied to the bond interface between UHPC and NC, aiming to study the bond interface morphology between the two types of concrete.

2 Rough bonding surface

Based on the concepts of spatial frequency and fundamental waves, rough surface data are synthesized through the sum of trigonometric functions.

2.1 Characterization of rough surface

Suppose that the shape function of a rough surface is a cosine. The following double summation was used to represent a rough surface[10]:

$$f(x,y)=\sum_{m=-N}^{N}\sum_{n=-N}^{N}\omega(m,n)\cos(2\pi(mx+ny)+\phi(m,n)) \tag{1}$$

where, x and y are spatial coordinates; m and n are spatial frequencies; $\omega(m, n)$ is amplitude ; $\phi(m, n)$ is the phase angle, N represents the value range of m and n.

2.2 Quantified roughness

The average roughness is expressed as the mean depth of sand filling, which is obtained by dividing the sand-filling volume by the bonding area of the UHPC-NC interface[11].

$$R_m = h = \frac{V}{ab} \tag{2}$$

where h is the average sand-filling depth (mm); a and b are the length and width of the concrete bonding surface, respectively (mm); V is the sand-filling volume (mm^3).

2.3 Build a rough surface

The rough surface constructed according to the theoretical description in Sections 1.1 and 1.2 is shown in Fig. 1, and its roughness Rm=8.54mm.

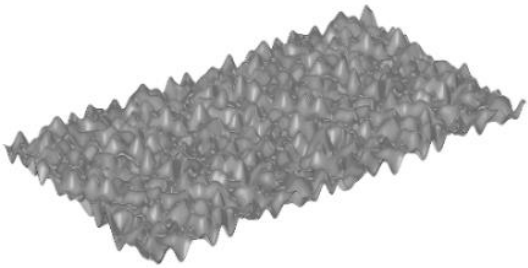

Fig. 1. Rough surface

3 Finite element model

3.1 Model size

This study uses the "Z"-shaped direct shear specimen as a model to study the influence of UHPC-NC bonding surface morphology and roughness on the interface shear characteristics. After design, the rough surface constructed in Section 1.3 is inserted between UHPC and NC, its dimensions are shown in Fig. 2.

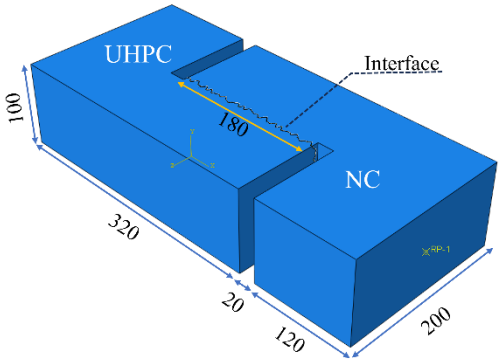

Fig. 2. Specimen size drawing

3.2 Determination of constitutive relations

It employs stress-strain relationships to define material properties of concrete, as illustrated in Fig. 3. The interface constitutive model adopts the traction-separation bilinear constitutive model, as illustrated in Fig. 4[12,13].

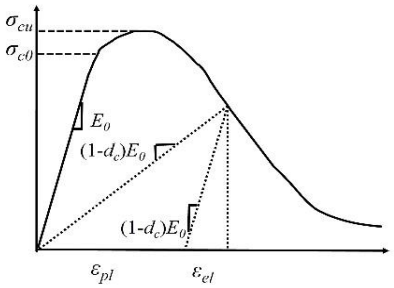

Fig. 3. Stress-strain curve of concrete under uniaxial compression

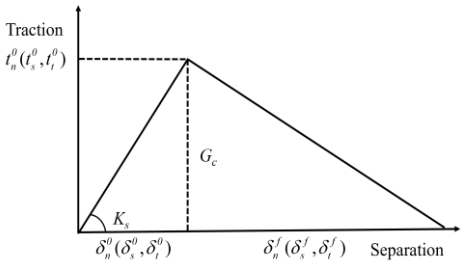

Fig. 4. Traction-separation constitutive model

3.3 Result analysis

Phenomenon analysis.

SDEG (Stiffness Degradation) signifies the decrease in stiffness due to damage. According to numerical simulation results, the post-shear failure morphology of the specimen is illustrated in Fig. 5. It is evident that a portion of the interface bonding in the model exhibits cracking, and concurrent damage occurs in the vicinity of the bonding surface in the Normal Strength Concrete (NC). Some partially peeled-off NC remains bonded to the Ultra-High-Performance Concrete (UHPC). The mechanical interlocking forces provided by the rough bonding surface transform the failure of the UHPC-NC bonding surface into a simultaneous failure of the NC and the interface. This is attributed to the fact that one of the mechanisms through which roughness influences the UHPC-NC bonding surface is by promoting mechanical interlocking forces[3]. Therefore, the finite element calculations align well with the observed real-world scenario.

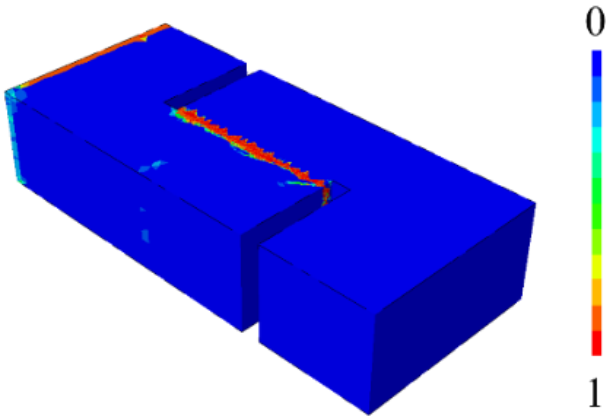

Fig. 5. SEDG cloud chart

Load-slip curve.

Based on the results obtained from finite element calculations, the load-slip curve is plotted, as shown in Fig. 6, and the curve aligns well with real-world observations. The initial phase of the curve exhibits linear growth, reaching a peak where bonding surface damage occurs, and the effective bonded area decreases. Subsequently, the mechanical interlocking forces provided by the rough bonding surface come into play, transferring the interface damage to the NC and initiating the yielding stage. The curve then demonstrates a distinct ductile failure. Through analysis, it is determined that shear loading is predominantly borne by the effective bonded area and mechanical interlocking forces[14].

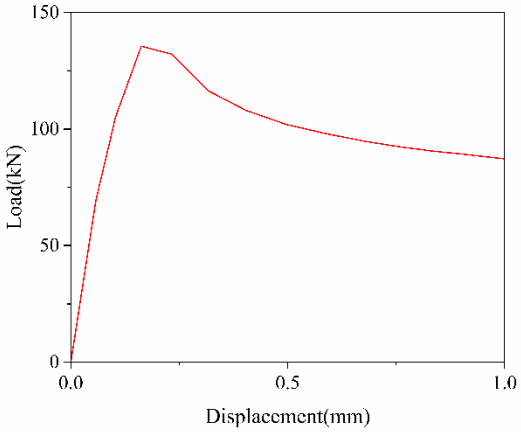

Fig. 6. Load-slip curve

4 Conclusion

(1) The randomly rough surfaces generated using the spatial frequency content method exhibit a uniform distribution of concave-convex features, with minimal localized defects that could introduce discrete effects. This characteristic makes them suitable for application to the bonding interfaces of both types of concrete, allowing for the exploration of three-dimensional morphology and the effects of rough bonding surfaces.

(2) In this study, a "Z"-shaped direct shear model for UHPC-NC was established, incorporating randomly rough surfaces at the bonding interface. Through analysis, the simulated phenomena align with real-world observations, indicating the reliability of the simulation results.

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