Numerical Analysis of Anchor Bolt Pull-out Test by Cohesive Zone Model Combined with Finite Element Method

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Abstract: In this paper, to characterize the pull-out process of anchor in concrete, we combined the cohesive zone model and the finite element method. The embedding cohesive elements simulate the contact effect of the bolt interface. The results show that the numerical predictions are in good agreement with the experimental results. With the change of pull-out load, the shear stress of anchorage interface changes correspondingly until it is destroyed, which is consistent with the laboratory test. The strengths of the anchorage material and the concrete have a positive correlation with the bond strength of anchor bolt. The radial and lateral stresses acting along the bolt are similar. Therefore, in bolt anchorage, the bond strength increases as the radial (lateral) stresses increase.

1. Introduction
Since the late 19th century, the bolt was used in the England coal mine. Moreover, bolt support has been widely developed around the world because of its economy and efficiency. Various forms of bolts with high strength, high pre-tightening, abnormality, and yield pressure are constantly developed; numerical models of bolt anchoring are also developing.

Over the years, the mechanical behavior of bolt anchoring under different conditions has been studied using theoretical analysis, field and laboratory tests, and numerical simulation. For example, Stillborg [1] carried out many tests on different steel strands in concrete and in-situ hard rock and then summarized the loading-slip curves and interface shear effect. Li et al. [2] studied the pull-out tests of different water-cement-ratio materials and different anchorage lengths and then analyzed the critical anchorage length and adhesive force. By using screw steel, Chen and Li [3] and Bennokhrane et al. [4] analyzed the distribution of axial force, the deformation and failure of the bond surface, the stress and deformation of the surrounding body, and the failure form of anchorage. Kong et al. [5] obtained the analytical solution of the ideal elastic-plastic model and analyzed the interaction mechanism of the soil-anchor interface. Yu et al. [6] used the Mindlin theory to derive the elastic solution of the full-length anchorage, analyzed its stress characteristics, carried out the laboratory pull-out test, and then studied the mechanical behavior of the interface between the bolt and the rock or soil. Ma et al. [7] and Ren et al. [8] put forward the analytical model of anchorage to analyze the mechanism of the bolt breaking under the condition of full anchorage; their experimental tests were in good agreement with the field data. Chang et al. [9] used numerical simulation to reproduce the cracking and progressive failure of the reinforced concrete bond and simulated and analyzed the pull-out process. Zhu et al. [10] employed the plastic model of anchorage material to simulate the stress between anchorage interfaces. Zhao et al. [11] used particle flow code to characterize the stress distribution and failure characteristics of the rock anchorage, in which they found that their prediction is consistent with the test results.
Generally, the bond force between bolt and anchorage solids is divided into three components: (1) chemical adhesive force between the gel and surface of the bolt, (2) the friction force between the interface of the bolt and the mortar, and (3) mechanical interlocking force between the concave-convex part of the bolt’s surface and mortar. Failure of the bolt mainly includes the bolt breaking, the cracking of the grouting body in the anchorage section, and the sliding and pull-out of the bolt along with the interface. The main failure mode of bolt support is usually the interface failure between the bolt and the surrounding rock [11]. Thus, it is very crucial to study the stress and failure of the interface between bolt and anchorage material.

In this paper, to simulate the interface shear stress transfer process and the sliding process between the rebar and the concrete, we employed a cohesive zone model (CZM). Also, to explain the failure mechanism by the micro-fracture process of the interface, we analyzed the bond force distribution and anchorage failure form of the anchorage section in the pull-out process of the bolt and anchor solid. The trial-and-error method determines the CZM’s parameters.

2. CZM and its finite element formulation

In the cohesive zone, there is a crack opening displacement $\Delta$, which is less than a critical decohesion value $\Delta_m$ and is dependent upon the cohesive stress $\sigma$. All CZMs mostly focus on how to establish the function that characterizes the relation between $\sigma$ and $\Delta$, which is generally defined by the so-called traction–separation laws. As a typical example, initially, the stress increases with growing distance up to a maximum, which is called the cohesive strength $\sigma_c$ of the material. If the separation has achieved a critical decohesion length $\Delta_m$, then the material is wholly separated, and no stress can be transmitted. According to the definition of the specific fracture energy per surface area, $G_c = 2\gamma$ originated from the Griffith, integrating the separation law up to failure $\Delta'_m$ yields the area under the curve that corresponds to the dissipated work during a material’s separation (Figure 1).

$$G_c = \int_0^{\Delta'_m} \sigma d\Delta \quad \text{Energy of separation} \quad (1)$$

![Figure 1. CZM and its form of separation law](image)

2.1. Cohesive element formulation

In the present work, intrinsic cohesive elements are inserted into all bulk elements in a region of the model before the beginning of the simulation. This would allow the fracture to propagate freely within that region. The intrinsic cohesive element technique is particularly appropriate when unstructured meshes in fracture simulations are fine enough to trace and capture fracture paths [20], which is what is employed in this work.

When a cohesive zone formulation is employed to model crack initiation and subsequent growth, it implies the introduction of the notion of a cohesive force ahead of the crack that prevents propagation. The micro-mechanisms of material deterioration and fracture are thus embedded into the constitutive law that relates the cohesive traction with the local separation. Damage is restricted to evolve along with the intrinsic cohesive interfaces, where cohesive elements are randomly distributed in the mesh.
Indeed, when absenting body forces, the weak form of equilibrium equations for a body of volume \( \Omega \) and external surface \( \Gamma \) renders

\[
\int_{\Omega} \mathbf{S} : \delta \mathbf{E} d\Omega + \int_{\Gamma} \mathbf{T}^e \cdot \delta \mathbf{u} d\Gamma = \int_{\Gamma} \mathbf{T}^{ext} \cdot \delta \mathbf{u} d\Gamma
\]  

(2)

where \( \mathbf{E} \) is the Green strain tensor in the domain \( \Omega \), \( \delta \mathbf{u} \) indicates the virtual displacement on the boundary \( \Gamma \), \( \mathbf{T}^e \) is the external traction, \( \mathbf{S} \) is the second Piola–Kirchhoff stress tensor, and \( \mathbf{T}^e \) is the cohesive tractions acting on fracture surface \( \Gamma^c \), which corresponds to the virtual separation \( \delta \Delta \). Using the Galerkin method, we can write the stiffness matrix contributed by the cohesive elements as

\[
[K]_{el} = \int_{-1}^{1} \int_{-1}^{1} \mathbf{B}^T \mathbf{Q}^T \mathbf{C}_i \mathbf{Q} \mathbf{B} d\xi d\eta
\]

(3)

\[
[F]_{el} = \int_{-1}^{1} \int_{-1}^{1} \mathbf{B}^T \mathbf{Q}^T \mathbf{t}_i d\xi d\eta
\]

(4)

where \((\xi, \eta)\) indicates the reference coordinates and \( J \) is the Jacobian determinant. The global displacement-separation matrix, \( \mathbf{B} \), is a \( 3 \times 3N \) matrix (where \( N \) is the number of shape functions) that computes the relative opening of the crack at any point in the cohesive element. The orthogonal matrix, \( \mathbf{Q} \), transforms from global to local coordinates, as shown in Figure 2. The local constitutive matrix, \( \mathbf{C}_i \), and the local force vector, \( \mathbf{t}_i \), are functions of the particular choice of the cohesive model.

![Figure 2. Stress vector and relative displacements of interface](image)

2.2. Constitutive relation of the cohesive element

In the present work, cohesive elements are initially of zero thickness and are compatible with either linear brick or linear tetrahedral elements, as illustrated in Figure 3. It is emphasized that the constitutive model selected for the bulk elements should accommodate to describe the mechanical response of the bulk solid, which is independent of that for the cohesive elements.

![Figure 3. Cohesive elements (highlighted in orange) are initially of zero thickness and are compatible with (a) linear brick and (b) linear tetrahedral bulk elements.](image)

In the cohesive modeling, the behavior of interface is represented in terms of its response to a purely normal tensile traction and a single shear, as shown in Figure 4. The interface initially responds elastically, with a constant stiffness \( k_0 = T_{\text{max}}/\Delta_0 \), so that \( T_n = k_0 \Delta_n \). As long as \( \Delta_n \leq \Delta_0 \), the interface is reversible and undamaged. If the displacement exceeds \( \Delta_n = \Delta_0 \), the interface begins to accumulate irreversible damage, which causes the stress to drop. At the same time, the damage reduces the stiffness of the interface so that during unloading the traction-displacement relation remains linear, but with a reduced slope. The traction separations are related to the relative displacement in a local coordinate system by an elastic potential \( \Psi(\Delta_n, \Delta_s, \Delta_t, D) \) as follows:
During 2.5.

where \( T_n, T_s, \) and \( T_t \) are the stress vector components along the normal, the first, or the second shear directions, respectively. The scalar parameter \( D \) varies from 0 to 1 to the undamaged intact material and fully damaged material, respectively. \( D \) quantifies the irreversible damage accumulated by the interface. Generally, the incremental traction–separation relation is written in an incremental form:

\[
dT = \frac{d\tau_n}{d\varepsilon_n} \begin{pmatrix} C_{nn} & C_{ns} & C_{nt} \\ C_{sn} & C_{ss} & C_{st} \\ C_{tn} & C_{ts} & C_{tt} \end{pmatrix} \begin{pmatrix} \Delta_n \\ \Delta_s \\ \Delta_t \end{pmatrix} = (1 - D)\mathbf{C}_t: (1 - D)d\mathbf{T}_{\text{eff}}
\]

where \( \mathbf{C}_t \) is a stiff matrix that could be a diagonal when the coupling effect between normal-tangent strengths is ignored, and \( d\mathbf{T}_{\text{eff}} \) denotes the effective stress vector.

![Figure 4. Typical damaged response](image)

2.3. Damage evolution law

The cohesive constitutive law is completed by an appropriate equation governing the evolution of damage \( D \). It is noted that \( D \) remains constant if the traction on the interface is less than its current strength, if the interface is unloaded, or if \( D \) reaches 1. Otherwise, \( D \) has to evolve so that the strength of the interface decreases progressively from its initial value \( T_{\text{max}} \) to zero as the effective displacement \( \Delta_m = \Delta_{m0}^{\Delta} + \Delta_{m}^f \) increases from \( \Delta_m = \Delta_{m0}^{\Delta} \) (the effective displacement at damage initiation) to \( \Delta_m = \Delta_{m}^f \) (the effective displacement at complete failure) by an exponent form, where the symbols < and > used in the present discussion represent the MacAulay bracket with the usual interpretation. Our experience shows that the linear damage evolution holds better stability and convergence in the fracture modeling of concrete in the Abaqus.

2.4. Damage initiation criterion

The process of degradation begins when the stresses and strains satisfy certain damage initiation principles. In the Abaqus, the damage is assumed to initiate when the maximum nominal stress component ratio reaches a value of 1, which can be represented as

\[
\text{MAX} \left( \frac{\sigma_n}{\sigma_{\text{max}}}, \sigma_s, \sigma_t \right) = 1
\]

where \( \sigma_{\text{max}}^n, \sigma_{\text{max}}^s, \) and \( \sigma_{\text{max}}^t \) denote the peak values of the nominal stress when the deformation is either pure normal to the interface or pure in the first or the second shear direction; the other symbols are as the same meanings mentioned previously.

2.5. Cohesive element failure and solid element contact

During the simulation, a cohesive element is said to have failed when all section points at any one integration point have lost their load-carrying capacity, that is, fully damaged. By default, failed cohesive elements are deleted from the mesh once the element is fully degraded. After all the failure cohesive elements are eliminated from the mesh, the occupied computer core memory can be partially released. Once cohesive elements are completely failed, solid elements in contact are immediately
identified in the Abaqus. Generally, the general contact command in the Abaqus should be activated suitably to detect contact and impact between solid elements, which could speed up the computational processes.

To describe the process of bolt pull-out failure, we employ the cumulative damage evolution model. Three constitutive models are used for rebar: elastic hardening, elastic-plastic hardening, and ideal elastic-plastic model [18][19]. The constitutive relationship of the interface is defined by reference to the bond stress slip between concrete and hot-rolled ribbed bar (HRB) based on the code for the design of concrete structures. Compared with ordinary materials, the analysis of interface failure is more complex, and the failure process is divided into linear elastic, splitting, descending, residual, and unloading. Therefore, the constitutive interface relation can be expressed in the form of a table in the damage evolution criterion, and the specific parameters can be calculated and selected in combination with the pull-out test conducted in [15].

3. Simulation and analysis

3.1. Numerical model

According to the pull-out test conducted in [15], a three-dimensional model was established with the dimension of 150 × 150 × 150 mm, with bolt length of 195 mm (the loading section is 30 mm exposed, the free end is 15 mm exposed), and with a diameter of 18 mm. C3D4 solid element is used in the mesh, and the mesh is randomly divided to avoid the mesh-dependent result of the simulation. The element size is approximately 4 mm, the nodes are 108254, and the solid elements are 30307. The cohesive elements (COH3D6) are added in batches at the interface of concrete, concrete, and bolt, as shown in Figure 5b,c. The embedded cohesive elements are 52346, and the total elements are 82653. Moreover, the boundary around the side of the loading end is fixed, which is consistent with the boundary conditions of the test. The friction coefficient used is set to 0.2 to simulate the influence of friction between the bolt and concrete.

![Figure 5. Numerical model of pull-out test: (a) numerical physical model, (b) cohesive elements of concrete, and cohesive elements of the interface](image)

3.2. Model parameters

The rebar used is HRB400 with a diameter of 18 mm, which is a type of steel bar representing HRB with a yield strength of 400 MPa. The elastic modulus is taken as 200 GPa and Poisson's ratio as 0.25 according to the relevant code [18][19]. For the concrete tests, we adopted the Xiong's pull-out test using three strength grades C30, C40, and C60. In this paper, the validity of the verification test is taken: concrete strength grade is C30, its Poisson's ratio is 0.17, and the elastic modulus is 28 GPa. The tensile strength is taken as 1.43 MPa, according to the related references. Table 1 shows the simulation parameters used in the model.

The representatives of cohesive element parameters are tensile strength, shear strength, fracture energy, normal and tangential stiffness, and other parameters that are not given in the test. In this study, they are calculated and selected in combination with the approximate parameters and relevant formulas. Table 2 shows the specific parameters.
3.3. Analysis of simulating results
The simulation of this work was realized in the Abaqus/explicit system. To avoid the penetration phenomenon after the failure of elements, we set the universal contact between all elements. The explicit algorithm is used in the calculation process.

3.3.1. Failure process analysis
To ensure the consistency between the simulation and the actual loading in the laboratory, we carried out the preloading in the early stage of loading. To ensure the stability of simulation, we loaded the loading end slowly and linearly at a uniform speed. To ensure the stability of the subsequent pull-out simulation, we mainly used the preloading so that it will not be included in the effective simulation calculation. The numerical simulation took approximately 30 h at a desk computer.

| Table 1. Simulation parameters of the materials |
|-----------------------------------------------|
| Material type | Density (kg/m³) | Elastic modulus (GPa) | Poisson's ratio | Yield strength (MPa) |
|----------------|------------------|------------------------|----------------|--------------------|
| Concrete       | 2500             | 28                     | 0.17           | —                  |
| Rebar          | 7800             | 200                    | 0.25           | 400                |

| Table 2. Simulation parameters of the cohesive element (CE) |
|-------------------------------------------------------------|
| CE type | $t_\text{e}$ (MPa) | $k_n$ (N/m²) | $k_s$ (N/m³) | $G_{1c}$ (N/m) | $G_{IIc}$ (N/m) |
| Concrete | 1.43 | 1.8e12 | 8e11 | 5 | 50 |
| Interface | 3.1 | 2.8e12 | 1.3e12 | 10 | 100 |

Note: $t_\text{e}$ is tensile stress, $k_n$ is normal stiffness, $k_s$ is shear stiffness, $G_{1c}$ is the mode I fracture energy, and $G_{IIc}$ is the mode II fracture energy.

Figure 6. Comparison of cracks of a pull-out test in the numerical simulation and the laboratory test

Figure 6 shows the simulation results describing the distribution of cracks in the anchorage body. The results are in agreement with the macro-crack distribution obtained from the test. In the process of rebar breaking, there are cone-shaped cracks in the free end and loading sections and also longitudinal cracks along with the rebar, which both first occur at the interface. However, there are some differences in the distribution of detailed cracks because of the following reasons: in the test, the rebar and concrete may cause various defects such as the location of the rebar, the uneven mixing of the aggregate, the pores at the interface between the sand and the cement slurry, and the corrosion of the reinforcement due to the human and environmental factors. In the numerical simulation, as to facilitate the calculation, the mesh division is not fine enough, and the element is randomly divided, so there are some factors such as contingency.

By sorting out numerical simulation results, we can show the sliding displacement state of the anchor bolt and anchor solid body, as shown in Figure 7. By considering the condition of Mises stress in the interface layer, we found the following.
(1) In the linear elastic micro slip stage, at the beginning of pull-out loading, the bond force plays a role, and there is no slip at the free end. The slip at the loading end is caused by the elastic deformation of the interface between the rebar and the concrete. With the continuous loading, the bond force near the loading end fails, and then the bond force transfers to the free end along the embedded length of the rebar; the increase of friction and mechanical bite force on the interface also transfers and redistributes in real time. In this stage, the bond stiffness of rebar is large, and the slip curve at the loading end is close to the straight line, which can be regarded as a micro slip stage of linear elasticity. (2) In the crack initiation and development stage, when the chemical cementation force is transferred to the free end, it begins to slip when the cementation force disappears completely, and the friction force reaches the peak. As the load continues to increase, the sliding speed of the loading end is accelerated, and the expansion tensile stress of the concrete around the steel bar increases rapidly, resulting in circumferential and radial cracks to appear in the concrete. The macroscopic performance is that bond stiffness of the rebar decreases, and the concrete as brittle will lead to a small block collapses at the loading end. (3) In the cracking stage, as the load continues to increase, the cracks at the interface continue to expand, and concrete fracture occurs. While the longitudinal cracks also gradually appear, the bond stiffness of rebar further reduces, and the slip of the rebar increases rapidly that lead to the concrete split; the sliding displacement of the loading end can reach approximately 10 mm. (4) In the residual failure stage, with continuous loading, the displacement and pull-out force will fluctuate up and down. This is because the concrete contacting the rebar surface has different states under the crack propagation, which makes the concrete and the rebar surface fluctuate under the strong contact friction and weak mechanical bite. In other words, because of the effect of concrete occlusion teeth, the steel bar still holds certain residual stress after experiencing a large slip displacement.

Figure 7. Failure process of the pull-out test by the numerical modeling: (a) linear elastic micro slip, (b) crack initiation and development, (c) cracking failure, and (d) residual failure
In conclusion, the bond strength of bolt and concrete mainly depends on chemical adhesion, mechanical bite, and friction. The influence of chemical adhesion is very small, and the friction will occur when there is relative sliding between the bolt and concrete. Under the pull-out process, there are two ways of sliding: (1) the rib of rebar under the wedging action makes the concrete shear fracture around the radial direction and (2) the rib crushes the concrete. When the concrete is crushed into the compressed powder, it remains in front of the ribs. Moreover, in the process of sliding and separation, the transverse cracks along the bar and the splitting failure around the concrete block will also occur. The main failure mode is that concrete broken into columns around the radial direction of the rebar, and bond-slip and dense small cracks appear and then spread to the concrete surface. When the strength is low, the failure mechanism of the loading end is that the broken wedge expands radially and produces transverse pull-out; when it is high, the radial expansion is restrained, and shear failure usually occurs along with the interface, forming a small range of broken wedge at the loading end, and friction pull failure occurs along with the rebar. In this paper, concrete C30 was used as a hard material, and the simulation failure process is in good agreement with the failure process of the experimental tests. Meanwhile, the simulation discussed previously effectively shows the crush broken between the interface and the broken expansion deformation within the anchorage range. When the bolt is pulled, at the linear elastic micro slip stage, the corresponding stress transfer and obvious stress concentration at the interface are all occurred, and at the interface near the loading section, the damage also appears in the bolt and concrete. In the stage of crack initiation and crack failure, gradual failure appears at the interface from the loading section to the free end, and the Mises stress is shown in Figure 8.

![Figure 8. Mises stress distribution at the interfaces (a) during the pull-out test and (b) after the destruction](image)

3.3.2. Bond strength analysis

By extracting the typical monitoring point data of the loading end’s interface from the simulation, we can obtain the contrast diagram of the bond strength-displacement relationship, as shown in Figure 9. It is observed that the pull-out load first increases with the increase of slip displacement, reaching the peak value of 10.45 MPa when the slip displacement is 0.95 mm, and then appears the strain-softening trend. With the continuous increase of pull-out displacement, the residual strength is approximately 1.05 MPa, and the slip displacement is 5.26 mm. It is found that the trend of the simulated bond strength-displacement curve is consistent with the laboratory test results, and the discrepancy mainly reflects in the peak bond strength error is approximately 0.26 MPa. The reason is that the model of homogeneous isotropy is adopted here, whereas for the laboratory pull-out test, the concrete mixing and curing lead to concrete heterogeneity and bolt installation artificially may cause test error. Therefore, it is understandable that there are slight differences.
3.3.3. Shear stress analysis
During the process of pull-out, the shear stress distribution along the depth of rebar is also concerned. By extracting the typical monitoring point data, we can show the curve of shear stress at the relevant monitoring points of the anchorage section, with the anchorage length of 150 mm under different pull-out displacement, as shown in Figure 10. When the displacement of rebar end is either 0.18, 0.59, or 0.96 mm, with the increase of the displacement of rebar end, the shear stress of each position increases synchronously, which is consistent with the results in [2]. When the rebar end's displacement is 0.96 mm, the shear stress of monitoring point #1 reaches the maximum, and the shear stress from monitoring points #2 to #8 keeps increasing when rod end sliding by 0.59 mm. When the rebar end’s displacement reaches 2.10 mm, the shear stress of monitoring points #1 to #4 decreases. Except for the slight increase of measuring point monitoring point #6, the shear stress of other monitoring points does not change much under other sliding states, which indicates that monitoring points #1 to #4 are in the state of failure, and monitoring points #5 to #8 are close to the critical state. When the rebar end's displacement reaches 4.86 mm, the shear stresses of all monitoring points decrease obviously, indicating that the whole anchorage section has reached failure, and the shear stress drop of each monitoring point slows down, and the value tends to be stable. This indicates that the anchorage section is in the stage of residual failure and that the pull-out process of the bolt is a progressive failure process.

To further reveal the interface friction characteristics of the anchorage section, we found the relationship between the shear stress and shear displacement at each monitoring point, as shown in Figure 11. It can be observed that the shear stress at each monitoring point first increases with the increase of shear displacement and then drops rapidly to a residual value. Meanwhile, the peak shear stress and the corresponding slip displacement of the rod end's different monitoring points are not the same. The closer to the loading end, the greater the peak shear stress and the smaller the corresponding shear displacement. The reason is that when the monitoring points close to the loading end, the rigid boundary constraint increases the normal pressure of the interface, which improves the interface stiffness and shear strength. The further explanation is that the pull-out of rebar is a progressive failure process from the loading end to the other end of rebar, which is consistent with the distribution of shear stress along with the rebar above.

3.3.4. Radial stress analysis
Figure 12 shows the normal stress corresponding to each monitoring point. The maximum normal stress of some monitoring points near the rod end can reach approximately 9 MPa. The closer to the loading end, the greater the normal stress it bears. The peak shear stress of different monitoring points is positively correlated with the normal pressure, and the changing trend is consistent. This shows that even under the same sliding displacement, because of the difference of the stress state, the shear stress of each anchorage section is not synchronous, which may be the reason for the progressive failure of the anchorage section. That is, the failure state is closely related to the radial confining pressure.
initial stress rise corresponds to the confining effect of micro-crack growth under the pull-out action, whereas the stress drop corresponds to the radial fracture and shear failure at the interface. With the increase of pull-out displacement, the radial confining pressure is controlled by the failure effect between the rod and interface. Among them, monitoring point #8 is relatively special, which shows that it initially bears normal compressive stress nearly 0.8 MPa and presents normal tensile stress approximately 0.9 MPa when the sliding displacement is 2.25–4.2 mm, and then gradually tends to 0 MPa. This implies the effect of progressive failure on the rebar tail in the bolt pull-out process, and the crack expands slightly to form compressive stress. Subsequently, tensile stress is formed by the bolt through the damaged interface when it is slipping.

![Figure 11. Shear stress along the bar under increasing slip displacement](image1)

![Figure 12. Normal stress distribution along the bar under increasing slip displacement](image2)

4. Parametric study

4.1. Strengths of anchoring materials

Presently, mortar and resin are commonly used anchoring bodies. In in-situ construction, because of the long cementing time required by the mortar anchoring material and the serious deformation of soft rock, the resin anchoring material is often used. In the previous numerical model, the cohesive element on the interface between the concrete and the bolt acts as the anchoring material, and the simulation effect is very good. Here, four anchoring materials with the tensile strength of 2.0, 3.1, 4.0, and 5.0 MPa are applied. The simulation results are shown in Figure 13. When the tensile strength of the anchoring agent changes from 2.0 to 3.1 MPa, the bond strength increases from 6.32 to 10.45 MPa. When the tensile strength of anchoring material is 4.0 and 5.0 MPa, the bond strength is 12.11 and 13.29 MPa, respectively. It can be found that when the mechanical properties of the anchoring materials are changed, the anchoring strength of the bolt is positively correlated with the anchoring material strengths, and that the increasing trend tends to decrease with the increase of the anchoring material strengths [1].

4.2. Concrete strength

In the field of construction, the rock masses and their state play an important role in solving the construction difficulty and anchoring effect. Thus, the difference in the anchoring solid strength is analyzed simply in this work. Four groups of simulation with the concrete of C20, C30, C40, and C60 were carried out, and the comparison results are shown in Figure 14. In [15], the bond strength of C30, C40, and C60 were 10.71, 12.49, and 14.55 MPa, respectively, whereas, in the simulation, the bond strengths of C20, C30, C40, and C60 are 8.12, 10.82, 12.75, and 14.21 MPa, respectively. The simulation results are quite consistent with the test results in [11][17]. With the increase of concrete strength, the bond strength also increases positively, which is mainly because of the increase of the anti-cracking ability of concrete and the increase of cementation between bolt and concrete. Conversely, from the perspective of failure pattern, the required slip displacement for bolt decreases gradually to reach the bond strength with the increase of concrete strength. This means the brittleness of bond failure and the concrete failure mostly emerges as a discrete failure of the large block.
4.3. Lateral (normal) stress
In the underground and slope engineering, the bolt is actually under the same stress state as the anchor activation. Under other conditions unchanged, the compressive lateral stresses of anchor solids are set as 0, 1, 3, and 5 MPa, and the corresponding simulation results are arranged, as shown in Figure 15. These imply that under the effect of lateral stress, the bond strength of bolt increases significantly, reaching 10.45, 12.26, 16.49, and 18.55 MPa. Compared with the no lateral stress, the bond strength as lateral stress for 1, 3, and 5 MPa increases to 17.3%, 57.8%, and 77.5%, respectively, and the results are similar to Mahdi and others’ tests [11][16][17]. Moreover, the slip displacement tends to increase when the pull-out load reaches the peak under conditions of lateral stresses increase, whereas the radial cracks tend to be densification and concentrated gradually.

5. Conclusions
We have employed the CZM with the finite element method to study the interface bonding performance of concrete bolt. The numerical simulation has been compared with the laboratory test in the literature. The main conclusions are as follows.
(1) The CZM to simulate the interface bond effect is valid by the numerical pull-out test of the concrete-anchor bolt joint body. The numerical predictions are consistent with the laboratory test results.
(2) When the pull-out load is small, the bolt is in the elastic stage, and the shear stress appears to peak at the end of the internal anchorage section. The load is mainly resisted by the adhesive shear stress at the anchorage top section. The peak of the shear stress distribution curve is at the top of the anchorage. When the load continues to increase, the bolt begins to slide, the top section's shear stress decreases, and the peak shear stress moves inward until the bolt is pulled out.
(3) The tensile strength of the anchorage material has a positive correlation with the bond strength, but the amplitude decreases with the increase of anchorage tensile strength. With the increase of concrete strength, as the improvement of the anti-cracking of the concrete and increase of bond between the bolt and concrete, the bond strength of the anchor increases accordingly.
(4) The radial pressure caused by the deformation along the radial direction of the bolt plays a key role in the anchoring effect of the rod. The larger the radial (lateral) pressure, the stronger the anchoring force.

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