Study on Bond-slip Behavior between Non-uniformly Corroded Reinforcement and Concrete

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Abstract. In order to improve the stress concentration in concrete at steel nodes caused by zero thickness springs, the improved Spring2 nonlinear spring model from ABAQUS is used to simulate the bond-slip behavior between non-uniformly corroded reinforcement and concrete. Based on the collected test results with different stirrup spacing, fitting the influence coefficients of bond stress under stirrup corrosion. With the combination of a non-uniformly corroded rebar distribution model, the refined numerical simulation of the drawing process of reinforced concrete specimens was carried out using ABAQUS. The study shows that the improved nonlinear spring model is better than the zero thickness spring model in terms of computational accuracy and efficiency. The stirrup correction coefficient is approximately linear with the stirrup spacing; the bond-slip relationship considering the effect of stirrup spacing, has a better consistency with the relevant tests in the simulation of the pullout test. Weibull distribution for the fitting of non-uniform corrosion of reinforcement is more reasonable than Gumbel distribution.

Keywords: reinforced concrete; bond property; non-uniform corrosion; numerical simulation.

1. Introduction

Experimental methods and numerical simulation methods are the main methods to study the bonding and sliding behavior of non-uniformly corroded steel bars and concrete. At present, most of the research on the influence of non-uniform corrosion on the mechanical properties of steel bars and the bonding properties between reinforced concrete are conducted by experimental means. In the previous model, stirrup spacing is one of the important factors. Lin et al. found in the test that stirrup spacing has different influences on the bonding stress of stirrup corrosion specimens [1]. However, due to the limited test data, no relation is given considering the influence of stirrup spacing. Therefore, the influence of stirrup spacing on the corrosion of longitudinal stirrups still needs to be further studied.

Numerical simulation methods can be broadly categorized into direct and indirect approaches. In the direct approach, a bonding unit is directly established for simulation purposes. For instance, Zhao et al. incorporated springs within concrete units and steel bar units to simulate tangential interaction between steel bars and concrete [2]. In the indirect approach, bonding slip is simulated by modifying reinforcement constitutive methods. For example, Zhao and Sritharan altered the stress-strain relationship of zero-thickness element to a stress-slip relation in Opensees for simulating bonding slip behavior [3]. Each of these methods has its merits, but they also have limitations.

In this paper, the stress concentration problem of traditional zero-thickness element is improved by improving the spring distribution. Based on experimental results, a fitting method was employed to determine the bond strength influence coefficient for stirrup corrosion, taking into account the effect of stirrup spacing. Combined with the probability distribution model and the improved bond-slip constitutive model, the pull-out numerical model of a non-uniformly corroded RC member is established, and the whole pull-out process is simulated based on ABAQUS. The impact of the modified model on simulating the bond-slip curve is discussed, and the influence of non-uniform corrosion of steel bars on the stress distribution of RC specimens and the bond stress distribution in the bond section are presnted.

2. Computational model

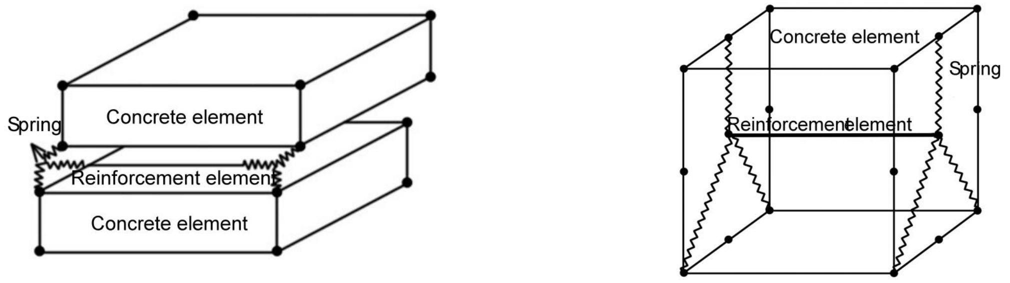
2.1 Nonlinear spring element model

To improve the stress concentration of the traditional spring element method, the new spring element model adopts the “spring 2” spring inherent in ABAQUS, which is distributed in a "Y" shape. One end is located at the steel bar node while the other end is positioned at an adjacent node. The specific model is shown in Figure 1 (a) (b). Spring2 element is a two-node spring, and the spring force of each spring can be decomposed into three directions of the global coordinate system, the direction parallel to the steel bar and the two perpendicular directions perpendicular to the steel bar. The spring force in the direction perpendicular to the reinforcement is negligible due to the close contact between the steel bar and the concrete in this direction and the small value of the relative normal displacement. The spring tension in the direction of the parallel bar is determined by the following formula:

$$F = \tau(s_i) \times A_i \quad (1)$$

Where: F - spring tension corresponding to different slip; $\tau(s_i)$ - the average bond strength corresponding to different slips; A_i - Exterior area of the rebar unit.

This "Y" shaped spring changes the stress of a single concrete joint into multiple concrete joints, so that the stress of the concrete specimen is relatively uniform, and the stress concentration of the zero-thickness spring element is avoided. The rebar element of the new model can be placed in the center of the concrete element or can be overlapped with the concrete element, which is more flexible than the traditional model.



（a）Traditional Spring Element Model （b）New Spring Element Model

Fig. 1 The Model of nonlinear spring

2.2 Corroded RC specimen parameters

The objects of numerical simulation are the RC test specimens with both longitudinal reinforcement and stirrup corrosion conducted in the Ref. [4]. Detailed dimensions of concrete specimens are shown in Figure 2. The displacement of 12 mm is applied to the loading end of the steel bar, and the loading rate is 0.5 /($m \cdot s^{-1}$). The corrosion of the steel bar is accelerated by electric corrosion. The corrosion rates of the longitudinal and stirrup of the corroded specimens are shown in Table 1.

Table 1. Corrosion level of longitudinal steel bars and stirrups

Number	*c*/mm	Longitudinal reinforcement corrosion rate	Stirrup corrosion rate
LAS2-1	25	1.77%	12.02%
LAS2-4	25	7.53%	32.63%
LAS4-3	25	1.30%	15.85%
LAS4-4	25	2.97%	26.41%
LBS2-2	35	2.81%	21.14%
LBS2-5	35	12.89%	32.25%
LBS4-3	35	0.89%	28.54%
LBS4-5	35	2.54%	24.16%

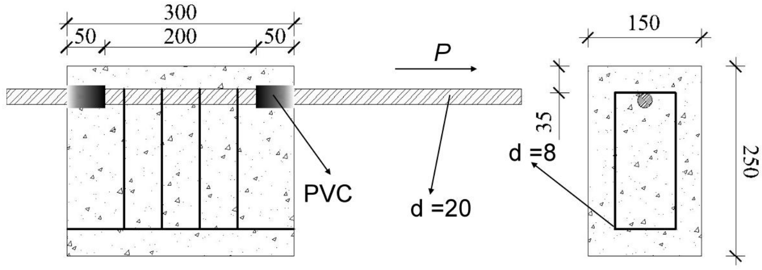


Fig. 2 Dimensions of pull-out test specimens (unit: mm)

2.3 Simulation of non-uniform corrosion of steel bars

In order to accurately simulate stress variation caused by non-uniform corrosion of steel bars during pull-out, the residual cross-sectional area model of steel bars given in Refs.[5,6] as adopted to simulate the non-uniformity and randomness of non-uniform corrosion of steel bars. Existing studies show that Weibull distribution and Guembert distribution fit the residual cross-sectional area of non-uniformly corroded steel bars well, and the probability density function of the two models is as follows:

$$f(x) = \frac{k}{\lambda}\left(\frac{x-\theta}{\lambda}\right)^{k-1} \exp\left[-\left(\frac{x-\theta}{\lambda}\right)^{k}\right] \tag{2}$$

$$f(x) = \frac{1}{\beta} \exp\left[-\left(\frac{x-\mu_G}{\beta}\right) - \exp\left(-\left(\frac{x-\mu_G}{\beta}\right)\right)\right] \tag{3}$$

Formula (2) is Weibull distribution and formula (3) is Gumbel distribution. Where: x and $f(x)$ are random variables and probability density functions; θ, k and λ are the position parameters, shape parameters and scale parameters of the Weibull distribution, and the values are referred to Ref.[5]. μ_G and β are the positional and scale parameters of the Gunbell distribution, and their values are referred in Ref. [6]. According to formula (2) and formula (3), the residual cross-sectional area of non-uniformly corroded steel bars conforming to Weibull distribution and Gumbel distribution can be generated in Matlab, and then the generated cross-sectional integral section is assigned to the steel bar cross-section parameters in ABAQUS to simulate the non-uniform corrosion of steel bars.

2.4 Bond slip constitutive model considering the effect of stirrup spacing

For the bond strength of corroded specimens, the relevant calculation formula (4) is given in Ref. [4]:

$$\tau_u(\eta, \eta_{st}) = \tau_u(0) R_m D_{st} \quad \#(4a)$$

$$R_m = \begin{cases} 1 & \eta \leq 1.5\% \\ e^{-\delta(\eta - 1.5\%)} & \eta > 1.5\% \end{cases} \# \quad (4b)$$

$$D_{st} = 1 - 0.68\eta_{st} \# \quad (4c)$$

where, $\tau_u(\eta, \eta_{st})$ represents the bond strength of the specimen whose longitudinal reinforcement corrosion rate is η and the stirrup corrosion rate is η_{st}, $\tau_u(0)$ represents the bond strength of the specimen without corrosion, R_m and D_{st} are the influence coefficient of bond strength considering longitudinal reinforcement corrosion and stirrup corrosion respectively, and δ is the deterioration coefficient of longitudinal reinforcement corrosion.

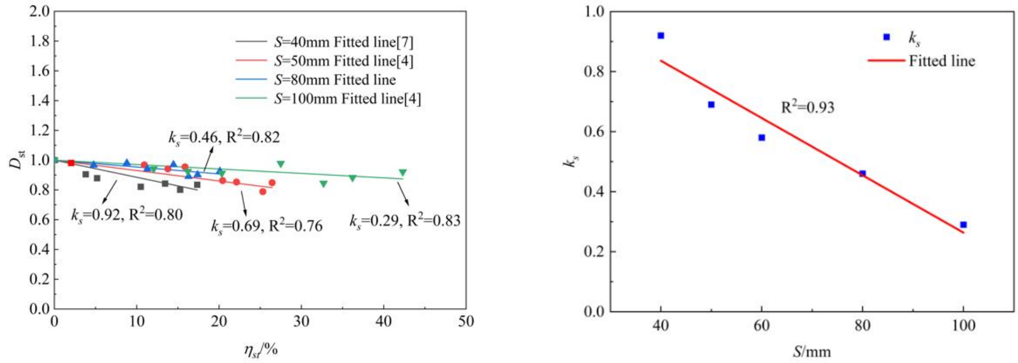
Ref. [4] points out that the size of stirrup spacing has an impact on D_{st}, and the smaller the stirrup spacing, the more adverse the effect of stirrup rust on the bond strength of specimens. To establish the calculation formula of D_{st} considering the influence of stirrup spacing, the coefficient k_s is introduced to modify equation (4c) as follows:

$$D_{st} = 1 - k_s \eta_{st} \tag{5}$$

where k_s is the correction factor considering the stirrup spacing.

Based on the partial pull-out tests completed by our group and the test results of 32 specimens given in Refs.[4,8], the D_{st} corresponding to different stirrup corrosion rates were plotted in Figure 3 (a). It can be seen that k_s decreases with the increase of stirrup spacing. After fitting the data, it is found that there is a linear relationship between k_s and stirrup spacing S, as shown in Figure 3 (b). The specific expression is as follows:

$$k_s = 1.249 - 0.009S \tag{6}$$



（a）Variation of D_{st} with η_{st} （b）Relation between S and k_s

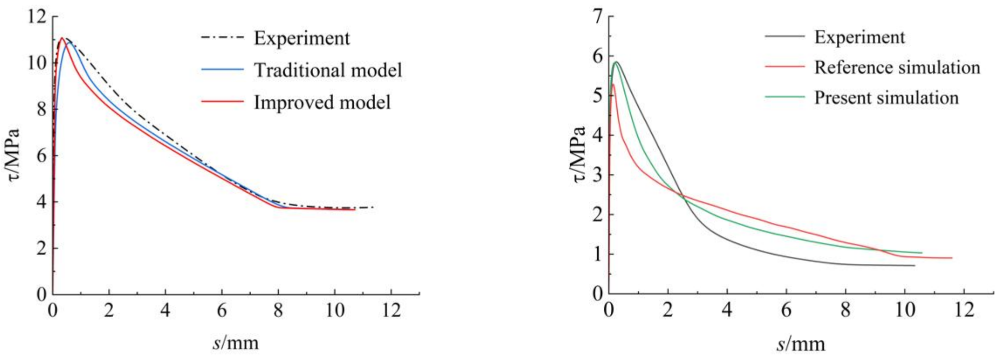
Fig. 3 Calculation for the correction coefficient k_s

3. Simulation results and analysis

3.1 Bond slip constitutive curve

To verify the computational efficiency and accuracy of the model, the traditional modeling method and the improved model were compared with LAS2-1 as an example. On a computer with an R7 4800H processor and 16G of RAM, the average calculation time of the traditional model is close to 50 minutes, and the average calculation time of the improved model is 20 minutes. The latter model is much less than the traditional model in the number of iterations, and significantly superior to the traditional model in computational efficiency. The calculated bond-slip curve is shown in Figure 4 (a), and it can be seen that the improved model is more accurate in terms of slip amount.

In addition to the improved accuracy of the model, the correction of D_{st} also affects the accuracy of the simulation results. Figure 4 (b) shows the comparison between the simulated curve in this paper and the simulated curve in Ref. [4] and the observed bond-slip curve in the experiment. In Ref. [4], the existing formula (4c) was used to calculate D_{st}, and the improved formula (6) was used to calculate D_{st} in this paper. It can be seen that for the specimen with a stirrup spacing of 100 mm, the simulated ultimate bond force in the literature is too small. This is because the original formula does not consider the influence of stirrup spacing on D_{st}, and only applies to the specimen with stirrup spacing of 50 mm. When the specimen's stirrup spacing changes, the calculation accuracy will be reduced. The modified formula takes into account the variation of stirrup spacing, so the simulation results are more accurate.

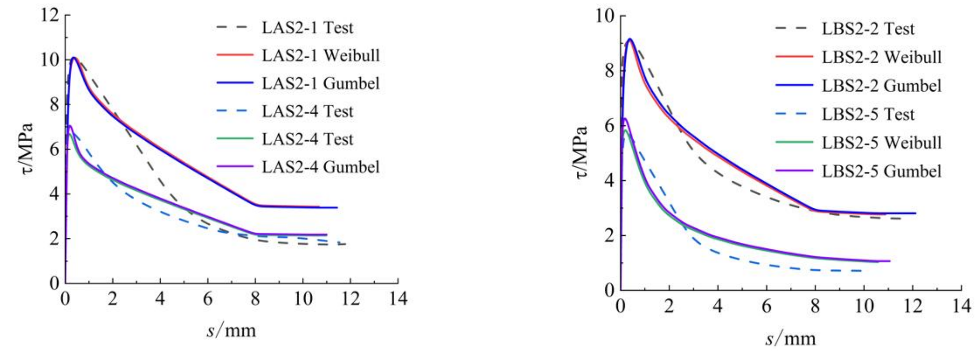


（a）LAS2-1 （b）LBS2-5

Fig. 4 Bond stress-slip curves under different models

3.2 Analysis of non-uniform corrosion of rebar

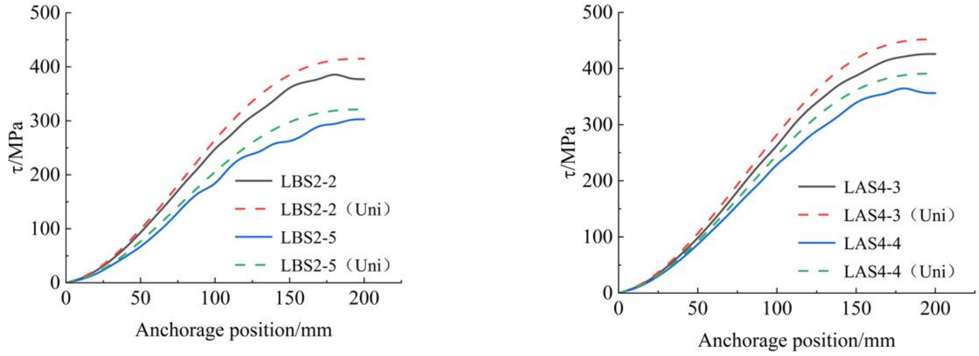
Figure 5 shows the comparison between the bond-slip curves under different non-uniform corrosion models and the measured curves of LAS2 and LBS2 specimens. It can be seen that the curves of the two non-uniform corrosion models are the same when the longitudinal corrosion rate is low. However, when the longitudinal reinforcement corrosion rate increases, the ultimate bond strength comparison test of the Gumbel distribution model has a little error, which is 0.28 MPa at 7.53% longitudinal reinforcement corrosion rate and 0.5 MPa at 12.89% corrosion rate. This is because the average cross-sectional area of the longitudinal reinforcement generated by the Gumbel distribution is relatively large. At low corrosion rates, the cross-sectional area loss of the longitudinal reinforcement is small， so the difference between simulation results is not large. However, at a high corrosion rate, the cross-sectional area loss is serious, so the ultimate bond strength of the Gumbel distribution model is larger than the measured value. Therefore, the fitting result of the Weibull distribution model will be relatively better when the longitudinal corrosion rate is large.



（a）LAS2 （b）LBS2

Fig. 5 Bond stress-slip curves under different non-uniform corrosion models

In order to study the difference between reinforcement stress under non-uniform corrosion and uniform corrosion, the stress curve of each group of specimens along the pulling direction was drawn in Figure 6. It can be seen from the figure that the stress of the steel bar under non-uniform corrosion is lower than that under uniform corrosion, and the stress curve under non-uniform corrosion will fluctuate. This is because when the distribution of steel rust layer is not uniform, rust expansion cracks will appear in the more concentrated parts of the rust in advance, resulting in the reduction of the bond strength between steel and concrete. The bond stress between reinforcement and concrete is reduced, and the stress of reinforcement itself along the anchoring length is also reduced.



（a）LBS2 （b）LAS4

Fig. 6 Distribution of reinforcement stress along the anchorage length

4. Summary

The improved spring model can better simulate the bond-slip behavior between reinforcement and concrete, improve the stress concentration of the traditional model, and improve the convergence and accuracy of the calculation to a certain extent. The simulation results are in good agreement with the measured results. The results obtained by using the nonlinear model with the effect of stirrup spacing are more similar to the experimental results. At a high corrosion rate, the Weibull distribution model has a better simulation effect than the Gumbel distribution model. Compared with the steel bar under uniform corrosion, the stress distribution of the steel bar under non-uniform corrosion shows fluctuation, and the bonding stress is reduced, which is not conducive to the improvement of the bond property of reinforced concrete.

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