MESOSCALE SIMULATION OF BOND BEHAVIORS BETWEEN REINFORCEMENT AND CONCRETE UNDER THE EFFECT OF FROST DAMAGE WITH 2-D RBSM

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1. INTRODUCTION

Frost damage is one of the main environmental actions which leads concrete structures to faster degradation. The detrimental effects owing to freezing and thawing cycles usually lie on two aspects: concrete materials and bond properties between reinforcement and concrete. Mass of studies have been focused on the materials deterioration on the effect of frost damage but few has been put forward on the bond behaviors under FTC. Several test results using one way pulling-out specimens could be found with short embedment length (5 times of rebar diameter), such as Xu et al. (2017), etc. Among these results, it was found that with accumulation of frost damage, the bond strength showed obvious decreasing while slip value when reaching maximum bond stress was increasing. Nevertheless, no study has been available on the numerical analysis of bond behavior under frost damage. The main purpose of this paper is to develop a mesoscale approach to simulate the bond degradation due to the effect of frost damage. Rigid body spring model for concrete was adopted with applying the reinforcement element and the FTC analytical process.

2. RBSM PROGRAM

2-dimensional rigid body spring model, known as 2-D RBSM, is a discrete numerical analysis method, which is suitable for small deformation and cracking simulation. The model is divided into polyhedron elements which are connected by normal and shear springs with two translational and one rotational degree of freedom at central gravity (Nagai, et al., 2004). RBSM has been adopted to simulate the material behaviors of concrete material including compression and tension under the effect of frost damage by Gong et al. (2015). Besides, Muto et al. (2004) succeeded in applying the rebar elements into 2-D RBSM to simulate the bond behavior between concrete and reinforcement which demonstrates the applicability of this approach. In this study, the program which could simulate the bond behaviors under FTCs was developed with one way pulling-out specimens. The constitutive relationships of normal and shear springs for mortar and aggregate were adopted as suggested by Nagai et al. (2004) with adding reinforcement elements following Muto et al. (2004). Based on the internal pressure model during ice formation by Gong et al. (2015) and modified mesoscale constitutive model which considered the residual plastic strain under FTC by Ueda et al. (2009), time-dependent FTC analysis was applied into 2-D RBSM to achieve the frost damage simulation.

3. SIMULATION MODEL

One way pulling-out specimens were modeled based on the test by Xu et al. (2017). The dimension of concrete was 100 x140mm and the diameter of reinforcement was 16mm where embedment length was set to be 80mm (5 times of rebar diameter), as shown in Fig. 1(a). The detailed information of rebar was drawn in Fig. 1(b). It was mentioned by Xu et al. (2017) that the rebars were covered with PVC pipes with diameter of 25mm and plastic foam at un-bonded regions to prevent flowing concrete during pouring and flowing water during FTCs. Thus, the vacant parts were also adopted in the simulation models.
The tensile strength, elastic modulus and Poisson's ratio of mortar were 3.48MPa, 21.876GPa and 0.18. The elastic modulus and Poisson's ratio of aggregate and reinforcement were 50GPa, 0.25, 200GPa and 0.3, respectively. Maximum crack width of normal springs w_{max} for mortar and interface was set to be 0.03mm and 0.01mm as suggested by Nagai et al. (2004). For criterion of shear springs for interface, Mohr-Coulomb model was adopted and the pure shear strength c and the angle of internal friction Φ were 2.69MPa and 35. The interface tensile strength was assumed half of the tensile strength for mortar. FTC process followed the one adopted by Xu et al. (2017) where temperature varied between 10℃ and -17℃. Specimens were conducted with one way pulling-out after 0, 100 and 200 FTCs. It should be mentioned that full constraints were given to all boundaries of concrete and load was provided by displacement with 0.01mm/step at the bottom boundary of the reinforcement.

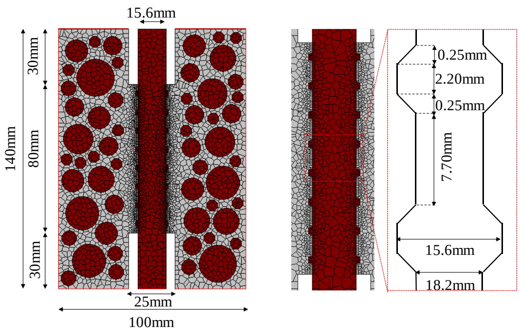

Fig. 1. (a) Schematic of one way pulling-out specimen (b) Details of the reinforcement

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4. RESULTS AND DISCUSSIONS

The simulation results of bond stress-slip relationships are shown in Fig. 2 with the test results from experiment by Xu et al. (2017), which indicates that the pulling out behavior could be simulated by the 2-D RBSM program. Similar as what was observed in the experiment by Xu et al. (2017), the bond strength showed decreasing and slip at maximum stress increased with the accumulation of frost damage. The reason is considered that: after frost damage, the intercostal concrete, which was the conclusive constituent for bond behavior, would show smaller strength and stiffness but better ductility as the previous studies. Thus, the mechanical interaction between rebar and concrete would be weakened after FTCs, where the bond strength decreased while the peak slip increased. The cracking pattern at maximum bond stress was also drawn in Fig. 3 where the red lines stand for the cracks. It could be seen cracks initiated evenly through sound concrete but after FTCs an obvious diagonal main crack (black circle in Fig. 3) took place which could lead to the decreased bond strength. Compared with Xu's data, the values of bond stress and slip at peak stress were found larger in RBSM simulation, which might mainly relate to the over-set boundary conditions. Since fully restrictions were applied for the boundaries of models to assure that failure took place at the intercostal concrete due to the presence of stirrups as Xu's experiment, the bond strength and slip at peak stress were probably over-estimated in the simulation. The normalized bond strength and slip at peak stress from RBSM simulation were also plotted in Fig. 4, together with the experiment results by Xu et al. (2017). From the comparison, it could be seen the simulation results coincided well with the test results excepting for the value of peak slip with specimen suffering 200 FTCs. Satisfactory agreement between RBSM simulation and experimental data strongly demonstrated the reliability and applicability of the program developed in this paper to analyze the degradation of bond behavior under the effect of frost damage.

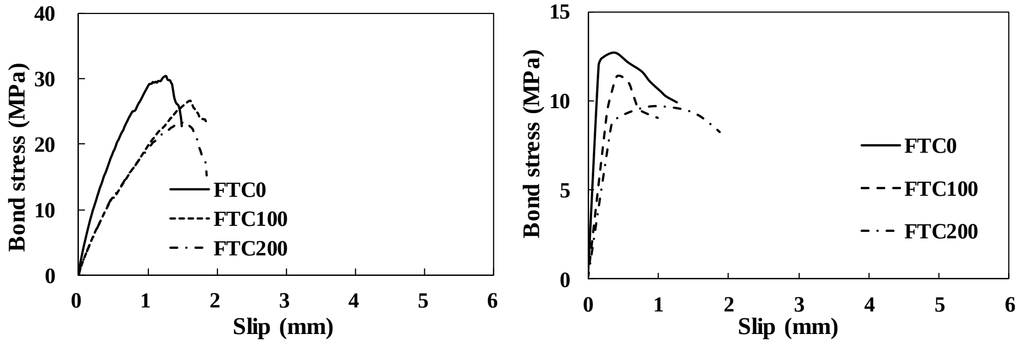

Fig. 2. Bond stress-slip curve for specimens with 0, 100 and 200 FTCs from RBSM (left) and Xu et al. 2017 (right)

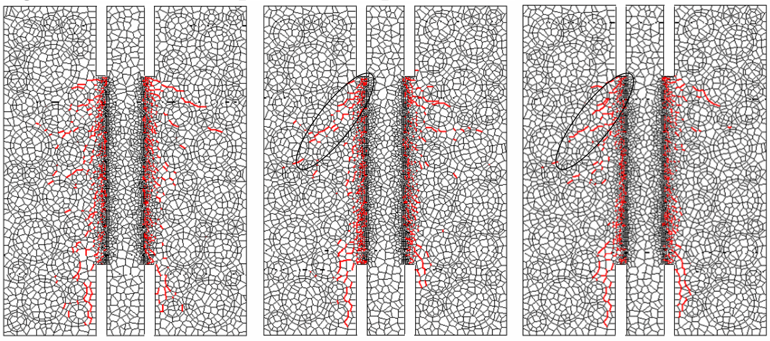

Fig. 3 Cracking pattern at peak stress for case FTC0, 100, 200

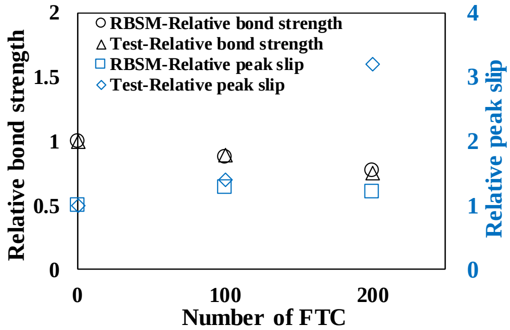

Fig. 4. Relative bond strength and peak slip

5. CONCLUSIONS

Mesoscale simulation program with 2-D RBSM was developed to investigate the bond degradation between concrete and reinforcement under the effect of frost damage. Following conclusions could be made according to the research grogram:

(1) Frost action has obvious effect on bond properties between concrete and reinforcement. That is, with increasing number of FTC, the bond stiffness and bond strength would decrease whereas the slip at peak bond stress increase. Similar tendency could also be found in several experimental results.

(2) After frost damage, the intercostal concrete would have a smaller strength and stiffness but better ductility, which accounts for the decreasing of bond strength but increasing of peak slip. Besides, diagonal cracks would take place in concrete after FTCs which would also result in the smaller value of bond strength.

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