3D Numerical Simulation of Pullout Behavior of FRP Embedded in Concrete using RBSN Method

Kim Jang-ho* Li Jing** Tran Tuan Kiet** Hong Jong Suk** Kim Yun Ho **

ABSTRACT

RBSN Method, Rigid-Body-Spring Network Method, is a structural analysis method that overcomes the problems faced in FEM analysis of concrete or crack forming structures. In RBSN, irregular lattices are used to model structural components consisting of bulk material, curvilinear reinforcements, and their interfaces. Because reinforcements and their interfaces in the bulk material are freely positioned, meshing is irrespective of the geometry of the representing bulk material. In this paper, RBSN method of 3D is applied in simulating the pull-out test of FRP (Fiber Reinforced Polymer) embedded in concrete. The comparison of analysis results to experimental results shows that RBSN method simulates the shear-slip behavior very precisely. From the analysis results, 3D RBSN method is proven to be an effective and accurate analysis method for concrete structural analysis. Also, the results show that RBSN method can be a potential analysis method for concrete structures that can replace the current FEM analysis.

1. Introduction

Computer numerical simulation has been thoroughly studied in past few decades for structure analysis usage due to its efficiency, accuracy and facility. But for conventional simulation method, the effectiveness of numerical analysis is often limited by a number of factors such as large analysis preprocessing demands, lack of general applicability of the analysis method, and difficulty in interpreting and revising the computational model. For these reasons, irregular lattice method has been being studied to overcome the limitations, which are restricting numerical analysis methods from becoming automated analysis tools. In this paper, RBSN method, Rigid-Body-Spring Network Method, is introduced as the irregular lattice method for analyzing the behavior of concrete materials. In RBSN, the numerical model of concrete structure is defined as a system consisting of three phases: bulk matrix material, reinforcement, and their interface. One important feature of this method is that the reinforcement embedded in concrete is freely positioned in the domain and that its arbitrary placement is totally irrespective of the geometry of the lattice representing the matrix phase. RBSN is demonstrated to give better simulation results for fracture behavior analysis of concrete structure overcoming the limitation of conventional simulation method, such as FEM, FDM, etc. In this paper, pullout test of FRP (Fiber Reinforced Polymer) rod embedded in concrete has been analyzed by using RBSN method in 3D case. Because of the higher capacity in tensile strength, FRP rod is used as reinforcement instead of regular steel bar for a higher performance. All of the process of modeling and analyzing of this pullout simulation are discussed in detail. The comparison between simulation and experimental results shows that RBSN method is a very effective simulation method, which gives more reasonable and precise results. Furthermore, RBSN method could be developed as a potential automated simulation method for concrete structure analysis.

2. Rigid-Body-Spring Network Method

* KCI Member, Assistant Professor, Department of Civil and Environmental Engineering, Sejong University
** KCI Member, Graduate student, Department of Civil and Environmental Engineering, Sejong University

RBSN is Rigid-Body-Spring Network Method, in which concrete is partitioned into a collection of rigid bodies, or cells, which are interconnected by spring sets defined as local to cell boundaries. The numerical model of RBSN consists of three components: the matrix material, curvilinear reinforcement, and the interface between these two components. The matrix component is represented by a lattice model, whose geometry and properties are based on a Voronoi diagram formed from a set of irregularly positioned points. By the use of the Voronoi diagram, the RBSN provides an accurate modeling of the elastic and fracture properties of concrete structures. The reinforcing components, which can have curvilinear trajectory, are represented as a series of ordinary beam-column elements that can be freely positioned in the structural domain, irrespective of the rigid-body-spring discretization of the concrete. For the interface, the reinforcement is connected to the concrete via conventional link elements, which represents nonlinear bonding behavior, and constraint equations representing local motions of the rigid cells, so it allows for realistic stress transfer and slippage between the material and reinforcement.

In 3D case, Voronoi diagram is formed from a set of convex polyhedra. The modeling procedures of matrix material include threes steps (Fig. 1): ① Semi-random point generation. ②Delaunay tessellation (tetrahedron) generation. ③ Voronoi diagramgeneration. All the procedures are processed automatically by a computer program, so people can save more time from complicated preprocessing work to consider more about model approaching subjectively.

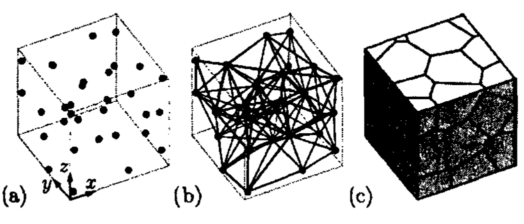

Fig. 1Modeling of matrix material

Curvilinear reinforcement is discretized into a series of 1D structural elements. The trajectory of each length of reinforcement is defined by a series of user-specified points in 3D space irrespective of the Voronoi diagram. The discretization of the interface between the matrix material and the reinforcement is based on the discretization of the reinforcement. The effects of the interface are lumped at the reinforcement nodes through the actions of bond-link elements.

3. Pullout test of FRP rod embedded in concrete

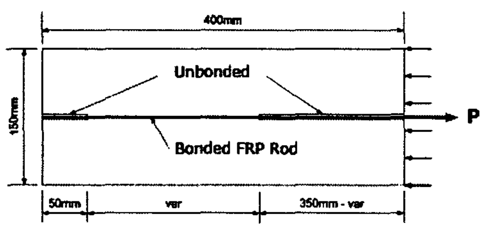

Fig. 2 Dimension of the specimen

Pullout test has been widely researched for studying the behavior of RC in civil engineering field. In this paper, FRP rod is used as reinforcement instead of conventional steel bar for developing FRP reinforced concrete structure. Fiber-reinforced polymer (FRP) composites have become very popular in the last few years due to the needs for maintaining and upgrading essential infrastructure in all over the world. FRP is well-known for the advantages of good corrosion resistance characteristic and easiness of handling due to their light weight. In addition, its tensile strength capacity allows construction of high tension resisting RC structure.

Pullout analyses of FRP rod embedded in concrete of different material and bonding parameters have been performed. The dimension of specimen is 150×150×400mm with the FRP in the center. In the test, the FRP reinforcement is not totally but partly bonded where the bonded length varies for different tests. Test model is shown in Fig. 2 and the parameters are shown in table 1.

Table 1 Parameters of material

		FRP		Concrete	
Test name	Bonding length (mm)	Young's Modulus (GPa)	Compression strength (MPa)	Young's Modulus (GPa)	Compression strength (MPa)
GI-9-90	90	53.5	28.5	90.11	36.09
GD-9-90	90	44.5	23.0	82.55	30.29
GG-9-90	90	54.8	17.3	89.64	35.71
GN-9-90	90	54.8	37.9	90.11	36.09
GD-9-45	45	44.5	12.8	82.55	30.29
GD-9-135	135	44.5	35.1	90.37	36.30
GD-9-180	180	44.5	37.7	90.37	36.30

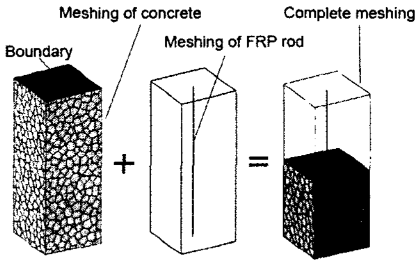

Fig. 3 Meshing of pullout test

3.1 Modeling of pullout in RBSN

By the definition of RBSN, pullout specimen can be modeled into three parts: matrix material, reinforcement, and their interface. For this analysis, concrete is the matrix material, FRP rod is the reinforcement, and the interface means the bonding condition, which describes the interaction between concrete and FRP rod.

Meshing of concrete and FRP rod is the modeling of matrix material and reinforcement, which is shown in Fig. 3. Whole meshing process is completed automatically by computer program. However, a little decision making is necessary by the user to implement more reasonable numerical simulation, especially in the setting of boundary. In this case, boundary is set as a thin layer of nodes at the end of the model, which have the same coordinates in longitudinal direction.

After meshing, input files of main analysis is made using the information of material parameter, bonding condition, and boundary condition. Bonding condition is the modeling of interface, which is represented by the relationship of shear stress and corresponding slip. In this study, bonding condition is set based on the experimental data, which isshown in Fig. 4. Since this simulation is based on displacement controlled testing of pullout test, the boundary is set by the displacement controlled setting of concrete and FRP rod. Concrete boundary is selected as fixed nodes and FRP boundary is selected as 45mm displacement node (Fig. 5).

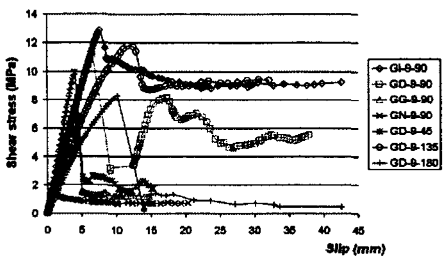

Fig. 4 Shear stress-slip curve for pullout bonding

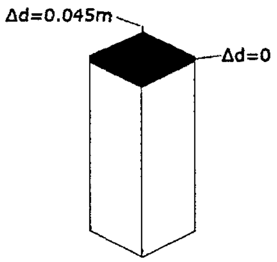

Fig. 5 Boundary setting of pullout

3.2 Comparison of results

Results are shown in Figs. 6~12. Figures show that simulation results match the experimental data very accurately.

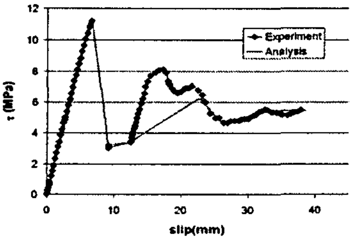

Fig. 6 Analysis for GD-9-90

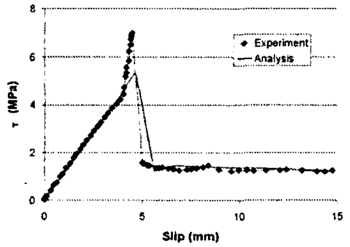

Fig. 7 Analysis for GG-9-90

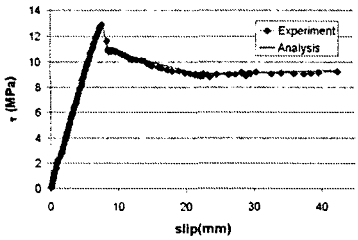

Fig. 8Analysis for GI-9-90

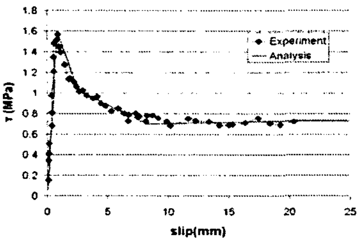

Fig. 9 Analysis for GN-9-90

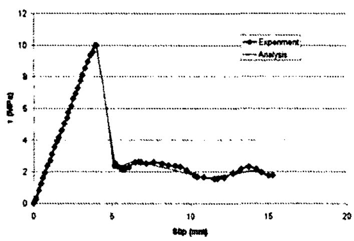

Fig. 10 Analysis for GD-9-45

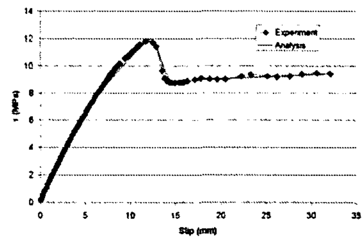

Fig. 11Analysis for GD-9-135

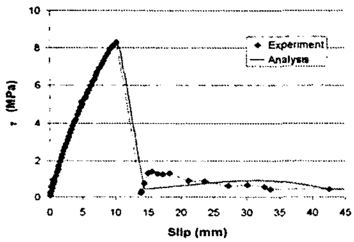

Fig. 12 Analysis for GD-9-180

4. Conclusion

The simulation results show good agreements with the experimental results. The good results are due to the totally different approach of RBSN than that ofthe conventional simulation methods. In RBSN, all of the elements are "0" size spring element connecting meshes where the meshing effect is eliminated. Also, since the reinforcement passes through the elements of the matrix material in any random directions, the realistic behavior of the structure can be simulated. Furthermore, the application of irregular lattice in meshing allows formation of random cracking path overcoming the meshing limitation of the regular lattices. From the study, RBSN method has been proven to be an effective and precise simulating method, which can be developed further for advanced concrete structure analysis. Also, the study shows that FRP, a material with high tensile capacity, can be used as reinforcement for constructing concrete structure members with superior tensile capacity.

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Reference

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