Numerical Simulation of Failure of RC Beam-Column Joint by 3DRBSM

その他のタイトル	三次元離散解析手法による鉄筋コンクリート柱梁接合部の破壊シミュレーション
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論文の内容の要旨

論文題目 Numerical Simulation of Failure of RC Beam-Column Joint by 3D RBSM
（三次元離散解析手法による鉄筋コンクリート柱梁接合部の破壊シミュレーション）

氏　　名 リヤント エディ

Because of the demand of the current specification, reinforcement congestion occurs in the beam column joint that causes difficulties during compaction and increases the construction time. As the result, poor quality of concrete is obtained. However, the specification of anchorages has not been changed for many years and was developed based on the simple arrangement of reinforcement bars so that there is a possibility to reduce the reinforcement congestion based on the mechanical behavior in the congested joint. Meanwhile, based on the experimental works, it is not easy to understand the behavior because complex cracks occur due to the complex arrangement of reinforcement bars and the loading history.

Meanwhile, mechanical anchorage can be one way to reduce the reinforcement congestion. However, the use of mechanical anchorages is still limited because the behavior has not been well understood. If the mechanical anchorages are placed near the surface of the beam column joint, anchorage failure occurs in the beam column joint. To avoid this failure, additional reinforcement should be placed along the anchorages. However, the best or rational way to strengthen this anchorage system has not been found yet because the internal condition has not been well understood. Many experiments were necessary. It is inefficient and takes time.

Simulation can be a beneficial tool to understand the behavior through the study of the internal stress and internal cracks. In this study, meso-scale analysis by 3D RBSM is proposed. The study by 3D meso-scale discrete analysis is useful since the reinforcement can be modeled in an accurate manner, i.e. ribs of a reinforcement bar and 3D shape of a reinforcement bar, local failure can be predicted precisely as the result of the discontinuous deformation of concrete and the interaction of concrete and the reinforcement at meso-scale level, and cracks can be simulated directly as the displacement between two elements. Based on the previous study, the simulation can simulate the local failure at the anchorages of beam column joints. However, the simulation system was not enough to simulate the beam column joint with complex arrangement of reinforcement bars, the meshing of a reinforcement bar was complex, and the constitutive models have not fixed yet.

In RBSM, a little attention to the mesh size is necessary. The mesh size of simulation models should be selected in an appropriate way to represent the real cracking pattern of concrete. Since in the normal concrete, microcracks occur at the interface between the mortar and aggregate or at the mortar between two aggregates, 10x10x10 – 20x20x20 mm^3 of mesh size is selected to represent the real cracking pattern in the normal concrete that is determined by the aggregate size and location. Based on this selected mesh size, the constitutive models will be decided. For other types of concrete, different mesh size and constitutive models should be decided to represent the real cracking pattern.

In this study, the simulation system is developed by introducing a simple meshing of a reinforcement bar so that the computational time can be reduced. Furthermore, various shapes of reinforcement bars can be modeled, so that at this time the same model and reinforcement bars arrangement as the real condition can be modeled.

A unified constutive models of RBSM is proposed based on the simulations in the material scale. Simulations of concrete under uniaxial compressive and tensile loading, and biaxial compressive loading are conducted to upgrade the constitutive models. A bi-linear model is introduced for the tension softening of normal springs of concrete elements. A new failure criterion of concrete is introduced. Furthermore, strain hardening region is also introduced for the normal springs of steel elements. Parametric studies are conducted to investigate the effect of each constitutive model on the macroscale behavior of the material.

In order to investigate the applicability of RBSM in modeling bond between concrete and a reinforcement bar, simulations of tension stiffening model are conducted. Two numerical models having different yield strength of reinforcement are simulated. Based on the simulation results, as the load increases, cracks can propagate gradually because of the bond between concrete and the reinforcement bar. Furthemore, simulation results show a good agreement with the experimental results.

By using the well-developed simulation system, some achievements have been obtained.

First, by this simulation system, it can be understood how the loading position and the local shape of the reinforcement affect the local cracks in the corbel because the local shape of the reinforcement is modeled directly. Furthermore, a simple method to repair the damage corbel can be proposed. Second, by the simulation system, it can be understood how complicated cracks occur in the beam column joint with complex arrangement of reinforcement bars since three dimensional shape of reinforcement bars is modeled directly. And last, by the simulation system, it can be understood how each reinforcement bar contributes to the failure behavior of the beam column joint with the mechanical anchorages. Furthemore, a failure process of the beam column joint with the mechanical anchorages is proposed through the study of the internal stress and cracks of simulation results.

Some bearing pads of corbels were designed at the wrong position, at the edge of the corbel. Consequently, local failure, anchorage splitting failure occurs in the corbel because of this wrong detailing. This condition does not satisfy the specification code. By simulation, the cause of this local failure can be understood because the local shape of reinforcement bars is modeled directly. Different loading positions show different capacities. Local cracking in the edge causes the significant drop in capacity. By simulating the existing damage in the corbel, a simple method to repair the damage corbel can be proposed. Based on the simulation results, just by changing the loading position can be the simplest way to recover the capacity of the damage corbel. This kind of residucal capacity simulation can be conducted.

Based on the simulation of a beam column joint with complex arrangement of reinforcement bars, since the complex arrangement of reinforcement bars is modeled as the same as the experimental specimen, the same cracking pattern as the experimental specimen can be simulated. Cracks parallel to the bending portion of anchorages can be simulated due to a moment that tends to open the beam column joint, since the bending shape of the reinforcement bar is modeled directly. Compression strut occurs due to a moment that tends to close the beam column joint. Simulation results show the same tendency as the experimental results.

Based on the past researches of beam column joints with mechanical anchorages, since the internal stress condition and cracks have not been understood, many experiments were necessary to find a rational reinforcement arrangement in the beam column joint with mechanical anchorages. Based on experiments, there are two possible ways to strengthen this anchorage system, i.e. by placing stirrups along the anchorages, and by adding concrete block at the top surface of the beam column joint. Simulations are conducted based on the past experiments. Simulation results show the same tendency as experimental results. Furthemore, the surface cracks of numerical models are roughly the same as those of experimental specimens. Through the study of the internal stress and cracks of simulation results, the failure process of the beam column joint with mechanical anchorages is proposed. First, bond works along the development length of anchorages. Second, diagonal cracks occur in the beam column joint. Third, cracks propagate to the surface of the beam column joint. Final Step is the opening of diagonal cracks. Furthermore, based on the simulation results, the meaning of stirrups along the development length has been understood, i.e. stirrups increase the bond performance along the development length of anchorages and restrict the opening of diagonal cracks. Meanwhile, the meaning of additional concrete block at the top surface of the beam column joint and reinforcement inside the concrete block is to increase the bond performance along the development length of anchorages and to restrict the crack penetration to the surface of the beam column joint.