論 文 の 内 容 の 要 旨

論文題目　Nonlinear Dynamic Frame Analysis on 3D Shaking Table Tests of a Full-Scale Four-Story Reinforced Concrete Building
（実大四層RC建物の三次元震動台実験の非線形骨組地震応答解析）

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Comprehensive reinforced concrete beam-column joint models (interior joint, T shaped exterior joint, L shaped knee joint) used for nonlinear frame analysis are proposed and verified in this paper.

Some of the latest research on the failure mechanism of reinforced concrete beam-column joint and the damage observed after some recent earthquakes (1995 Kobe Earthquake and 2011 Great East Japan Earthquake) show that despite of the measures of avoiding joint damage prescribed in the current building code in Japan, beam-column joint could be damaged during earthquakes. Usually, the failure of a beam column joint is understood as the shear failure of concrete within the joint. This type of failure mechanism usually leads to severe and rapid strength degradation as well as stiffness and energy dissipation degradation. The current building code in Japan ensures that the shear capacity of concrete in joint zone is higher than demand to prevent such failure mode. However, according to Shiohara's research, for a joint in which the flexural strength ratio of column to beam is close to 1, it could fail despite of enough shear capacity of concrete. In this case, the longitudinal reinforcements inside the joint yield, and the concrete cracks in diagonal pattern without being crushed, leading to significant degradation of strength, stiffness and energy dissipation capacity. The phenomenon is not expected to occur and it may lead to unexpected seismic performance of RC buildings with flexural strength ratio of column to beam of 1~1.5, which is common in Japan. In order to avoid catastrophe caused by unexpected seismic behavior of numerous existing buildings with potential vulnerable beam-column joints, the study of RC buildings with joint being damaged is necessary. In practice, the influence of joint damage to the entire structure can only be studied by numerical analysis. Although various beam-column joint models have been proposed for nonlinear analysis, they are either too empirical, inaccurate or too computationally expensive. In fact, very few models are able to accurately estimate joint strength for the case that joint fails in reinforcement yielding rather than concrete crushing.

A 2D joint model proposed by Seitaro Tajiri, which is based on the rigid joint face assumption and fixed concrete crack angle, was found to be explicit in mechanism and is able to estimate strength, stiffness and hysteresis in a fairly accurate degree. This model models beam and column as an integrated part of a joint and the hysteretic behavior is derived from uniaxial constitutive relationship of steel, concrete and bond without using other empirical relationships. However, it contains a large number of degrees of freedom and bond elements. Bond element has relatively complicated hysteretic behavior, and a large number of them usually cause convergence problems and consume too much computational time. Furthermore, if this model is modified and adapted to a three dimensional environment the number of bond element will be astonishing and impractical for frame analysis. Additionally, the model is not able to consider the influence of joint details such as anchorage length and therefore it cannot predict the hysteretic behavior of T and L shaped joint accurately. A few years later, this benchmark joint model was modified by Zhemin Piao by reducing the number of nonlinear sections along beams and columns, and the number of bond elements within the joint zone. Although a large number of degrees of freedom have been reduced, the number in a 3D environment is still unacceptable and computational convergence due to the complexity is still not guaranteed. Moreover, it still cannot take account of the influence of anchorage type and length.

In this paper, beam-column joint models (interior joint, T shaped exterior joint, L shaped knee joint) are proposed. These models are developed based on the benchmark model with basic assumptions that the four joint faces remain plane and the concrete cracks with fixed angles. The main difference is that the beam and column are not modeled as an integrated part of the joint model for the proposed joint model and the influence of anchorage is taken into account. Also, the modeling of slab within the joint zone and the implementation of the joint models to a 3D frame analysis environment is introduced. Compared to the benchmark model, the required computational time can be reduced to at least 50% in a 2D environment. More importantly, the proposed models are compatible with traditional beam column line elements and can be implemented in a 3D frame analysis environment with ease.

The proposed models have been verified by a large number of quasi static cyclic tests of RC beam-column joint subassembly and a series of 3D shaking table tests of a full-scale four-story RC building. The proposed models were generally found to be accurate in estimating strength, slightly overestimating stiffness, and accurate in estimating hysteresis for joint damage case. Implementing the proposed models to 3D shaking table tests of a full-scale four-story RC building was found to be effective in tracking damage evolution and improving the estimate of deformation under severe damage condition.

By using the proposed beam-column joint models, the seismic behavior of numerous existing buildings (of which the flexural strength ratio of column to beam is between 1.0 and 1.5) that could potentially fail in reinforcement yielding at beam-column joint could be studied. Furthermore, the proposed models could be used in performance based building design to increase economic efficiency.