# 論 文 内 容 の 要 旨

## 1. Introduction

### 1.1. Brief introduction of Shiohara theory

Shear failure of beam column connections have attracted many researchers since it can lessen significantly the seismic resisting capability of a reinforced concrete (RC) frame building. For many years, with strong attention to this object, researchers have conducted numerous exprimental works, introduced theories to explain failure mechanisms, proposed analytical models, and developed design criteria to enhance joint stiffness. In calibrating joint models, theory with respect to joint shear deformation is indispensable, and for many previous works, Paulay strut and truss mechanism have been preferable to explain transferring action of shear force in a shear or moment resisting mechanism. This mechanism includes a diagonal strut represents compressive concrete and horizontal and vertical ties represent reinforcements in joint region. An equilibrium of forces is formed between strut and ties, then when ties is tensioned to resist shear force, strut is compressed and confinement in joint core occurs. The failure of a joint is attributed by strut crushing or poor anchorage of ties, yielding of reinforcements. This mechanism exhibits advantages of consisting some material parameters when computing the joint capacity such as concrete strength, amount of reinforcing bars, size of anchorage reinforcements in joint regions but fails to integrate the flexural strength of adjacent frame members. Shiohara points out an essential deficiency of this mechanism that it lacks of a parameter with respect to discriminating different type of joint like interior, exterior and corner to determine the empirical allowable joint stress. By examining result data of series of tests on seismic behaviors of interior beam-column joints, it was found that joint shear and story shear are not proportional since story shear degrades but joint shear continues to develop till the end of tests. The shear resisting capacity of joints is, therefore, considered to be reserved. Shiohara then proposed joint shear hinging failure mechanism with aspects of a moment resisting component exibiting advantages in explaining the above behaviors successfully. The mechanism considers joint shear deformation caused by rotation of four rigid bodies respect to hinging points. As a part of the theory, a mathematical basic model has been introduced to predict joint moment capacity.

1.2. Objectives of the study

- Develop a two dimensional (2D) macro element directly based on Shiohara mechanism to simulate behaviors of RC beam column connections under lateral loading by:
    - Proposing a set of deformations for a joint element
    - Defining joint components such as concrete struts, bar springs and bond-slip springs from rotation of rigid bodies in Shiohara mechanism to represent concrete, reinforcing bars and bond between bars and surrounding concrete respectively
    - Building compatibility relationship regarding deformation of joint components with joint deformation and establishing joint stiffness
    - Verifying the new joint model with case of interior joint under monotonic loading with and without perfect bond condition, under cyclic loading with and without perfect bond condition
- Validate the joint model on analyzing cyclic performance of 2D RC exterior joints, 2D RC knee joints, and 2D RC frame

## 2. Suggestion of A New Beam-Column Joint Model and Application on Investigating Cyclic Response of Interior Joints

A beam-column connection has four surfaces connecting to beams and columns, which are often modeled as line elements, through centers of those surfaces. The joint element is defined as a rectangular element with four nodes located at center of four rigid plates representing rigid bodies in Shiohara mechanism. Each node has three DOFs including a rotation and two translations, and there are twelve DOFs for a joint in total. With this definition, the deformation of a joint model can be expressed as a combination of nine independent components: four axial deformations, four bending deformations and a shear deformation. Complementary to this set of deformations are nine independent internal forces : four axial forces, four bending moments and an anti-symmetric bending moment.

Shiohara firstly introduces joint hinging mechanism into RC beam column interior connections. Based on joint behavior at the shear failure mode, the mechanism assumes that joint deformations are caused by rotation of four triangular rigid bodies respect to hinging points. These bodies attach to each other by springs representing reinforcement in joint region. On each bodies, there are equilibriums of forces regarding resultant compressive forces of concrete through hinging points, resultant forces in reinforcement springs and external forces. To analyze the expansion of crack forming hinging mechanism, Shiohara explained strain and stress state in a joint core from before cracking to after cracking, and until ultimate state. Before cracking, it was said that bi-axial stress state existed in both tensile areas and compressive areas. After cracking, stress state in compressive areas became uniaxial; meanwhile, there was no stress in tensile areas. Because stress before cracking is small, this study neglects bi-axial stress state and assumes uniaxial state for all loading stages. Generally speaking, there are four compressive zones and four tensile zone at a loading stage due to rotation of rigid bodies. Compressive zones near joint center are parallel to joint diagonals while compressive zones near joint corners are normal to diagonals in order to resemble orientation of concrete resultant forces in Shiohara mechanism. Boundary of these zones is determined by displacement of joint center and joint corners in diagonal orientation and in direction perpendicular to diagonals. These displacements can be computed from nine independent joint deformations mentioned above. In this study, eight concrete struts are defined to represent respectively tensile zones and compressive zones, attaching to rigid plates. To determine stress in struts, it is assumed that concrete strain distributes linearly on joint diagonals, and to satisfy this distribution, length and direction of compressive struts are assigned for those of adjacent tensile struts which cross the same half-length of diagonal. From strain distribution, stress distribution can be established using constitutive rules of concrete. By defining width, length and orientation of concrete struts, strut axial forces can resemble corresponding resultant forces in Shiohara mechanism. In an idealized case with perfect bond between longitudinal reinforcing bars and surrounding concrete, rotation of four rigid bodies results in relative displacements between joint nodes and rigid plate located at position of reinforcements in Shiohara mechanism, which inspires the study to define bar springs. Joint compatibility and stiffness are then established while constitutive laws of reinforcement and concrete are also included. A series of tests on reinforced concrete joint subassemblages regarding series of interior joint subassemblage with different sizes and reinforcing details is adopted for verification. With perfect bond condition, the new model results in pretty good correlation between simulation and observation for response of five interior joint subassemblages under monotonic loading. A definition of bond slip springs and a method of incorporating their stiffness with bar springs stiffness for purpose of building compatibility relationship is suggested in order to apply the model with normal bond condition. Later analytical results then show that there is also a good agreement between analysis and test data. To apply for analyzing joint performance under cyclic loading, some calibrations on computing deformation of concrete related to plastic deform of reinforcing bar are included. Detailed verification by experimental data has been conducted with both cases of cyclic loading with and without assumption of perfect bond condition. Results indicate good agreement between simulation and experimental data regarding the load deflection relationship, yielding point of reinforcement. The case of adopting joint shear strength following AIJ 1999 into a joint model for computation is also included and returns in less reliable joint performance than cases with the proposed element. Results from examining influence of different anchoring conditions regarding normal bond and perfect bond to joint response agrees well with a conclusion of Shiohara that there is no proportional relationship between bond strength and joint strength since the influence is little, and bond capacity does not affect significantly joint strength with J-mode. However, it makes sense in explaining the case of 3D joint in which transverse beam exists and reinforces bond capacity, as a result, there is observed increase of joint strength.

## 3. Application on Investigation Cyclic Response of Exterior Joints, Knee Joints and RC Frame

Application of the proposed beam column joint model to investigate response of 2D exterior joints, knee joints, and a plane RC frame under reverse loading is conducted. Since the joint stiffness matrix is defined in the previous part for interior joints, calibration related to a partial anchorage length of longitudinal reinforcement in beams is input for cases of exterior joints while a full anchorage length of beam bars is used for knee joints without modifications.

In RC beam column exterior joints, with partial anchorage length, dominant cracks develop from top and bottom edge at beam or column face to opposite face crossing anchorage points. Calibration here focuses on changing size and shape of rigid bodies in computing deformation of struts, rearranging location and adjusting length of some bar springs and bond slip springs. The same procedure as mentioned for interior joints is generated to establish stiffness matrix for exterior joints. Tests on five series of tests with 1/3 scale exterior joints are chosen for simulation with different size, different reinforcing properties, and the flexural strengths of frame members of each specimen are smaller than the strength at maximum observed story shear so that applicability of the new joint model is demonstrated by J-mode failure. The relationship of story shear versus story drift from experiments of joint sub-assemblages is utilized for verifications, beside details of yielding point of bars in joint regions. The shear failure mode of exterior joints from analysis is also compared and agrees well to that of a study regarding mathematical method predicting moment capacity of exterior connections.

An experiment on response of RC knee joints under cyclic loadings consisting of two specimens with a same size but different reinforcement in beam is chosen for simulation. Results show disagreement between simulation and observation indicates that the new joint model needs some further modification to predict cyclic performance of knee joints. A calibration of size and location of rigid bodies is maybe necessary. Moreover, test results imply big difference between maximum story shear in opening and closing mode. Other modifications regarding the participation of some struts and bar springs in different modes should be also considered.

To apply for 2D frame analysis, performance of a RC frame under cyclic loading is studied and verification with test result is also conducted. The frame has two stories with beams and columns simulated by 2D force-based line elements and joints modelled by the present beam-column connection element including five interior joints and six exterior joints. The result indicates reliability of the joint element in predicting well load deflection relationship of the frame. Analysis also shows advantages in comparison to cases of using rigid joint and using joint shear strength which overestimate the overall performance. Damage regarding deflection of the first floor, however, is not different between cases since it is often apparent on higher floor level.

## 4. Conclusion

Following conclusions are results of the research:

- A new 2D analytical model to simulate reversed performance of beam column joints derived from Shiohara joint hinging theory is proposed.
- Joint compatibility is successful introduced into Shiohara mechanism.
- The new joint element shows reliability regarding application on 2D interior joints, 2D exterior joints and 2D frame.
- Application of the model on analysis cyclic behaviors of knee joints returns in unreliable outcome, and further modifications are necessary.