論文 Effect of Strain Gradient on Confinement of Reinforced Concrete Columns

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ABSTRACT: Three-dimensional finite element analysis, which incorporating three-dimensional elasto-plastic and continuum fracture model, was utilized to study the effect of strain gradient on confinement of reinforced concrete columns. Section capacity was calculated based on stress-strain relationship for each local fiber in concrete section. For section with strain gradient, the capacity of reinforced concrete section increases significantly for the case of higher axial load, while ductility increases for lower axial load.
KEYWORDS: confinement, strain gradient, reinforced concrete columns, finite element analysis

1. INTRODUCTION

Nowadays, there are two general approaches to calculate the section capacity of reinforced concrete. The first approach is based on plain concrete stress-strain relationship as suggested by ACI Building Code [1]. This approach will give a conservative value, especially for reinforced concrete section heavily confined by lateral ties. The second approach is based on confined concrete stress-strain relationship under uniaxial compression as suggested by New Zealand Code [2].

Many stress-strain curves for plain and confined concrete have been proposed. Most of these models were derived empirically from experimental data of reinforced concrete columns loaded in uniaxial compression. Sheikh and Yeh [3] has extended the model to include the effect of flexural strain gradient. In calculating section capacity, this curve was used to represent stress-strain relationship for all fiber in the concrete section, regardless the location of the fiber. In fact, the amount of confinement across the concrete section under combined axial load and flexure is different. It causes stress-strain relationship across the section be different. The difference can be traced from the stress field and local inelasticity inside the concrete. For this purpose, analytical approach utilizing three-dimensional elasto-plastic and continuum fracture model was applied to understand the confinement mechanism for the section under combined axial load and flexure.

The aim of this study is to computationally investigate the effect of strain gradient on the confinement of reinforced concrete columns. To study the effect on section capacity, interaction diagram of axial load and bending moment for both unconfined and confined concrete section were calculated and compared. The effect on ductility was considered from the stress-strain curves of extreme fiber of concrete section. Local fiber stress-strain relationship along the depth of section was also studied to understand the effect of strain gradient on the confinement of reinforced concrete columns.

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2. THREE-DIMENSIONAL ELASTO-PLASTIC AND CONTINUUM FRACTURE MODEL

Nonlinear behavior of concrete is indicated by internal damage and plasticity. Internal damage represents the loss of elastic shear stiffness induced by the occurrence of micro-defects and the internal stress intensity, while plasticity denotes residual deformation. Micro defects were found not to affect the volumetric elastic energy capacity of concrete but elastic energy capacity in shear mode. Maekawa et al.[4] introduced fracture parameter K to indicate continuum damage occurring in the shear elasticity of concrete. Second invariant of elastic strains J_{2e} was proposed as a primary indicator of internal stress intensity, which evolves the continuum damage associated with the assembly of micro-defects. The damage is formulated of being suppressed by the three-dimensional confinement denoted by I_{1e} as well. Thus, the following indicators of concrete nonlinearity are used [4]:

Indicator of fracturing damage,

$$K = \frac{J_2}{2G_o J_{2e}} \tag{1}$$

Indicator of plasticity,

$$J_{2p} = \int \frac{\partial J_{2e}}{\partial \varepsilon_{eij}} d\varepsilon_{pij} \tag{2}$$

Indicator of internal shear stress,

$$J_{2e} = \sqrt{\frac{1}{2} e_{eij} e_{eij}} \tag{3}$$

Indicator of internal confinement,

$$I_{1e} = \frac{\varepsilon_{ekk}}{3} \tag{4}$$

Indicator of total shear stress,

$$J_2 = \sqrt{\frac{1}{2} s_{ij} s_{ij}} \tag{5}$$

Fracture parameter K represents continuum damage of concrete in terms of elastic shear strain energy. The smaller the value of K, the smaller the capacity of the concrete to absorb and release the elastic shear strain energy due to the induced micro defects. G_o is defined as the initial elastic shear modulus. Plastic indicator J_{2p} represents induced permanent deformation in shear mode and isotropic plastic indicator $I_{1p}(=\varepsilon_{pkk}/3)$ represents inelastic dilatancy. Notations ε_{eij} and ε_{pij} mean elastic and plastic strain tensors, respectively. The values of K and J_{2e} are related to the strength gain of confined columns and J_{2p} to the ductility. Constitutive laws were proposed incorporating the above nonlinear indicators. Details are discussed in reference [4].

3. SECTION ANALYSIS

Study of strain gradient effect on the confinement of reinforced concrete column was carried out by using section analysis. In this analysis, the local fiber stress-strain relationship along the height of section is needed to calculate the capacity of the section. Three dimensional finite element analysis, which is formulated based on constitutive laws described in previous chapter, was utilized to obtain the stress-strain relationship of confined concrete subjected to combined axial load and flexure across the section. Half of the spacing was taken as finite element domain. In this domain, neutral axis was determined and a linear displacement was enforced to the compression part of the section as shown in

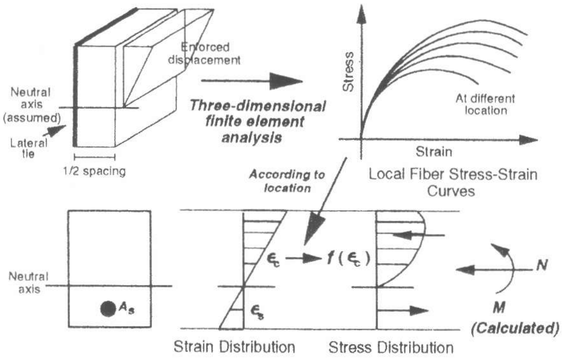

Fig. 1 Sectional Analysis of the Effect of Strain Gradient on the Confinement of Reinforced Concrete Columns

Fig. 1. Linear enforced displacement was used to create linear distribution of strain along the height of compression part of the section. Enforced displacement was increased proportionally until the stress at the extreme fiber declined. At each integration point, local fiber stress-strain relationships were obtained. Then, the average stress-strain relationships for each fiber where the integration points are located were calculated and recorded.

After the local fiber stress-strain relationships were obtained, the calculation of sectional capacity was conducted based on the strain compatibility along the height of the section. For a specific strain distribution, stress distribution can be obtained from the local fiber stress-strain relationships. Using this strain distribution, the strain in the longitudinal reinforcing bars was also calculated. Elasto-perfectly plastic relationship was used to get the stress at longitudinal reinforcing bar. Finally, by imposing force equilibrium condition, capacity of the section were calculated. In this calculation, tensile stress contribution from concrete was neglected and perfect bond between reinforcing bars and concrete was assumed. **Figure 1** shows the procedure to obtain the capacity of reinforced concrete section.

4. STUDY CASE

4.1 MATERIAL PROPERTIES AND FINITE ELEMENT DISCRETIZATION

Study case was performed to understand the effect of strain gradient on the capacity and ductility of reinforced concrete column. Two reinforced concrete columns with cross section size of 400 x 600 mm were selected. One of the column was unconfined and the other was confined by lateral ties. For confined column, volumetric lateral reinforcement ratio and spacing between the lateral ties were 2 % and 100 mm, respectively. Longitudinal reinforcement ratio for both columns was 2 %. Compressive strength of concrete was 30 MPa, while the yield strength of reinforcing bar was 300 MPa.

Half spacing of concrete was taken as domain for finite element analysis to obtain the local fiber stress-strain relationship of confined concrete across the section. Isoparametric 20-node solid element and Timoshenko beam element were applied to represent concrete and lateral ties, respectively. Two solid elements were used to discretize the half spacing concrete, while six solid elements were used along the height of the section. Due to symmetry, only half of the column was considered in the width direction and discretized by two solid elements. Totally, twenty-four solid elements were used to model the concrete in the analysis to obtain the local fiber stress-strain relationship of confined concrete subjected to the combination of axial load and flexure. The finite element discretization can be found in **Fig. 2**. From the finite element analysis, local fiber stress-strain relationships were obtained.

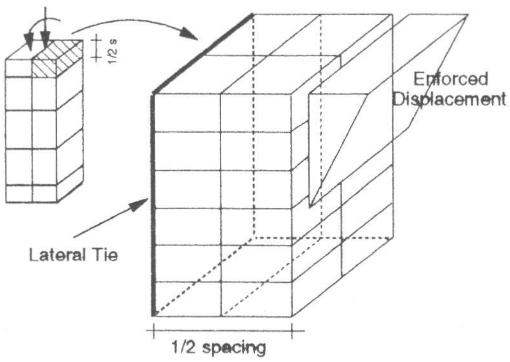

Fig. 2 Finite Element Discretization

Using these local fiber stress-strain relationship, the capacity of section was calculated by applying the strain compatibility and force equilibrium in the section. By changing the position of neutral axis, the load eccentricity was changed and a new set of axial and bending moment load combination capacity was obtained. Finally, a full interaction diagram between axial and bending moment can be drawn. The calculation for both cases, unconfined case where there is no lateral ties and confined case where the lateral ties was applied around the cross-section, were conducted.

4.2 RESULTS AND DISCUSSIONS

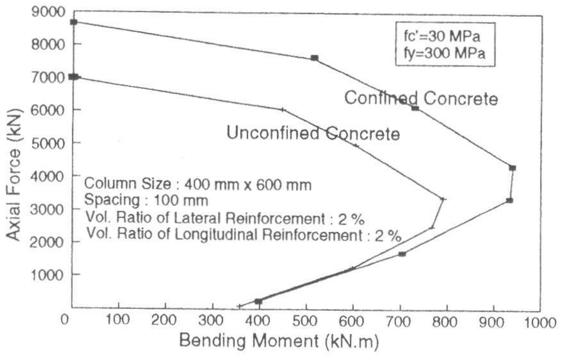

Fig. 3 Comparison of Interaction Diagram between Unconfined and Confined Section

Figure 3 shows the result of interaction diagram between axial load and bending moment for both unconfined and confined concrete. Since different combination of axial load and bending moment means different strain gradient, the effect of strain gradient on confinement can be studied by comparing these interaction diagrams.

The effect of strain gradient on confinement, which in turn affects the capacity of reinforced concrete columns is significant for the case of high axial load. **Figure 3** shows section capacity of confined concrete is higher than the capacity of unconfined concrete especially when subjected to larger axial load. This phenomena was previously observed experimentally by Priestley and Park [5] and Sheikh and Yeh [6]. For smaller axial load or when the column is under pure bending moment, there is no significant section capacity improvement due to confinement. This can be attributed to the fact that section capacity is relatively independent of the concrete strength at and below balanced load. Although the concrete strength is greatly affected by the confinement due to the strain gradient, the effect to the section capacity is therefore considerably small. At large axial load level, since the strength of concrete has significant effect on its section capacity, the capacity difference between unconfined and confined section is significant as shown in **Fig. 3**.

The effect of strain gradient on the ductility can be observed from the stress-strain relationship of extreme fiber as shown in **Fig. 4** and **Fig. 5** for unconfined and confined concrete, respectively. For unconfined concrete, the closer the neutral axis from the extreme compression fiber of concrete, which

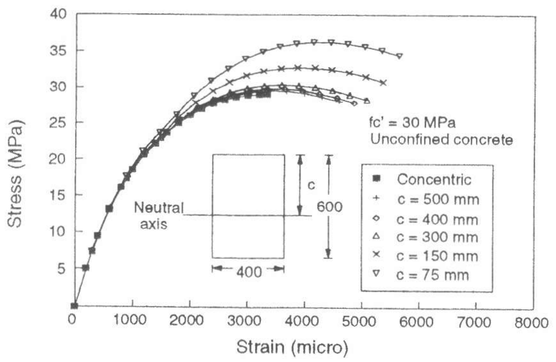

Fig. 4 Effect of Strain Gradient on Stress-Strain Relationship of Extreme Fiber for Unconfined Concrete Section

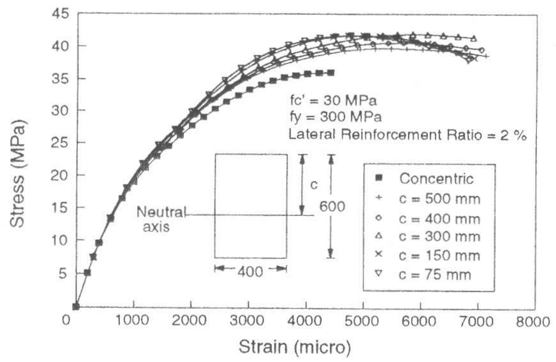

Fig. 5 Effect of Strain Gradient on Stress-Strain Relationship of Extreme Fiber for Confined Concrete Section

means the smaller the axial force, the ductility of extreme fiber increases as shown in **Fig. 4**. Similar effect was experimentally observed by Zhang et al. [7]. For confined concrete, as the neutral axis is closer to the extreme compression fiber, the ductility increases, but then the ductility decreases when the condition is approaching to the condition of pure bending moment as observed in **Fig. 5**. In both cases, the strength and ductility of extreme fiber of concrete under strain gradient is higher than the strength and ductility of concentric loaded concrete. The effect of confinement can be also observed from **Figs. 4** and **5**, the stress-strain relationship of extreme fiber of confined concrete as shown in **Fig. 5** has a higher strength and ductility compared to the unconfined one in **Fig. 4**.

To compare the result of section analysis conducted by using finite element analysis and the method suggested by different codes, interaction diagram between axial load and bending moment were also calculated based on plain concrete stress-strain relationship as suggested by ACI Building Code [1] and confined concrete under uniaxial compression load as suggested by New Zealand Code [2].

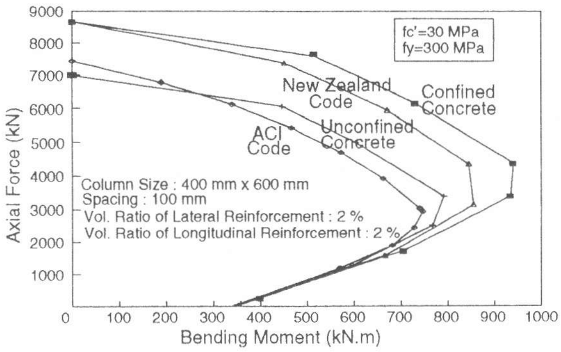

Fig. 6 Comparison of Interaction Diagram between the Result from Finite Element Analysis and Analyses Suggested by Some Codes

Comparison between the result from finite element analysis for unconfined and confined concrete and from the analysis suggested by ACI Building code and New Zealand code are shown in **Fig. 6**. The calculation suggested by ACI Building Code is close to the finite element analysis for unconfined column, while the calculation suggested by New Zealand Code gives the result close to finite element analysis result for confined concrete column. It conforms that the method suggested by New Zealand Code is more realistic than the one suggested by ACI Building Code in predicting the capacity of reinforced concrete column confined by lateral ties subjected to the combined axial load and flexure. **Figure 6** shows that New Zealand Code underestimates the effect of confinement on the capacity of confined concrete for the case of larger axial loads. It indicates that in this case the average stress-strain relationship of reinforced concrete column with strain gradient is higher than the stress-strain relationship of concrete subjected to concentric load, on which the New Zealand Code was based.

5. LOCAL FIBER STRESS-STRAIN RELATIONSHIP

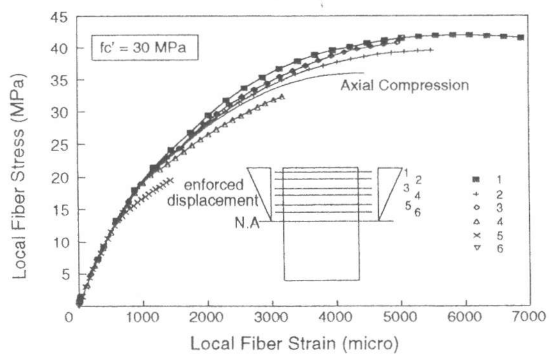

Fig. 7 Local Fiber Stress-Strain Curves

To observe confinement mechanism due to strain gradient, it is important to look at the local fiber stress-strain relationship in each fiber along the height of section. **Figure 7** shows local fiber stress-strain curves for the above mentioned confined reinforced concrete column used as a study case where the neutral axis is at the middle of cross section. The extreme fiber of this section experiences confinement from lateral ties and there is a significant improvement of capacity and ductility of this fiber. Stress-strain relationship for extreme fiber is higher than the stress-strain from the concentric loading. The effect of confinement on the concrete fiber reduces as the location of fiber is closer to the neutral axis. Stress-strain curve of the fiber near to the neutral axis is lower than that of concentric loading. It indicates that due to the strain gradient, the level of confinement in each fiber is not constant and the average behavior is not similar to the stress-strain relationship under concentric loading. It is the source of discrepancy between the result of interaction diagram between the case of confined concrete calculated by finite element analysis and the analysis suggested by New Zealand Code, which uses the stress-strain of section under uniaxial compression.

However, as a simplified method New Zealand method gives a good approximation for the capacity of reinforced concrete columns subjected to combined axial load and flexure.

6. CONCLUSIONS

Three-dimensional elasto-plastic and continuum fracture model can be applied to obtain local fiber stress-strain relationship. Stress-strain relationship of each fiber across the section subjected to strain gradient was found not similar to the one subjected to uniaxial compression.

Strain gradient affects local fiber stress-strain relationship of concrete across the section. Strain gradient increases the peak stress and ductility of extreme compression fiber for both unconfined and confined concrete. The peak stress and ductility of this fiber is higher than those of section subjected to uniaxial compression

Capacity of the section with strain gradient increases significantly due to the confinement for high axial loads, while the ductility increases for lower axial loads.

Analysis method using stress-strain relationship of concrete under uniaxial compression as suggested by New Zealand Code gives good and realistic section capacity estimation for the section subjected to combined axial load and flexure.

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