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論 文

[2111] Effect of Flexural Stiffness of Lateral Reinforcement on Confinement of Reinforced Concrete Columns

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1. INTRODUCTION

A way to achieve the required ductility in the critical regions of seismic resistant reinforced concrete columns is to use lateral reinforcement. Lateral bars that surround the core concrete will give some resistance in the form of three-dimensional confinement to the core concrete. As widely known, this confinement will increase the strength and ductility of the core concrete. Degree of influence of lateral bars to three-dimensional stresses and in turn to the strength gain and ductility of core concrete depends on geometrical factors, such as volumetric ratio of steel, shape and distribution of reinforcement, spacing, and properties of steel and concrete.

Since lateral bars will affect the stress distribution inside core concrete, accurate modeling of the lateral bars in the analysis is crucial. In general, truss modeling of lateral bars, which is rooted in axial stiffness of bars and causes "corner action", is regarded as appropriate for lightly reinforced lateral steel [1,2,3]. However, it was also reported that large reinforcement induces additional confinement owing to the shear and flexural stiffness of bars [4]. The aim of this study is to experimentally and analytically verify how large the influence of beam actions of ties to the confinement of core concrete and how effectively it gives rise to the strength and ductility gain.

2. FLEXURAL RESPONSE OF LATERAL TIES

Most of previous analytical studies discussed the confinement action based on the concept that reinforcing bar work as truss element with just axial stiffness. On the basis of this model, for square and rectangular sections, the confinement action comes from corners of the section as shown in Fig. 1. Truss modeling of ties corresponds to no contact between tie arms and core concrete. On the other hand, if reinforcing bar is modeled as beam elements with axial, shear and flexural stiffness, confinement action develops not only at the corners, but also from the contact between tie arms and core concrete.

Truss modeling can be justified, if the diameter of the lateral bar is small enough compared to the core size where shear and flexural stiffness of reinforcing bars can be neglected compared to the axial

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stiffness. However, when larger diameter is used and contact between tie arms and concrete is present, the validity of this modeling is questionable [4].

The difference between both mechanisms of confinement can be recognized from the curvature profile which arises along tie arms of reinforcing bars. Induced moment along the tie bar is proportional to the curvature profile under elasticity. Beam action is not prominent if the curvature along the bar is negligibly small and truss-element assumption for ties can be adopted for this case..

To consider the effect of beam action of reinforcing bars, two pairs of experiments were conducted. Each pair consists of two columns with the same size of bar diameter. Size of core concrete in the first pair is different, but the ratio of spacing is relatively similar. The core size of the first column is 200 mm x 200 mm, and another one is 150 mm x 150 mm. It can be seen from Fig. 2a that column with smaller core section produces higher curvature in its tie arms than the one with larger core size. In the second pair, two columns with the same size of core and bar diameter, but different spacing are compared. Fig. 2b shows that the column with smaller spacing gives higher curvature in its tie arm. From these experiments, it is shown that the curvature is influenced significantly by the confinement arrangement.

Different curvature profile from the above observations will give rise to different bending moment in the ties. This moment must be equilibrated with both the shear of steel and contact forces acting on the core concrete. The higher the moment, the larger contact forces and confinement along the tie arms will be induced.

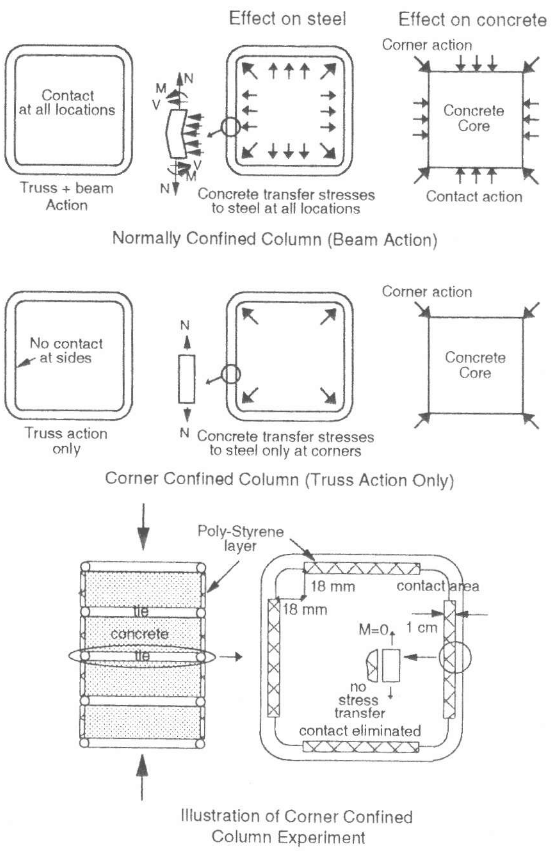

Fig.1 Different Mechanisms of Confinement

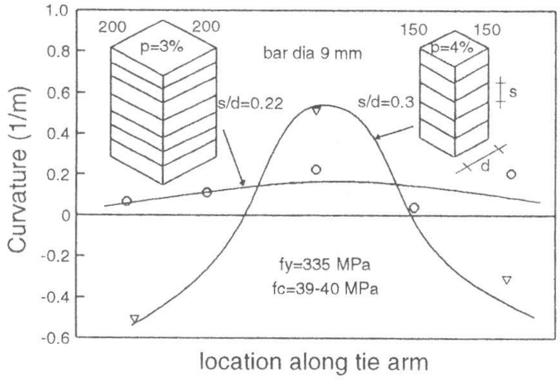

Fig. 2a Curvature Profiles along Lateral Tie in Columns with Different Core Size

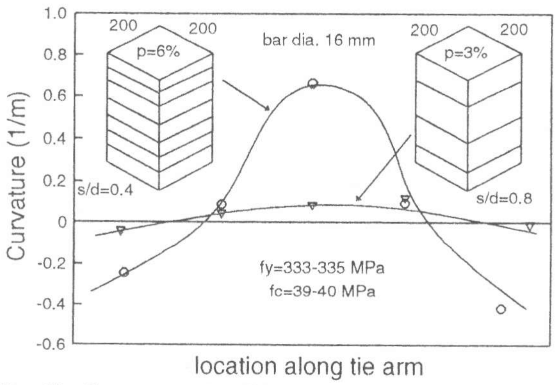

Fig. 2b Curvature Profiles along Lateral Tie in Columns with Different Spacing

3. BEAM ACTIONS OF TIES ON CONFINEMENT

In order to clarify the role of flexural stiffness in reinforcing bars, one experiment which consists of two columns has been conducted. Two columns with the same material properties and configurations, but different contact condition between tie arms and core concrete were tested as shown in Fig. 1. In the first column, all parts of tie arms are in contact with the core concrete. In another column the contact is allowed only at the corners, the contact along the tie arms was cut off by means of Poly-Styrene layer, which can easily deform. By cutting off the contact along the tie, the transfer of forces along the tie is prevented, even though tie possesses shear and flexural stiffness. The stress transfer between steel bars and concrete happens only through the corners. It simulates the reinforcing bars that act as truss element without any flexural stiffness. Details of experiment can be found in ref. 5. Figure 3 shows the curvature profiles obtained at the peak strength of core concrete. Higher curvature is induced along the tie bar in normally confined column compared to the one with corner confined.

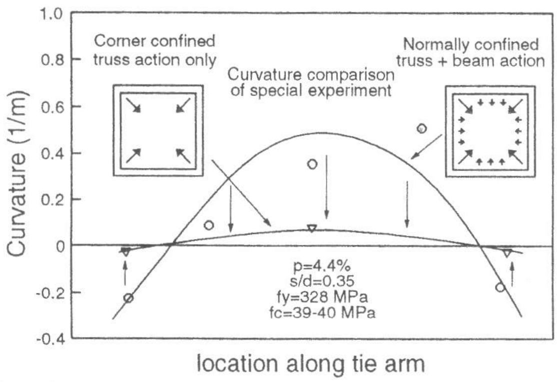

Fig. 3 Curvature Profiles of Lateral Ties in Corner and Normally Confined Columns

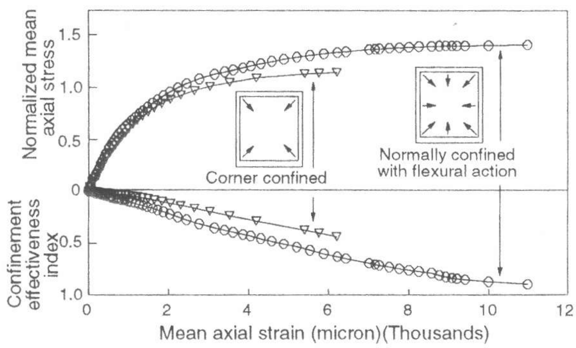

Fig. 4 Mean Axial Stress-Strain and Confinement Level Relations of Corner and Normally Confined Columns

To quantify the confinement level in core concrete, confinement effectiveness index (α) is used as a representative quantity. This index is a ratio of volumetric averaged confinement in core concrete (σ_v) to the maximum confinement that can be produced by confining agents as shown in eq.1. σ_v can be obtained from the lateral confining stress developed in core concrete and based on the equilibrium can be expressed in terms of stress generated in lateral ties [4]. The maximum level of confinement will be achieved when the lateral ties yield. ρ is volumetric ratio of lateral ties and f_y is the yield stress of lateral ties.

$$\alpha = \frac{\sigma_v}{\frac{1}{2}\rho f_y} \qquad (1)$$

Although the maximum available confinement capacity is similar, it can be seen from Fig. 4 that the corner confined column produced considerably less confining stress compared to the normal one with the beam action. The reduction of confinement effectiveness can be attributed to the absence of confinement transferred along the ties with shear and flexural stiffness. Due to the reduction of the effectiveness of confinement, the peak strength and ductility of corner confined column is lower than that of the normally confined column as shown in Fig.4. The reduction of strength gain is around 60% and ductility is reduced around 40%. From these experiments, it is found that the inclusion of beam action of reinforcing bars in the analysis is indispensable in enhancing the prediction of confinement effectiveness, especially for higher reinforcement ratio with larger diameter bars as compared to the core size.

4. FINITE ELEMENT STUDY

Since confinement produced by lateral bars on the core concrete creates complex triaxial state of compression [3], three-dimensional finite element analysis is substantial for doing the analytical study. Three-dimensional computer program "COM3" [6] was utilized for this purpose. In COM3, an elasto-plasticity and fracturing model [7] that can evaluate the internal damage and the plasticity of damaged continuum under three-dimensional stress states is adopted for concrete. On the basis of this model, material state variables indicating the induced damage K and plasticity J_{2p} are introduced in the constitutive laws. The value of fracture parameter K indicates the degradation of shear mode elasticity caused by micro-cracks and defects and the value of J_{2p} indicates the accumulated plasticity in the shear mode of damaged continuum [7]. Reinforcing bar is modeled as an elasto-plastic material.

Solid 20-node isoparametric element and either three-dimensional truss or Timoshenko's beam element are used to represent concrete and reinforcing bars, respectively. Detail of discretization of finite elements is similar to previous study [3]. Since our main concern is until the peak stress, geometical non-linearity is not considered. Comparison of the results from FEM analysis and experiments can be seen in Fig. 5. In general, FEM predictions are in good agreement with the results from experiments for both strength and ductility.

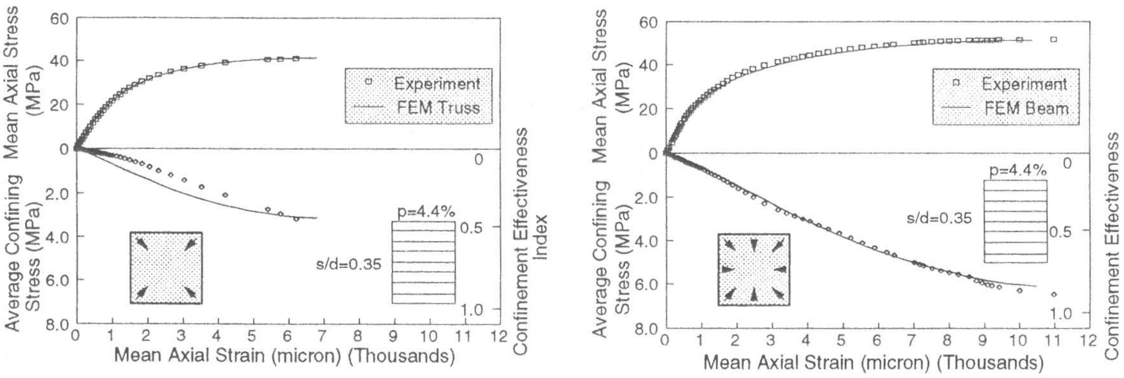

Fig. 5 Comparison of Results from FEM Analysis and Experiments

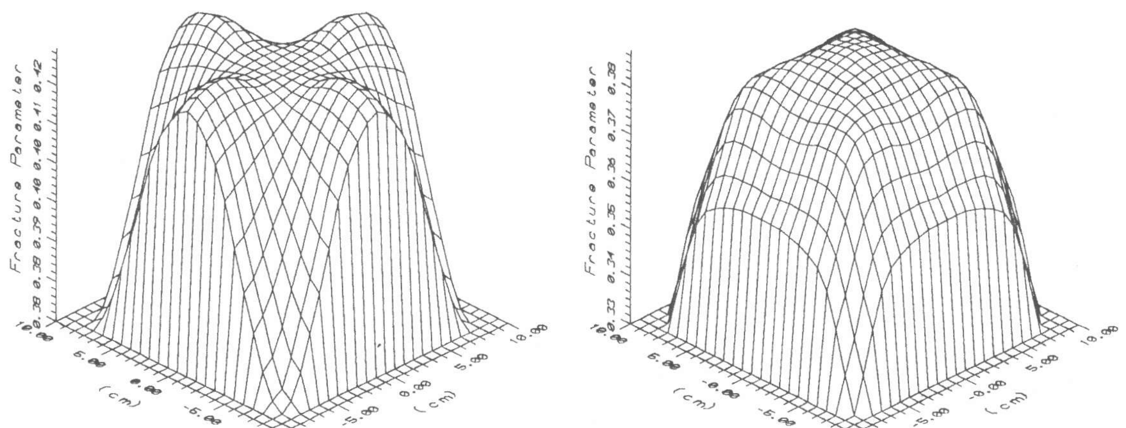

Fig. 6a Spatial Distribution of Damage of Truss-idealized Analysis at Critical Section

Fig. 6b Spatial Distribution of Damage of Beam-Idealized Analysis at Critical Section

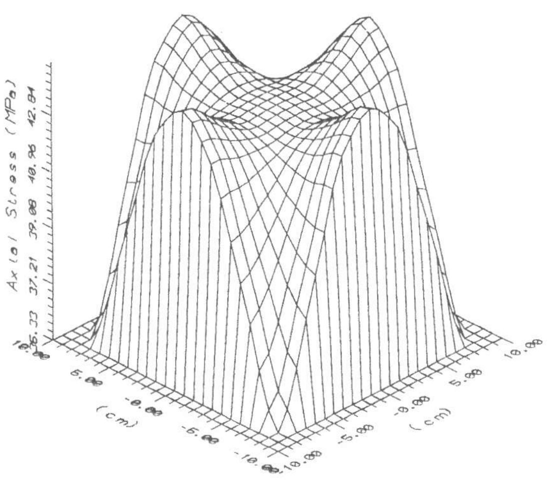

Fig. 7a Distribution of Axial Stress of Truss-idealized Analysis at Critical Section

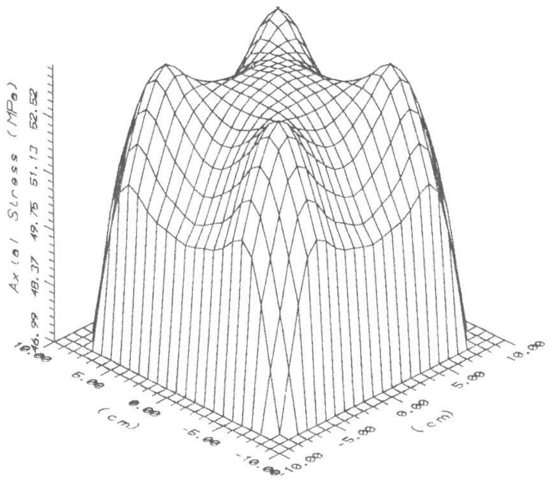

Fig. 7b Distribution of Axial Stress of Beam-idealized Analysis at Critical Section

Clearer and better understanding about the mechanism of confinement can be achieved from studying the distribution of local damage and plasticity which can be obtained from FEM analysis. Fracture parameter indicating the continuum damage at peak stress condition at a critical section between two ties of truss-idealized and beam-idealized analysis is shown in Fig. 6a and Fig. 6b, respectively. It should be noted that lower values of fracture parameter indicates more micro-cracks and defects which occur in core concrete. Figures 7a and 7b show axial stress distributions at peak stress condition at a critical section of truss-idealized and beam-idealized analysis, respectively.

It is shown that the beam-idealized analysis gives more uniform distribution of both fracture parameter and axial stress at critical section compared to the truss-idealized analysis. It is attributed to the presence of beam action along tie arms of lateral bars. Owing to the mechanically effective utilization of tie steel, core concrete in beam-idealized analysis can carry more loads compared to truss-idealized analysis, although higher damage is induced in beam-idealized case.

5. INFLUENCING RANGE OF BEAM ACTION

To justify the use of truss-idealized reinforcing bars in the analysis, the range in which beam action is negligible should be identified. Since beam action is directly related to the flexural stiffness of tie members, the ratio of flexural stiffness to axial stiffness of tie section is an appropriate basic parameter to be used in this identification. For circular cross section of the bar, this ratio is proportional to the square of the ratio of bar diameter to its span, $[(\phi/L)^2]$. It also should be noted that for square section column, the value of $[(\phi/L)^2]$ will be fixed for certain amount of lateral ties and spacing.

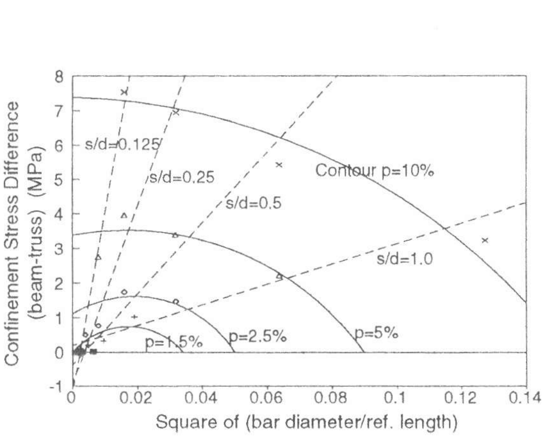

Fig.8 Influencing Range of Beam Actions on Confinement

Since the two models of reinforcing bars will give rise to different confinement stress for the same amount of steel and spacing, the identification is done in terms of the difference of this stress arising in lateral ties based on beam- and truss-idealized analysis. From Fig. 8 it is seen that for lateral reinforcement ratio below 1.5% and the square of bar diameter to its span $[(\phi/L)^2]$ less than 2%, the effect of flexure stiffness is negligibly small.

6. CONCLUSIONS

It is concluded that from experiments and analytical study that shear and flexural stiffness of lateral bars will affect the stress and fracture distribution in core concrete. Shear and flexural stiffness of lateral bars will improve the confinement to the core concrete, which will create more uniform distribution of stress and fracture. This additional confinement will increase the strength gain and ductility.

Triaxial elasto-plasticity and continuum fracturing concrete model based finite element program "COM3" is verified to be able to predict the stress-strain of confined column and confinement stress arising in the reinforcing bars quite well for both truss- and beam-idealized analyses of reinforcing bars.

It is also shown that for square section, shear and flexural stiffness (beam action) is negligibly small if the lateral reinforcement ratio is smaller than 1.5% and the square of bar diameter to its span $[(\phi/L)^2]$ is less than 2%. Above this range, beam action of lateral ties should be taken into account in the analysis of three-dimensional reinforced concrete column members. Here, full three-dimensional finite element analysis was used as a simulator in order to reproduce the perfect truss and beam actions and to separate their effects.

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