NONLINEAR ANALYSIS OF LATERALLY LOADED REINFORCED CONCRETE PILES

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ABSTRACT: Reinforced concrete piles embedded in homogeneous sandy soil were analyzed using a three-dimensional nonlinear finite element program, COM3, developed in Concrete Laboratory, The University of Tokyo. Nonlinear space frame element was used for the modeling of reinforced concrete piles. The applicability of the models was checked by comparing the analytical results with the experimental ones. It was found that the analysis was able to predict the behavior for general cases, but in the case of large deformation, the analysis underestimated the inelastic axial deformation. The difference of the analytical and experimental results was thought to be caused by the spalling of cover concrete and buckling of reinforcing bars. Hence, both cover concrete spalling and reinforcement buckling were modeled and included in COM3. Significant qualitative improvement was observed in the inelastic axial deformational behavior of the RC piles.

KEYWORDS: cover concrete spalling, inelastic axial deformation, reinforcement buckling

1. INTRODUCTION

In laterally loaded piles, the ultimate failure and the horizontal inelastic behavior are mainly governed by the surrounding soil foundation because the stiffness of soil is comparatively higher than that of the piles. Hence, the RC piles can be loaded until the compressive strains in the reinforced concrete fibers are large enough to cause significant cover concrete spalling and reinforcement buckling. However, in superstructures, the ultimate strength is governed by the strengths of reinforced concrete itself. Hence, the columns usually fail by shear or flexure and the contribution of spalling of cover concrete and buckling of reinforcement in the ultimate stage is not so significant. Moreover, the relative cover in case of piles is larger than that of large-scale columns. Hence, in order to get the reliable response of soil-pile structures in highly inelastic range, cover concrete spalling and reinforcement buckling mechanisms should be considered in the analysis. In the past, various experimental and analytical studies have been done on the buckling of bare bar reinforcement [1,2,3]. However, fewer studies have been done regarding the spalling behavior of cover concrete and integration of spalling and buckling behavior to be applied in reinforced concrete [4]. COM3 includes fiber model for reinforced concrete frame elements. Existing fiber model does not consider the cover concrete spalling and reinforcement-buckling behavior. In this study, both spalling and buckling behavior are modeled and incorporated into COM3. The verification and application of the presented models are also discussed.

2. ANALYTICAL MODELS

2.1 FIBER MODEL

In fiber model [5], the member cross section is divided into a mesh of cells or sub-elements. Within each sub-element, the strain is assumed constant and equal to the strain at the center of gravity of that

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sub-element. Non-linear path-dependent constitutive models are used for concrete and steel existing in each cell (fig. 1). Those models have been verified in the element and member levels with satisfactory results, and have been incorporated in COM3 for three-dimensional analysis of reinforced concrete under monotonic and cyclic loading [6]. In order to consider the phenomenon of localization of tension stiffening, effective RC zoning method proposed by An et al [7] is used, in which the concrete fibers are divided into RC and PL zones depending on the distance of the fiber from nearby reinforcing bar. The tensile response of the two zones is different as shown in figure 2.

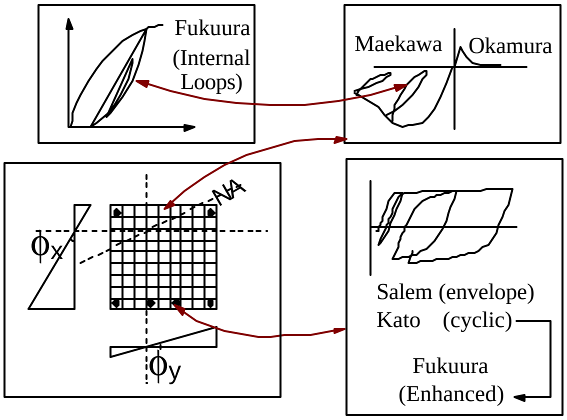

Fig. 1. Constitutive Models of Constituents of Each Fiber

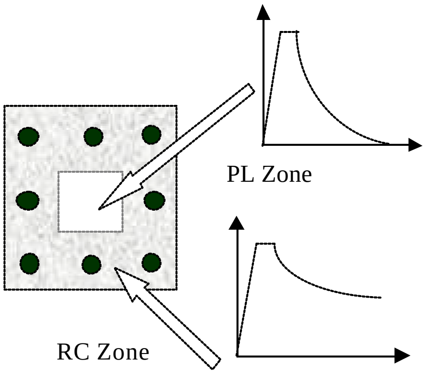

Fig. 2. RC Zoning (An et al, 1996)

2.2 BUCKLING MODEL OF BARE BAR

A trilinear post-buckling stress-strain relationship as shown in figure 3 is simply proposed based on some experimental results [9]. After the yielding strain in compression is reached, stiffness is determined depending on the yield strength of steel and the spacing of stirrups to longitudinal bar diameter ratio. For cyclic behavior, a smooth transition curve asymptotic to the tangents at the point of stress reversal and the point of maximum or minimum strain in the loading history, as proposed by Pinto et.al [8], is used (fig. 3).

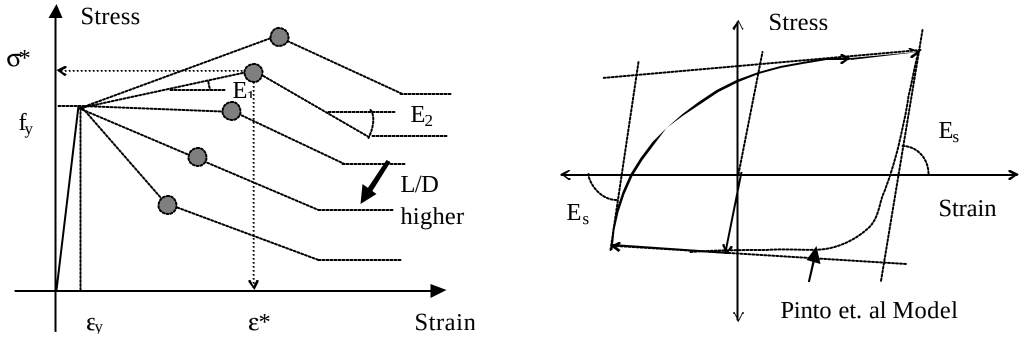

Fig. 3. Monotonic and Cyclic Buckling Model

$$\frac{e^*}{e_y} = 1 + 2.5\frac{E_s}{f_y^{1.8}}\left(14 - \frac{L}{D}\right) \qquad \text{For L/D <12} \qquad \text{Eq (1)}$$

$$\frac{e^*}{e_y} = 1 + 5\frac{E_s}{f_y^{1.8}} \qquad \text{For L/D >12} \qquad \text{Eq (2)}$$

$$\frac{s^*}{f_y} = \frac{470}{f_y}\left(\frac{5000 + 3f_y}{1000} - \frac{L}{D}\right) \quad ; \frac{s^*}{f_y} \geq 0.5 \qquad \text{Eq (3)}$$

$$E_1 = \frac{s^* - f_y}{e^* - e_y} \quad ; s = -f_y + E_1(e + e_y) \qquad for(-e_y \leq e \leq -e^*) \qquad \text{Eq (4)}$$

$$E_2 = 0.03 * E_s \quad ; s = -f_y + E_1\left(e^* + e_y\right) + E_2\left(e + e^*\right) \qquad for(e < -e^*) \qquad \text{Eq (5)}$$

$$s \leq -0.6 * s^{*} \qquad \text{Eq (6)}$$

2.3 MODEL VERIFICATION

The results of the proposed analytical model are compared with experimental results of Monti et al [9]. A series of monotonic and cyclic tests on steel rebars having nominal yield strength of 440 MPa and with different *L/D* ratio were carried out. As shown in figure 4, the proposed model is in fair agreement with the monotonic and cyclic experimental results. It is found that the lower the *L/D* ratio, buckling effect decreases. For *L/D* ratio equal to 5, buckling effect nearly diminishes and the response becomes same as that in tension. Moreover, the cyclic response of reinforcement in tension is independent of *L/D* ratio and the extent of buckling attained in the past loading history.

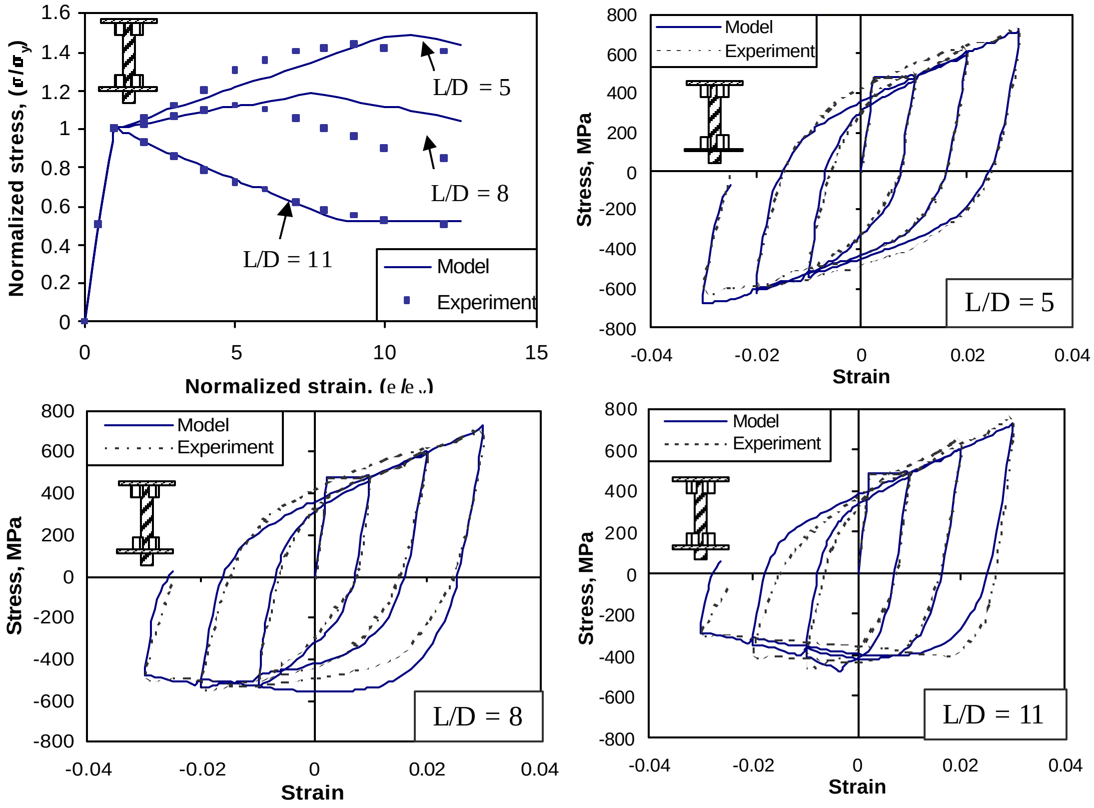

Fig. 4. Model Verification for Monotonic and Cyclic Cases

2.4 SPALLING AND BUCKLING CRITERIA FOR FIBER MODEL

The buckling of reinforcement takes place only after the cover concrete spalls. At this stage, the core concrete provides lateral support to the reinforcement so that the reinforcement buckles outwards, where the cover concrete is already spalled. It is assumed in this study that the reinforcement buckles between the lateral ties, which was experimentally observed in compression tests of Bresler et al [10]. Depending on the arrangement and strength of lateral ties, it is also possible that the buckling length extends to several tie spacing. But if the size of the lateral ties is designed properly so that the stiffness of the stirrup is high enough to provide a rigid support to the longitudinal bar, the former assumption holds good.

For the spalling of cover concrete, strain based criterion is used. Concrete fibers are divided into two parts. The concrete fibers outside the longitudinal reinforcement are modeled as cover concrete and the rest as core concrete. As shown in figure 5, once the compressive strain in the cover concrete fibers exceeds the peak strain of the concrete, the stresses transferred by these fibers are reduced to zero. Pre-spalling behavior of cover concrete is represented by elasto-plastic and fracture model, which is same for the core concrete behavior.

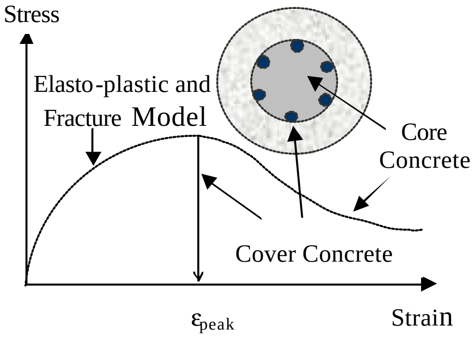

Fig. 5. Spalling of Cover Concrete

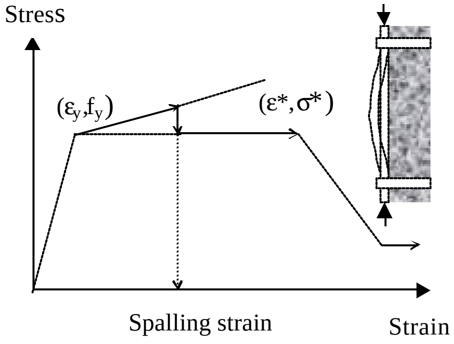

Fig. 6. Buckling Model of Reinforcement

In order to cope with the fact that spalling precedes buckling, the bare bar buckling model is modified so that buckling effect is not considered before the surrounding cover concrete is completely spalled out. The buckling model modified for reinforced concrete is shown in figure 6.

3. APPLICATION TO SOIL-PILE STRUCTURE

3.1 TARGET STRUCTURE

The experimental study of Tsuchiya et al. [11] is taken. The setup consists of a reinforced mortar pile enclosed in sandy soil. The height of the soil specimen is 800 cm and the cross section is 250*250 cm. The pile is located in the center of the soil and it extends to the mid-depth of the soil layer. The pile is fixed against rotation at the top. A compressive stress of 2 MPa is applied at the top of the pile. The pile is circular with 15cm diameter and is reinforced with deformed bars, the reinforcement ratio is 0.96%. The soil layers in the upper half has the density of 0.0014kg/cm^3 and the SPT value ranges between 0 to 10. Whereas, for the lower half, the density is 0.0017kg/cm^3 and the corresponding SPT value is around 40. A shear plate confines the soil and the displacements are applied by horizontal jacks. Cyclic lateral loading is gradually applied in four cycles to the pile cap as shown in figure 7. Two cases, maximum applied lateral displacements equal to 6 cm and 18 cm, are taken into account.

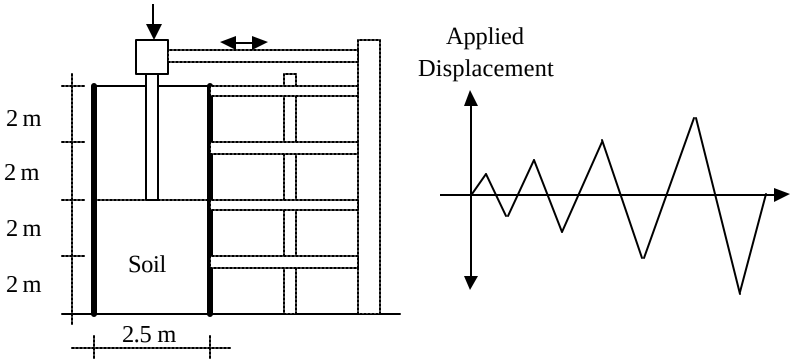

Fig. 7. Target Structure and Applied Loading

3.2 RESULTS AND DISCUSSION

For medium loading; i.e. maximum applied displacement is 6 cm, the analytical results without considering either spalling and buckling or geometrical nonlinearity are in good agreement with the experimental results (fig. 8). The load-displacement relationship, axial deformation of pile top, and the steel strain distribution could be reliably predicted by the analysis. In this case, the maximum compressive strain attained in the reinforcement is relatively small (less than two times of yield strain). Hence, the effect of spalling and buckling is found to be negligible. Consequently, the response could be fairly predicted without considering spalling of cover concrete and buckling of reinforcement.

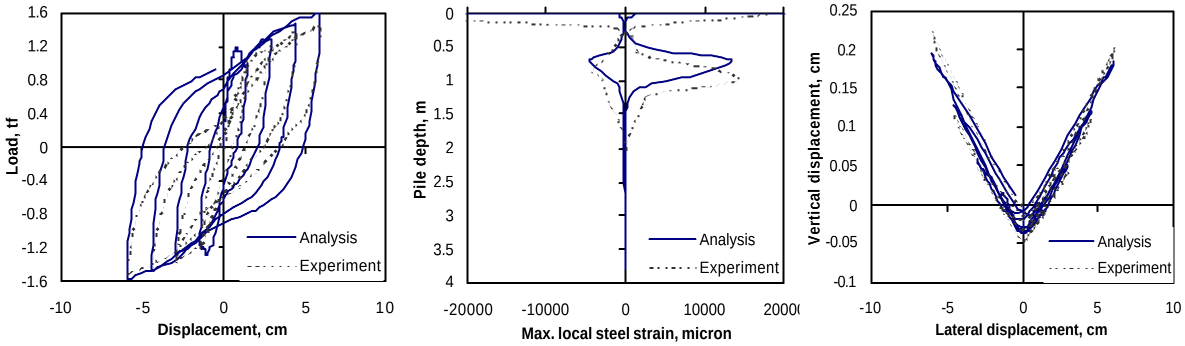

Fig. 8. Analytical and Experimental Results for Medium Loading

In spite of not considering spalling and buckling for large deformation case, the lateral load-lateral displacement relationship could be fairly predicted (fig. 9) because the lateral response in inelastic range is mainly governed by surrounding soil. The maximum steel strain in compression observed in experiment as well as analysis is very high. Moreover, spalling of cover concrete and buckling of reinforcement could be observed in experiments just below the pile cap and at 80 cm below the soil surface, which are close to the positions of maximum strain in the analytical results (fig. 10).

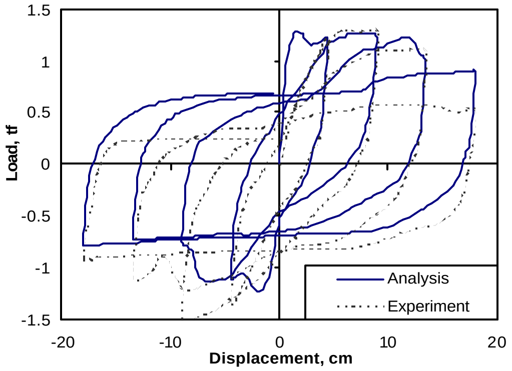

Fig. 9. Load Displacement Relationship

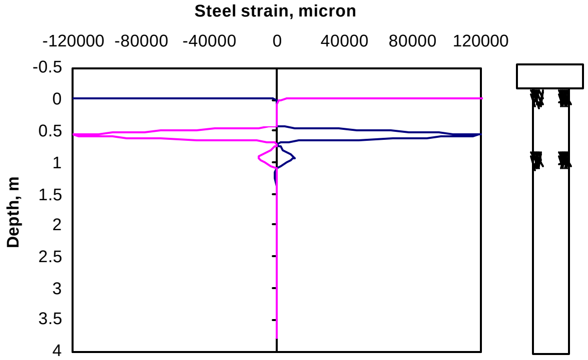

Fig. 10 Maximum Local Steel Strain in Analysis

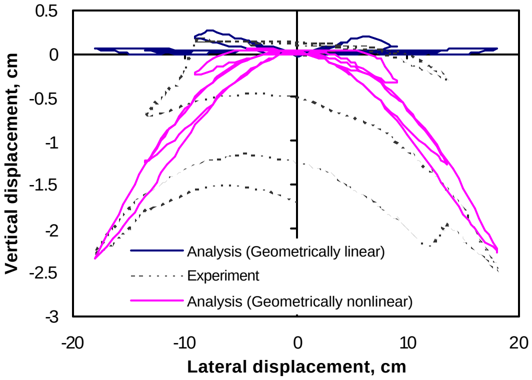

Fig. 11. Axial Deformation without Spalling & Buckling

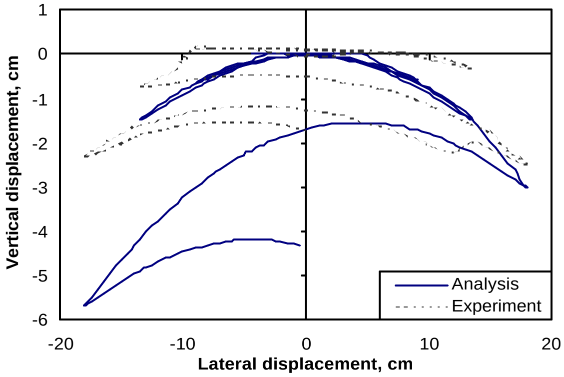

Fig. 12. Axial Deformation with Spalling & Buckling

Nevertheless, there exists a big difference between the experimental and analytical results regarding axial deformation (fig. 11). The axial deformation in inelastic range is considerably increasing in the experiments, whereas the analysis without considering spalling and buckling behavior could not capture this tendency at all. The discrepancy, which lies especially in the inelastic axial deformation of the pile, is thought to be caused by the spalling of cover concrete and buckling of reinforcement. However, after considering the geometrical nonlinearity, the curvilinear nature of the axial displacement could be captured, but the residual axial deformation is still nearly equal to zero (fig. 11). The same structure was re-analyzed after including spalling and buckling criteria in fiber model. Figure 12 shows the axial deformation-horizontal deformation relationship of the pile top. Significant qualitative improvement in axial deformation is found after incorporating spalling and buckling behavior in the analysis. The inelastic axial deformation is increased significantly. However, there still exists some quantitative difference between the experimental and analytical results.

4. CONCLUSIONS

A reinforcement buckling model is proposed and verified by comparing with some experimental results of bare bar compression. It is shown that the model can satisfactorily capture the monotonic and cyclic behavior of reinforcing steel. The buckling model of bare bar is combined with an assumed spalling criterion and included in fiber model for analyzing reinforced concrete structures. It is found that the fiber model can reliably predict the behavior of reinforced concrete pile for medium loading. In such case, the load-displacement relationship as well as steel strain distribution and axial deformation of pile also can be fairly predicted by fiber model without considering spalling and buckling. But in case of large deformation, the compressive strain in the outer concrete fibers and in the steel fibers are found large enough to cause sufficient spalling of cover concrete and buckling of reinforcement. Moreover, buckling and spalling take place only in the inelastic range, where the lateral response of underground pile is mainly governed by surrounding soil. Hence the lateral load-displacement behavior could be reliably predicted even without giving due consideration to spalling and buckling mechanism. It is found that the axial residual deformation in inelastic region is mainly governed by the spalling of cover concrete and buckling of reinforcement. After considering spalling and buckling behavior in the analysis, significant qualitative improvement was found. However, there still remains some quantitative difference, which needs to be dealt further in future.

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