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Reduction of Differential Column Shortening in Tall Buildings

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***Abstract*—**The differential column shortening in tall buildings can be reduced by improving material and structural characteristics of the structural systems. This paper proposes structural methods to reduce differential column shortening in reinforced concrete tall buildings; connecting columns with rigidly jointed horizontal members, using outriggers, and placing additional reinforcement at the columns. The rigidly connected horizontal members including outriggers reduce the differential shortening between adjacent vertical members. The axial stiffness of columns with greater shortening can be effectively increased by placing additional reinforcement at the columns, thus the differential column shortening can be reduced in the design stage. The optimum distribution of additional reinforcement can be determined by applying a gradient based optimization technique.

***Keywords*—**Column shortening, long-term behavior, optimization, tall building.

I. Introduction

DIFFERENTIAL column shortening should be closely evaluated at the design stage or construction phase of a tall building because this may damage not only structural elements but also nonstructural elements such as partitions, curtain walls, and mechanical pipes [1]. The common method for preventing serviceability malfunction and structural damage due to differential column shortenings is raising a column during the construction phase. However, raising a column during the construction phase requires accurate construction techniques and additional cost and labor. Column shortening is normally examined after the structural design against major building loads like gravity and wind is completed. Therefore, in order to reduce column shortening, making changes in the material properties, sectional area of the column, and frame layout is not appropriate. In this paper, a few structural methods to reduce the differential column shortening are proposed. Using rigidly connected horizontal members like outriggers was proposed as one of the methods to reduce differential column shortening in the design phase [2]. Another approach is placing additional reinforcements to the columns which show greater shortening to increase the axial stiffness of the columns. The optimum distribution of additional reinforcement can be determined by applying a gradient based optimization technique. The effect of each method was investigated by analyzing the column shortenings of an 80 story shear wall building with a reinforced concrete frame.

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II. Differential Column Shortening

A. Post-Installation Shortening

Shortening in a tall building can be divided into pre-installation shortening and post-installation shortening [1]. In cast-in-place RC structures, the amount of shortening before slab installation is not important because the forms are usually leveled when the concrete is placed for each story slab; this means that pre-installation shortening is automatically compensated for as shown in Fig. 1. The post-installation shortening developed in a typical tall RC building normally reaches maximum differential column shortening around the middle stories. Damage due to differential column shortening is proportional to the slope of the horizontal members, so the distance between the columns must be considered when setting a limit to differential column shortening.

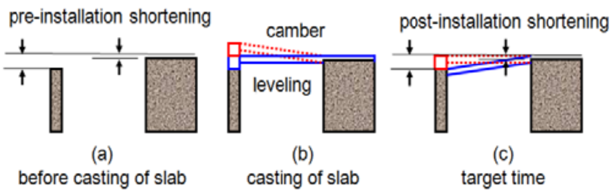


Fig. 1 Pre and post-installation shortening and automatic compensation

B. Long-Term Analysis of Reinforced Concrete Building

The total strain at time t under a constant stress $\sigma(t_0)$ applied at time t_0 is the sum of the instantaneous strain, the time-dependent strain due to creep, and the shrinkage and strain due to the temperature gradient. Thus, the total strain is given by the following equation [3]:

$$\varepsilon(t) = \varepsilon_e(t_0) + \varepsilon_{cr}(t) + \varepsilon_{sh}(t) + \varepsilon_T(t) \tag{1}$$

Creep is usually expressed as a creep coefficient $\phi(t,t_0)$, which is the ratio of creep strain to instantaneous strain. These values can be obtained by using either a concrete model or an experiment. The total strain of unrestrained concrete under constant stress is given by

$$\varepsilon(t) = \frac{\sigma(t_0)}{E_c(t_0)}\left[1 + \phi(t,t_0)\right] + \varepsilon_{sh}(t) + \varepsilon_T(t) \tag{2}$$

where $E_c(t_0)$ is the elastic modulus of concrete at the time of loading.

The strain due to the temperature gradient is excluded in this study because it does not have any significant effect on column shortening. If the concrete is restrained, the stress in the concrete is redistributed. The total strain of restrained concrete is given by

$$\varepsilon(t)=\frac{\sigma(t_0)}{E_c(t_0)}[1+\phi(t,t_0)]+\int_{t_0}^{t}\frac{1+\phi(t,t_0)}{E_c(\tau)}\frac{\partial\sigma(\tau)}{\partial\tau}d\tau+\varepsilon_{sh}(t) \quad (3)$$

The integral term in (3) expresses the strain due to the stress variation and cannot be expressed as an analytic equation because the stress variation is unknown. Several analysis methods have been developed to solve the equation numerically. A step-by-step method that uses numerical integration (SSM), an effective modulus method (EMM), an age-adjusted modulus method (AEMM), and a rate of creep method (RCM) are well-known long-term analysis methods [3], [4]. SSM was used in this study.

III. Effect of Horizontal Members

A numerical example of an 80 story reinforced concrete frame with shear walls and mega columns was chosen for the purpose of investigating how horizontal members affect column shortening. The length of the beams, as shown in Fig. 2, is 8 m; for the sake of clarity, only the first story of the 80 story analysis model is shown. A CEB model [5] is applied to the concrete model, where the relative humidity is 60% and the cement type is normal. It is assumed that the reinforcing bars are placed symmetrically at the top and bottom and that the distance from the center of the bars to the edges of the sections is 50mm. It is assumed that the columns and the shear walls do not crack and the beams are the only members that can crack, so the effective second moment is used for the stiffness of the beams and the second moment of the transformed uncracked section is used for the columns and the shear walls.

Column shortening analyses of examples with horizontal members with different levels of bending stiffness are conducted to investigate how horizontal members affect column shortening. The bending stiffness is altered with various beam widths of 2.0m, 1.0m, 0.2m, and zero. Examples with reinforced concrete outriggers are also analyzed to determine how the outriggers affect the column shortening. One outrigger is constructed at the 30th story and the other at the 60th story. The only difference between the two examples with outriggers is the time of construction. The outriggers in the first example are constructed at 145 days and 295 days, during the placement of the 30th story and the 60th story. In the second example, the outriggers are constructed at 400 days and 420 days, some days after all the frames are constructed. The beam width of the example with outriggers is 0.2m.

Fig. 3, which shows the differential shortenings at 1,000 days after the beginning of construction between the columns and the shear walls, confirms that the stiff horizontal members reduce the differential shortening between two vertical members adjoined by horizontal members. The differential shortening of the examples with outriggers at 145 days and 295 days is less than that of the example without outriggers. Note that the differential shortening at the 30th story and the 60th story, where the outriggers are constructed, is significantly reduced. The example with outriggers constructed at 400 days and 420 days, at which time there has already been considerable shortening, shows a slightly reduced differential shortening.

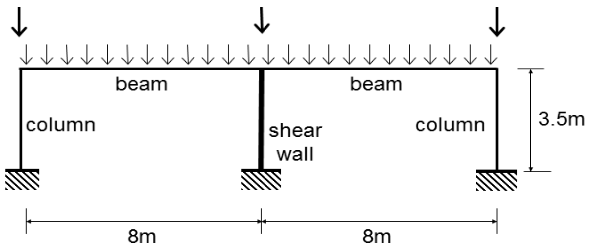


Fig. 2 Analysis model of an 80 story structure, with only the first story shown

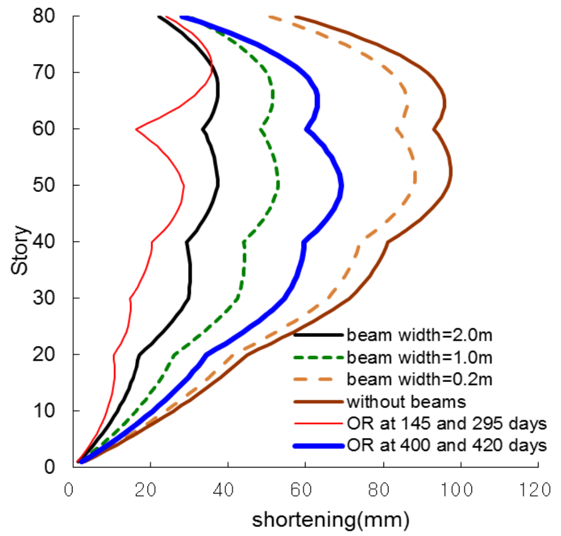


Fig. 3 Differential column shortenings when changing the horizontal members

IV. Effect of Additional Reinforcement

The effect of additional reinforcement on the differential column shortenings of the same building structure shown in Fig. 2 was investigated. Additional steel bars which corresponds 1%, 2%, 3% and 4% of steel ratio were added to the columns of the analysis model with zero beam stiffness. Fig. 4 shows the differential column shortening between the shortenings of columns and those of shear walls for the cases of additional reinforcements. It can be noticed that the more additional reinforcements were placed, the more reduced the differential column shortening were. The maximum differential column shortening were reduced 15.9%, 29.5%, 41.2% and 51.7% from that of the model without additional reinforcements by increasing steel ratio of 1%, 2%, 3% and 4%, respectively.

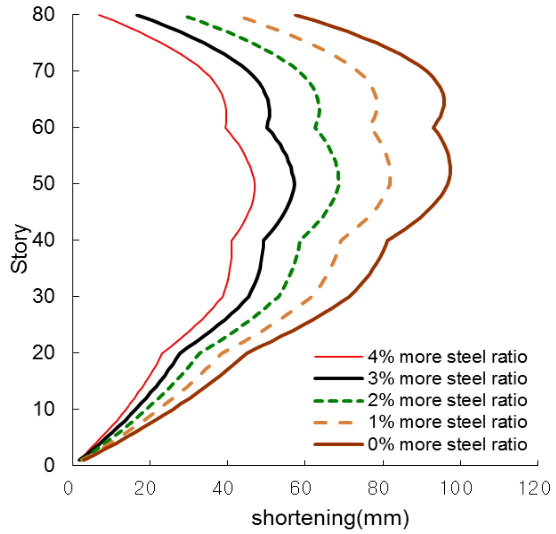


Fig. 4 Differential column shortenings when placing the additional reinforcements

V. Optimum Distribution

It was shown that the differential column shortening can be controlled by placing additional reinforcements to the columns which were expected to show greater column shortening. However, the additional reinforcement for each story was determined by one design variable. Since each story has different column size, loading condition, and built time, the effect of the same amount of additional reinforcement to each story would be different. Furthermore, the effect of reinforcement is not linear as shown in Fig. 5 which shows the ratio between the reduced strain according to the steel ratio and the strain without reinforcement. It can be observed that the slowdown in reduction effect becomes outstanding as steel ratio increases. When placing reinforcement corresponding to an 8% steel ratio, which is the maximum steel ratio for a reinforced concrete column, the total strain was reduced to 31% of the strain without reinforcement. The slope of the curve was more inclined when the steel ratio was low; this means that it is more efficient to place additional reinforcement when the current steel ratio is low.

The optimum distribution of additional reinforcement can be determined by solving a constrained optimization [6] which can be formulated as (4).

$$\begin{aligned} &\text{Min} \quad f(\mathbf{x}) \\ &\text{subject to:} \\ &\quad g(\mathbf{x}) - b \le 0 \\ &\quad x_i^l \le x_i \le x_i^u, \; i = 1,2,\ldots,n \end{aligned} \tag{4}$$

where $f(\mathbf{x})$ is an objective function which yields total volume of additional reinforcements. $g(\mathbf{x})$ is a constraint function and it gives the post-installation column shortening of target story for the current design state $\mathbf{x}$, which is a vector of design variables $\{x_1, x_2 \ldots x_n\}$. x_i is the volume of additional reinforcement of *i*-th story or region. x_i^l and x_i^u are lower and upper limit of x_i. b is target shortening of target story.

Prior to developing an optimization program for the optimum distribution of additional reinforcement, two-variable design problem for two analysis models was investigated. Two design variables x_1, x_2 are the amount of reinforcement placed on the lower and upper half, respectively. Constant-section model means cross section of each story column is the same and Constant-stress model has different cross section which was adjusted as constant axial stress develops. Fig. 6 shows the contour plot of two-variable column shortening problem. Horizontal axis shows the amount of reinforcement placed on lower half and vertical axis means that on upper half. The optimum points of the constant-section model lie on the lower part of the diagonal which means equal reinforcement on the lower half and the upper half. On the other hand, most of the optimum points of the constant-stress model lie on the lower limit of x_1 which is the amount of reinforcement placed on the lower half.

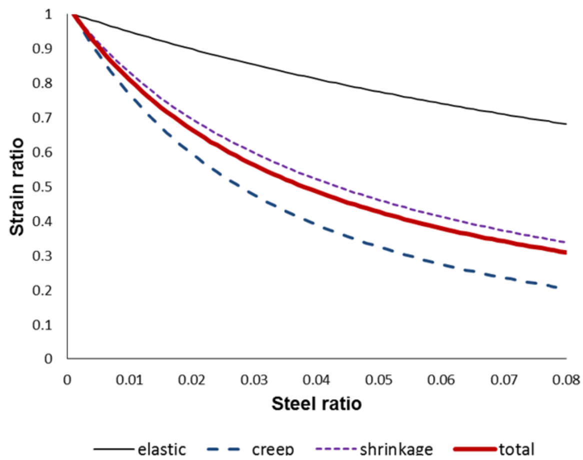
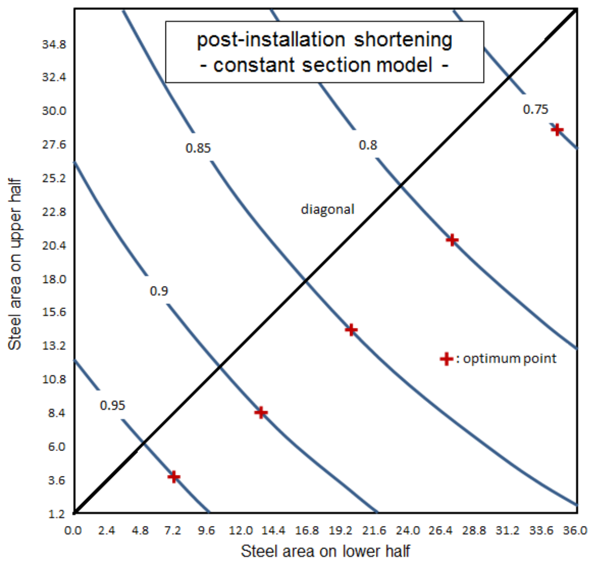


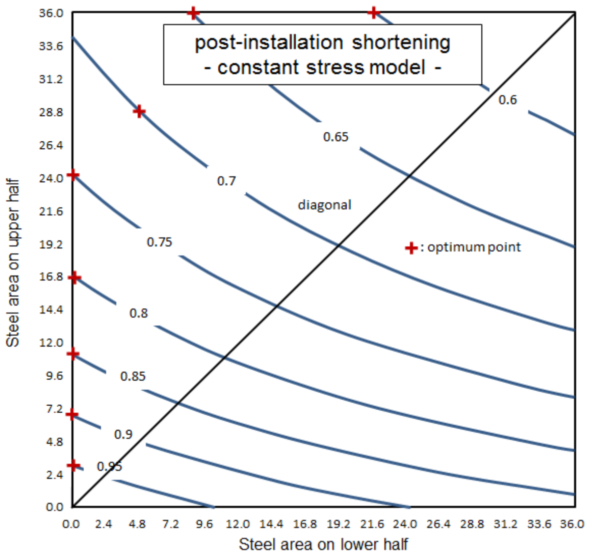
Fig. 5 Axial strain ratio according to reinforced steel ratio of column

VI. Conclusion

This paper proposed a few structural methods to reduce the differential column shortening in reinforced concrete tall buildings; connecting columns and shear walls with rigidly jointed horizontal members like high stiff beam or outriggers and placing additional reinforcements at the columns. The column shortenings of an 80 story shear wall building with a reinforced concrete frame were investigated as numerical examples. The results show that horizontal members, such as beams and outriggers, reduce the differential shortening between adjacent vertical members, and that the stiffest beams achieve the greatest reduction in the differential shortening. Also, the differential column shortening can be reduced by placing additional reinforcement at the columns with larger shortening than at adjacent vertical members. The optimum distribution of additional reinforcement can be determined by solving the constrained optimization problem and the relevant study is being conducted.



(a) Constant-section model



(a) Constant-stress Model

Fig. 6 Post-installation shortening contour of two-variable optimization problem

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