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DOI: 10.4028/www.scientific.net/KEM.348-349.781

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Stiffness Reduction for Flat Plate Systems due to Cracking

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Keywords: Flat Plate, Crack, Stiffness Reduction Factor, Effective Beam Width Method, Experimental Test

Abstract. The purpose of this study is to propose a stiffness reduction factor for flat plate systems under lateral loads. According to current design provisions, slab stiffness under lateral loads should account for stiffness reduction due to the effects of cracks. Several researchers have conducted for evaluating the stiffness reduction in flat plate slab systems under lateral loads. However, no research is found for establishing strength reduction factor with respect to the level of applied moment. This study attempted to propose equations for calculating stiffness reduction factor with respect to the level of applied moment ($M_a$) represented by the ratio of $M_a$ to the cracking moment of the slab ($M_{cr}$). For this purpose, test results of 20 interior slab-column connections were collected. For each specimen, stiffness reduction was measured with respect to $M_a/M_{cr}$. To verify the proposed factor, this study conducted the experimental test of interior connection under quasi-static cyclic loading, from which load-deformation curve was obtained. The curve was compared with that obtained from the effective beam width method with the proposed stiffness reduction factor. It shows that the proposed factor accurately predicts stiffness reduction in flat plate systems.

Introduction

For lateral load analysis of flat plate systems, ACI 318-05[1] requires to consider the effects of cracks for calculating stiffness of slabs. When uncracked stiffness of the slab is used, the distributed moment on slab can be more increase than actual action and the lateral drift of the whole frame can be underestimated.

Many researchers attempted to evaluate reduction factors for lateral stiffness in order to reflect stiffness reduction effect on slab analysis. ACI 318-05[1] recommends that it is normally appropriate to reduce slab stiffness to between 1/2 and 1/4 of the uncracked stiffness. However, these factors are too simply to reflect material properties or gravity and lateral loads.

Grossman [2] suggested the reduction factor considering the drift ratios of flat plate structure, which based on the UCB test results [3]. But, this factor cannot reflect the variation of gravity load.

Luo and Durrani [4] suggested stiffness reduction factor using the effective moment of inertia ($I_e$) in ACI 318-05 [1]. However, it is difficult to use this factor on the design level where the reinforcement area is not determined, since inertia moment of cracked section ($I_{cr}$) includes the reinforcement area in slabs. In addition, the effective moment of inertia ($I_e$) was obtained from the test results of simple supported beam applying uniformed loads and not verified for flat plate slabs.

This study analyzed the test results of 20 interior slab-column connections and selected the ratio of applied moment to cracking moment ($M_a/M_{cr}$) as main variable. As results, this study proposes the stiffness reduction factor obtained from non-linear regression analysis of 20 test results. To verify the proposed factor, this study conducted the experimental test of interior connections under lateral loads. Load-deformation curve obtained from the test was compared with that obtained from the effective beam width method using the proposed factor.

Stiffness Reduction Factor for Flat Plate Slab

Variable for Stiffness Reduction. To propose the stiffness reduction factor, this study analyzed the variables having an effect on stiffness reduction in the prior test results of slab-column connection. First of all, it can be assumed that flat plate slab is governed by flexural behavior in the initial stage.
because of low ratios of length to depth. Thus, the cause of cracking can be the applied moment on slabs and the stiffness reduction can be affected by the level of moment directly.

The influence of applied moment for the stiffness of concrete members is already reflected on ACI 318-05[1], calculation of effective beam stiffness ($E_I$) for deflection. Moreover, Luo and Durrani [4] proposed also reduction factor using the effective moment of inertia ($I_c$).

This study analyzed also the variable that affected stiffness reduction based on effective moment of inertia ($I_c$). It is noted that calculation of inertia moment of cracked section ($I_c$) composing effective moment of inertia ($I_c$) requires reinforcement area. To find effects of reinforcement area for stiffness reduction, this study used test results conducted by Morrison and Sozen [5]. Fig.1 shows that reinforcement area affects maximum strength but hardly affect initial stiffness reduction. Test specimens, S1, S2, and S3 used reinforcement area as main variable. This study selected the ratio of applied moment to cracking moment ($M/I_c$) as a unique main variable of stiffness reduction. And stiffness reduction factor is applied to the effective beam width method proposed by Banchick.

$$\alpha_c L_2 = \left(5c_1 + 0.25L_c \right) / \left(1 - v^2 \right)$$  \hspace{1cm} (1)

where, $c_1$ and $L_c$ = the width of column and slab, respectively, $L_2$ = the width of slab perpendicular to $L_c$, and $v$ = the poisson’s ratio.

### Proposal of Stiffness Reduction Factor

Test specimens of interior slab-column connection subjected to laterally static cyclic load were used to propose stiffness reduction factor for flat plate.
systems. Table 1 shows dimensions, material properties, and lateral stiffness of analysis method.

This study examined the tendency of stiffness reduction according to the $M_a/M_{cr}$. Also, initial lateral stiffness are obtained from finite element method ($K_{EBWM}$), and the effective beam width method using effective stiffness of column which is $0.7E_Ic$ ($K_{EBWM}$). In this study, the lateral stiffness of each test specimens ($K_{exp}$) is defined by peak to peak stiffness definition.

Fig. 2(a) and (b) shows the ratio of $K_{exp}$ to $K_{EBWM}$ and the ratio of $K_{exp}$ to $K_{EBWM}$ according to the $M_a/M_{cr}$, respectively. Fig. 2(a) and (b) show similar tendency for stiffness reduction, but Fig. 2(b) displays minimum data dispersion. Based on the Fig. 2(b), it is possible to assume that stiffness reduction should be considered on flat plate analysis and effective stiffness of $0.7E_Ic$ recommended in ACI 318-05 [1] is appropriate value.

Stiffness reduction factor ($\beta$) in Eq. (2) is acquired from nonlinear regression analysis using fmins.m which is one of the Matlab subroutine programs. Factor ($\beta$) determined by regression analysis is defined as median value of and standard deviation, factor of variation, and factor of correlation are determined 0.07, 0.27, and 0.85, respectively.

$$\beta = 0.4 + 0.27 \left[ \left( \frac{M_a}{M_{cr}} \right)^{0.5} - \left( \frac{M_a}{M_{cr}} \right)^{0.5} \right]$$

(2)

where, $M_a =$ the applied moment (summation of moment for gravity load and lateral load), and $M_{cr} =$ the cracking moment for effective beam width of slab.

Verification of Proposed Stiffness Reduction Factor

Experimental Test. Purpose of this experimental study is to verify the proposed the stiffness reduction factor through analyzing the behavior of flat plate slab subjected to high level gravity load which is 37% of slab shear strength ($V_g/\varphi V_e=0.5$).

Table 2 Properties of specimen RI-50

<table>
<thead>
<tr>
<th>Mark</th>
<th>$c_1=$c_2 [cm]</th>
<th>h [cm]</th>
<th>$l_1$ [cm]</th>
<th>$l_2$ [cm]</th>
<th>H [cm]</th>
<th>$\rho_{s, top}$ [%]</th>
<th>$\rho_{s, bottom}$ [%]</th>
<th>$f'_c$ [MPa]</th>
<th>$f_y$ [MPa]</th>
<th>$V_g/\varphi V_e$ [kN]</th>
<th>$\theta_y$</th>
<th>$\theta_\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI-50</td>
<td>30</td>
<td>13.2</td>
<td>360</td>
<td>360</td>
<td>210</td>
<td>0.64</td>
<td>0.27</td>
<td>32.3</td>
<td>392.4</td>
<td>0.5</td>
<td>-1.9</td>
<td>-3.7</td>
</tr>
</tbody>
</table>

$c_1='$c_2: dimension of rectangular column; h: slab thickness; $l_1$: span length parallel to loading direction; $l_2$: span length transverse to loading direction; H: story height; $\rho$: ratio of top/bottom rebar ($s, top/s, bottom$) in the slab within $c_1=3h$; $V_g/\varphi V_e$: gravity shear ratio, where $V_g =$ direct gravity load, $V_e =$ nominal shear strength, $\varphi=0.75$;
A ten-story flat plate slabs and reinforce concrete shear walls were designed to resist gravity load and earthquake loads, respectively. Interior slab-column specimen (RI-50), approximately two-thirds scaled specimen is designed corresponding to the prototype design. Dimensions, properties and test results of specimens are summarized in Table 2.

**Comparison with Test Result of RI-50.** Fig. 3 depicts lateral load versus drift ratio relation for the RI-50, along with analytical result of the effective beam width method using reduction factor of Eq. (2). Also, Fig. 3 display results using ACI equivalent frame method, effective beam width method, factor proposed by Grossman [2], and factor proposed by Luo and Durrani [4]. Those analysis results overestimate for the RI-50. However, the proposed factor in this study accurately predicts stiffness reduction in the RI-50.

**Conclusions**

Based on analytical and experimental study for flat plate connection, the following conclusions were reached:

1. When uncracked stiffness of the slab is used, the real stiffness of the slab could be overestimated, and the displacement of structure, moment, and shear force could be not estimated reasonably. Thus, it is important to consider the effect of cracks for calculating slab stiffness under lateral loads.

2. Stiffness reduction is caused by crack of slab and it is appropriate that predominant factor of crack is the applying moment. In this study, it is concluded that main variable of stiffness reduction is the ratio applied moment to cracking moment ($M_a/M_{cr}$).

3. The stiffness reduction factor is proposed through nonlinear regression analysis, based on analyzing the test results of existing interior slab-column connection.

4. Analytical result obtained from effective beam width model using the proposed factor of this study accurately predicts stiffness reduction of test specimens, RI-50.

**Acknowledgements**

The work presented in this paper was sponsored by MOST R01-2006-000-10722-0 and SRC/ERC R11-2005-056-04002-0. The views expressed are those of the authors, and do not necessarily represent those of the sponsor.

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