13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 680

EFFICIENT SEISMIC ANALYSIS OF FLAT PLATE SYSTEM STRUCTURES

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SUMMARY

The flat plate system has been adopted in many buildings constructed recently taking advantage of the reduced floor height to meet the economical and architectural demands. Structural engineers commonly use the equivalent frame method with equivalent beams such as the one proposed by Jacob S. Grossman in practical engineering for the analysis of flat plate structures. However, in many cases, when it is difficult to employ the equivalent frame method, it may be necessary to use a refined finite element model for an accurate analysis. But it would take significant amount of computational time and memory if the entire building structure were to be subdivided into a finer mesh. An efficient analytical method is proposed in this study to obtain accurate results in significantly reduced computational time using the finite element approach. The proposed method employs super elements with fictitious beams. The stiffness degradation in the flat plate system considered in the equivalent frame method was taken into account by reducing the modulus of elasticity of floor slabs in this study. Static and dynamic analyses of example structures were performed and the efficiency and accuracy of the proposed method were verified by comparing the results with those of the refined finite element model and the equivalent frame method.

INTRODUCTION

The flat plate system, in which columns directly support floor slabs without beams, is adopted for many building structures recently constructed. Since flat plate system was primarily developed to resist the gravity loads, many researches on the resistance capacity for lateral loads have been undertaken [1-4]. In the analysis of a flat plate structure subjected to gravity loads, direct design method or equivalent frame method is generally used for the rectangular slabs while commercial software such as SAFE [5] and MIDAS/SDS [6] is used for the slab with irregular plan.

However, the equivalent frame method is commonly used for the analysis of the flat plate structures subjected to lateral loads in practical engineering [7-10]. In the equivalent frame method, the flat plate system is modeled as equivalent frame and an elastic analysis is performed. The floor slab has larger flexural deformation around the columns when the structure is subjected to lateral loads. Therefore, the

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floor slab is divided into column strip and middle strip in the analysis and design of flat plate structures. The floor slabs are modeled using equivalent beams having effective width assuming that the equivalent beams have the same flexural stiffness as the floor slab system. The depth of the equivalent beams in the equivalent frame method was taken to be the thickness of floor slabs. The determination of the effective width for a slab is one of the most important procedures in the equivalent frame method and many researches have been performed on an effective width [10-13]. The method proposed by Jacob S. Grossman for the determination of the effective width [7] is one of the methods widely used in practical engineering. Grossman proposed an improved method to account for the degradation of the stiffness of the slabs depending on the level of the lateral drifts by introducing the stiffness degradation factor based on the tests [1] performed at U.C. Berkeley. In the work by Grossman [7], it was difficult to account for the stiffness degradation in the slabs depending on the lateral drifts in the finite element method. However, it may be feasible to include the stiffness degradation effect by adjusting the modulus of elasticity of the slabs in the finite element approach to have a similar effect as using the equivalent beams with the effective width in the equivalent frame method.

ANALYSIS OF FLAT PLATE STRUCTURES USING THE EQUIVALENT FRAME METHOD

The equivalent frame method widely used in practical engineering has some limitations in the application because it was derived from buildings with regular arrangements of columns. The concept and limitations of the Grossman method are presented below to develop an improved method which can be used for the wider range of structures.

Grossman method for effective width determination

Various studies on the resistance capacity for the lateral loads were performed by previous researchers [1-4]. Grossman concluded that the flat plate system has a good resistance capacity for the lateral loads as well as gravity loads provided a proper detailing in the joint between the column and the slab through the reviews of previous researches [7]. And a new formula for the effective width was proposed by Grossman as shown in Eq. (1) by modifying the previous procedures for the equivalent frame method.

$$\alpha l_2 = K_d[0.3l_1 + C_1(l_2/l_1) + (C_2 - C_1)/2](d/0.9h)(K_{FP}) \quad (1)$$

with limits: $(0.2)(K_d)(K_{FP})l_2 \le \alpha l_2 \le (0.5)(K_d)(K_{FP})l_2$

where, α = equivalent width factor

αl_2 = effective width of slab at center line of support

K_d = factor considering degradation of stiffness of slabs at various lateral load levels

l_1 = length of span of supports in direction parallel to lateral load

l_2 = length of span of supports in direction transverse to lateral load

C_1 = size of support in direction parallel to lateral load

C_2 = size of support in direction transverse to lateral load

d = effective depth of slab

h = slab thickness

K_{FP} = factor adjusting αl_2 at edge exterior and corner supports

(1.0 for interior supports, 0.8 for exterior and edge supports, 0.6 for corner supports)

In case of exterior columns, adjustments are made by multiplying effective width (αl_2) by $[l_3 + (l_2/2)]/l_2$ where l_3 equals the distance between the column centerline and the parallel edge of the slab. The values in

Table 1 are used for the stiffness degradation factor K_D in Eq. (1) depending on the lateral drift. The terms in Eq. (1) for effective width can be classified into three groups; the terms used to represent the elastic deformation of floor slab system, the term depending on the arrangement of the reinforcing bars in the slab and the term used to account for the stiffness degradation in the slab. The bracketed term ($[0.3l_1 + C_1(l_2/l_1) + (C_2 - C_1)/2]$) is for the effects of the slab length and cross section of columns on the effective width of an equivalent beam and the factor (K_{FP}) is concerned to the column location. These two terms can be simply considered in the finite element analysis. It is usually reasonable to assume the term considering the effective depth of slab and the arrangement of the reinforcing bars (d/0.9h) as 1.0. However, in the case of very thin slabs when d/h is less than 0.9, it is recommended to reduce the stiffness of the slab in the finite element analysis. However, the stiffness degradation in the slab depending on the lateral drift and the effective depth of slab cannot be easily included in the finite element analysis. The factor K_D is introduced to account for the stiffness degradation in the slab. Therefore, if this effect could be considered properly, the finite element method can be an alternative to the equivalent frame method.

Limitations in the equivalent frame method

Equivalent frame method can be easily applied to a flat plate structure having rectangular plan shown in Fig. 1(a). However, it is hard to apply the equivalent frame method to flat plate structures having irregular plans as shown in Figs. 1(b), 1(c), 1(d) and 1(e). In the case of the plan shown in Fig. 1(b), there is a slab in which of the three quadrants around the inside columns but not in the other quadrant. The factor (K_{FP}) for the column location in this case was not defined in the Grossman method. In many cases, commercial buildings using the flat plate system usually have slabs with openings to accommodate escalators or equipments shown in Fig. 1(c). It is difficult to apply the equivalent frame method to the structures having openings in the slab. Since the length of span (l_1, l_2) and column location factor (K_{FP}) can not be easily determined for the structures having plans as shown in Figs. 1(d) and 1(e), it is hard to apply the equivalent frame method to those structures.

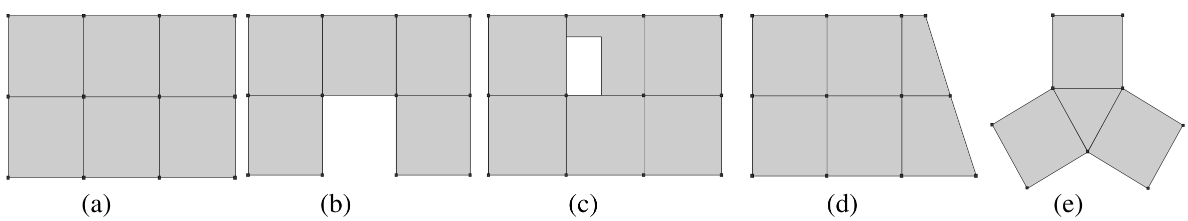


Fig. 1. Various types of plan of flat slab structures

ANALYSIS OF FLAT PLATE STRUCTURES USING THE FINITE ELEMENT APPROACH

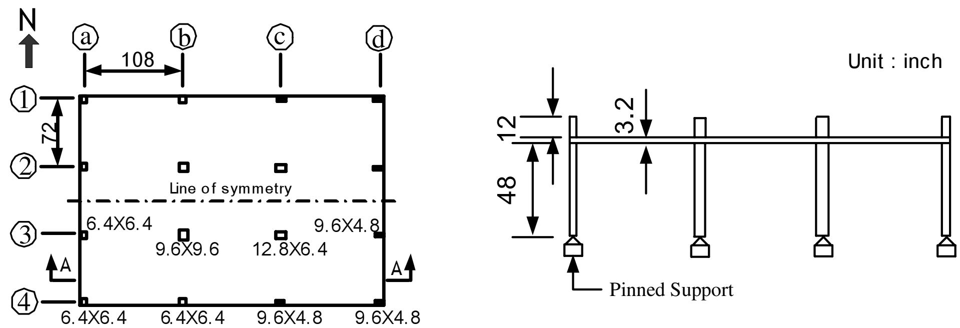
The structures having irregular types of plans with which the equivalent frame method has limitations in analysis can be analyzed without any difficulties by the finite element method. However, the stiffness degradation in the slab could not be considered in the finite analysis method as Grossman mentioned in his study. Finite element analyses of flat plate structures were performed including the stiffness degradation in the slab by using the reduced modulus of elasticity depending on the lateral drifts to investigate the possibility of using the finite element method to overcome the shortcomings of the equivalent frame method.

The stiffness degradation in the slab depending on the lateral drift

The stiffness degradation in the slab is usually remarkable in the case of flat plate structures subjected to lateral loads [1, 2]. Therefore, Grossman proposed the stiffness degradation factor (K_D) that can reduce the effective width of the equivalent beams depending on the lateral drift in his study based on the tests performed by Prof. Moehle at U.C. Berkeley in 1990 [1]. Test structure used at U.C. Berkeley is a one-story flat plate structure having various cross sections of columns as shown in Fig. 2. The stiffness degradation factor (K_D) listed in Table 1 was used by Grossman to represent the stiffness degradation in the slab depending on the increment of lateral drift.

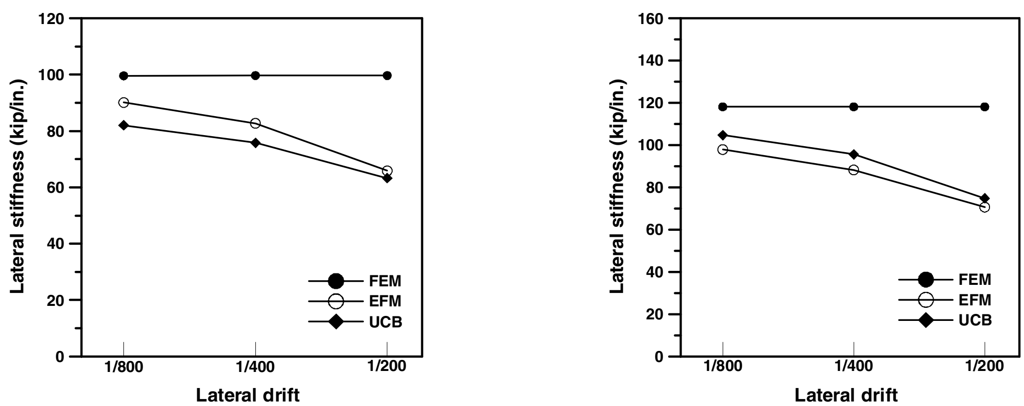
Table 1 Stiffness degradation factor depending on the lateral drift

Lateral drift	K_D
$h_s/800$	1.1
$h_s/400$	1.0
$h_s/200$	0.8
$h_s/100$	0.5



(a) Plan (b) Section A-A

Fig. 2 Layout of test slab at UCB



(a) NS-direction (b) EW-direction

Fig. 3 Variation of lateral stiffness of flat slab structure depending on the lateral drift

Figure 3 shows the variation of lateral stiffness depending on the lateral drift in EW and NS direction for the test structure shown in Fig.2. It can be noticed that the lateral stiffness of the structure predicted by the finite element method (FEM) is constant regardless of the lateral drift while that from the test performed at U.C. Berkeley(UCB) is reduced as the lateral drift increases. The equivalent frame method (EFM) proposed by Grossman shows a reduction in the lateral stiffness depending on the lateral drift in a similar way to the UCB because the effective width of slabs was reduced by the stiffness degradation factor. The stiffness of EFM is larger in NS direction and is smaller in EW direction than that of UCB because the same stiffness degradation factor listed in Table 1 regardless of directions was used for EFM while the stiffness degradation in UCB was different in both directions due to the difference in the arrangement of columns and the location of reinforcement.

If the lateral stiffness of the FEM model were reduced depending on the lateral drift in a similar manner to the stiffness degradation factor proposed by Grossman, the stiffness degradation in the slab could be accounted for by the finite element method. Therefore, the stiffness reduction factor (R_K) was introduced to reduce the stiffness of the FEM model depending on the lateral drift by dividing the lateral stiffness of the EFM model (K_{EFM}) by that of the FEM model (K_{FEM}) shown in Fig. 3 as follows:

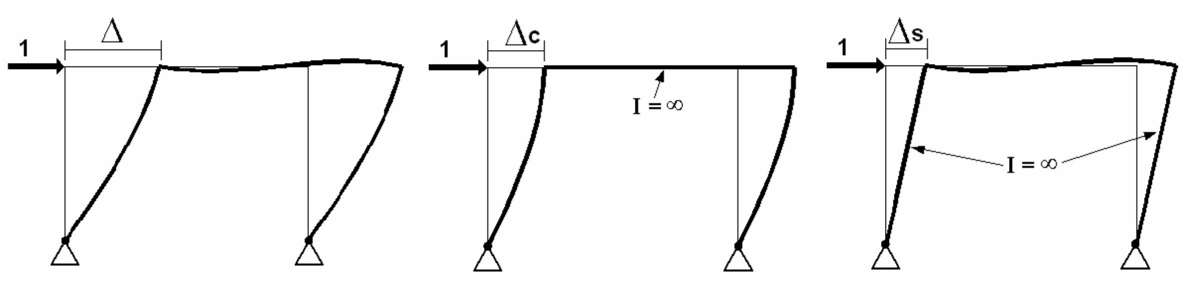
$$R_K = \frac{K_{EFM}}{K_{FEM}} \tag{2}$$

Stiffness reduction factor for slabs

The stiffness degradation in flat plate structures subjected to lateral loads may occur in columns as well as in slabs. However, the stiffness degradation in the column was not considered in this study on the purpose to compare with the results of the Grossman method since this study is focused on investigating an improved analytical method to overcome the limitations in the equivalent frame method by introducing the stiffness degradation in the slab in the finite element method. For the purpose of practical engineering, stiffness degradation in the column can be considered by using reduced stiffness properly. The lateral displacement(Δ) of the portal frame shown in Fig. 4 representing a simple flat plate structure can be decomposed into the displacement due to the column deformation(Δ_C) and the slab deformation(Δ_S) as follows:

$$\Delta = \Delta c + \Delta s \tag{3}$$

The columns are assumed to deform elastically while the slab has stiffness degradation. The lateral displacement of the structure (Δ / R_K) can be decomposed into the displacement due to the column deformation (Δ_C) and the slab deformation (Δ_S / R_{KS}) with stiffness degradation shown in Eq. (4).



(a) Deformation of whole structure (b) Deformation of columns (c) Deformation of slabs

Fig. 4 Components of lateral displacements of simple flat slab system

$$\frac{\Delta}{R_K} = \Delta c + \frac{\Delta s}{R_{KS}} \tag{4}$$

where, R_K = stiffness reduction factor for structure

R_{KS} = stiffness reduction factor for slab

Rearranging Eq. (4), the stiffness reduction factor for slabs can be obtained as shown in Eq. (5).

$$R_{KS} = \frac{\Delta s}{\frac{\Delta}{R_K} - \Delta c} \tag{5}$$

The lateral displacement of structure (Δ), the displacement due to the column deformation (Δ_C) and the slab deformation (Δ_S) for the test structure shown in Fig. 2 were obtained by the finite element analysis in the elastic range. The stiffness reduction factor for structure (R_K) was obtained from Eq. (2) using the lateral stiffness shown in Fig. 3. Finally, the stiffness reduction factor for slab (R_{KS}) was obtained from Eq. (5) for three levels of the lateral drifts in each direction as shown in Table 2. Since the modulus of elasticity of slabs was adjusted by using the stiffness reduction factor for slabs, the stiffness degradation in the slab depending on the lateral drift is expected to be considered in the finite element method. The stiffness reduction factors in EW and NS directions are somewhat different as listed in Table 2 because the location of reinforcement, the arrangement of columns and the cross section of columns are different in each direction. To use the same stiffness reduction factor in each direction in the finite element method depending on the lateral drift, the average of the stiffness reduction factors for slabs in EW and NS direction was calculated for three levels of lateral drift. The relation between the slab stiffness reduction factor and lateral drift is illustrated in Fig. 5.

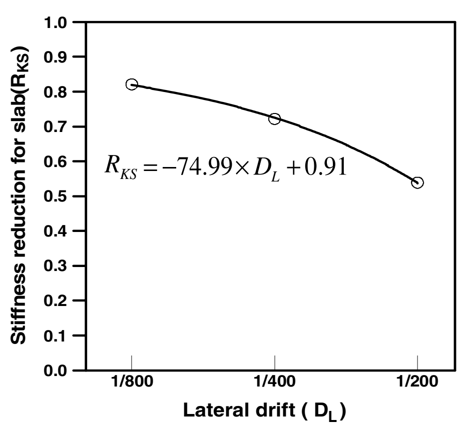


Fig. 5 Stiffness reduction factor for slabs

Application of the stiffness reduction factor to finite element analysis

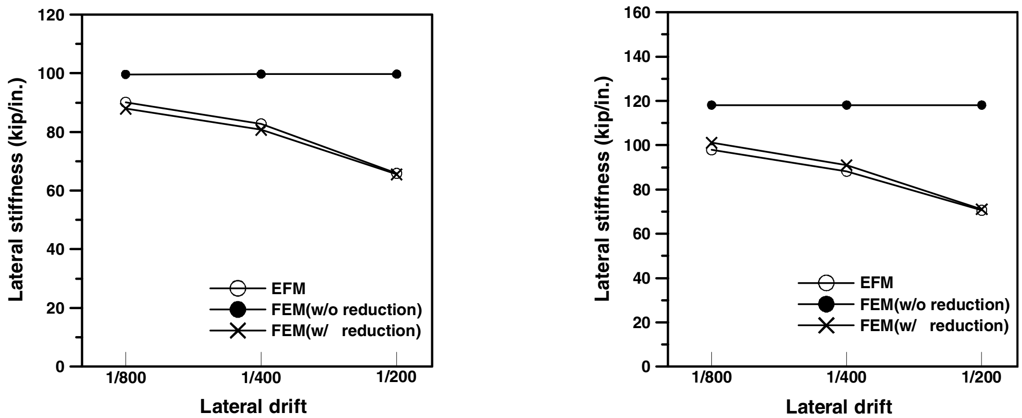
The modulus of elasticity of slabs is adjusted to consider the stiffness degradation in the slab depending on the lateral drift as shown in Eq. (6).

$$E_R = R_{KS} \times E \tag{6}$$

where, E_R = reduced modulus of elasticity

E = original modulus of elasticity

When the slab stiffness is reduced, the in-plane stiffness of slab as well as the bending stiffness is reduced in the same ratio. However, the in-plane stiffness of the slab is much larger than the flexural stiffness and thus a minor reduction of the in-plane stiffness will result in ignorable difference in the analysis results. Figure 6 illustrates the results of the finite element analysis using the stiffness reduction factors for three levels of lateral drift listed in Table 2 in a good comparison to those of the EFM.



(a) NS-direction (b) EW-direction

Fig. 6 Comparison of lateral stiffness depending on the lateral drift

Table 2 Stiffness reduction factors of structure and slab

Lateral drift	Direction	Δ	Δ_C	Δ_S	R_K	R_{KS}	Avg. of R_{KS}
1/800	NS	0.0546	0.0333	0.0213	0.9047	0.8527	0.8210
	EW	0.0642	0.0496	0.0146	0.8290	0.7892	
1/400	NS	0.1104	0.0673	0.0431	0.8298	0.7482	0.7218
	EW	0.1296	0.1001	0.0295	0.7471	0.6953	
1/200	NS	0.2304	0.1404	0.0900	0.6607	0.5427	0.5386
	EW	0.2544	0.1965	0.0579	0.5979	0.5345	

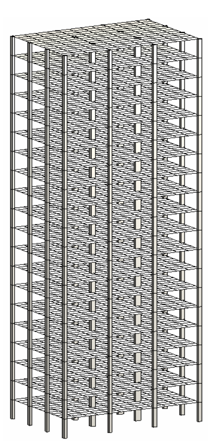
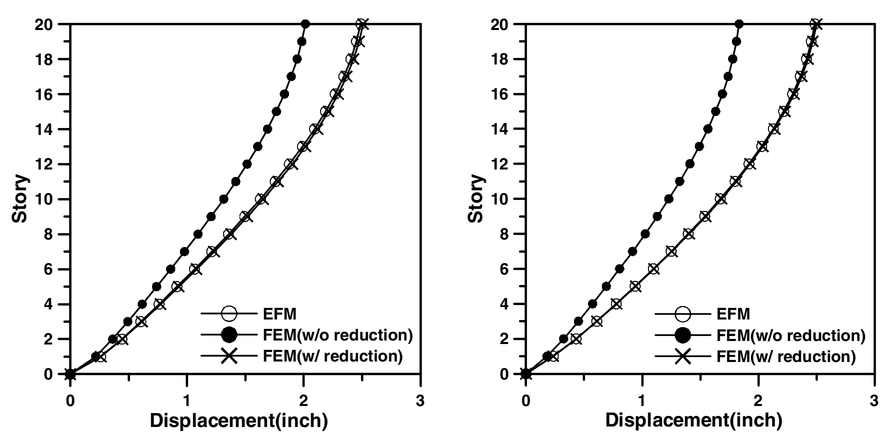


Fig.7 Example structure



(a) NS-direction (b) EW-direction

Fig. 8 Static lateral displacement

Static analysis of an example structure was performed to investigate whether the stiffness degradation effects in high-rise building structures can be appropriately considered by the finite element method. The 20-story example structure shown in Fig. 7 is assumed to have a plan as shown in Fig. 2. It was assumed that all columns have the same cross section in each story for the convenience in the modeling to avoid the troublesome calculation of the effective width because the effective width should be recalculated whenever the column size is changed in the structures along the height in the equivalent frame method. This assumption is not expected to result in significant effect in the comparison of the displacements by the finite element method and equivalent fame method.

The lateral loads in the linear distribution were applied to induce $h/400$ of roof displacement. The lateral displacements obtained by the finite element analysis with and without the stiffness reduction are compared to those by the equivalent frame method in Fig. 8. From this figure, it could be observed that the stiffness reduction factor is introduced in the finite element analysis leading to the stiffness degradation in the slab in a good agreement with the equivalent fame method.

SUPER ELEMENTS FOR ANALYSIS OF FLAT PLATE STRUCTURES

It is necessary to use a refined finite element model to represent openings in the floor slab with various shapes and sizes and represent the more accurate stress distribution in the slab. But if the entire flat plate structure were subdivided into a finer mesh with a large number of finite elements, it would cost a large amount of computational time and memory. Therefore, an efficient analytical method using super elements was proposed to save computational time and memory in this study.

Super element for flat plate structures

Most of the slabs can be divided by column lines in a rectangular subregion and the same slabs are repeatedly used in many floors in a flat plate structure. Thus it is very efficient to use super elements in the analytical model. The modeling procedure with super elements for the example structure shown in Fig. 2 is illustrated in Fig. 9. The refined mesh model of a typical flat plate system using many finite elements for the purpose of an accurate analysis is shown in Fig. 9(a). This refined mesh model can be separated into rectangular subregions of the slab having the same configuration as shown in Fig. 9(b). The node at the corners of the subregion is necessary for the connection between slabs and columns and the nodes at the boundary are to satisfy the compatibility condition at interface of subregions. Thus, all of the DOF's except those of the node at the boundary and corners can be eliminated by using the matrix condensation technique [18] for the efficiency of the analysis. And finally the super elements illustrated in Fig. 9(c) can be generated. Then the slab system in a floor is constructed by joining the active DOF`s of super elements as shown in Fig. 9(d). If the structural configurations are identical in many floors, the same assemblage of super elements can be used repeatedly in such floors for the convenience in the modeling of flat plate structures.

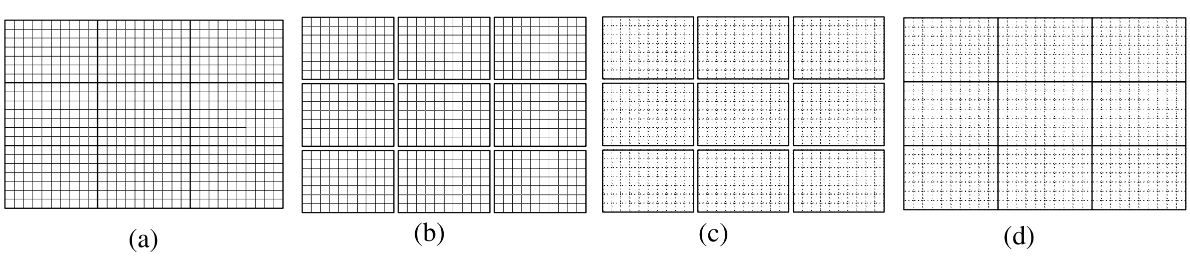


Fig. 9 Modeling procedure of flat slab system using super elements

The static equilibrium equation for a rectangular subregion of the slab can be rearranged by separating the DOF`s for the nodes at the boundary from those in the inner area of the subregion as follows;

$$\begin{bmatrix} \mathbf{S}_{ii} & \mathbf{S}_{ib} \\ \mathbf{S}_{bi} & \mathbf{S}_{bb} \end{bmatrix} \begin{bmatrix} \mathbf{D}_i \\ \mathbf{D}_b \end{bmatrix} = \begin{bmatrix} \mathbf{A}_i \\ \mathbf{A}_b \end{bmatrix} \tag{7}$$

where S is stiffness matrix, D is displacement vector, A is load vector and subscripts b and i represent the DOF`s for the nodes at the boundary and inside of the subregion respectively. Eliminating the DOF`s for the inside by the matrix condensation procedure, the static equilibrium equation for the super element with the DOF`s only at the boundary of the subregion can be obtained as follows;

$$\mathbf{S}^*_{bb}\mathbf{D}_b = \mathbf{A}^*_b \tag{8}$$

where, $\mathbf{A}^*_b = \mathbf{A}_b - \mathbf{S}_{bi}\mathbf{S}_{ii}^{-1}\mathbf{A}_i$ and $\mathbf{S}^*_{bb} = \mathbf{S}_{bb} - \mathbf{S}_{bi}\mathbf{S}_{ii}^{-1}\mathbf{S}_{ib}$

The matrix $\mathbf{S}^*_{bb}$ is the stiffness matrix and the vector $\mathbf{A}^*_b$ is the load vector for a super element having nodes only at the boundary and Eq. (8) is the equilibrium equation for a super element.

Use of fictitious beams for super elements

When a flat plate structure is modeled using the super elements developed in previous section, the number of DOF`s to be used in the analysis can be significantly reduced compared to the refined finite element model. However, the efficiency in the analysis can be significantly increased if the nodes on the boundary on the super element, except the node at the corners, can be eliminated while a compatibility condition is satisfied. Very stiff fictitious beams introduced to enforce the compatibility conditions at the interfaces of super elements by Lee et al. [14-17] were employed in this study. The role of the fictitious beams used in the development of super elements for the slabs is illustrated in Fig. 10. Fictitious beams are added to the boundary of the slab as shown in Fig. 10(a). Then, all of the DOF`s in the slab except those for the nodes at corners of the slab are eliminated using the matrix condensation technique as shown in Fig. 10(b). The surplus stiffness introduced by the fictitious beams can be eliminated by subtracting the flexural stiffness of fictitious beams from the stiffness of the super element as shown in Fig. 10(c). It should be noticed that the fictitious beams in Fig. 10(a) are subdivided into many elements to share nodes with plate elements while the fictitious beam in Fig. 10(c) has nodes only at both ends.

The boundary of the super element shown in Fig. 10(b) will be enforced to deform approximately in a cubic curve by the fictitious beams. This effect still remains in the super element after the elimination of fictitious beams. Therefore, the deformation compatibility condition at the boundary between two adjacent super elements will be satisfied approximately with active node only at corners of the super element.

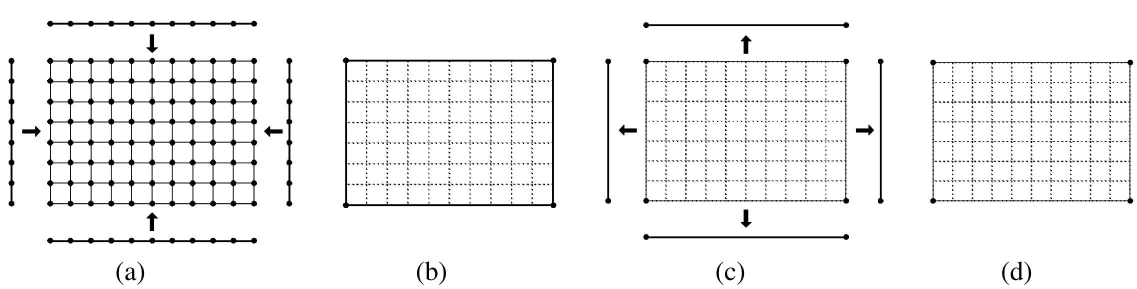


Fig. 10 Use of fictitious beams for flat slab

ANALYSIS OF EXAMPLE STRUCTURE

Analysis of a flat plate structure was performed to verify the efficiency and accuracy of the proposed method. The first example structure with a regular plan was used to compare the analysis results of the proposed method (PM) using super elements with fictitious beams to those of the equivalent frame method (EFM) and the finite element analysis (FEM) with refined mesh model. The proposed method can be applied to flat plate structures to which it is difficult to apply the equivalent frame method because of the irregularity in the plan.

The example structure is a 20-story flat plate structure with regular plan as shown in Fig. 11 and thickness of the slab was assumed to be 20 cm in each floor. Static and dynamic analyses were performed using the equivalent frame method, finite element method and proposed method respectively. The effective width by the Grossman method was used in the equivalent frame method and the stiffness reduction factor for slab (R_{KS}) illustrated in Fig. 5 was used for the refined finite element model and proposed model to account for the stiffness degradation in the slab.

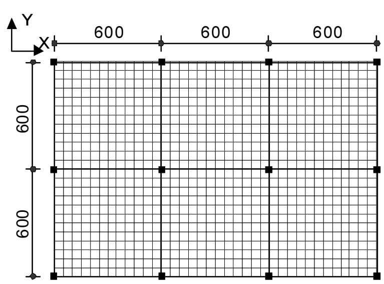


Fig.11 Plan of example structure

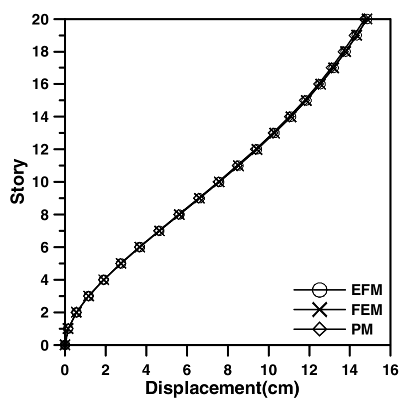


Fig.12 Lateral displacements

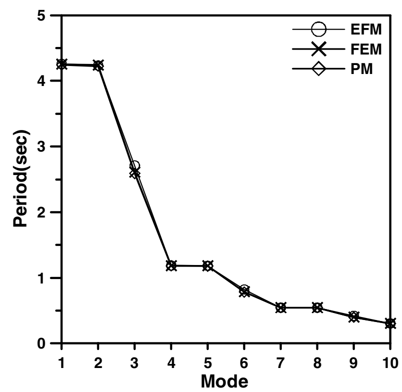


Fig.13 Natural periods of vibration

Table.3 Number of DOF's and computational time required for analysis

Models	Number of DOF's	Computational time(sec)				
		Assembly M&K	Static analysis	Eigenvalue analysis	Time history analysis	Total
FEM	55500	230.22	394.38	17406.66	281.58	18312.84
EFM	1740	2.61	0.36	19.69	7.67	30.33
PM	780	13.70	0.12	5.75	3.36	22.93

The inverse triangular loads that would induce $h/400$ of the roof displacement were applied in the Y direction for the static analysis. The lateral displacements from the equivalent frame method, finite element analysis and proposed method were almost identical as shown in Fig. 12. The natural periods of vibration from three methods had no significant difference as could be observed in Fig. 13. The mass of each floor slab was lumped to the ends of each column in the equivalent frame method instead of using the mass of the equivalent beams that is not appropriate to represent the mass of a floor.

The ground acceleration record of the El Centro earthquake (NS, 1940) was used as the input ground motion in the Y-direction for the time history analysis. The roof displacement time histories from the equivalent frame method, finite element analysis and proposed method which are almost identical as shown in Fig. 14. However, it could be noticed that the computational time and number of DOF`s used in the analysis for each method were significantly different as listed in Table 3. Since the number of DOF`s for the finite element analysis was significantly larger than those of the other methods, the finite element analysis required more than 600 times of the computational time for the other methods. The proposed method has nodes only at the connection between slabs and columns. However, additional nodes are required at the points where the effective width changed in the equivalent frame method because the effective width of the slab may change between columns. Thus, the number of DOF`s in the equivalent frame method was more than that of the proposed method.

Although the computational time for the assemblage of stiffness and mass matrices in the proposed method was slightly longer than that in the equivalent frame method owing to the process of developing super elements, it could be noticed that the other computational time of the proposed method was shorter than that of the equivalent frame method as shown in Table 3 because the number of DOF`s in the proposed model was less than that of the equivalent frame method leading to a small difference in the total computational time. Therefore, it does not matter whether the equivalent frame method or the proposed method is used in case of obtaining static displacement, natural periods, and displacement time history. However, the proposed method could provide the stress distribution in the floor slab with a similar accuracy to that from the finite element method which would cost significant amount of computational time.

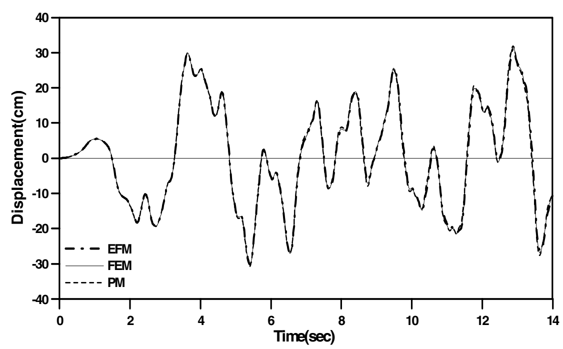


Fig.14 Roof displacement time histories

CONCLUSIONS

An improved analytical method that can consider the stiffness degradation effect in the slabs depending on the lateral drifts using super elements was proposed in this study for the efficient and accurate analysis of flat plate structures. The super elements and fictitious beams were used for the efficient analysis and the accuracy and the efficiency of the proposed method were investigated through the analysis of example structures. The major observations and findings could be summarized as follows:

1. The stiffness degradation in the flat plate system could be taken into account by the equivalent frame method for flat plate structures with regular plan. However, in the case of structures with irregular plan or slabs with openings, it is hard to use the equivalent frame method because of the difficulty in the determination of the effective width for the equivalent beams.

2. Structural analysis of a flat plate structure having irregular plan or slabs with openings can be performed and stress distribution of floor slabs can be easily represented using the finite element method if the stiffness degradation in the slab could be considered properly.

3. The stiffness degradation in the flat plate system could be represented by the reduced modulus of elasticity of floor slabs in the finite element method. The modulus of elasticity was reduced based on the UCB test results in this study. However, any further research results regarding to the stiffness degradation in the slab can be used in the same manner for the proposed method.

4. The proposed method using super elements developed by introducing fictitious beams could reduce the computational time and memory significantly in the analyses. The static and dynamic analyses results by the proposed method were very similar to those of the refined mesh model in all cases of the example structures.

ACKNOWLEDGEMENT

The Brain Korea 21 Project supported this work and this work was partially supported by the Korea Science and Engineering Foundation (KOSEF) through the Korea Earthquake Engineering Research Center (KEERC) at the Seoul National University (SNU).

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