Efficient Shoring System in RC Frame Structures

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Summary

In this paper, systematic analyses for the shoring systems installed to support the applied loads during construction are performed on the basis of the numerical approach. On the basis of a rigorous time-dependent analysis, structural behaviors of reinforced concrete (RC) frame structures according to the changes in design variables such as the types of shoring systems, shore stiffness and shore spacing are analyzed and discussed. The time-dependent deformations of concrete such as creep and shrinkage and construction sequences of frame structures are also taken into account to minimize the structural instability and to reach to an improved design of shoring system because these effects may increase the axial forces delivered to the shores. In advance, the influence of the column shortening effect, generally mentioned in a tall building structure, is analyzed. From many parametric studies, it has been finally concluded that the most effective shoring system in RC frame structures is 2S1R (two shores and one reshore) regardless of the changes in design variables.

Keywords: *Construction Sequence, Shoring System, Shore Stiffness, Shore Spacing*

1 Introduction

In accordance with the development of industrial society and global economic expansion, the construction of high-rise reinforced concrete (RC) buildings has increased. Moreover, the construction methods related to the shoring system have undergone refinement, and they have been further developed to reduce construction time and cost while maintaining the safety during construction. Since there is a risk of damage or collapse in structures if the forms are removed too soon before the concrete has gained sufficient strength to bear the dead loads and constructions loads, the design of the shoring system must provide a margin of safety so that construction can proceed without danger of collapse. Nevertheless, formwork removal may be scheduled at the earliest possible time since formwork represents a high proportion of the total construction cost and time of concrete structures. A reasonable shoring system, therefore, needs to be determined on the basis of the time-dependent analysis of structures considering the construction sequence, the early-age properties, and the long-term behaviors of concrete such as the creep and shrinkage.

It is common practice in multistory construction to support a freshly placed floor on a number of lower floors though vertical props between them. Each floor in such a system then shares in carrying the weight of all floors in the system plus the formwork. Basically the intension is that higher floors will be relieved of loads, while lower floors will carry loads greater than their self-weight. Therefore, the current load conditions on each floor must be analyzed in determining a reasonable shoring system. If freshly placed floors are supported by propping from a number of previously placed floors in a regular cycle, loads of more than twice the dead load of one slab can be imposed on lower floors at ages earlier than that at which the design strength of the concrete is attained.

To assess structural safety during construction, a thorough understanding of load distribution at each construction step must be preceded. Many design codes such as the Australian Formwork Code AS 3610 [2] and the ACI Committee 347 [1] provide general guidelines regarding formwork removal and loads carried by slabs and shores. Nevertheless, a number of concrete construction disasters has occurred as a result of early formwork removal and/or using less formwork [5, 9]. To avoid possible failure, it is necessary to check construction loads and make sure that the slab loads are less than their available strength as mentioned above. This is why analytical models for shoring system, which can simulate the construction loading process and calculate the slab and shore loads on the basis of rigorous time-dependent analysis, must be developed.

A few studies have been constructed on the development of analytical models. On the basis of a few assumptions related to the stiffnesses of shores and reshores, Neilson [11], Grundy and Kabaila [4] introduced simplified methods for the calculation of construction loads on supporting floors. In advance, a lot of implementations to improve previous numerical models have also been achieved by considering many influencing factors ignored, and many improved numerical models have been proposed [3, 9]. However, more improvements of numerical models and more considerations of influencing factors affecting the shoring system are still required to simulate more closely the actual behavior of the structure under consideration.

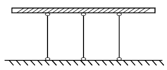
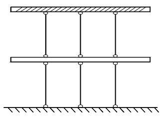
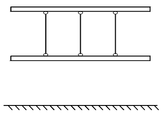
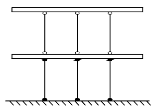
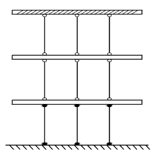
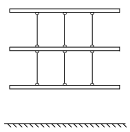
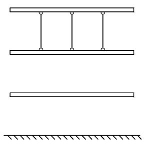
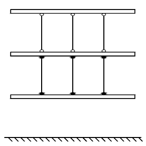
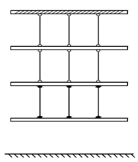
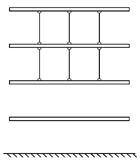
On the basis of parametric studies for the influence of many factors (such as the creep of concrete, the stiffness of shoring system, and unequal settlements in columns, etc.), in advance, very comprehensive discussions for the shoring problems are made, together with a conclusion that the most efficient shoring system will be 2S1R (two levels of shoring and one of reshoring).

2 Shoring loads on supporting slabs

ACI Committee 347 introduces a guideline to determine the construction loads imposed on slabs and formwork on the basis of the simplified methods proposed by Grundy and Kabaila [4], in which the following assumptions are made: (1) the axial stiffness of shores and reshores are infinite; (2) all slabs are assumed to possess equal flexural stiffness, and stiffness is time-dependent; and (3) the foundation is assumed to be rigid. In spite of its simplicity adopted in the assumptions, moreover, good agreement was also observed between the predictions made by the simplified analysis and the experimental results [9]. Hence, the simplified method can be considered straightforward and easy to use.

Results of a typical load analysis are shown in Table 1. This table presents the case of construction with two floors of shores and one of reshore (2S1R), without allowing for construction loads or the weight of forms and shores. There are three basic operations performed in the same sequence throughout most of the operation: (1) set up a story of shores and forms and place the fresh concrete; (2) remove the reshores at lowest interconnected level, and remove forms and shores from next story above; and (3) place reshores snugly under the slab just stripped, but without reshores carrying any load when they are first placed. As shown in Table 1, the slabs carry no load until the first level of shores is removed, and each then bears its own weight. As the cycles proceed, when each fresh slab is placed, it is assumed that the load is distributed equally among interconnected slabs in the system. The load in shores at the end of each step is also calculated on the basis of a summation of vertical forces [6].

Table 1 Simplified Analysis of Loads on Shores and Slabs (2S1R)

Step	Operation	Status of structure	Slab Load (in Multiples of D)	Shore Load
1	Place level 1		0	1.0 D
2	Place level 2		0 0	1.0 D 2.0 D
3	Remove shores (level 1)		1.0 D 1.0 D	0
4	Place reshores (level 1)		1.0 D 1.0 D	0 0
5	Place level 3		0 1.0 D 1.0 D	0 1.0 D 1.0 D
6	Remove reshores (level 1)		0.33 D 1.34 D 1.33 D	0.67 D 0.33 D
7	Remove shores (level 2)		0.5 D 1.5 D 1.0 D	0.5 D
8	Place reshore (level 2)		0.5 D 1.5 D 1.0 D	0.5 D
9	Place level 4		0 0.83 D 1.83 D 1.34 D	1.0 D 1.17 D 0.34 D
10	Remove reshores (level 2)		0.11 D 0.94 D 1.95 D	0.89 D 0.95 D

The maximum slab load shown in Table 1 is on the second floor slab at step 10, where it is carrying 1.95D, where D is the dead load weight of concrete slab. The most heavily loaded slab in any system is always the last slab cast before shores at the ground level were removed. As construction proceeds upward, cycles begin to repeat, and the maximum slab load at higher levels is about 1.9 times the slab dead load [6]. On the other hand, when the loads of forms (0.1D) and shores (0.05D) and the construction live load of 0.5D, recommended by the ACI Committee 347, are superimposed to the dead load of the concrete slab and distributed according to the same principles followed in developing Table 1, the maximum slab load also occurs on the second floor, but its magnitude changes to 2.11D in step 9, compared with a maximum of 1.95D shown in Table 1 where form and shore weight and construction live load were not considered. In advance, more details for the shore and slab loads can be found elsewhere [3, 4, 9].

The analysis shows that the maximum loads carried by the slabs and shores may not be proportional to the load ratios even in the case of no change in the analysis procedure. In advance, in spite of a good agreement between a few field measurements and the simplified method, obviously the assumptions adopted are not precisely true. The consideration of the time-dependent deformations and material properties of concrete will enlarge the differences from the actual behavior of the structure. Thus, the need for more improved analysis considering many influencing factors ignored in the simplified method has been increased, and one of the main purpose for this paper is to calculate more realistic slab and shore loads by simulating the actual structural behavior as closely as possible.

3 Numerical analyses

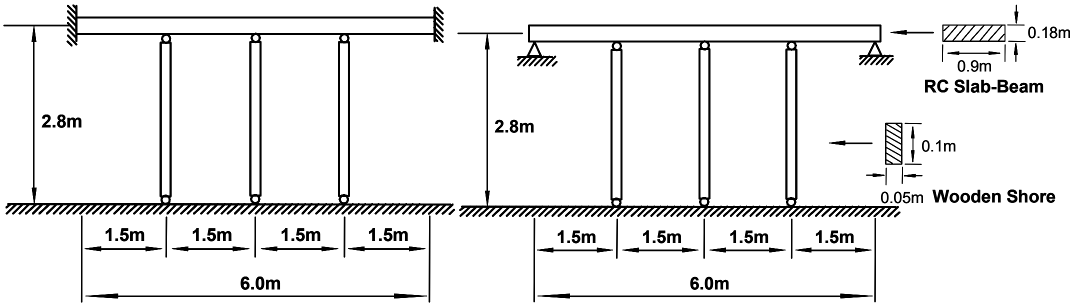
A lot of analysis methods for the shoring system as well as the simplified method mentioned in the ACI Committee 347 have been introduced. With the use of matrix methods for structural analysis, Liu, Chen, and et al. [9] introduced the refined analysis. The basic assumptions used are: (1) the slabs behave elastically and their stiffnesses are time-dependent; (2) the shores and reshores behave as continuous uniform elastic supports, and their axial stiffnesses are time-dependent; and (3) the joints between the shores and slabs are pin-connected. Although the refined analysis also gives a good agreement with the simplified analysis in predicting the location and step of maximum shore and slab loads, there are still differences in values for the slabs and shores between two methods due to the variation of the basic assumptions adopted. Disregarding the history of the structure reflecting the effect of accumulated deformations within successive stages of construction in the two methods increased the need for more improved analysis methods, and an improved analysis method has been introduced by El-Shahhat and Chen [3]. Beyond the assumptions used in the refined method, this method utilizes the deflection approach by updating the deflection to the current stage of construction and forming a system of equations in the unknown shore loads based on the deformed configuration of the structure.

Surely reasonable numerical results for the shore and slab loads can be obtained by the refined and/or improved method. Nevertheless, more improvements need to be continued in determining the best shore system to a typical structure because the shore behaviors including the shore and slab loads are expected to be influenced by the construction sequence and time-dependent deformations of concrete. Since all the factors which affect the structural behavior (such as creep of concrete, early-age properties of concrete, stiffness of shores and reshores, construction sequences in multi-story structures, boundary conditions at the joints connecting the columns and slabs, and unequal axial deformations between the adjacent two columns, etc.) must be taken into account to obtain a precise theoretical solution and, in advance, to determine the most effective shoring system on the basis of an exact estimation for the structural behavior, the numerical approach which can consider all these effects, is used in this paper.

To establish the validity of the proposed model, the same example structure with that analyzed by many previous researchers [3, 8, 9, 10] is selected in this paper. As shown in Fig. 1, the example structure considered two boundary conditions of fixed-end slabs and simply supported slabs. The axial deformations of the columns were neglected, and only dead load of the slab was considered. However, since the axial deformations of the columns are taken into account in this paper, columns need to be added as shown in Fig. 2 instead of assuming the end boundary conditions of slabs as in Fig. 1..

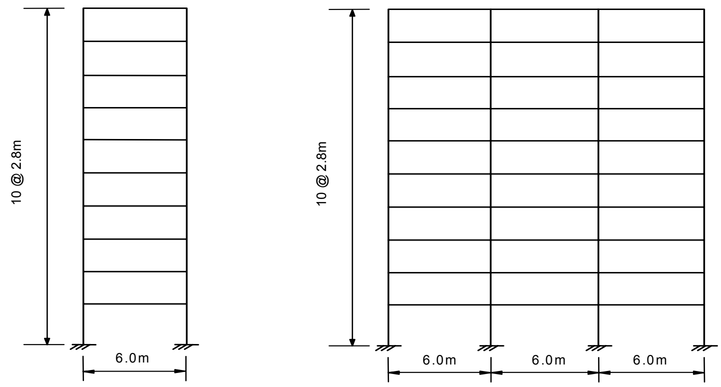
The following material properties are assumed in this paper: (1) the ultimate creep coefficient ϕ_{cr}^{∞} and the ultimate shrinkage strain $\varepsilon_{sh}^{\infty}$ of concrete are 2.5 and 300×10^{-6} regardless of the member location; (2) the compressive strength of concrete is $280 kg/cm^2$; and (3) the load carried by the slab is considered as a distributed load applied on the beams and its magnitude becomes w_{slab}=27.0kg/cm ($2.54 t/m^3\times6.0m\times0.18m$) on the basis of the slab thickness of 18cm and the column spacing of 6.0m×6.0m. Besides, another plane frame of one-bay (see Fig. 3(b)) is also considered to investigate the influence of the unequal column shortenings between the adjacent two columns to the slab loads and the shore loads. Analyses are based on 2S1R shoring system, and the same shore intervals with those used in the previous study [3] are assumed.

In advance, to investigate the structural behavior according to the stiffness of shores and reshores, two types of wood shores with A_w=10cm×10cm, $E_w=7.74\times10^4 kg/cm^2$ and tubular steel shores with $A_s=8.58cm^2$, $E_s=2.1\times10^6 kg/cm^2$ were taken into consideration to compare with the simplified analysis mentioned in the ACI Committee 347, where the axial stiffness of shores are assumed to be EA=∞. In advance, unlike an assumption that the shores are spaced close enough to treat the shore reactions as a distributed load, the shores arranged with a uniform interval usually deliver the concentrated loads to the structure under construction. In order to consider the effect of the shore spacing, a similar analysis has been conducted and compared when the shore spacings are *S*=60cm, 100cm, and 150cm representing the lower and upper boundary values usually adopted in practice, respectively.



(a) Fixed-Ended Slab (b) Simply Supported Slab

Fig. 1 Calculation Model [3]



(a) One-bay structure (b) Three-bay structure

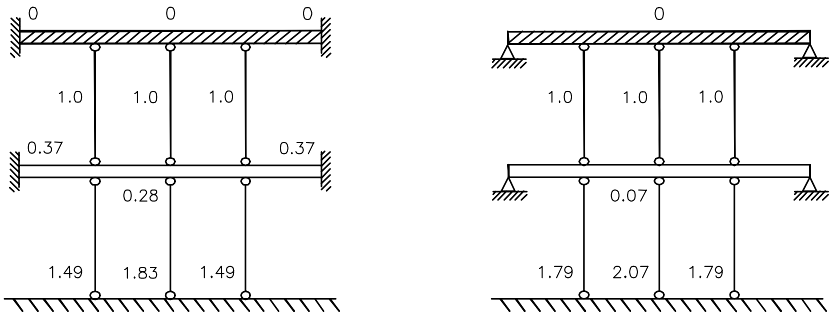
Fig. 2 RC Frame Structures

Table 2 Material Properties and Section Dimensions for RC Frame Structures

Floor	Member	Width×Depth (B×H)	Gross Area of Concrete (A_c)	Steel Area
10	Beam	22.5cm × 57.5cm	1293.8 cm^2	A_{st}=A_{sc}=29.8 cm^2
7 – 9		22.5cm × 60.0cm	1350.0 cm^2	A_{st}=A_{sc}=31.1 cm^2
4 – 6		25.0cm × 62.5cm	1562.5 cm^2	A_{st}=A_{sc}=35.9 cm^2
1 – 3		25.0cm × 65.0cm	1625.0 cm^2	A_{st}=A_{sc}=37.4 cm^2
7 – 10	Column	25.0cm × 40.0cm	1000.0 cm^2	A_s=40.0 cm^2
6		25.0cm × 42.5cm	1062.5 cm^2	A_s=42.5 cm^2
5		25.0cm × 47.5cm	1187.5 cm^2	A_s=47.5 cm^2
3 – 4		27.5cm × 50.0cm	1375.0 cm^2	A_s=55.0 cm^2
2		27.5cm × 52.5cm	1443.8 cm^2	A_s=57.8 cm^2
1		32.5cm × 60.0cm	1950.0 cm^2	A_s=78.0 cm^2

3.1 Slab load

Table 1 gives the values of shore and slab loads. The shore load is defined as the ratio between the load carried by a shore and slab dead load arranged to be carried by a shore, and the slab load is the ratio of the slab moment to the moment due to dead load. Both the shore and slab loads mentioned in Table 1 are not identical for the improved method [3] and the analytical approach introduced in this paper because of differences in the assumptions adopted. In advance, the elastic behavior of slabs and restraint to the rotation at the ends of slabs give the different values at the both the middle and end of a span. Since two boundary conditions of the fixed-end slabs and simply supported slabs as shown in Fig. 3 are considered in the improved method, the slab moments obtained from these two different boundary conditions with the shore spacing of *S*=150cm are mentioned in Table 3. On the other hand, in the case of the introduced numerical method, exact end conditions can naturally be determined according to the bending stiffness ratios between the columns and slabs because the frame structure itself is taken into consideration, instead of assuming the end boundary conditions as in the simplified and/or improved methods.



(a) Fixed Boundary (b) Simply Supported Boundary

Fig. 3 Shore and slab loads obtained by improved method at step 2 in Table1

Accordingly, the slab loads mentioned in Table 3 are determined by the following equation.

$$slab\ load = \frac{M_{\max}\ (M^{+}_{\max}\ or\ M^{-}_{\max})}{M_0\ (M^{+}_0\ or\ M^{-}_0)} \tag{1}$$

where M_0 is the slab moment by the self-weight of slab, w_{slab}, and can be calculated from the beam theory which gives the positive moment of $M_0^+ = w_{slab} \cdot L^2/24$ and the negative moment of $M_0^- = w_{slab} \cdot L^2/12$ in a clamped beam, and $M_{\max}$ represent the corresponding maximum slab moment occurred during construction at the same point where the slab moment by the self-weight is determined.

The results in Table 3 indicate that the maximum slab loads occur on the second floor slab at step 10 regardless of differences in the analysis methods introduced in the previous studies [3, 4, 9], and the resulting maximum slab loads seem to be occurred at the lowest one among the slabs, which is still supported by shores, even though construction proceeds upward with the repeated shoring, reshoring, and removing of shores. However, the present study gives the maximum values at the second floor slab at step 9 at both cases of considering and not considering the time-dependent deformations at the frame structure (see (3) and (4) in Table 3). This result is reasonable, since the direct consideration of column members instead of assuming the boundary conditions will definitely reduce the moment values in proportional to a decrease of unequal settlements between the columns and shores. Moreover, the creep deformation of concrete induces the continuous redistribution of the applied load through entire members in the frame structure and decreases the moment differences along the members.

Table 3 Comparison of slab loads

*Step	Level	(1)	Fixed Boundary				Simply Supported Boundary		This Study			
			(2)		(3)		(2)	(3)	(4)		(5)	
			(+)M	(-)M	(+)M	(-)M	(+)M	(+)M	(+)M	(-)M	(+)M	(-)M
1	1	-	-	-	-	-	-	-	-	-	-	-
2	1	0.00	0.37	0.28	0.37	0.28	0.07	0.07	0.15	0.24	0.14	0.25
3,4	1	1.00	1.41	1.33	1.39	1.39	1.12	1.12	1.10	1.14	1.01	1.15
	2	1.00	0.67	0.59	0.61	0.61	0.88	0.88	0.92	0.85	0.98	0.86
5	1	1.00	1.60	1.54	1.59	1.60	1.20	1.21	1.16	1.23	1.07	1.25
	2	1.00	1.09	1.09	1.08	1.07	1.03	1.02	0.99	1.02	1.05	1.03
	3	-	-	-	-	-	-	-	-	-	-	-
6	1	1.33	1.78	1.75	1.73	1.83	1.52	1.54	1.44	1.43	1.21	1.30
	2	1.34	1.19	1.16	1.29	1.19	1.27	1.32	1.25	1.17	1.14	1.12
	3	0.33	0.06	0.05	0.12	0.08	0.20	0.14	0.34	0.39	0.61	0.60
7,8	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.96	1.03
	2	1.50	1.67	1.63	1.78	1.65	1.55	1.60	1.48	1.43	1.29	1.28
	3	0.50	0.37	0.33	0.35	0.22	0.45	0.40	0.53	0.57	0.74	0.71
9	1	1.34	1.21	1.18	1.21	1.18	1.31	1.31	1.33	1.29	1.41	1.52
	2	1.83	1.95	1.94	1.93	2.09	1.88	1.93	**1.82**	**1.76**	**1.64**	**1.60**
	3	0.83	0.87	0.85	0.89	0.70	0.80	0.75	0.87	0.95	1.07	1.09
	4	-	-	-	-	-	-	-	-	-	-	-
10	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.97	1.02
	2	**1.95**	**2.06**	**2.05**	**2.24**	**2.01**	**2.12**	**2.12**	**1.79**	**1.69**	**1.59**	**1.54**
	3	0.94	0.92	0.91	0.92	0.90	0.86	0.86	0.85	0.88	1.01	1.00
	4	0.11	0.03	0.03	0.14	0.07	0.02	0.02	0.37	0.43	0.42	0.45

Note : *Step – construction step mentioned in Table 1; Level – floor slab;
(1) simplified method [4]; (2) refined method [9]; (3) improved method [3];
(4) this study (considering concrete age only and using wood studs);
(5) this study (considering aging, creep and shrinkage of concrete and using wood studs);
(+)M – positive moment; (-)M – negative moment; Load=Self-weight(D)

Since the column members with finite axial and bending stiffnesses are taken into account, the obtained numerical results can be expected to be located between the two boundary values obtained by assuming the simply supported and clamped boundary conditions. Nevertheless, no remarkable correspondence in the results were detected (see (2), (3), (4) and (5) in Table 3). But, the results surely depend on the differences in the axial and bending stiffnesses between the columns and shores, the shore intervals, and the shore systems adopted because, unlike the assumed boundary conditions in which all the loads are delivered through the shores only, the loads are transmitted to lower floors through the columns and shores.

Table 4 represents the maximum slab loads according to the consideration of the time-dependent deformations of concrete at each shore system, and the following can be inferred: (1) no remarkable differences in the maximum slab loads exists in spite of changes in considering effects; (2) the slab loads usually increase or decrease in proportional to the stiffness of shores and represent a maximum difference of about 7 percent for the positive moment and 15 percent for the negative moment; (3) relatively small slab loads occur at the shoring system adopting the reshoring procedure (see 1S1R and 2S1R cases in Table 3) due to the load redistribution through the repeated release and reinstallation of shores; (4) consideration of the time-dependent deformations of concrete decreases the slab loads at the shore systems of 2S1R and 3S and increase the slab loads at the shore system of 1S1R and 2S; and (5) these trends for the slab loads seem to be maintained regardless of the shore intervals. It means that the use of a larger shore interval does not require any additional consideration in addition to the strength and serviceability of the slab form.

Table 4 Maximum load ratios for slabs when the applied load is D

	Shore System	(1)		(2)		(3)		(4)		(5)	
		(+)M	(-)M	(+)M	(-)M	(+)M	(-)M	(+)M	(-)M	(+)M	(-)M
Shore Spacing (60cm)	**1S1R**	1.53	1.60	1.54	1.55	1.58	1.59	1.74	1.68	1.74	1.71
	2S	2.04	2.08	2.03	1.98	2.00	1.92	2.03	1.92	2.06	1.97
	2S1R	1.88	1.88	1.86	1.81	1.82	1.76	**1.69**	**1.64**	**1.72**	**1.69**
	3S	2.24	2.27	2.21	2.08	2.11	1.96	1.99	1.92	2.05	2.02
	Shore System	(1)		(2)		(3)		(4)		(5)	
		(+)M	(-)M	(+)M	(-)M	(+)M	(-)M	(+)M	(-)M	(+)M	(-)M
Shore Spacing (100cm)	**1S1R**	1.55	1.57	1.56	1.57	1.62	1.64	1.76	1.66	1.77	1.73
	2S	2.07	2.05	2.07	2.30	2.00	1.86	2.04	1.89	2.09	2.04
	2S1R	1.90	1.86	1.91	1.85	1.81	1.72	**1.67**	**1.60**	**1.74**	**1.75**
	3S	2.28	2.23	2.28	2.20	2.04	1.86	1.99	1.85	2.12	2.10

Note : (1) considering concrete age only and using rigid studs;
(2) considering concrete age only and using steel studs;
(3) considering concrete age only and using wood studs;
(4) considering aging, creep and shrinkage of concrete and using wood studs;
(5) considering aging, creep and shrinkage of concrete and using steel studs;
(+)M – positive moment; (-)M – negative moment; Load=Self-weight(D)

Table 5 Maximum load ratios for slabs when the applied load is 1.5D

	Shore System	(1)		(2)		(3)		(4)		(5)	
		(+)M	(-)M	(+)M	(-)M	(+)M	(-)M	(+)M	(-)M	(+)M	(-)M
Shore Spacing (60cm)	**1S1R**	1.78	1.89	1.78	1.82	1.86	1.89	2.04	1.96	2.05	2.00
	2S	2.30	2.36	2.30	2.24	2.26	2.16	2.32	2.20	2.33	2.25
	2S1R	2.02	2.06	2.02	1.98	1.98	1.92	**1.84**	**1.80**	**1.88**	**1.86**
	3S	2.42	2.46	2.39	2.23	2.26	2.09	2.19	2.09	2.21	2.20

Note : (1) considering concrete age only and using rigid studs;
(2) considering concrete age only and using steel studs;
(3) considering concrete age only and using wood studs;
(4) considering aging, creep and shrinkage of concrete and using wood studs;
(5) considering aging, creep and shrinkage of concrete and using steel studs;
(+)M – positive moment; (-)M – negative moment; Load=Self-weight(D)+Construction Live Load(0.5D)

As shown in Table 4, the slab loads represent the minimum values at 2S1R shore system (see (4) and (5) in Table 4), which means that 2S1R is the most effective shoring system because the relatively small loads carried by slabs will minimize the structural problems which might be caused by the early release of shores. The same analysis procedure was conducted with the applied loads of 1.5D instead of 1.0D in Table 4 to consider the additional construction live load of 0.5D, and the obtained results, when the shore interval is 60cm, are presented in Table 5 to compare with those mentioned in Table 4.

Similar results for the slab loads are also obtained in the case of considering the additional construction live load of 0.5D. The construction step and the shore system which give the minimum slab loads are not changed. Only the maximum values of slab loads mentioned in Tables slightly increase up to 7~15% in spite of additional load of 0.5D (an increase of 50%). This phenomenon results from the fact that the construction live load is not sustained but removed after concreting each floor.

3.2 Shore load

Unlike an assumption, adopted in the simplified method, that the shores with an infinite axial stiffness are spaced close enough to treat the shore reactions as a distributed load, the shores are installed with a uniform distance in practice. This causes unequal shore reactions between the exterior and interior shores and, in advance, even in the interior shores due to the elastic deflections of slabs and shores with a finite axial stiffness. To investigate the changes in shore loads according to the shore intervals, therefore, numerical analyses for the structures with typical shore intervals are conducted, and the obtained results can be found in Table 6. Especially, the maximum values in Table 6 means the maximum force ratios of the shore loads directly calculated from the numerical analysis to those obtained from the idealized load distribution as shown in Fig. 4. The average shore loads are also calculated by averaging all the shore loads for the shores installed at the same floor where the maximum shore load is determined.

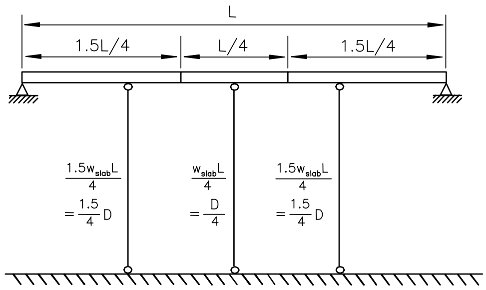


Fig. 4 Idealized load distribution

Since the stiffnesses of all the composed members such as the columns, slabs and shores are taken into account, different shore loads from those obtained by the simplified method are expected, and the differences seem to be enlarged by the additional time-dependent deformations of structural members. However, when the rigid axial stiffness of shores is assumed, the obtained maximum shore loads ((1) in Table 6) represent almost the same values with those mentioned in Table 1 regardless of the shore intervals. Comparisons of (4) and (5) with (3) and (2) in Table 6 also show that the time-dependent deformations of concrete increase the shore loads in the case of 1S1R shore system but decreases the loads for the other shore systems. This result can be explained by the fact that, in 2S, 2S1R and 3S shore systems which require a longer shoring time than 1S1R system, the slabs and columns also sustain large portion of loads delivered to the down stairs after releasing the shores because the shoring time is usually sufficient for curing the concrete.

Table 6 also shows that the stiffnesses of shores cause minor changes to the maximum shore loads but a lot of changes to the average shore loads. The average shore loads decrease in proportional to the shore stiffness. This means that relatively large changes in shore loads are not caused at the shores located at mid-span where the maximum shore load is usually calculated but caused at the shores located at the end-span because relatively large portion of dead loads is delivered to a stiffer one between two members of a shore and a column. From Table 6, it can be also inferred that the maximum shore loads ((2) to (5) in Table 6) might be larger than those calculated by the design code ((1) in Table 6). Therefore, a rigorous analysis considering the time-dependent deformations of concrete and the construction sequence might be necessary to reserve the safety during construction.

Table 6 Maximum and average shore loads

	Shore System	(1)		(2)		(3)		(4)		(5)	
		Aver.	Max	Aver.	Max	Aver.	Max	Aver.	Max	Aver.	Max
Shore Spacing (60cm)	**1S1R**	0.91	**1.00**	0.77	1.05	0.71	1.09	1.10	**1.60**	1.17	**1.53**
	2S	1.82	**2.00**	1.54	2.11	1.43	2.17	1.51	**2.15**	1.61	**2.05**
	2S1R	1.82	**2.00**	1.54	2.11	1.43	2.17	1.51	**2.15**	1.61	**2.05**
	3S	2.72	**3.00**	2.13	3.24	1.88	3.13	2.43	**3.13**	2.85	**2.94**
	Shore System	(1)		(2)		(3)		(4)		(5)	
		Aver.	Max	Aver.	Max	Aver.	Max	Aver.	Max	Aver.	Max
Shore Spacing (100cm)	**1S1R**	0.85	**1.01**	0.75	1.09	0.67	1.08	1.04	**1.62**	1.11	**1.57**
	2S	1.69	**2.01**	1.45	2.16	1.33	2.15	1.42	**2.19**	1.52	**2.16**
	2S1R	1.69	**2.01**	1.45	2.16	1.33	2.15	1.42	**2.19**	1.52	**2.16**
	3S	2.53	**3.01**	1.97	3.21	1.68	2.91	2.12	**3.13**	2.43	**3.16**

Note : (1) considering concrete age only and using rigid studs;
(2) considering concrete age only and using steel studs;
(3) considering concrete age only and using wood studs;
(4) considering aging, creep and shrinkage of concrete and using wood studs;
(5) considering aging, creep and shrinkage of concrete and using steel studs;
(+)M – positive moment; (-)M – negative moment; Load=Self-weight(D)

Table 7 Maximum Shore and Slab Loads Determined Considering the Unequal Column Shortenings.

Slab Loads

	Shore System	(1)		(2)			Shore System	(1)		(2)	
		(+)M	(-)M	(+)M	(-)M			(+)M	(-)M	(+)M	(-)M
Shore Spacing (60cm)	**1S1R**	1.58	1.66	1.73	**1.50**	Shore Spacing (100cm)	**1S1R**	1.62	1.72	1.74	1.81
	2S	2.00	1.90	2.01	1.91		**2S**	1.99	1.84	2.02	1.87
	2S1R	**1.81**	**1.73**	**1.67**	**1.48**		**2S1R**	**1.80**	**1.68**	**1.65**	**1.58**
	3S	2.10	1.97	1.97	2.00		**3S**	2.03	1.87	1.97	1.91

Shore Loads

	Shore System	(1)		(2)			Shore System	(1)		(2)	
		Aver.	Max	Aver.	Max			Aver.	Max	Aver.	Max
Shore Spacing (60cm)	**1S1R**	0.70	1.08	1.09	**1.60**	Shore Spacing (100cm)	**1S1R**	0.65	1.07	1.02	**1.62**
	2S	1.40	2.17	1.49	**2.15**		**2S**	1.30	2.14	1.40	**2.18**
	2S1R	1.40	2.17	1.49	**2.15**		**2S1R**	1.30	2.14	1.40	**2.18**
	3S	1.86	3.10	2.42	**3.12**		**3S**	1.65	2.87	2.10	**3.11**

Note : (1) considering concrete age only and using wood studs;
(2) considering aging, creep and shrinkage of concrete and using wood studs;
(+)M – positive moment; (-)M – negative moment; Load=Self-weight(D)

3.3 Effect of Unequal Column Shortenings

A frame structure with more than one-bay, as shown in Fig. 3(b), accompanies the unequal column shortenings between the exterior and the adjacent interior columns due to the differences in dead loads carried, and these differences will be enlarged with time because of additional time-dependent deformations of concrete. In addition, these differences develop the secondary stresses between each structural member while redistributing the loads to reach to an equilibrium state and also cause the different structural behaviors from those assumed in calculating the slab and shore loads.

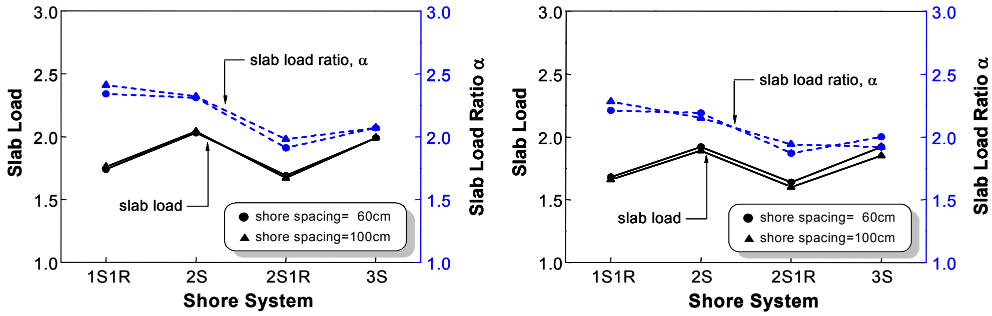
To investigate the effect of unequal column shortenings on the shore and slab loads, a three-bay 10-story frame structure shown in Fig. 3(b) is analyzed. All the material properties and section geometries are the same with those mentioned before in describing the example structure in Fig. 3, and the obtained results are shown in Table 7. On the basis of comparisons between Table 7 and Tables 3 and 5, the following can be inferred: (1) no dominant effect by the column shortenings appears in the case of the slabs loads, but slight decreases at 1S1R and 2S1R systems in Table 7 were observed. These differences seem to be caused by the stress redistribution during the reshoring procedure; (2) no remarkable difference was detected in the case of the shore loads; (3) Therefore, the unequal column shortening effect can be ignored in calculating the shore and slab loads.

3.4 Slab load considering concrete age

As shown in Eq. (1), the slab loads were defined in this paper as the ratios of the maximum slab moments occurred during construction to the slab moments by the self-weight after construction, and these slab loads can directly be used to design the slabs considering the construction sequence and concrete age. In advance, since a slab is designed as a beam with unit width and its resisting capacity is proportional to $f_c^{'} \cdot bd^2$, the ratio of the moment M to $f_c^{'} \cdot bd^2$ can be used as an index in expressing the relative magnitude of the moment, where $f_c^{'}$ is the compressive strength of concrete and b and d mean the section width and effective depth, respectively. The magnitude of the moments developed during construction, however, represents very small value because a lot of shores are installed with a uniform interval. To solve this problem and to take into account the compressive strength variation with time, the following normalized equation is introduced to define a slab load ratio, α.

$$\alpha = \frac{\dfrac{M_{\max}(t)}{f_c^{'}(t) \cdot bd^2}}{\dfrac{M_0}{f_c^{'}(28) \cdot bd^2}} = \frac{M_{\max}(t)}{M_0} \cdot \frac{f_c^{'}(28)}{f_c^{'}(t)} = (slab\ load) \cdot \frac{f_c^{'}(28)}{f_c^{'}(t)} \tag{2}$$

where $f_c(28)$ and $f_c^{'}(t)$ represent the compressive strength at 28 days and at age t.



(a) For Positive Moment (b) For Negative Moment

Fig. 5 Slab Loads and Slab Load Ratios

Fig. 5 shows the slab loads and corresponding slab load ratios. Different from relatively small slab load in the case of 1S1R system, its load ratio represents the largest value among the four shore systems. It means that the slab moment at 1S1R system represents the maximum value at earlier time than the other shore systems because the compressive strength of concrete is relatively small when the shores are released. Especially, the load ratio distributions imply that (1) a slight difference is detected between two groups of shoring systems, 1S1R and 2S systems. 1S1R and 2S systems where shores are installed through two connected stories give larger slab load ratios than 2S1R and 3S systems which require the shoring through three stories, and the same reason with that mentioned in the case of 1S1R can be inferred; and (2) finally, the most effective shore system is 2S1R regardless of the changes in design parameters.

4. Conclusions

The representative RC frame structures were analyzed with the purpose of investigating the relative effects of design variables related to shoring systems and the following conclusions were obtained: (1) determination of the shore interval is not governed by the resisting capacities of slabs and shores but affected by the serviceability conditions such as the deflection. Therefore, the shore interval can be increased as large as possible with in the range which does not cause any serviceability problem; (2) ignoring the time-dependent deformations of concrete in designing the shore system produces conservative results to the slabs loads and underestimated results to the shore loads. It means that an equation or method for the shore design, which can take into account the time-dependent deformations of concrete, needs to be proposed to reserve the safety, even though it gives a conservative result; and (3) it can be concluded that 2S1R is the most effective shore system.

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