Design Guidelines for Safe Concrete Construction

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In multistory reinforced concrete (RC) building construction, the early-age concrete slabs with partial strength and formwork consist of a temporary supporting system which carries all loads for a given construction plan by contractors. The construction schedule and supporting system must be designed properly for safely erecting buildings. There is a need to balance safety and economy in the design process.[1-3] This study focuses on developing practical design guidelines for the supporting system in multistory building construction.

There are mainly four available documents in the United States for general construction practices:

1) ACI 347R-94, "Guide to Formwork for Concrete";

2) Chapter 6 of ACI 318-95, "Building Code Requirements for Structural Concrete";

3) ANSI A10.9 (1983), American National Standard for Construction and Demolition Operations-Concrete and Masonry Work-Safety Requirements; and

4) OSHA (1988), Construction Safety and Health Regulations.

In ACI 347 and ANSI A10.9, the minimum construction loads are suggested. In addition, the ASCE Structural Division also drew up a working draft, Proposed Guide/Standard for Design Loads on Structures during Construction (1993). These documents establish a state-of-the-art technology to provide basic requirements for safe construction. It is clearly seen that there are no sufficient detail specifications for safe construction in all these documents, and the suggested minimum construction loads also need more investigation. Contractors and formwork designers need to know more about the load characteristics and structural behaviors during construction in order to develop a rational design guideline for safe construction.[4,5] The large number of failure accidents during construction[6] also shows the necessity of improving the current guidelines of construction.

There are many factors which affect the behavior of a slab-formwork supporting system. These factors can be classified into the following three categories:

1) Design decisions by structural designers: including concrete type, column and slab sizes, reinforcement arrangement, and so on.

2) Construction schedules made by construction contractors: including method of shoring and reshoring, construction cycle, method of concrete placement (concrete bucket dropping, pumping, concrete placing paths).

3) Environmental conditions: ambient temperature, wind condition, and other possible natural excitations.

To develop a proper design guideline for safe construction, all these factors should be taken into account. In the slab design requirements of the ACI Building Code (ACI 318-92), the partial factor design formula is used in which the load factors for dead and live loads are different during service. But due to lack of sufficient field data and large variation of live load during construction, live load should be evaluated by analysis and field measurements together. Treating the dead and live load factors as identical, the general design formula for slabs at any critical time can be written as:

Factored resistance ≥ Effect of factored loads, or

$$\phi R_n \geq 1.4(D+L) \qquad \text{Eq. 1}$$

where R_n, D, and L are nominal member resistance, specified dead load, and live load during construction, respectively. ϕ is the resistance factor for slabs during construction. The load factor for dead and live load is 1.4. The reliability level based on this design formula is beyond the scope of this article.

The design formula for formwork using allowable stress design (ASD) can be written as:

$$R_n \leq S/K_{fs} \qquad \text{Eq. 2}$$

where R_n is nominal resistance, S is specified load effect, and K_{fs} is a factor of safety. The specified load effect is the subject of this article.

The load effects on formwork and slabs in a multi-level supporting system may be different even though they are subject to the same construction load.[7-9] Thus, the design of the supporting system for a given construction schedule includes two parts:

1) for slabs: to determine the specified load effect on slabs and to ensure the safety of the partial strength slabs during construction;

2) for formwork: to determine the specified load effect on formwork to design formwork by the ASD method.

This article is aimed at providing a reference for safe construction, not a design guideline for direct construction use.

Construction loads

Gravity load: including dead load and live load

Dead load includes slab weight and formwork weight (about 0.1 times the slab weight). The dead load is assumed to be uniformly distributed during construction. Live load includes workers, equipment, material storage, the effect of nonuniform loading during concrete placement, impact effect of concrete bucket dropping and buggy moving, shore removal, and so on.

ACI Committee 347[10] recommends a minimum construction live load of 50 psf (2.4 kPa) for workmen, equipment, runways, and impact, and 75 psf (3.6 kPa) when using buggy transporting. The minimum design load for combined dead and live loads should be 100 psf (4.8 kPa), or 125 psf (6.0 kPa) when using buggy transporting.

Dead load and live load act on a supporting system in dif-

Table 1 — Dead load in field measurements during concrete placement in Taiwan reported by Huang[12]

No.	Locations	Steel wt. (kip)	Conc. wt. (kip)	Total wt. (kip)	Area (ft^2)	Unit wt. (psf)
1	Chung-Hsing U. (1)	187	1270	2478	2944	150
2	Chung-Hsing U. (2)	110	829	1596	3528	81
3	Dali Elementary Schl.	73	421	840	1367	109
4	Chung-Hsing U. (3)	816	3483	7308	7577	172
5	China Medical College	194	862	1795	3243	99
6	Wamei W. St. (1)	364	1082	2458	5144	85
7	Tsungder Rd.	216	1215	2432	4082	106
8	Taiyuan N. Rd.	196	1250	2458	5800	76
9	Tanchi (1)	73	562	1080	2102	91
10	Chung-Hsing U. (4)	546	4808	9092	9616	170
11	Sungdru Rd.	49	280	558	889	112
12	Dadwing 17th St.	49	170	370	593	112
13	Tanchi (2)	44	370	706	1229	102
14	Dayei Rd.	104	540	1093	1777	111
15	Tanchi (3)	46	390	743	1164	114
16	Wamei W. St. (2)	229	825	1793	2492	129
17	Chung-Hsing U. (5)	370	1444	3084	3948	140
18	Tanchi (4)	79	802	1499	2813	95
19	Wamei W. St. (3)	207	937	1944	2472	141
20	Kuokang Rd.	377	1102	2515	3397	132

ferent ways. Dead load accumulates on the shores and slabs until shore removal or reshoring begins after each concrete placement. As reported by El-Shahhat, et al.,[11] the specified dead load can be about 1.0 times its mean value and the coefficient of variation of dead load is about 0.06 to 0.10. On the other hand, live load has a low mean value of about 0.2 times the dead load but a high coefficient of variation (COV), from 0.25 to 1.0. To better evaluate the live load, a more accurate analytical method is needed to improve the evaluation of live load effect.

The field measurements of 20 construction sites given in Table 1 in Taiwan was reported by Huang[12] for dead and live loads during concrete placements. The average dead load is about 110 psf (5.3 kPa), in which slab and beam weight as well as part of the column weight are included. The coefficient of variation (COV) of dead load is 0.22, higher than that of the dead load on slabs during service. The average live load is about 15 psf (0.72 kPa). Although these data in Taiwan may not be suitable for construction practice in the United States and other countries, the principle of developing a design guideline for construction is similar.

Horizontal load: including wind, buggy moving, concrete pumping, impact, and so on

Horizontal load is treated in a simple way as suggested by ACI 347[10] as either 100 lb per linear ft (1.5 kN/m) or 2 percent of the total superimposed dead load, whichever is larger. Both ACI 347-88 and ANSI Standard A10.9 require a minimum design wind load of 15 psf (0.72 kPa). A more rational method was given by Rosowsky[13] using a conversion factor to transform the design wind load in service time to the design wind load during construction.

Special load: including temperature, earthquake, and so on

Field measurements[14] showed that temperature changes can cause variations of self-balanced inner forces in slab-shoring system during curing. This effect can be neglected because of its small magnitude. Earthquake load is not considered herein for ordinary building construction because the construction period is usually short, much shorter than service time of a building.

Load combination

Gravity load, including dead load and live load, is the main load for the construction of multistory buildings in load combination.

For formwork design, the most critical loads occur during concrete placement. Thus, the load effects of dead and live loads on formwork are specified during this procedure.

For concrete slabs, concrete placement and shore removal are the two most critical procedures. Therefore, the effects of accumulated factored dead load and live load on slabs are determined for these conditions.

Load effect analysis

Construction loads during concrete placing influences formwork and slabs differently and should be studied separately. The Equivalent Uniform Load Distribution (EULD) method has been adopted in this study because of its simplicity for practical use. Thus, all nonuniform loading effects are transformed into uniform loading effects at first in the present load effect analysis.

The EULD for the factored slab load is determined during concrete placement and shore removal for slab load evaluation. The path of concrete placement and nonuniform configuration of shoring locations have little influence on slab load and can be neglected. Then, the load effect on slabs can be calculated using the simplified method[15] or the improved simplified methods.[7-9] In slab-shore load analysis, we need to:

1) Establish EULD model for dead and live loads.

2) Determine the influence of shore stiffness on the slab-shore load evaluation in multi-level shoring systems as follows:

(a) Determine the slab-shore stiffness ratio defined as

$$\alpha_S' = \frac{K_{shore}}{K_{slab}} = \frac{\dfrac{H}{E_{shore}A}}{\gamma\dfrac{L^2}{E_{c28}I}} \quad \text{Eq. 3}$$

where the nominator represents the deflection of shores in a panel under a unit force distributed uniformly, and the denominator represents the deflection at the center of a slab under a unit force distributed uniformly on the slab. The slab-shore stiffness ratio α_S' represents a comprehensive mea-

Table 2 — Development of concrete tensile strength, reported by Gardner[16]

	Type I cement			Type III cement		
Age (days)	73 F (22.8 C)	55 F (12.8 C)	40 F (4.4 C)	73 F (22.8 C)	55 F (12.8 C)	40 F (4.4 C)
1	0.31	0.15	0.03	0.54	0.33	0.11
2	0.47	0.28	0.11	0.65	0.50	0.30
3	0.59	0.40	0.18	0.74	0.62	0.43
4	0.66	0.49	0.24	0.78	0.66	0.54
5	0.72	0.57	0.32	0.81	0.70	0.63
6	0.76	0.63	0.39	0.83	0.73	0.70
7	0.79	0.68	0.44	0.85	0.75	0.77
8	0.81	0.72	0.48	0.86	0.77	0.80
9	0.83	0.75	0.52	0.88	0.79	0.82
10	0.85	0.77	0.56	0.89	0.81	0.84
11	0.86	0.80	0.59	0.90	0.82	0.86
12	0.88	0.82	0.62	0.91	0.84	0.88
13	0.89	0.84	0.64	0.92	0.85	0.89
14	0.90	0.86	0.67	0.92	0.86	0.90
21	0.96	0.94	0.80	0.97	0.93	0.99
28	1.00	1.02	0.88	1.00	0.96	1.07

Note: Linear interpolation can be used for a given treatment.

surement of geometry and material properties and boundary conditions of the supporting system. For example, α_s' is small for the weak-slab and strong-shore case, mostly in large panel flat plate construction.

(b) For calculation of dead load distribution in construction: when slab-shore stiffness ratio $\alpha_s' < 0.4$, use the simplified method; otherwise, use the improved simplified method by Duan and Chen,[7-9] or increase the maximum slab and shore load from the simplified method by 10 percent as an approximate treatment.

(c) For calculation of live load distribution in construction: when $\alpha_s' < 0.2$, use the simplified method; otherwise, use the improved simplified method.

3) account for creep and shrinkage effects (for a construction cycle of about 7 days) as follows:

(a) In the case of steel shores, the creep and shrinkage effect can be neglected when the slab-shore stiffness ratio α_s' is larger than 0.40; otherwise, consider increasing the slab load on the topmost slab by 10 percent and reduce the other slab loads equally.[7-9]

(b) In the case of wooden shores, the creep and shrinkage effect should be considered by increasing the slab load on the topmost slab by 15 percent and reducing other slab loads equally.

This is because the simplified method is applicable only for the case of small slab-shore stiffness ratio and slight creep and shrinkage effects. The refined simplified methods should be used whenever necessary.

The possible maximum EULD (specified load) effect on shore load is determined during concrete placing by amplifying the dead load. The effects of nonuniform loading, impact loading, and material storage during concrete placement should be considered for formwork design.

Table 3 — Comparison of cement strength reduction factors between compressive strength and tensile strength in different temperatures, normalized from the report by Gardner[21]

(a) Type I cement concrete

Curing temperature	T= 0 C		T= 10 C		T= 20 C		T= 30 C	
Age (days)	Compressive strength ratio	Tensile strength ratio	Compressive strength ratio	Tensile strength ratio	Compressive strength ratio	Tensile strength ratio	Compressive strength ratio	Tensile strength ratio
1	0.11	0.20	0.22	0.34	0.29	0.45	0.41	0.54
3	0.35	0.51	0.49	0.68	0.57	0.75	0.57	0.67
7	0.57	0.79	0.71	0.78	0.79	0.76	0.69	0.73
13	0.76	0.79	0.80	0.94	0.88	0.95	0.79	0.85
28	0.84	0.90	0.92	0.96	1.00	1.00	0.93	0.92

Note: Cement concrete with water-cement ratio = 0.55, cured in water.

(b) Type III cement concrete

Curing temperature	T= 0 C		T= 10 C		T= 20 C		T= 30 C	
Age (days)	Compressive strength ratio	Tensile strength ratio	Compressive strength ratio	Tensile strength ratio	Compressive strength ratio	Tensile strength ratio	Compressive strength ratio	Tensile strength ratio
1	0.13	0.31	0.47	0.68	0.55	0.73	0.62	0.73
3	0.79	0.94	0.76	0.88	0.80	0.89	0.72	0.82
7	0.90	0.94	0.86	0.91	0.85	0.90	0.82	0.88
13	1.05	1.09	0.92	1.09	0.92	0.99	0.94	0.92
28	1.00	0.99	0.95	1.00	1.00	1.00	0.97	1.06

Note: Cement concrete with water-cement ratio = 0.55, cured in water.

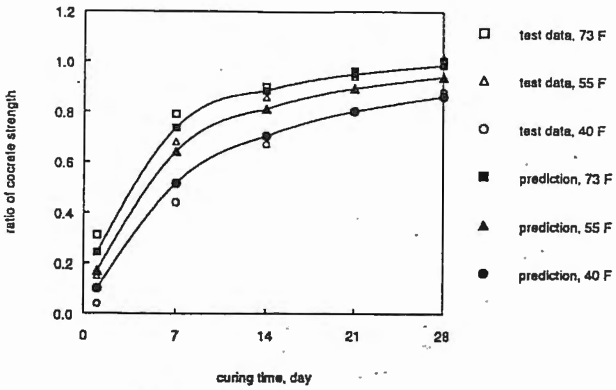

Fig. 1 — Tensile strength development of Type I cement in different ambient temperatures.

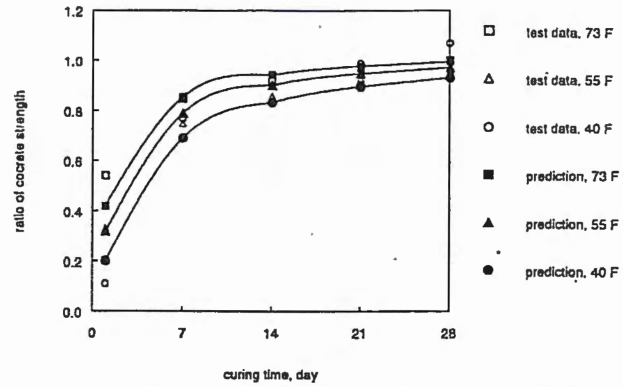

Fig. 2 — Tensile strength development of Type III cement in different ambient temperatures.

Resistance capacity

The resistance capacity of a slab-formwork supporting system comes from formwork and partial strength slabs. Thus, they will be discussed separately.

Slab resistance capacity

Multistory buildings such as residential and office buildings have common characteristics. The design dead load during service is 20 to 40 psf (1.0 to 1.9 kPa) in addition to slab weight, and the live load varies from 40 to 50 psf (1.9 to 2.4 kPa). To find the strength of a slab with partial strength during construction, the strength of the slab at 28 days must be first defined; the strength reduction effect due to immaturity of concrete during construction can then be estimated. The full strength of the slab can be written as

$$R_n = (1.4D_s + 1.7L_s)/\phi_s \qquad \text{Eq. 4}$$

where R_n, D_s, and L_s are nominal resistance of the slab, dead load, and live load effects on the slab during service time, respectively. ϕ_s is a resistance factor for flexural or shear limit state during service time. Thus, the factored resistance of the slab with partial strength during construction can now be written as

$$U_n = \phi_c \beta R_n \qquad \text{Eq. 5}$$

where β is the strength reduction factor accounting for concrete early-age effect and ϕ_c is a resistance factor for flexural or shear limit state for the slab during construction. For the time being, ϕ_c can be taken as the same value as ϕ_s for simplicity.

Substituting Eq. 4 into Eq. 5, the design strength of a slab at early-age can be written as

$$U_n = \beta(1.4D_s + 1.7L_s) \qquad \text{Eq. 6}$$

The strength reduction factor due to immaturity of concrete is the ratio of the concrete strength at a specific time in its maturation period to its 28-day strength. Table 2 shows the test data of normalized tensile strength development β_t for cement Type I and Type III in different ambient temperatures.[16] The ratio of compressive strength of cement develops slower than that of tensile strength, as shown in Table 3. Their relationship can be derived according to the relationship between compressive and tensile strengths in the ACI Building Code as

$$\beta_t = \beta_c^{0.5} \qquad \text{Eq. 7}$$

where β_t and β_c are the tensile and compressive strength development ratios, respectively.

There are mainly two types of failure modes for early-age slabs: shear punching failure for flat-plate or flat-slab system and flexural failure for slab-beam system. The shear punching capacity depends largely on concrete tensile strength; on the other hand, the flexural capacity depends largely on concrete compressive strength. Therefore, the design strength of slab with partial strength in Eq. 6 can be written as

$$U_n = \beta_t(1.4D_s + 1.7L_s) \text{ for flat-plate or flat-slab system} \qquad \text{Eq. 8a}$$

$$U_n = \beta_c(1.4D_s + 1.7L_s) \text{ for slab-beam system} \qquad \text{Eq. 8b}$$

The concrete tensile strength β_t is a function of curing time t and effective ambient temperature T.[17] To perform a regression analysis with two variables, curing time and temperature, for the test data given in Table 2, β_t is expressed in a form of double parameters as

$$\beta_t = \frac{M}{a + bM} \qquad \text{Eq. 9}$$

$$\text{where } M = \int (T - T_0)\, dt \qquad \text{Eq. 10}$$

is the maturity of the concrete and T_0 is the datum temperature (T_0 = 14 F here),[17] such that M is the average temperature increment multiplied by curing time. The regressive parameters of tensile strength for Type I and Type III cement are

$$a = 190 \text{ and } b = 0.90 \text{ for Type I cement} \qquad \text{Eq. 11a}$$

$$a = 100 \text{ and } b = 0.95 \text{ for Type III cement} \qquad \text{Eq. 11b}$$

The regression curves for Type I and Type III cement concrete are shown in Fig. 1 and 2, respectively.

The rules of concrete strength development herein are from normal lab tests and may be subject to correction in the field. In particular, for construction in very low temperatures, additional measures should be taken to enhance the speed of concrete curing.

Formwork capacity

For low clearance building construction, steel or wooden shores are commonly used and their capacities can be evaluated with the specifications of current formwork design.[18] Shores are used for many times for different projects. The quality of shores should be checked before reusing. Sufficient lateral braces should be provided to maintain integrity of the supporting system in case of uplifting to prevent shore buckling and resist horizontal load.[19]

For high clearance building construction, scaffold structures are mostly used, and their capacities can be evaluated using practical methods as proposed by Peng,[20] Huang,[12] and others. For high clearance scaffold systems, stability problems control failure patterns.

General design guidelines

The slab-shore supporting system must carry all possible loads during a complete process of construction.

Slabs must attain sufficient strength and rigidity before concrete is placed or shores removed in order not to generate excessive stress and deflections.

Formwork must be designed to have sufficient strength to safely transmit gravity load to slabs during concrete placement and horizontal load to permanent structures before and during concrete placement.

In planning a construction schedule using a multi-level shoring system, contractors should consider the following factors:

1. Design load for slabs during service time by structural designers.
2. Design weight of concrete including the weight of slab, beam, and formwork.
3. Construction live load involved, such as crews, equipment, material storage, path of concrete placement, and impact due to concrete dropping and equipment moving.
4. Construction cycle.
5. Developed strength of concrete when performing concrete placement and shore removal.
6. Type of formwork system, i.e., steel or wooden shores, individual shore load.
7. Span and thickness of slabs and elasticity of shores.
8. Wind before concrete placement and temperature during curing.

Design procedures

In general, a construction schedule includes the selected method of shoring and reshoring, construction cycle, and the method of concrete placement. The goal of design here is to find feasible construction schedules such that the construction load effect will not be greater than the capacity of early-age slabs and formwork at any critical time. The design guideline includes the slab safety check and formwork design as summarized in the following:

Slab safety check

For a given construction schedule, the slab safety check can be performed in the following steps:

1) Determine factored construction load in the form of EULD:

$$P_s = 1.4(1.0 + \alpha_d + \alpha_m)D \text{ during concrete placing} \quad \text{Eq. 12a}$$

$$P = 1.4\,\alpha_{shore}D \text{ during shore removal} \quad \text{Eq. 12b}$$

where α_d and α_m are amplification factors for impact load effect and other live load effect such as workers, equipment, and material storage during concrete placing. α_{shore} is a shore load ratio. D is the uniform dead load.

According to the field measurements of 20 construction sites in Taiwan reported by Huang,[12] we can use the following procedures to evaluate the specified dead load and live loads as:

For dead load:

with calculation: $D \geq 85$ psf (4.25 kPa)
(minimum dead load = $\bar{m} - \sigma$) Eq. 13a

without calculation: $D = 125$ psf (6.25 kPa)
(specified dead load = $\bar{m} - 0.5\sigma$) Eq. 13b

For workers, equipment and material storage:

with calculation: $\alpha_m D \geq 15$ psf (0.75 kPa)
(minimum load = $\bar{m}$) Eq. 13c

without calculation: $\alpha_m D \geq 20$ psf (1.0 kPa)
(specified live load = $\bar{m} - 1.5\sigma$) Eq. 13d

The impact load:

$$\alpha_d = \frac{1}{N} \quad \text{Eq. 13e}$$

where N is the number of batches of concrete bucket dropping.

2) Calculate accumulated factored load effects C_t:
Using the simplified method or the refined simplified methods to evaluate the load effects considering the effects of elasticity of shores and creep-shrinkage.

3) Calculate the capacity of partial strength slabs:

$$U_n = \beta(1.4D_s + 1.7L_s)$$

where β is the compressive or tensile strength reduction factor of the slab as given by Eqs. 8a and 8b for the resistance part.

4) Check the safety of slabs:

$$U_n \geq C_t \quad \text{Eq. 14}$$

If Eq. 14 is satisfied for all slabs, the construction schedule is feasible; otherwise, the construction schedule should be changed. Some measures need to be taken such as increasing the period of construction cycle or changing the methods of shoring-reshoring and concrete placement. For construction in low temperature, it is efficient to improve the ambient conditions for concrete slabs to enhance the maturity of concrete slabs.

Serviceability of slab

In most cases, a construction schedule may not cause safety problems but may produce excessive deformation and a severe degree of cracking due to a relatively high level of loading on the early-age slabs. This is because the early-age concrete slabs have partial strength and stiffness and a high rate of creep and shrinkage. The influence of construction on the long-term deflection of a slab can be expressed as:

$$\Delta_{total} = (1 + \alpha_c + \alpha_s)\Delta_{es} \leq \Delta_{allowable} \quad \text{Eq. 15}$$

where Δ_{total} and $\Delta_{allowable}$ are total deflections during construction and service time and allowable deflections, respectively. α_c and α_s are irrecoverable deflection ratios due to creep and shrinkage during construction and service time, respectively. Δ_{es} is the elastic deflection under sustained load in service time.

Formwork design

1) Determine the specified construction load in the form of EULD:

$$P_{fm} = (1.0 + \alpha_{nu} + \alpha_d + \alpha_m)D \text{ during concrete placing} \quad \text{Eq. 16}$$

where D, α_d, and α_m have the same meaning and values as in the slab safety check (Eqs. 12a to 12e). α_{nu} is an amplification factor due to nonuniform loading during concrete placement and nonuniform shoring configuration. According to field measurements and structural analyses,[7-9] we may take

$$\alpha_{nu} = 0.7 \quad \text{Eq. 17}$$

2) Capacity of formwork:

For low clearance building construction, steel or wooden shores capacity can be evaluated in the current formwork design. For high clearance building construction, the capacity of scaffold structures can be evaluated using a practical method as proposed by Peng[20] and Huang.[12]

3) Check the safety of formwork under vertical load effect P_{fm} using the ASD method.

Shores are designed mainly to resist vertical loading. Lateral impact may not be important for low clearance supporting systems. It can be resisted by lateral bracing. Scaffold are designed to resist both vertical and lateral loading.

The effects of local pre-pressure, changing temperature and the variation of shore loads within a panel should obtain proper consideration.

Checklist

Some important procedures in the form of a checklist should be followed to facilitate safe construction:

Concrete placement:

1. Before concrete placement, make sure that the supporting slabs have attained sufficient strength.
2. Select a concrete placement path that follows a symmetric principle to minimize the nonuniform loading effect on shores.
3. Drop concrete from a low height level and at a slow speed to minimize impact effect on slabs and shores.

Shore removal:

1. Before shore removal, make sure that slabs have attained sufficient strength.
2. If shores are removed one by one, remove the shores from the center of a panel toward the outside columns to minimize the effect of shore load accumulation.

Lateral bracing:

1. Single post shores should be laced and braced to reach sufficient stability to prevent buckling and instability when uplift occurs.
2. The bracing system must be tied to a solid ground or permanent structure unless it is multi-directional with sufficient X-bracing to assure its internal rigidity.
3. Lateral support is important to improving the load carrying capacity for high clearance scaffolds and should be provided whenever possible.

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Received and reviewed under Institute publication policies.

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