

FORMWORK



Compilation 26

American Concrete Institute

Preface

ACI Compilations combine material previously published in Institute periodicals to provide compact and ready reference on specific topics. The Material in a compilation does not necessarily represent the opinion of an ACI technical committee — only the opinions of the individual authors. However, the information presented here is considered to be a valuable resource for readers interested in the subject.

Samuel A. Greenberg
Chairman, ACI Committee 347
Formwork for Concrete

On The Cover: A self-spanning steel forming system was of considerable help in speeding construction of a new basketball arena for the University of Arkansas, Fayetteville. With each bent cast in one piece, erection of the support for the cantilevered tier of seats and the roof progressed at almost two bents per day. The building scale for the 18,000 seat Bud Walton arena was designed so as not to dominate other buildings on campus. (See article starting on p. 39.)



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Formwork

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Contents

3	Construction Live Load Caused by Powered Buggies , by Hui-Ming Lee, Wai-Fah Chen, and Xi-La Liu	42	Formwork for Architectural Concrete at North River Water Pollution Control Plant , by Martin Fradua and Ted Long
8	Interactive Vertical Formwork Selection System , by Awad S. Hanna and Victor E. Sanvido	47	Formwork Removal and Architectural Concrete , by Joseph A. Dobrowolski
15	Construction Load Analysis of Slabs and Shores Using Microcomputers , by Pericles C. Stivaros and Grant T. Halvorsen	52	Formwork Release Agents
21	Interactive Horizontal Formwork Selection System , by Awad S. Hanna and Victor E. Sanvido	55	Air-Supported Forming: Will It Work? , by Robert B. Haber
28	Shore and Reshore Scheduling Using a Microcomputer , by N. J. Gardner and A. Muscati	60	Movable Air Form Structures for Containing Airborne Releases , by Richard A. Kaden
33	Textile Form Method to Improve Concrete Durability , by Marton Marosszeky, Michael Chew, Massi Arioka, and Phillip Peck	66	Fabric Forms for Concrete , by Bruce A. Lamber-ton
39	Steel Forms Speed Construction of Upper Deck Bents for University Basketball Arena , by Russell Brown and Matt Boone	76	Modular Structural Forming System for Shotcrete , by Dale Pearcey
		78	Precast Concrete Stay-in-Place Forming System for Lock-Wall Rehabilitation , by James E. McDonald

Construction Live Load Caused by Powered Buggies

by Hui-Ming Lee, Wai-Fah Chen, and Xi-La Liu

Motor-driven buggies are widely used to transport the ready-mixed concrete in the construction of reinforced concrete buildings. In general, the buggies travel on very young concrete slabs and are the main source of construction live load. In a traditional formwork design, buggies are treated as a uniformly distributed load of 75 psf (3.58 kPa), but there are few theoretical justifications for using this design live load. Since most construction disasters occur while concrete is placed, it is necessary to investigate the actual effects of concrete buggies on construction safety.

A practical formwork system design subjected to live load caused by powered buggies has been examined. To this end, a realistic calculation model considering the effects of formwork decking, and wooden joists, stringers, and shores has been established.

The interaction between the structural components and the construction loads has been studied for different concrete ages. The results show that if more than two buggies are used in the same floor span, the applied load on shores can be greater than the design limit. Concrete age has little influence on the load distribution. The effects of decking, joists, and stringers can reduce the bending moment of concrete slab by about 7 percent and increase the axial forces of shores by about 2 percent. The end restraint effects of the connected slab-beams or the load distribution also have been studied.

Research significance

Numerical studies of the effects of combinations of variables such

as construction techniques, material properties, weather forces, and rate of construction operation on the load distribution of the supporting system have shown that construction live loads have the most significant influence. Since motor-driven buggies are the main source of the construction live loads, ideally, this design live load should be derived by a rigorous structural analysis and defined on a statistical basis.

Theoretical and statistical evidence to define the live loads in this way is not yet available, so they have been taken as equal to a uniformly distributed load of 75 psf (3.58 kPa) as laid down in current regulations. Attempts have been made here to provide some theoretical justifications about design live load due to powered buggies in a practical formwork system. It has been found that a design value 85 psf (4.06 kPa) is more realistic than that of the present in-service value of 75 psf.

Impact load caused by buggies

It is well-known that substantial impact loads can be generated when the buggies travel at some speed. The impact live load acts on the partially hardened slabs and the supporting formwork system. According to the AASHTO Standard Specification for Highway Bridges (1989), the impact load factor can be calculated by

$$I = \frac{50}{L + 125} \leq 0.3 \quad (1)$$

where L is the bridge span in feet. Obviously, the impact load factor should depend also on the driving speed; when the driving speed is

zero, the load factor also should be zero. In the construction field, the maximum speed of buggies is limited to 12 mph (19.3 km/h). Eq. (1) is based on highway vehicles at a speed of about 50 mph (80.5 km/h); therefore, the impact load factor for the buggies can be estimated roughly by a linear interpolation using the relationship

$$I' = I \frac{v_c}{v_r} \quad (2)$$

where v_c is the speed of concrete buggies and v_r is the speed of vehicles traveling on highways.

Peurifoy (1964) presented a complete construction formwork design process using the live load 75 psf (3.58 kPa). Assuming a concrete slab thickness of 6 in. (15 cm), the necessary sizes of decking, joists, stringers, and the shores can be determined to sustain the total load including the self-weight of concrete and the construction live load. For example, for a deck size of 1 in. (2.5 cm), the joist is 2 x 8 in. (5 x 20 cm) spaced 30 in. (10 x 10 cm) shores are used. The safe span of stringers is 5 ft (1.5 m). Using these values, the calculated shore load is 4500 lb (20 kN). Since the load-carrying capacity of a 4 x 4 in. (10 x 10 cm) shore is 5250 lb (23.3 kN), its unbraced length is 10 ft (3 m).

The following material parameters are assumed: the 28-day cylinder strength of concrete $f'_c = 6000$ psi (41 MPa) and the modulus of elasticity of concrete is $E_{c28} = 5.1 \times 10^6$ psi (3.51×10^4 MPa); and the elastic modulus of wooden shores is 1.6×10^6 psi (1.10×10^4 MPa).

Calculation model

Fig. 1 shows the computation model used in the present study. The fol-

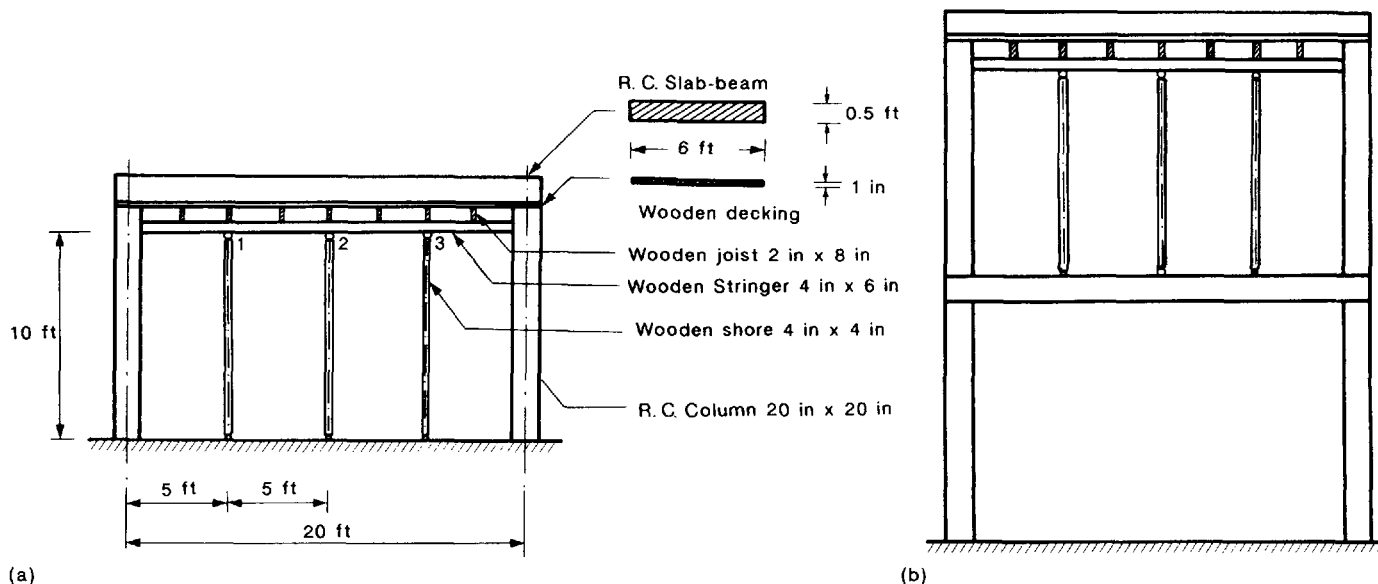


Fig. 1—Calculation model for determining: (a) maximum shore load; (b) maximum slab moment.

lowing assumptions are made for the calculations:

1. All slabs and columns behave elastically and their stiffnesses depend only on concrete age.
2. All the wooden decking, joists, stringers, and shores behave elastically.
3. The joints between shores and stringers are pin-ended.

Influence of buggies

The total weight of a fully loaded buggy is around 3000 lb (13.3 kN). The live load caused by the powered buggies is assumed here to be uniformly distributed, and the length is assumed to be 5 ft (1.5 m). Including the effect of impact, the live load can be estimated by

$$q = \frac{3000}{5} (1 + I')$$

$$= 642 \text{ lb/ft (9.35 kN/m)} \quad (3)$$

When buggies are traveling on the concrete slab, the maximum bending moment and shore forces depend on the buggy location. The influences caused by different numbers of buggies have been studied, with the number varying from one to four, and all possible combinations due to buggy positions have been considered. Concrete ages considered were 3, 5, and 7 days.

Formwork systems vary significantly in actual construction. The number of shored floors varies from 1 to 5 or even more. The maximum shore load under a newly cast

slab occurs when the shores are erected on the foundation or on the top slab of the basement, which often is assumed to be rigid. On the other hand, the maximum bending moment occurs when only one shoring level technique is used, that is, only one slab supports the currently casting slab.

In this example, the assumed construction cycle is 7 days, so the age of supporting slab is $(t + 7)$ days, where t is the slab age. Obviously, the shore load and the bending moment of other supporting techniques will result in a lower value than these two critical values. These two values give upper bounds of the possible construction load.

Fig. 2 shows the shore loads when only one buggy travels on different locations on the slab under consideration. Fig. 3 shows the bending moment distribution. The concrete age is assumed to be 3 days. From these, it can be concluded that the maximum shore load occurs when the buggy is at the midspan of the slab, but the maximum bending moment occurs when the buggy travels through the location between Shore 1 and Shore 2 due to the effects of the supporting shores.

In this way, the maximum shore loads and the maximum bending moments can be calculated when two to four buggies are on the same slab. The relationships between the maximum shore loads and the number of buggies on the concrete of different ages are shown in Fig. 4. The relationship between the maxi-

imum bending moment and the number of buggies is shown in Fig. 5. Table 1 shows the maximum shore loads for concretes of different ages for the case of four buggies. The maximum bending moments for this case of four buggies are shown in Table 2.

In spite of concrete age and number of buggies, the maximum shore loads always occur when the buggies are at midspan. Therefore, it can be concluded that concrete age has little influence on the load distribution, and the maximum difference between 3-day and 7-day concrete is only 4.6 percent. The maximum shore loads and bending moments depend largely on the number of buggies.

All results show that when more than one buggy is traveling the same span, the maximum shore load will be greater than the design value. When three or four buggies are traveling on the slab, the maximum shore loads will exceed the load-carrying capacity of 4 x 4 in. (10 x 10 cm) shores and failure will occur.

As far as the concrete slabs are concerned, the relationship between applied load and resistance can be analyzed by the following (Mosalam and Chen, 1990)

$$C_t \leq \frac{\beta(1.4D + 1.7L)}{1.3} \quad (4)$$

where C_t is the construction slab load at age t ; L is the design live load; D is the self-weight of concrete slab; and β is a modification

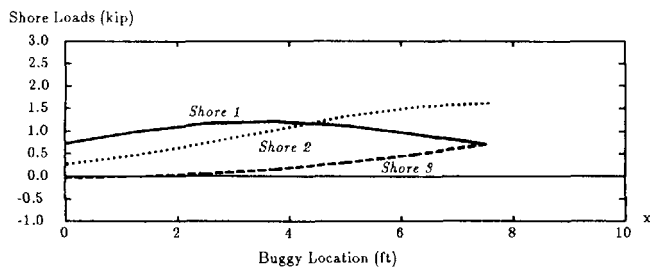


Fig. 2—Shore loads with one buggy.

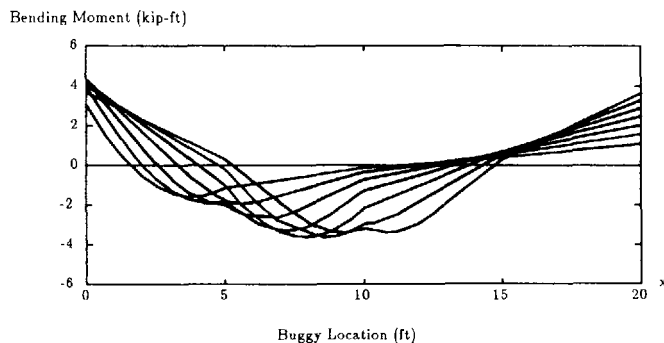


Fig. 3—Bending moments with one buggy.

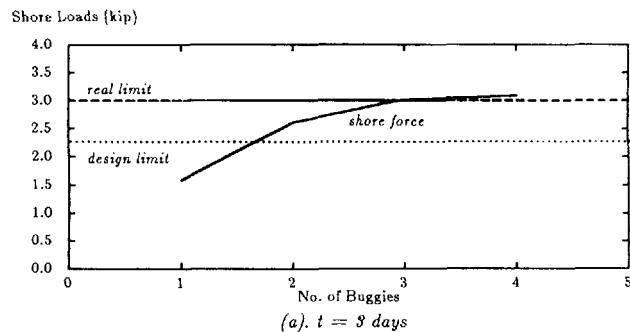
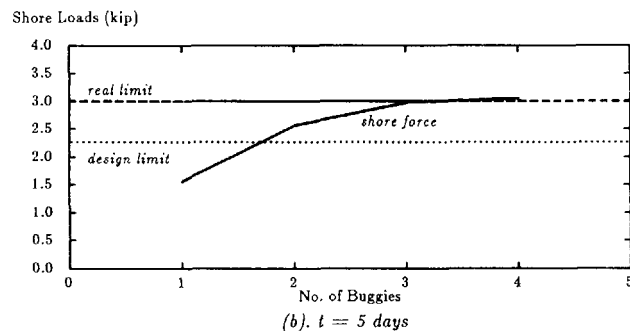
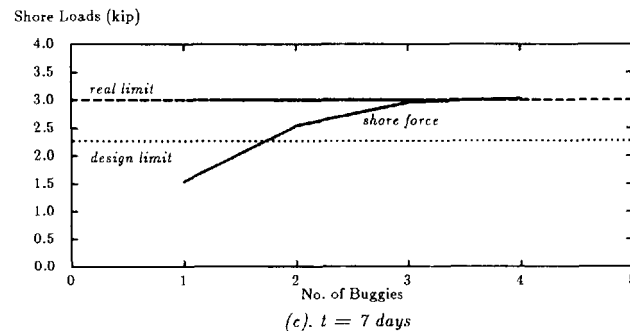

(a). $t = 3$ days

(b). $t = 5$ days

(c). $t = 7$ days

Fig. 4—Maximum shore loads versus number of buggies.

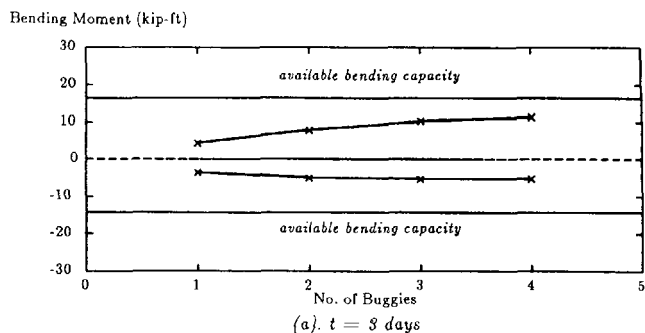
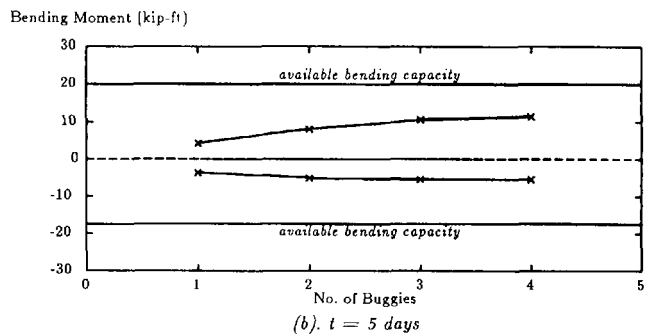
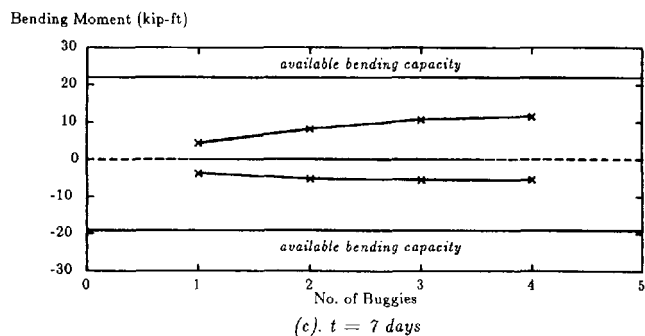

(a). $t = 3$ days

(b). $t = 5$ days

(c). $t = 7$ days

Fig. 5—Maximum bending moment versus number of buggies.

Table 1 — Maximum shore loads, kips

No. of Buggies	Concrete age			(1) (3)
	3 days (1)	5 days (2)	7 days (3)	
1	1.632	1.589	1.583	1.031
2	2.680	2.636	2.614	1.025
3	3.104	3.063	3.042	1.020
4	3.177	3.139	3.120	1.018

Table 2 — Maximum bending moment, kip-ft

No. of Buggies	Direction of moment*	Concrete age			(1) (3)
		3 days (1)	5 days (2)	7 days (3)	
1	Positive	4.30	4.28	4.33	.993
2		7.89	8.04	8.13	.970
3		10.28	10.51	10.64	.966
4		11.40	11.36	11.52	.990
1	Negative	3.62	3.70	3.73	.970
2		5.01	5.15	5.21	.961
3		5.31	5.47	5.54	.957
4		5.25	5.43	5.50	.954

*Positive moment indicates tensile stress at top of slab, negative moment indicates tensile stress at bottom of slab.

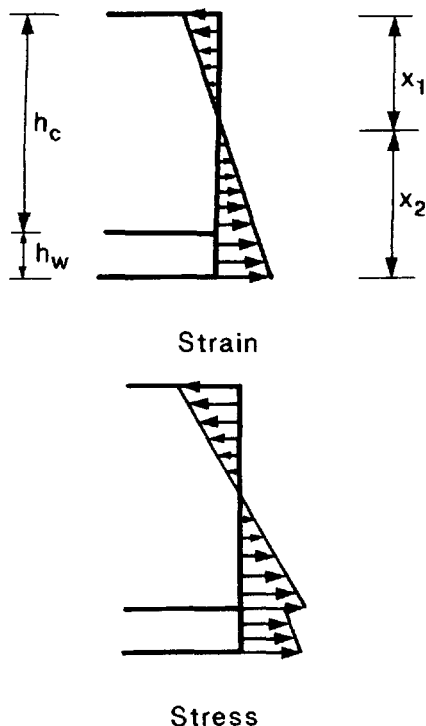


Fig. 6—Strain and stress distributions at slab-beam intersection.

coefficient dependent on concrete age, temperature, and cement type. According to Gardner (1985), β can be determined by Table 3.

The comparisons between slab loads and resistances for different concrete ages and different number of buggies are shown in Fig. 5. The results show clearly that the maximum bending moments caused by buggies will not exceed the slab capacity. That is, while concrete is placed, the most dangerous parts are the shores, especially the shore at midspan.

The results also show that the design live load of 75 psf (3.58 kPa) only allows for one buggy on each slab; therefore, when the number of buggies on one span exceeds one, the in-service design value of 75 psf (3.58 kPa) is questionable. In general, it is appropriate to consider two buggies in the same span, so the minimum design live load should be

$$L = \frac{(3177 + 1875)}{4500} 75 \text{ psf} \\ = 84.2 \text{ psf (4.03 kPa)}$$

where shore live load = 3177 lb and shore dead load = 1875 lb. Therefore, it is recommended here that the live load for formwork design should be 85 psf (4.06 kPa) and using more than two buggies on the same span should be avoided.

Table 3 — Development of concrete strength (Gardner, 1985)

Age, days	Type I cement			Type II cement		
	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	0.86	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: For a given treatment, β can be obtained by a linear interpolation.

Influence of the formwork

In recent years, several calculation models have been proposed to simulate the actual construction process of flat plate concrete multistory buildings [see, for example, Liu, Chen, and Bowman (1985) and Mosallam and Chen (1990)], but all ignore the effects of formwork decking, joists, and stringers. In the present study, the results of considering and neglecting these effects are given and compared to determine their actual influences on the load distribution.

After slab concrete has been cast on the formwork decking, the concrete gains its strength gradually with time. When an external load is applied, the formwork decking and the partially hardened slab work together to support the load. To include the interaction of concrete and wooden decking in an analysis, the wood has been transformed into an equivalent concrete contribution. Under uniaxial forces, the decking section area can be transformed into equivalent concrete section area by

$$A_w^e = \frac{E_w}{E_c} A_w \quad (5)$$

When the bending moment caused by the transverse load is considered, the strain and stress distribution at a cross section of the slab-beam is shown in Fig. 6. The position of neutral axis can be determined by

$$x_1 + x_2 = h_c + h_w \quad (6)$$

$$\frac{1}{2} E_c x_1^2 = \frac{1}{2} E_c x_2^2 \\ + \frac{1}{2} E_w (2x_2 - h_w) h_w \quad (7)$$

Thus, the equivalent concrete slab beam has a nominal height of $2x_1$ and the nominal elastic modulus is E_{ci} .

In Table 4, the results considering the effects of the formwork system and those that did not are compared, showing clearly the effects of formwork decking, joists, and stringers. The axial shore loads are increased by about 2 percent and the maximum bending moments are decreased by about 7 percent. This indicates the formwork system transfers very little load from the slab to shores. Although the error is small, a more realistic result can be achieved simply by modifying the results obtained from the usual calculation models adopted by Liu, Chen, and Bowman (1985) and by Mosallam and Chen (1990) by a coefficient 1.02 for shores and 0.93 for concrete slabs.

Restraint effect

A building has more than one span; hence, load distributions for slabs will be affected by other slabs. The models used by Liu, Chen, and Bowman (1985) and Mosallam and Chen (1990) neglect this restraint effect. No work has been reported on the study of this influence.

According to the current equivalent frame method for designing two-way slabs, we shall consider at

Table 4 — Comparison of present model with Mosallam's (1990) model

Loading condition*		Present model (1)	Mosallam's model (2)	(1) (2)
1 buggy, maximum shore load	shore load, kips	1.632	1.613	1.012
	+ moment, kip-ft	1.729	1.790	0.961
	– moment, kip-ft	1.038	1.110	0.935
1 buggy, between Points 1 and 2	shore load	1.341	1.328	1.010
	+ moment	2.375	2.455	0.967
	– moment	1.949	2.053	0.949
4 buggies	shore load	3.177	3.155	1.007
	+ moment	2.130	2.234	0.953
	– moment	5.198	5.429	0.957

*Positive moment indicates tensile stress at top of slab; negative moment indicates tensile stress at bottom of slab.

Table 5 — Comparison of the 1-span and 3-span models

Loading condition*		1-span model (1)	3-span model (2)	(1) (2)
1 buggy, maximum shore force	shore load (kip)	1.632	1.631	1.001
	+ moment(kip-ft)	1.729	1.729	1.000
	– moment(kip-ft)	1.038	1.044	0.994
1 buggy, between Points 1 and 2	shore load	1.341	1.339	1.001
	+ moment	2.375	2.366	1.004
	– moment	1.949	1.866	1.044
4 buggies	shore load	3.177	3.176	1.000
	+ moment	2.130	2.131	0.999
	– moment	5.198	5.194	1.001

* Positive moment indicates tensile stress at top of slab; negative moment indicates tensile stress at bottom of slab.

least three spans of slabs. Thus, when the load distribution of a slab is calculated, the end-restraint effects of at least two slab beams directly connected to each other must be considered. To evaluate the end-restraint effect, the internal forces of three-span and one-span models under the same loading conditions are used. The comparisons are listed in Table 5, where it can be seen that the end-restraint effects have little influence on the load distribution (≤ 5 percent).

In general, the load distribution due to end-restraint effects can be neglected. This supports the one-span two-dimensional model for practical use.

Summary and conclusions

A realistic calculation model considering the effects of formwork decking, joists, and stringers has been developed. Different live load combinations for several buggies on identical spans of different concrete ages have been considered, and data has been presented concerning the behavior and strength of formwork under construction live load caused by power buggies. From this information, the following conclusions can be made:

- The in-service design live load 75 psf (3.58 kPa) allows for only one loaded buggy traveling in each span.
- If two buggies are allowed on the same span, the design live load should be 85 psf (4.06 kPa).

- The age of concrete slab supporting the buggy has little influence on the load distribution between shores and slabs.

- In casting concrete slabs, the most critical areas are the supporting shores under the top-most slab.

Considering the entire formwork system consisting of decking, the joists, and stringers, the following conclusions can be made:

- The entire formwork system transfers negligible loads from slabs to shores.
- The shore loads are increased by about 2 percent, while the bending moments are reduced by about 7 percent.
- The end restraint of connecting slab beams has little effect on the load distribution, and the one-span calculation model is found to be adequate for determining internal forces during construction.

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Interactive Vertical Formwork Selection System

by Awad S Hanna and Victor E Sanvido

Shrinking construction markets and shorter construction periods are driving more and more contractors to execute critical path activities and large cost items with their own forces. Typically, the first item for a general contractor to do in-house is the structural concrete frame. The reasons for this are:

- It is a large cost item.
- It controls the project pace
- It is a phase of the work where labor is exposed to risky or unsafe conditions.
- The quality of the structure can

also dictate the quality of workmanship acceptable on the project to the trades that follow.

A large portion of the cost of the structural frame is the cost of formwork for columns and walls. Typically, the selection of a formwork system is made by a senior member of the contractor's organization. The decision is heavily based on that individual's experience. This article describes a tool that the authors developed to assist the formwork engineer/planner in selecting a vertical formwork system. The tool was developed by systemati-

cally capturing the expertise of people involved in all phases of the life of the formwork, from design through erection and concrete placement to removal. The end result is a body of decision rules and knowledge represented as an expert system.

Vertical formwork systems

Vertical formwork systems are those used to form the vertical supporting elements of the structure such as columns, core walls, and shear walls. The function of the vertical supporting systems is to transfer the floor loads to the foundations and to resist the lateral loads from winds and earthquakes. Consequently, the construction of vertical structural elements precedes flat horizontal work.

Typically, columns and walls are formed and placed one or two days ahead of the floor slab. Some formwork systems, however, offer the contractor an option to construct the vertical structural elements several floors ahead of the flat work, and sometimes to construct the entire core before the horizontal work starts. A field study¹ yielded five vertical formwork systems: conventional, ganged, slip, jump, and self-raising.

Conventional formwork

This all-wood forming system consists of sheathing made of plywood or lumber, supported by vertical wood studs.² Single or double horizontal wales are used to support the studs. Ties may be inserted through holes drilled in the wales (single wale) or inserted between them

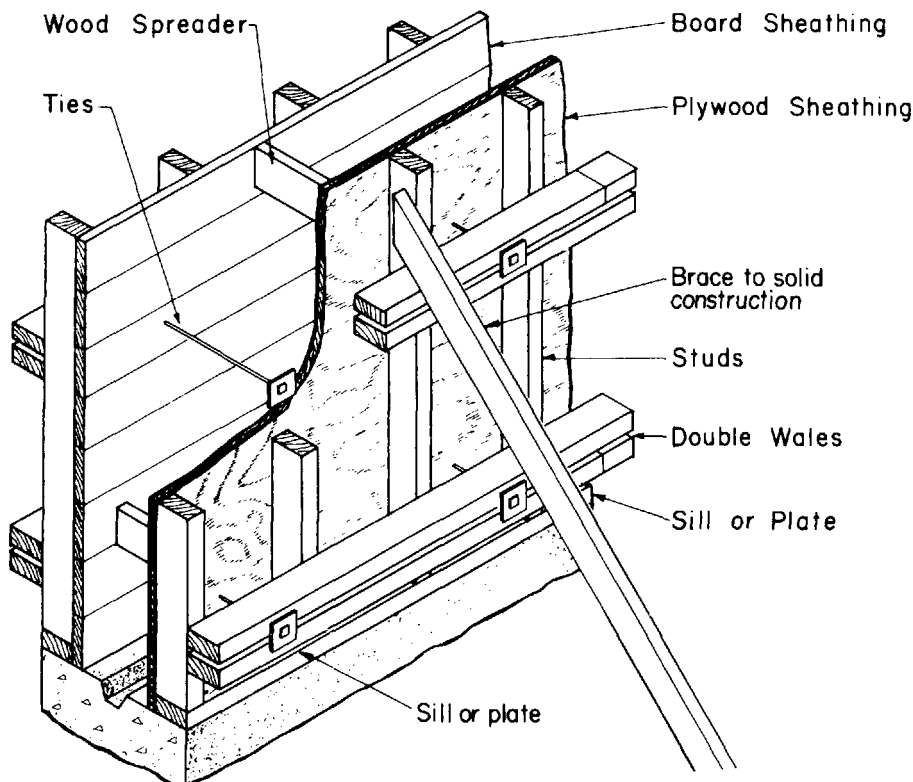


Fig. 1 — Conventional formwork.

(double wale) to resist the horizontal pressure of plastic concrete. An inclined bracing system is used to prevent forms moving (Fig. 1).

Ganged forms

Ganged forms are made of large panels joined together with special hardware and braced with strongbacks or special steel or aluminum frames. These large panels are usually built or assembled on the ground and raised into place by crane. In high wall construction, the ganged panels are frequently raised by crane to the next placement position and supported by steel brackets fixed to the lift below. Figure 2 shows some of the standard ganged forms available for contractors.³

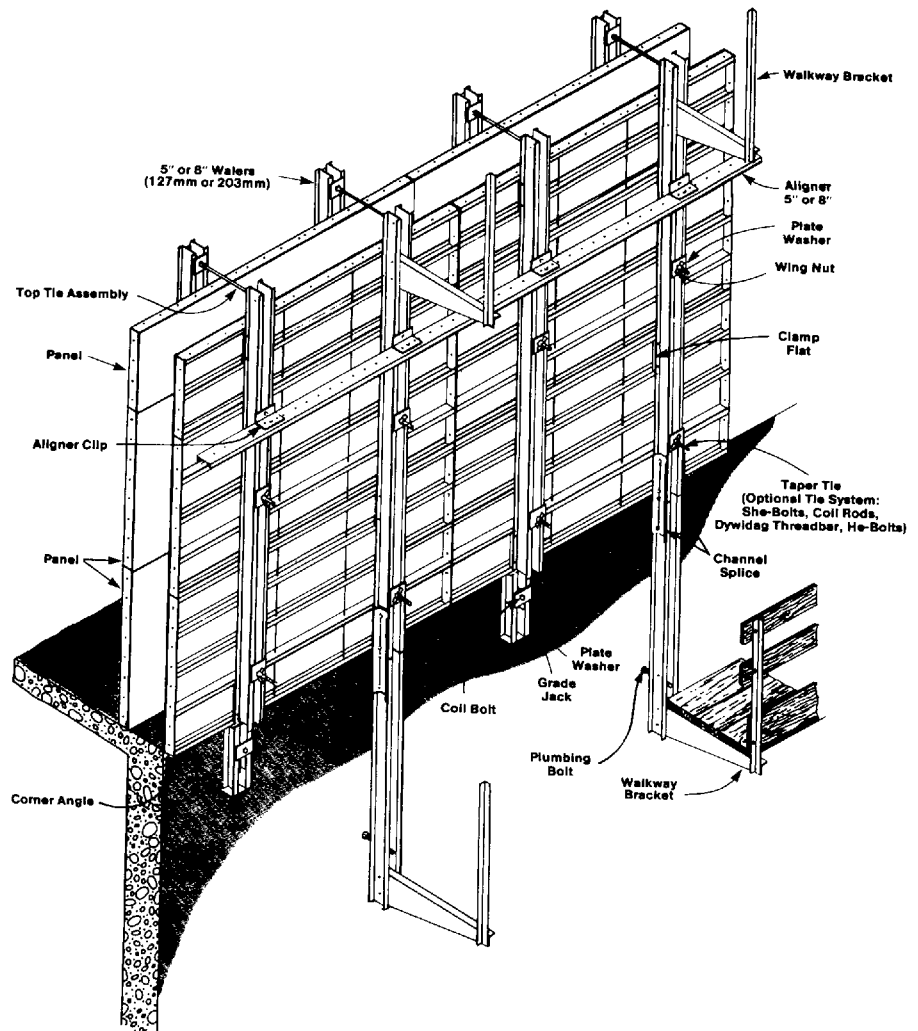


Fig. 2 — Ganged forms.

Slipforms

Slipforms are usually used to cast walls, piers, towers, and structural cores. Slipforms consist of inner and outer forms, 3.5 to 6 ft (1 to 1.8 m) high, using 1-in. (2.5-cm) thick lumber. Forms may be fabricated from wood or steel, and are supported by strong vertical yokes. The yokes are tied together at the top to give the form sides the rigidity needed.

Vertical sliding is accomplished by jacks climbing on smooth steel rods or pipes anchored at the base of the structure and embedded in the concrete (foundations) below the forms. The jacks may be hydraulic, electric, or pneumatic and operate at speeds up to 24 in./hr (61 cm/hr). Jacks usually have carrying capacities between 3 and 25 tons (2.7 and 22.7 Mg) and are spaced 4 ft (1.2 m) on centers (Fig. 3).

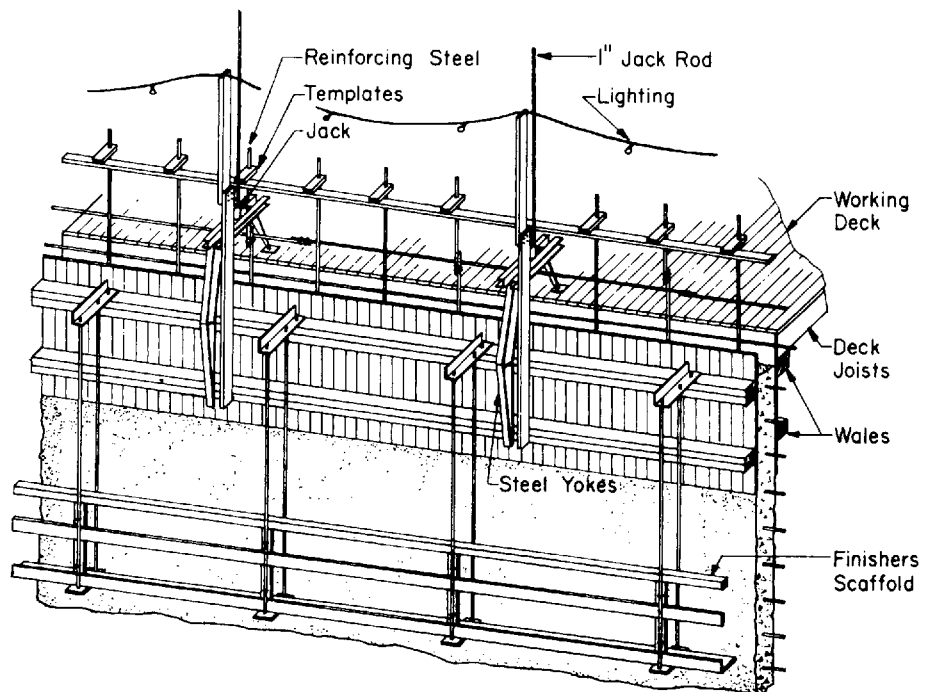


Fig. 3 — Slipforming system.

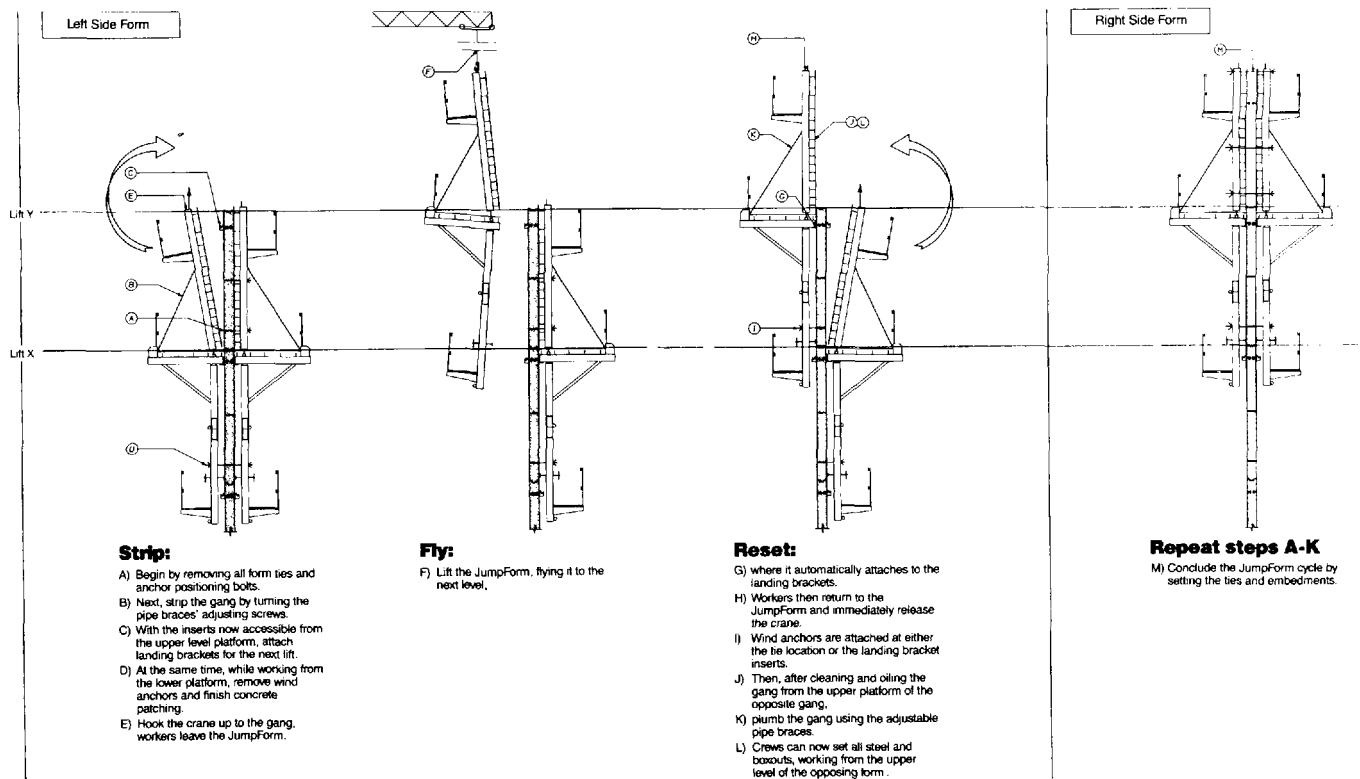


Fig. 4 — Typical jump form cycle.

Concrete is placed into the form from a working platform that is attached to and slides up with the inner form. Concrete is usually placed continuously, often 24 hours a day while the forms are moved upwards, until the structure is complete.⁴

Jump forms

Jump forms are used where no floor is available on which to support the wall formwork, or the wall and column proceed ahead of the floor. Jump forms consist of a framed panel attached to two or more strongbacks. They can be one floor high, supported on inserts set in the lift below. Two sets, each one floor high, that alternately jump past each other can also be used. Figure 4 shows a typical jump form cycle, which consists of three basic operations: strip, fly, and reset.⁵

Self-raising forms

This system consists of upper form(s) and lower lifters (self-raisers). The lifters are attached to the wall already cast below the form. Figure 5 is a schematic representation of a typical self-raising form cycle.^{6,7}

Factors affecting selection of formwork systems

Selecting the formwork system for cast-in-place reinforced concrete buildings is a critical decision affecting cost, safety, quality, and speed of construction. Many factors must be considered for the proper selection of the vertical formwork system.

Vertical and lateral support^{8,9}

Typically, columns and walls are utilized to support the vertical loads resulting from the dead loads and live loads. In high rise buildings, another vertical support system is needed to withstand the loads from winds and earthquakes.

Rigid frame. A rigid frame system consists of rectangles of vertical columns and horizontal beams connected together in the same plane. A bearing wall is a special case of the rigid frame system (Fig. 6a).

Shear walls. A shear wall formation is a thin slender beam cantilevered vertically to resist lateral forces (Fig. 6b). It can take the

form of a rectangular or box-shaped core, which can contain vertical transportation and energy distribution systems (e.g., stairs, elevators, toilets, mechanical shafts).

Framed shear wall. This system consists of a combination of frames which utilize beams and columns with the shear wall designed to resist lateral loads (Fig. 6c).

Framed tube. This is a structural system in which the perimeter of the building, consisting of vertical, closely-spaced supports, connected by beams or bracing members, acts as a giant vertical internally stiffened tube (Fig. 6d).

Table 1 — Structural systems and building height^{8,9}

Structural system	Optimum height
Rigid frame	Up to 20 stories
Shear wall	Up to 25 stories
Framed shear wall	Up to 30 stories
Framed tube	Up to 35 stories
Tube-in-tube	Up to 60 stories

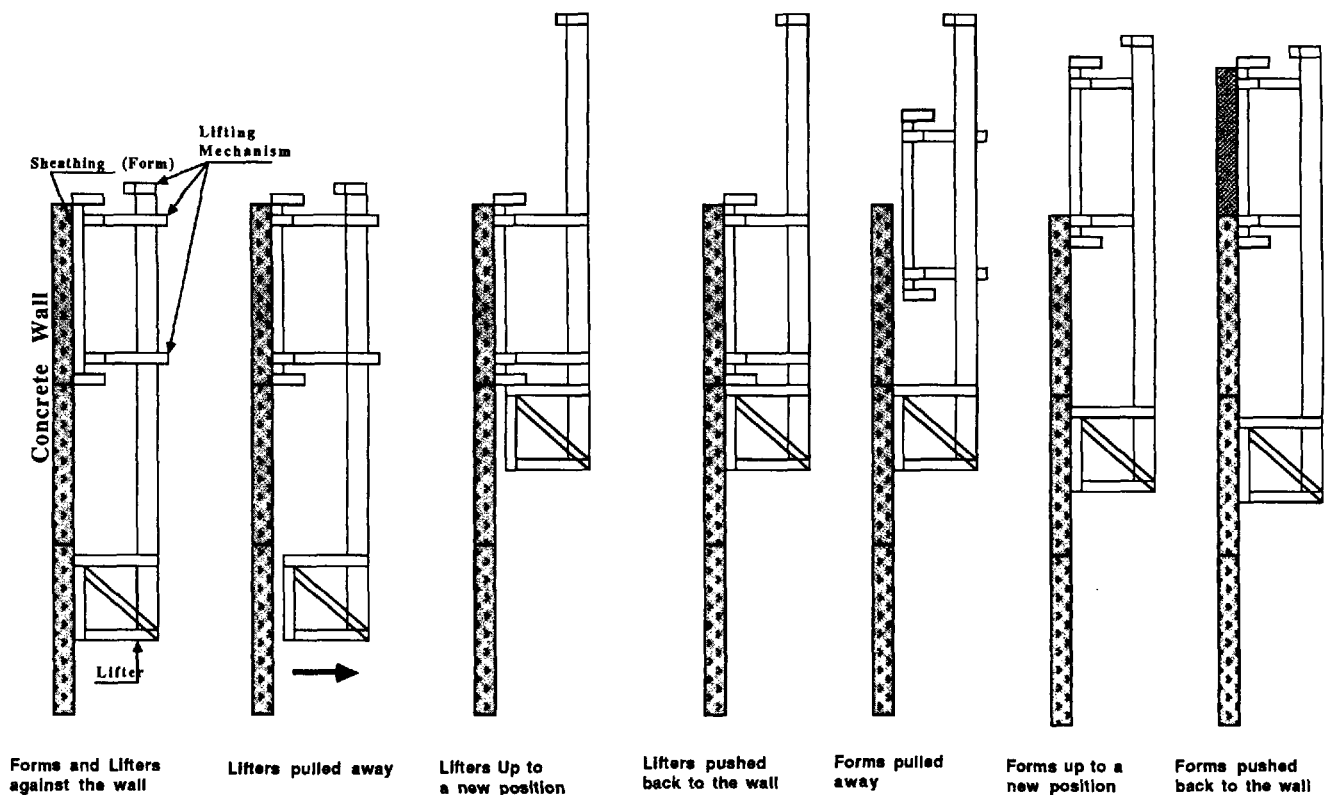


Fig. 5 — Typical self-raising form cycle.

Tube-in-tube. This system is a combination of the framed-shear wall, which acts as an interior tube, and the framed tube, which acts as an exterior tube. The floor structure ties the interior and exterior tubes together to allow them to act as a unit to resist lateral loads (Fig. 6E).

Table 1^{8,9} indicates the optimum height of each lateral support system and serves as a rough guide for determining the suitable lateral supporting system for each building height. Judgment, experience, and the personal preference of the designer are all-important factors in choosing the proper lateral support system.

Concrete finish

Surface quality and appearance is always referred to as the concrete finish. Concrete surfaces can be classified as rough finish as-cast surface, smooth exposed, or covered (with a special cladding material or painted), and textured (with an architectural surface texture and treatment).

As-cast concrete finish typically shows some irregularity and may contain concrete surface defects. An

as-cast finish is usually found in concrete buildings where appearance is not important, such as warehouses.

Exposed concrete finish is characterized by a smooth regular concrete surface and regular positioning of form ties. Exposed concrete surfaces are typically found in columns and bearing walls.

Architectural concrete is favored in vertical concrete elements (columns and walls). As a result, concrete finish must be considered as one of the major factors in the selection of a formwork system. Architectural concrete requires careful selection of a formwork system that includes stiffer form liners, tighter joints, smoother finishes, and more care in implementing chamfers and rustications.

Site characteristics

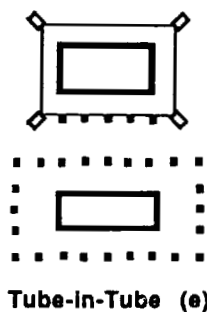
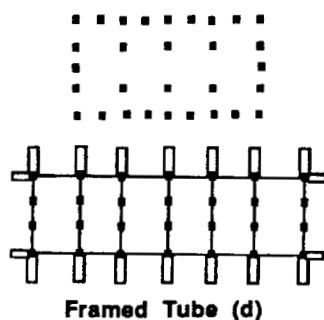
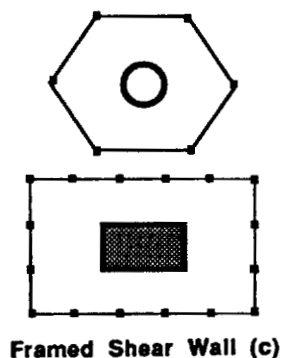
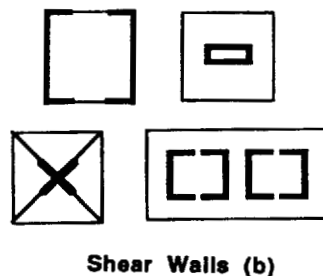
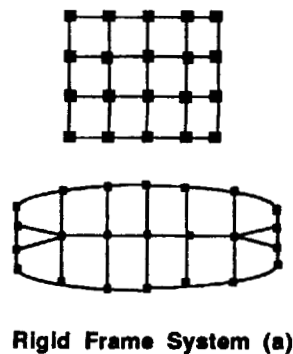
The building site may influence the selection of a suitable formwork system, because of site limitations and accessibility for construction operations. The feasibility of using ganged forms, for instance, is influenced by site characteristics such as accessibility, availability of a make-up area, and surrounding area re-

strictions such as property lines, adjacent buildings, power lines, and busy streets. In open and unrestricted suburban sites, all formwork systems are usable and some other considerations should be evaluated to determine the most efficient and cost effective system. In downtown restricted sites, the choice may be limited to slipforms and self-raising forms.

Hoisting equipment (cranes)

Some formwork systems require special handling techniques including adequate crane service. The ganged formwork system is a good example of crane influence on the selected system. The size of the ganged modules may be limited by the crane carrying capacity and its maximum and minimum lift radii.

Another important factor that influences the selection of the formwork system is the available crane time. In one case study,⁶ the limited crane time available for formwork erection to meet the project completion date was the major factor that led the formwork designer to choose the self-raising form alternative (which requires no crane time).



The WALLFORM vertical formwork selection system

WALLFORM is an expert system developed to assist the formwork engineer select a vertical formwork system. Expert systems are an effective tool for archiving the expert's knowledge on selecting the appropriate vertical formwork system for buildings. Expert systems are interactive computer programs incorporating judgement, experience, rules of thumb, intuition, and other expertise to provide knowledgeable advice about a variety of tasks.¹⁰

WALLFORM knowledge base

Knowledge for WALLFORM was acquired through literature review and unstructured and structured interviews. Twelve structured interview sessions were conducted with experts working for formwork subcontractors and manufacturers. The knowledge acquired was arranged in a tabular format. Table 2 shows the influence of various factors on the selected formwork systems for vertical concrete work. The information in the table represents the condensed form of the formwork selection knowledge base.

Knowledge representation for WALLFORM

Production rules chosen to represent the WALLFORM knowledge base were directly extracted from the tabular knowledge base. The tables were also used to create subgoals. For example, in developing the expert system for the vertical formwork system, there was a subgoal called "adequacy of hoisting equipment." This subgoal is a synthesis of availability of crane and crane time involvement, existence of adjacent buildings and other obstructions, and adequacy of crane carrying capacity.

Explanation facility

The WALLFORM explanation facility is designed to respond to two types of questions:

- During the consultation, the user may wonder why the system needs to know the information it is requesting. If the user types WHY, the system will respond by displaying the rule(s) for which it is trying to determine validity. The rules contain a textual note that clarifies their

purpose and the terminology associated with each rule. It also contains a reference telling the user where the information for the rule was obtained.

- At the end of the consultation session, the user may desire an explanation of a certain conclusion output. If the user types the line number of the choice or statement, the system will respond by displaying all of the rules used to determine the value of that choice or statement (line of reasoning).

Output of WALLFORM

WALLFORM contains 5 possible solutions (formwork systems) to the problem among which the expert system will decide. The goal of an expert system is achieved by selection of the most likely choice based on the data input, or by a list of all possible choices arranged in order of likelihood.

At the end of each run, the system will display the selected types of formwork followed by "probability =" or "confidence =" and a number. The number indicates the confidence that the choice is correct. The system utilizes a zero to 10 rating system. In this system, zero indicates definitely NO, and 10 indicates definitely YES. Values between 1 and 9 are degrees of certainty between the extremes. Values scored above 6 are strong candidates for selection, and the final selection may be based on system availability and area practices. In this mode, the final confidence factors are simply the averages of the fired (evaluated) rules which contain choices in their consequents. An assignment of zero or 10 to a choice by any rule, however, excludes all other confidence factors from consideration.

In a pure production system, rule ordering is not important. Therefore, addition and deletion of rules is quite simple. The only concern is the effect of the changes (addition or deletion) on the structure of the subgoals.

System features

The system was developed using a commercially available expert system shell. The shell has the capabilities of utilizing both forward and backward chaining techniques. However, the problem addressed by

Fig. 6 — Lateral support systems.

Table 2 — Factors affecting selection of vertical formwork systems

Formwork systems							
Influence factor		Conventional forms	Ganged forms	Jump forms	Slipforms	Self-raising forms	
Building design	Lateral support	Lateral support system	Most suited for frames and retaining walls	Shear walls Bearing walls Retaining walls	Shear walls Frames & framed shear walls	Shear walls Tube systems Tube-in-tube	
		Building height	Up to 120 ft	Up to 350 ft	Up to 350 ft	Average 400 ft Min. recorded = 60 ft Max. recorded = 600 ft	At least 300 ft No maximum
	Building shape	Column/wall size and location	System can handle variation of column/wall size and location		System can handle moderate variation of columns/walls size and location	Walls should be of the same location Wall size variation can be accommodated	System can handle reasonably modular design
		Openings/inserts	System can handle openings/inserts of different size and location	Variation in opening size and location can be accommodated at additional cost	Openings/inserts should be regularly occurring from floor to floor	Should be minimum Too many openings/inserts make this system impractical	System can handle moderate variation in opening size and location
Job specification	Speed of construction	Concrete finish	As-cast concrete finish	Produces smooth exposed concrete finish Tie pattern and number should be designed Form liners can be used for architectural concrete		System produces rough concrete finish No ties	Smooth concrete finish. Form liners can be used
		Construction sequence	Slabs and walls are placed concurrently	Slabs and walls are placed concurrently Walls can be placed ahead of the floor slab	System is used when no floor slab is available	Typically walls are placed entirely or at least several stories ahead of the floor	Walls are ahead of the floor. Other method is used for the first to 3 stories
		Cycle time	1 Floor/week	1 Floor every 3 to 4 days	1 Floor every 2 to 3 days	1 Floor every day. Rate of placing = 8 to 20 in./hour	1 Floor every 2 to 3 days
Supporting organization	Cost	Stripping	Hand strip High stripping cost	Crane is used to strip the system High stripping cost	Forms are equipped with mechanism for stripping Min. stripping cost	Forms are stripped at the end of the project Min. stripping cost	Forms are equipped with mechanism for stripping Min. stripping cost
		Reuse	Less than 10	Between 40 and 50 reuses horizontally or vertically	Between 15 and 30	Between 50 and 100 (i.e. between 200 ft and 400 ft high)	At least 30 reuses should be available vertically
	Hoisting equipment	Location of adjacent building and obstruction	Generally not a factor	A major factor; system must have a free space to be moved from floor to floor		Minimum free space should be available for crane movement	Not a major factor; system can be used in restricted areas
		Crane time	Not a factor; system can be hand set	Crane-dependent system Sufficient crane time is a must	System substantially reduces crane time Average crane time pick = 20 minutes	Crane is used only for materials delivery and concrete placing	Crane-independent system
		Operating system	Hand set system Crane increases system efficiency and reduces cost	Crane set system Crane serves two functions: lifting and supporting the forms	Crane is used only to lift the forms Crane is not used for form dismantling	Locomotion is provided by electric, pneumatic, or hydraulic jacks climbing on smooth steel rods	System is lifted by hydraulic, electric, or pneumatic lifters
	Safety	No special safety features required	Special care for handling the large ganged units by crane	Safety features Safe guarded platform No one need be on form during crane handling	For hydraulic systems, special safety precautions must be taken to prevent fire several hundred feet above the ground		
	Supporting yard facility, supplier or make-up area	Not a major factor, but system is more efficient if a local yard facility is available	A major factor; system must have an adequate make-up area of close-by supplier	System is rented or purchased	Continuous materials delivery is a must. Uninterrupted concrete placement must be assured.	System preassembled; make-up area is not a factor. Local supplier must be available	
Local conditions	Area practice		More efficient in areas of high quality, low cost labor force	Work best in areas of high cost, low quality labor force	System is easy to learn and adapt Short learning curve	System can be learned in 2 to 3 weeks	System requires high quality supervision
	Weather		Generally not a major factor	A major factor; walls should have sufficient strength before stripping which is largely influenced by weather conditions High winds limit the crane movement		Hot or cold weather affect the concrete rate of setting which slow the rate of rise	In cold weather, forms should be protected and concrete should be heated
	Site characteristics	Access to site	Generally not a factor for loose forms	Can be a major factor if the system is pre-assembled in a local yard facility	Site must be accessible, forms can be up to 16 ft high and 44 ft wide	System must have a limited access for material delivery	Min. site access is required for concrete placing and rebar delivery
		Site size	Not a factor	Can be a major factor if the forms have to be built on site	Not a major factor; forms are pre-assembled and unloaded directly	Not a major factor; system can be used in restricted small sites	

WALLFORM is a design problem characterized by a limited number of solutions (goal state), which warrants the use of backward chaining.

It is a rule-based expert system, designed to assist formwork designers and planners to select the optimum formwork system. WALLFORM selects the vertical formwork system and tie type, and recommends some formwork manufacturer's products.

The primary users of these systems are general contractors and formwork subcontractors. The system assumes that the user has some knowledge about formwork. The user would be at the early phase in the development of the project, with some information available about building shape, site conditions, and resources.

In multi-purpose high-rise buildings, each set of floors has certain functions and features which may result in the use of different formwork systems for each section. In this situation, the user is advised to run the system more than one time to determine the optimum system for each part of the building.

Expert's evaluation

To assure the validity and credibility of the implemented expert system, the tabular knowledge base was sent to a well known expert in formwork who reacted favorably to the tabular knowledge base. It should be noted that this expert was not a major source of knowledge for the research, and thus the expert's views were considered unbiased.

The second attempt at validation was provided an expert who acted as a major source of knowledge. The expert used the expert system to select a formwork system for one of his current projects. The system provided the answer he was expecting. The expert then changed some parameters and reran the system. It again provided him with the expected answer.

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Selected for reader interest by the editors.

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SLABFORM, an expert system for selecting horizontal formwork, will be the subject of a *Concrete International* article later this year. Information on obtaining software for WALLFORM and SLABFORM will be provided at that time.

Construction Load Analysis of Slabs and Shores Using Microcomputers

by Pericles C. Stivaros and Grant T. Halvorsen

Formwork failures and failures caused by improper shoring or premature removal of supports have been common throughout the history of concrete construction. A structure need not collapse to be influenced by premature removal of forms and shoring: construction failures or defects such as sagging or cracking can occur in the completed structure. If loaded prematurely, time-dependent deflections under load (creep) will be larger, and sags are more likely to be both noticeable and objectionable.

To avoid such unwanted long term effects or even a collapse during construction the contractor must be able to determine how the construction loads are distributed among the shoring system and the interconnected slabs and what the strength capacities of these young slabs are upon the application of the construction load. ACI's "Guide to Formwork for Concrete"¹ provides some guidelines regarding shoring, reshoring, and backshoring operations. However, it does not prescribe any procedure for determining the loads that will be transferred to the structure upon the new concrete placement or formwork removal. ACI's "Formwork for Concrete"² recommends the Grundy and Kabaila³ method (hereafter referred to as the simplified method) to evaluate the construction load distribution. There have also been several other efforts to evaluate construction loads by applying computer-based analytical methods.^{4,8} The pioneering work of Grundy and Kabaila has become the basis for most of the research work on the subject.

An alternative computer-based method for construction load analysis and slab safety check has been developed. The computer program is based on a two-dimensional structural model according to the equivalent frame method as described in ACI 318.⁹ This procedure (hereafter referred to as the equivalent frame method) is found to be effective and accurate for the evaluation of construction load effects, and can be implemented in a form usable at the construction site. Analyses conducted using the equivalent frame method showed comparable results to finite element plate bending models.¹⁰

With the advent of widespread use of computers, a more realistic model can and should be employed. The equivalent frame method computer-based procedure

takes into account the effects of structural continuity and the monolithic nature of concrete structures with a reasonable level of computational effort.

Strength adequacy of early age members

The load capacity of an early age slab is influenced primarily by the rate of concrete strength development and the total service live and dead load for which the slab has been designed. The flexure, shear, and bond strength capacities of the early age slab can be reasonably assumed to be proportional to the partially developed concrete compressive strength. Cracking and deflections are also dependent on the early age concrete tensile strength and modulus of elasticity, respectively.

The reserve slab strength for which the slab has been designed for both service live loads and superimposed dead loads (partition loads) is usually sufficient to carry the imposed construction loads when the building is being constructed. When the applied construction load on a slab is more than the slab's available capacity the proposed construction scheme is at risk and a failure may occur. In such a case there are two basic alternatives: either reduce the load on the slab at the critical age, or increase the concrete strength. The first alternative can be achieved by modifying the type of shoring system or the number of shored or reshored floor levels in such a way that the applied construction load is reduced to an acceptable level. The second alternative can be achieved primarily by using high-early strength concrete, by controlling curing temperatures to achieve the required early concrete strength, and by increasing the duration of the construction cycle to permit the concrete to gain enough strength before the application of a heavy construction load.

Construction loads

The construction dead load, which usually includes the slab dead load and the weight of the formwork, can be estimated with reasonable accuracy. The estimation of the construction live loads, however, can be a very difficult task. The construction live load includes the weight of workers, equipment, materials, runways, and impact produced by concrete placement or equipment operations. ACI 347,¹ "Recommended Practice for Concrete Formwork," suggests a construction live load

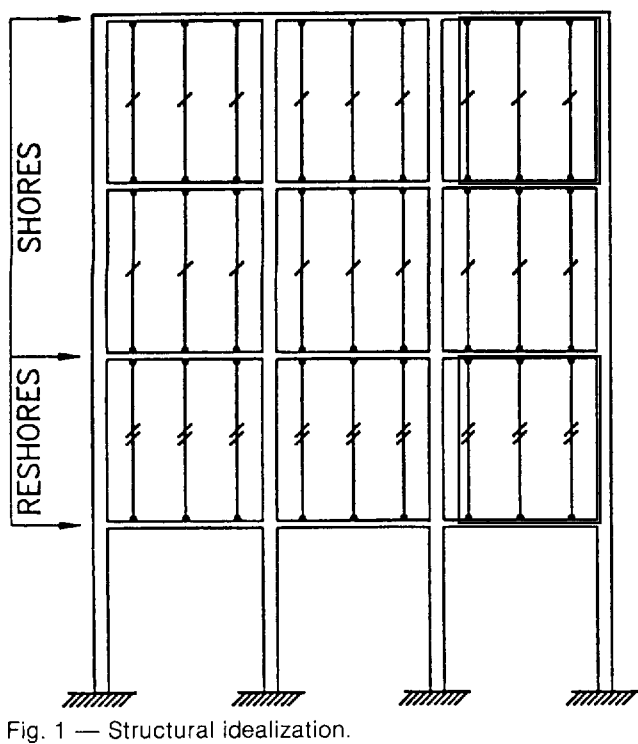


Fig. 1 — Structural idealization.

of 50 psf (2.4 kPa), while OSHA¹¹ requires at least 20 psf (1.0 kPa) for live load. A study by Fattal at the National Institute of Standards and Technology¹² indicates that when concrete is placed by bucket, the live load may be as high as 40 to 50 psf (1.9 to 2.4 kPa). The construction live load is usually applied to the uppermost slab during concrete placement on that slab, and it is assumed to be removed after the concrete placement is done.

Construction load factors

While ACI 318 specifies load factors for many load types it does not specify a load factor for construction loads nor member capacities at early age. ANSI A10.9 (1983)¹³ recommends a load factor of 1.3 for both dead and live construction loads. There is a divergence of opinion on the proper load factors. Gross and Lew¹⁴ contend that "construction loads are generally short in duration and the consequences of a failure are not as great as they would be in a fully occupied building." They suggest that the load factors should be less than those used for service conditions. On the other hand, Gardner¹⁵ maintains that "the construction workers spend all their working life on construction sites and their risk of injury should not be greater than the occupants of the completed structure." The variability of results from the available methods to evaluate construction dead loads and the uncertainty of construction live loads suggest high construction load factors. The writers prefer the more conservative load factors required by ACI 318 for service conditions, i.e., 1.4 and 1.7 for construction dead and live loads.

Structural model

A multistory building under construction is modeled according to the assumptions of the equivalent frame method. A schematic representation of an idealized two-dimensional structure is shown in Fig. 1. The shores and reshores are replaced by an equal number of elastic supports, each having a stiffness equal to the total stiffness of the corresponding shores. It is assumed that the reshores carry no load at the time of installation, i.e., the slabs are allowed to deflect under their own weight and construction loads applied prior to the installation of reshores. The load of the freshly cast concrete is applied to the top floor shores as concentrated loads. The load is shared among the shores according to their contributory areas. The connection between the shores or reshores and the floor slabs can be reasonably assumed as pin-jointed. At ground level, shores and reshores are assumed to be supported on a rigid foundation.

The equivalent frame method concepts are applied to determine the frame member stiffness coefficients. The idealized two-dimensional frame is analyzed elastically using conventional stiffness analysis procedures to evaluate the forces in the various frame members, including the shores and reshores.

Construction phases

A building under construction is a structural system that changes with time as the construction advances. Time also affects the strength and elastic properties of concrete.

In a typical construction cycle for a scheme that uses shores and reshores there are four repetitive operations, or construction phases, for each floor slab:

- Installation of the shores and formwork for casting the next floor.
- Removal of lowest level of reshores.
- Removal of lowest level of shores and formwork.
- Placement of upper level of reshores in the story where the shores and forms were removed.

If no reshores are used, the second and fourth phases are eliminated. An example of two levels of shores and one level of reshores in a three-bay multistory structure illustrates the four phases (Fig. 2).

During the first phase, the weight of the fresh concrete is distributed among the previously cast slabs through the shoring system. This load transfer mechanism is disturbed when the lowest level of reshores is removed. The floors below are relieved of the construction load, while the floors above are called on to carry all of the construction load alone. Similar load path disturbance to the structural system occurs when the lowest level of shores is removed. The installation of the reshores during the fourth phase does not disturb the system since the reshores are assumed to be relatively load free upon installation.

Computer program

A computer program was developed to determine the

construction load distribution. The operation of the program is broken down to five stages: data input, phase of construction, structural identification, stiffness analysis, and construction load analysis. These steps, except for data input, are repeated for each floor slab under construction, from the first floor to the roof. An abbreviated flow chart of the computer program is shown in Fig. 3.

Input data

The input data consists of structural, material, construction schedule, and load data.

The structural data includes the number of bays and stories, bay widths and story heights, slab construction type, and slab, beam, column, and shoring member sizes. Only the typical member sizes are input, the rest are generated internally by the program.

The material data includes the modulus of elasticity of the shoring system, the concrete unit weight, the concrete design strength for slabs and columns, and the ratio of the design concrete strength to the early age strength. The user inputs the concrete strength ratio and the program provides the capability of planning construction schedules of irregular rate.

The construction schedule data includes the number of shored and reshored floor levels and the shoring placement configuration, i.e., the number of shore and reshore props in each bay and their location.

The load data includes the construction live load, formwork load, design service dead and live loads, and factors for the construction dead and live loads.

Structural identification

The purpose of the structural identification process is to convert the "raw" input data to a form suitable for the stiffness analysis of the program. During this process all joints and structural members, including shores and reshores, are identified and numbered. The proper coordinates are then assigned to each joint. The joint coordinates are evaluated internally by the program based on the given geometry of the structure. The appropriate restraint conditions are also assigned to each support joint. The modulus of elasticity and concrete strength are assigned to each member according to its age. The shore and reshore members are treated as truss elements during the analysis, i.e., they are assumed to be subjected only to axial compressive forces.

The stiffness of the slab-beam elements is modified to account for the variation of slab thickness due to the presence of beams, drop panels and column capitals. The stiffness of the columns is also modified to include the torsional effects of the adjacent slab strips on both ends of the column. The equivalent column stiffness formula, which is given in ACI 318 Commentary R13.7.4, is strictly valid only for one-story building frames which assumes that the far ends of the columns are fixed. For multistory building construction, where several stories are involved in the construction load distribution, the ACI formula is extended here to take into

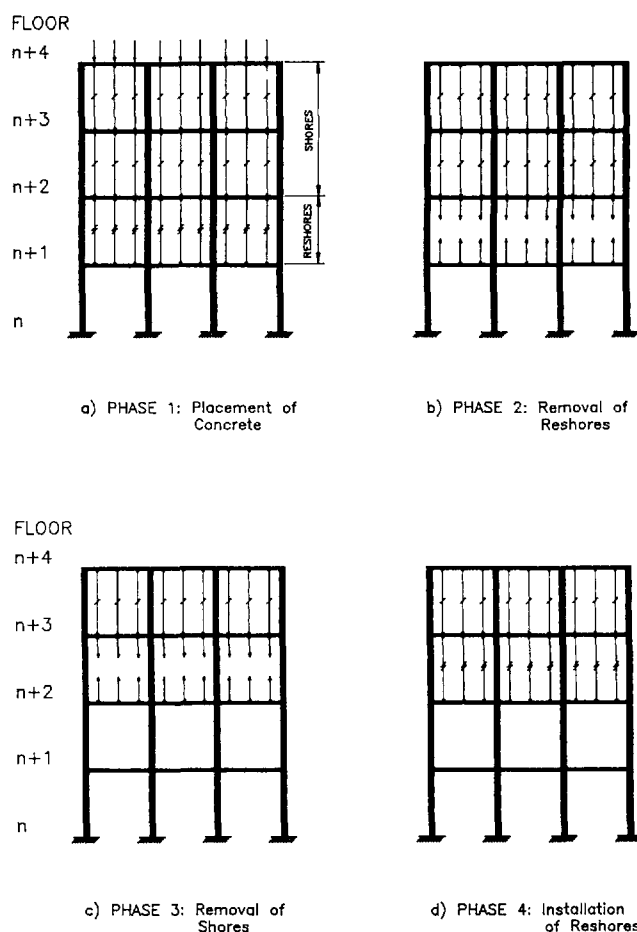


Fig. 2 — Construction phases.

account the torsional effects on columns from slabs on both ends of the column.

Phase of construction

After the structural data is processed, the program calls for the appropriate phase of construction to be considered. The program always starts from phase 1, casting of a slab, and then determines the next phase according to the given method of construction.

During this step the program determines the construction operation to follow, either concrete placement or shore removal, and evaluates the induced loading conditions due to the operation. The applied construction load is then assigned to the proper joints. For example, during phase 1 the applied load consists of the weight of the fresh concrete and the construction live load. This load is determined by the program and shared among the shore members supporting the fresh slab according to their tributary areas. The shore members transfer these loads to the floors below. The loads induced to the system due to the removal of the shores or reshores consist of the axial loading force in the members prior to their removal. These loads are applied at the end-joints of each member removed.

It is important to mention that all these procedures concerning the structural identification, data processing, and loading conditions are done without the interaction of the user. Defining the properties and location of all members, joints, joint coordinates, support re-

CONSTRUCTION LOAD ANALYSIS

COMPUTER PROGRAM

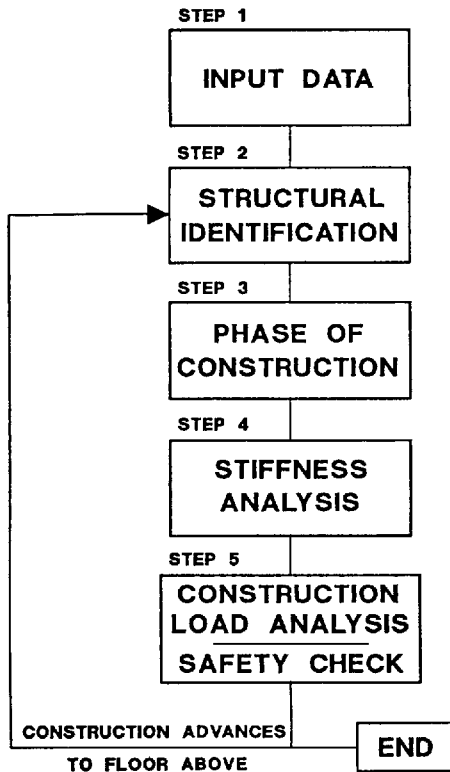


Fig. 3 — Abbreviated flow chart of the computer program.

straints, and loading conditions can sometimes be long and tedious. The user has to do none of these procedures for this computer program. All the required information is generated by the computer based on the basic building frame characteristics and method of construction given by the user.

Stiffness analysis

The structural member forces are determined through the stiffness analysis procedure. A modified direct stiffness method set up for this purpose takes into account non-prismatic members and mixed "beam" and "truss" elements.

For every construction phase a different structural configuration and loading condition is involved. Depending on the construction phase a member can be subjected to additional load or relieved from a previously applied load. Therefore, the member forces are evaluated for each phase and then they are superimposed on those evaluated from the previous phase.

The program insures that the shoring system does not go into tension by removing tensile forces (if they occurred) from the shores or the reshores and redistributing them among the interconnected slabs.

Construction load analysis

During this step, the computed member forces are further processed to determine the construction load carried by individual slabs and the shoring system. The amount of load carried by a slab is equal to the calcu-

lated shear forces of the slab-beam members transferred to the supported columns. The shoring system load is equal to the summation of the axial compressive forces of each individual shore or reshore member supporting that slab.

The evaluated construction loads are then multiplied by the specified construction load factors. Also during this step, the program evaluates the available factored load capacity of each slab, so a comparison can be made with the applied factored construction loads.

Construction example

A multistory flat plate structure was examined to illustrate the application of the computer program. The structure was assumed to have been designed according to ACI 318⁹ with a live-to-dead load ratio of 0.75. One level of a steel flying truss shoring system and three floor levels of wooden reshores with a construction rate of one floor per week was assumed. The shores and reshores were idealized as series of vertical truss-type elements with stiffnesses equivalent to the total stiffness of the shores or reshores on each row. The steel flying truss system was considered infinitely stiff relative to the concrete slabs. However, the compressibility of the wooden reshores was considered. The weight of the shoring system was assumed to be 10 psf (0.5 kPa). It was also assumed that the shores and reshores were removed and relocated a day before casting the top slab. A 50 psf (2.4 kPa) construction live load was considered to be present only during the concrete placement of the top slabs. A typical floor plan of the equivalent frame along with the location of the flying truss screw jacks and wood reshores is shown in Fig. 4.

Other assumed geometric and material parameters were: 10 ft (3.0 m) story height, 8.0 in. (200 mm) slab thickness, 28-day compressive strength of concrete $f'_c = 4000$ psi (27.6 MPa), and the wooden shores' modulus of elasticity $E_w = 1500$ ksi (10.3 GPa). The assumed ratio of the actual early-age concrete strength f_c to the 28-day strength is given in Table 1.

The results of the computer analysis are summarized in Table 1. The table shows the applied factored load on each slab, the slab age, and the slab load capacity based on the partially developed concrete strength. The load applied on the slabs is normalized to the self weight of each slab. As can be seen, the proposed construction scheme overloads all seven-day old slabs and consequently this construction procedure cannot be safely executed.

To make this building constructible, alternative construction procedures must be considered. One alternative is to increase the number of shored or reshored levels so that the maximum construction loads will be shared by older slabs that have more load capacity. A previous study by the authors¹⁶ shows that an increase of the number of shored levels results in an increase of the construction load applied to the older slabs. Sometimes, the resulting load is higher than the 28-day strength of the slabs. Indeed, that is the case for this example. An increase in the number of shored levels results in a factored construction load that is more than the designed capacity of the slabs. In such a case, a column-mounted shoring system may be used to transfer the construction load directly to the columns, thus eliminating the vertical shoring.

A second alternative is to increase the concrete strength. This can be achieved either by using high-early-strength concrete or by reducing the construction rate. If the construction rate is reduced from seven days to fourteen days per floor the applied construction load of $2.48D$ will be less than the available capacity of a fourteen day old slab which is $2.49D$, where D is the self weight of the slab. However, this alternative may not be a desirable solution because it will delay the completion of the project.

It is important also to mention that had the above structure been designed for live-to-dead load ratio equal to 1.0 then the 7-day slab capacity would have been about $2.5D$. In such a case the proposed construction scheme would have been safe. This shows how critical the coordination task undertaken by the construction engineers and contractors is in multistory building construction.

Simplified method

This construction example was also examined using the simplified method of Grundy and Kabaila. The ultimate factored construction loads on each slab are evaluated using the method suggested by Gardner.^{4,15} Gardner proposed to increase the construction dead loads determined from the simplified method by 10 percent to cover for the inherent errors of the simplified method. He also assumes that the construction live load is equally shared among the interconnected slabs. The dead and live loads were multiplied separately with the appropriate construction load factors.

The results of this analysis are shown in Table 1 in parenthesis. The analysis shows that only the seven-day old slabs No. 4 and 5 are overloaded. The simplified method failed to predict the overloading of the No. 1, 2, and 3 seven-day old slabs even with the 10 percent modification coefficient. This shortcoming of the simplified method stems from the fundamental assumption of the method that the shoring system is infinitely stiff as compared with the supported slabs. Based on this assumption, the No. 1, 2, and 3 seven-day old slabs are supposed to carry their own weight only, since the weight of the newly cast slab, the weight of the formwork, and any construction live load are assumed to be transferred to the foundation through the "rigid" shoring system. It is also interesting to observe that the slab overloading occurred after the first story reshores were removed, i.e., when the direct load path to the foundation was removed.

With compressible shores and reshores the structural system tends to shift the slab loads to the uppermost floors. The upper level floor slabs, being the most recently cast, may not have gained sufficient strength to carry the loads without overload and possible failure. This is especially true when reshored levels are used in combination with the shored floor levels.

Summary

This study recognizes the importance of the close cooperation between the design and construction teams to erect a structure safely, and also to maintain the serviceability of the building during its future use.

The use of multiple shored or reshored levels does

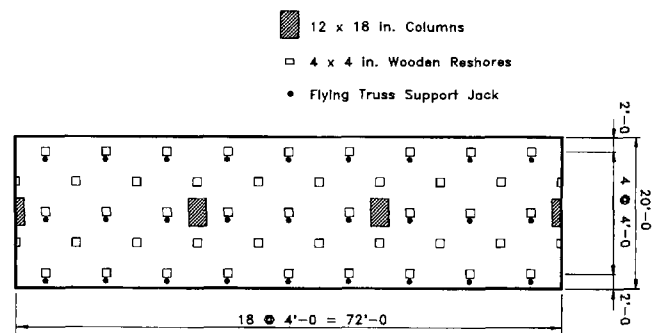


Fig. 4 — Typical floor plan for the construction example.

Table 1 — Shoring analysis computer results

Age (days)	f_c/f'_c	Available strength	Total factored construction load				
			Slab 1	Slab 2	Slab 3	Slab 4	Slab 5
6	0.76	$2.03D$	1.40 (1.54)*	1.40 (1.54)	1.40 (1.54)	1.40 (1.69)	1.40 (1.69)
7	0.79	$2.11D$	2.18 (1.54)	2.33 (1.54)	2.39 (1.54)	2.48 (2.33)	2.48 (2.33)
13	0.92	$2.46D$	1.35 (1.54)	1.33 (1.54)	2.26 (2.12)	2.22 (2.22)	2.22 (2.22)
14	0.93	$2.49D$	1.62 (1.54)	1.69 (1.54)	2.00 (2.33)	1.95 (2.33)	1.95 (2.33)
20	0.99	$2.65D$	1.33 (1.54)	1.80 (2.12)	1.87 (2.22)	1.82 (2.22)	1.83 (2.22)
21	0.99	$2.65D$	1.47 (1.54)	1.90 (2.33)	1.94 (2.33)	1.89 (2.33)	1.91 (2.33)
27	1.00	$2.68D$	1.97 (2.12)	2.04 (2.22)	2.08 (2.22)	2.06 (2.22)	2.06 (2.22)
28	1.00	$2.68D$	2.31 (2.33)	2.33 (2.33)	2.37 (2.33)	2.35 (2.33)	2.35 (2.33)

*Numbers in parenthesis are based on the simplified method.
D = Slab self weight.

not necessarily guarantee safe construction. A rigorous analysis must be performed to evaluate the safety and economy of alternate construction procedures. Special caution should be exercised when compressible wooden shoring systems are used. In such cases the construction load is shifted to the shored slabs of the upper floor. Due to its inherent shortcomings, the simplified method underestimates the construction loads. The 10 percent correction coefficient of the simplified method is not adequate for all construction procedures.

Our computer program model, based on the equivalent frame concept, can analyze multistory buildings having different floor types and thicknesses, spans, and shoring systems. The program runs on a desk top personal computer, thus making the method available to construction sites. The method is a very useful tool to develop rapid and safe construction schedules.

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ACT COMPILATION

Interactive Horizontal Formwork Selection System

by Awad S. Hanna and Victor E. Sanvido

In multistorey reinforced concrete building construction, selection of formwork to shape and support freshly cast concrete is largely based on the experience of the person selecting the system. There are typically one or two such experts in a company who make these decisions. This may often result in the selection of a particular system that is not the optimum. Also, the expert "Knowledge Czar" is not always available and an outside consultant is expensive to hire. This fact imposes some limitations especially for small and medium size contractors.

This article describes a computer system the authors developed to help the contractor select a horizontal formwork system. The expertise of several formwork engineer/planners was used to produce a body of decision rules and knowledge represented as an expert system.¹

Horizontal formwork systems

Horizontal formwork systems are those used to form the horizontal concrete work (slabs or floors). There are seven horizontal formwork systems that can be used to support slabs and roofs. Two of the systems — joist-slab and dome forms — are usually placed above the plywood sheathing. They are therefore considered special cases, because they can be used in conjunction with any of the five basic systems described below.^{1,2}

Conventional wood systems

Conventional wood systems consist of wood shores supporting wood stringers and joists, with the deck

surface made of plywood (Fig. 1). The deck may also be made of large panels tied or ganged together and supported by scaffold-type shoring.^{3,4}

Conventional metal systems

Conventional metal systems usually consist of wood or aluminum shores supporting aluminum stringers and joists, with the sheathing made of plywood (Fig. 2). The same type of deck forms can be made up of large panels tied or ganged together and supported by steel scaffold-type shoring.^{2,5}

Flying truss systems

Flying truss forms usually consist of large sheathing supported by steel or aluminum trusses (beams) that rest on screw jacks that allow the forms to be adjusted to the right level (Fig. 3). For stripping, after the concrete has gained enough strength, the system can be lowered away from the slab by turning down the jacks. The truss-mounted forms are then moved by crane from one casting position to the next.⁶

Column-mounted shoring systems

Formwork under cast-in-place slabs has typically been supported by shores resting on the floor or ground below. Another way to cast the slab without using the shoring system is to use long span form panels supported by up-and-down adjustable brackets attached to the bearing walls or columns of the building itself. The system consists of plywood decking that can be assembled on the ground or in place once the form has been flown and set on the columns (Fig. 4). The plywood decking is supported by

joists (headers) attached to the stringers (steel beams). For stripping, jacks are lowered until the framing beam of the deck rests on the rollers attached to the bracket and the entire form assembly is rolled out and carried by crane to the next floor.⁸

Tunnel formwork systems

Tunnel forms (also known as tunnels) are U-shaped or inverted L-shaped prefabricated steel forms that allow slab and supporting walls to be cast simultaneously (Fig. 5). After the concrete has gained enough strength the tunnels are removed and moved to the next level (Fig. 6). Half tunnels are used for spanning wide rooms, full tunnels for spanning narrow rooms. Standard modular panels offer a wide range of flexibility in room size. Forms range in width from 13 ft to 24 ft, in height from 7.5 ft to 10 ft, and in length up to 40 ft.^{9,10}

Joist-slab formwork systems

A one-way joist slab is a monolithic combination of regularly spaced joists arranged in one direction and a thin slab cast in place to form an integral unit with the beams and columns. One-way joist slabs have frequently been formed with standard steel pans. Any spacing between pans more than 30 in. is referred to as a wide-modular or skip-joist system.^{3,12}

Dome formwork systems

Standard size domes are usually used for waffle slab construction. They are based on two, three, four, and five foot modules.³ The two foot modules utilize 19 x 19 in. domes, with 5 in. ribs between

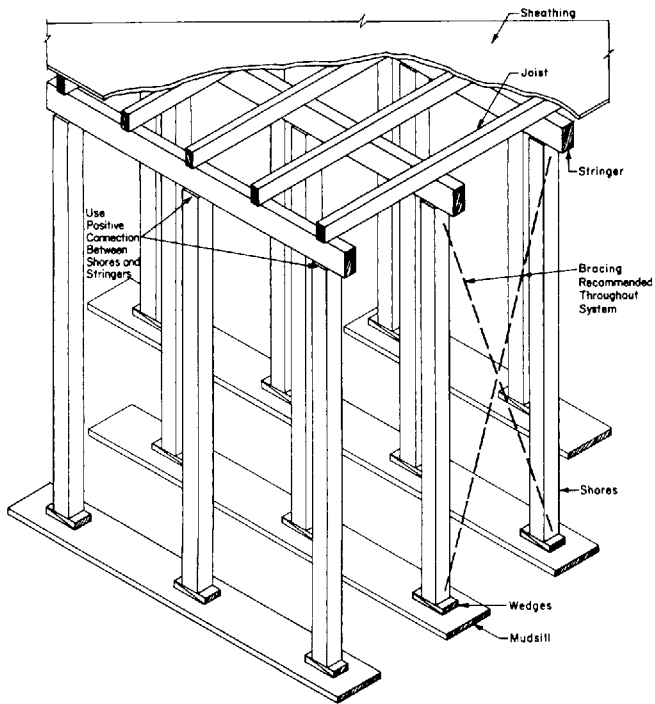


Fig. 1 — (above) Conventional wood formwork system.

Fig. 2 — (right) Conventional metal formwork system.

Fig. 3 — (below right) Flying truss formwork system.

Fig. 4 — (below) Column-mounted shoring system.⁷

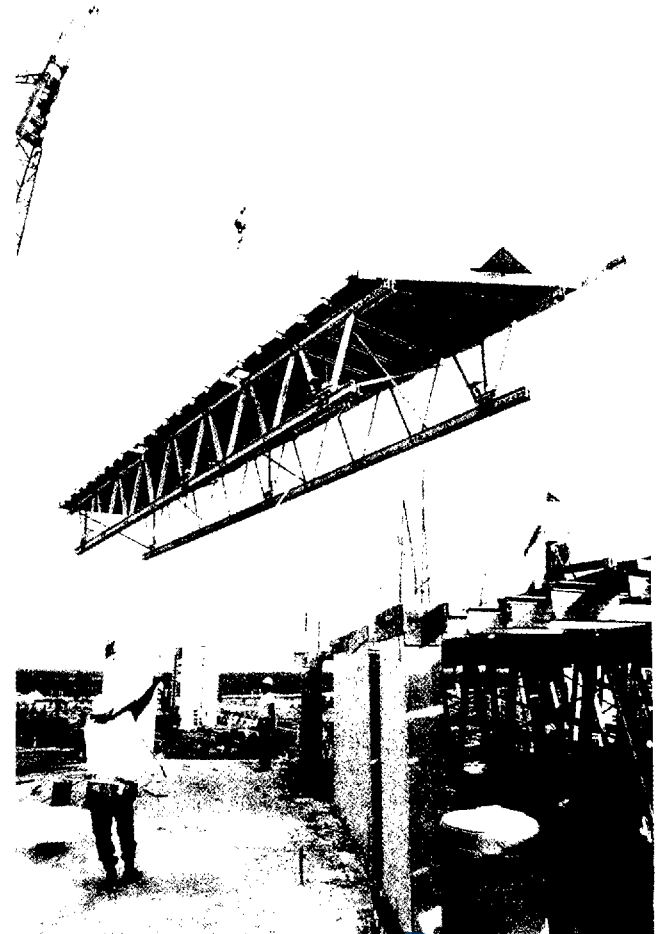
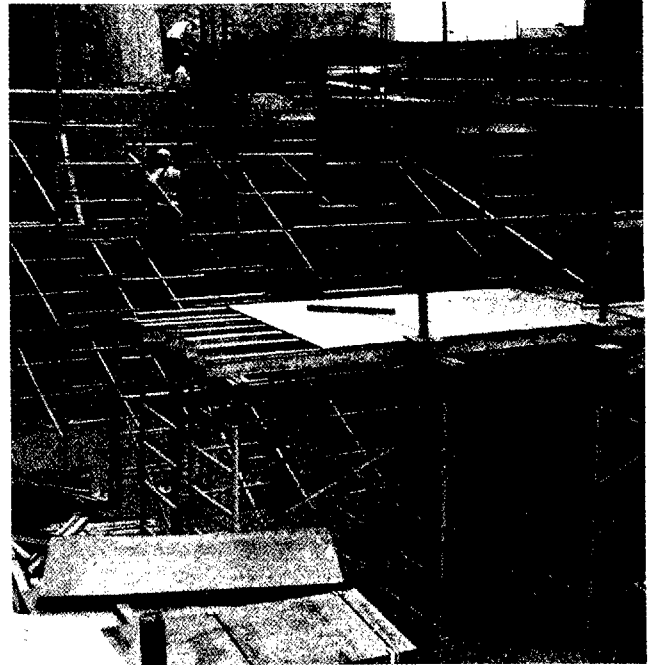
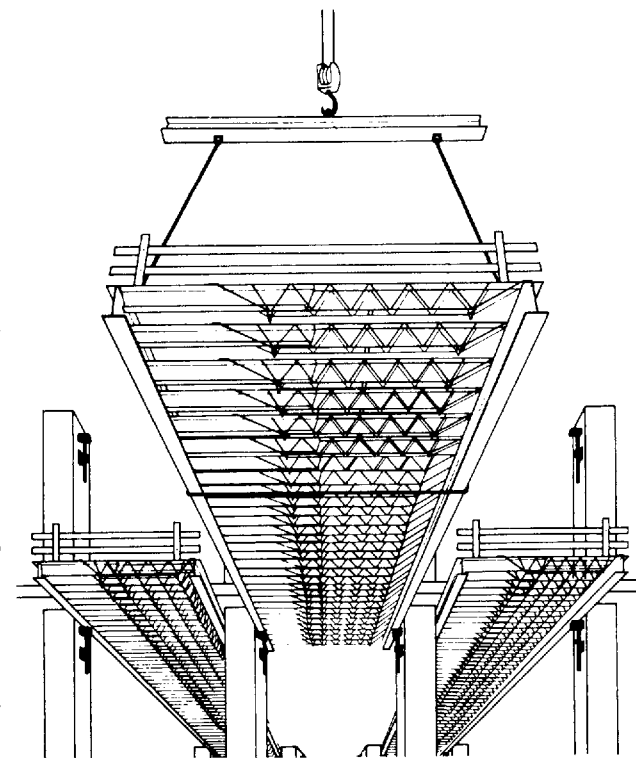


Illustration courtesy of Patent Scaffolding Co., a division of Harsco Corporation.



them. The three foot modules can be formed with 30 x 30 in. domes and 6 in. ribs.

The preceding sections presented five different horizontal formwork systems and two special ones, joist and waffle slab formwork systems. Two of these systems — the conventional wood system and the conventional aluminum system — are classified as hand-set systems. The remaining systems are classified as crane-set systems. Joist-form and dome forms can be handled by hand or attached to the surface deck of the flying form and flown as a unit.

Factors affecting selection of formwork systems

There are several ways to form any given concrete building. One of them will typically be the lowest cost method. Selecting the lowest cost method of formwork requires searching through a maze of formwork systems and their attributes.

The construction cost of slabs is often more than half the cost of structural framing systems, except in extremely tall buildings.⁴ Selection of the floor formwork system therefore deserves considerable attention to minimize cost.

Types of slabs

The selection of a formwork system should be made on the basis of the selected floor system that satisfies the structural loading conditions. Floor slabs in concrete buildings are classified into two basic types, based on the load distribution applied on the slab:

- Two-way slabs, in which the rectangularity ratio (slab length/width) is between 1 and 2, and the slab load is transferred to the supporting beams in two directions. Two-way slabs include flat plates, flat slabs, waffle slabs, and two-way slabs supported by drop beams.
- One-way slabs, in which the rectangularity ratio (slab length/width) is more than 2, and the slab load is transferred to the supporting beams in one direction. One-way slabs include solid slabs on beams or walls,

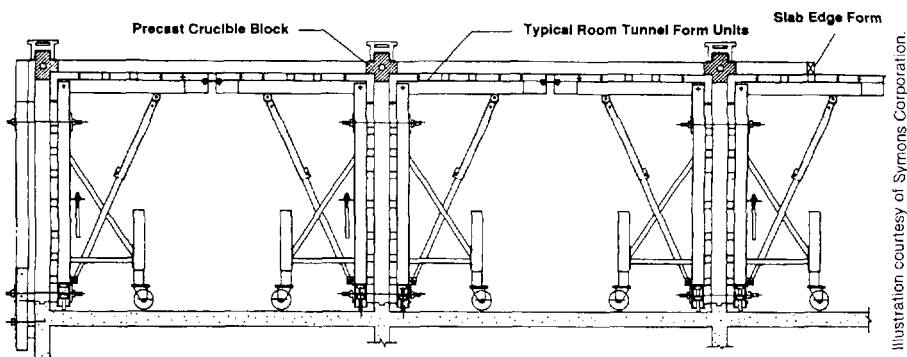


Fig. 5 — Tunnel formwork system.¹¹

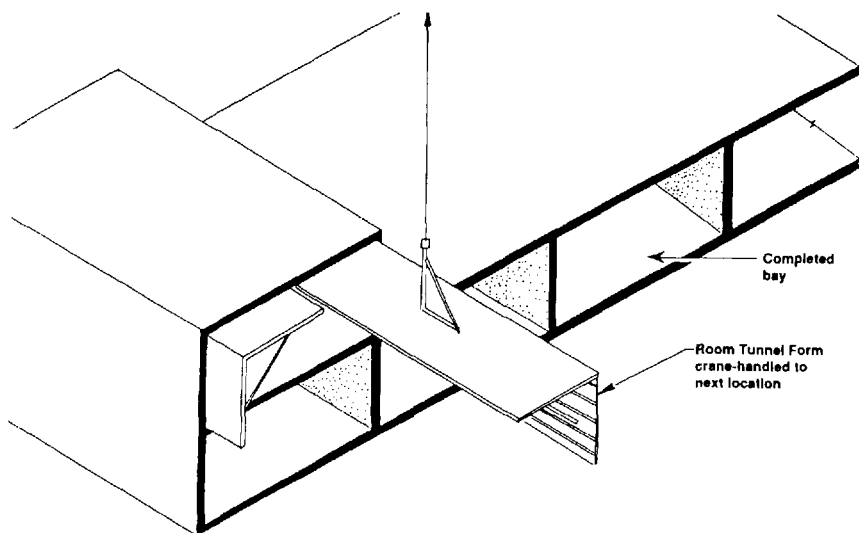


Fig. 6 — Stripping of tunnel form.¹¹

and one-way joist (ribbed) slabs supported by beams or bearing walls.

Two-way flat plate. A flat plate is defined as a structural floor system consisting of a concrete slab of constant thickness throughout, without beams or drop panels at the columns (Fig. 7a). The supporting columns for flat plates are usually equally spaced to facilitate the design and construction of such slabs. Flat plates can be constructed in minimum time because they utilize the simplest possible formwork.

Two-way flat slab. A flat slab is defined as a structural system consisting of a constant thickness concrete slab with drop panels at the columns (Fig. 7b). In earlier years, column capitals were used along with drop panels, but because of the higher form cost, column capitals are less favoured in today's construction practices.¹³

Waffle slab. Waffle slab construction (Fig. 7e) consists of rows of concrete joists at right angles with solid heads at the columns. Waffle slabs can be used for spans up to about 50 ft., and are used to obtain an attractive ceiling.

Two-way slab supported by beams. This system consists of a solid slab designed to span in two directions to either concrete beams or walls (Fig. 7g). The primary advantage of the system is the saving in reinforcing steel and slab section as a result of being able to take advantage of the two-way action. Formwork for the two-way system is complicated and usually outweighs the cost advantages associated with the saving in reinforcing steel and slab thickness.

One-way slab, beam, and girder. This system consists of a solid slab spanning to concrete beams uniformly spaced apart. Girders at

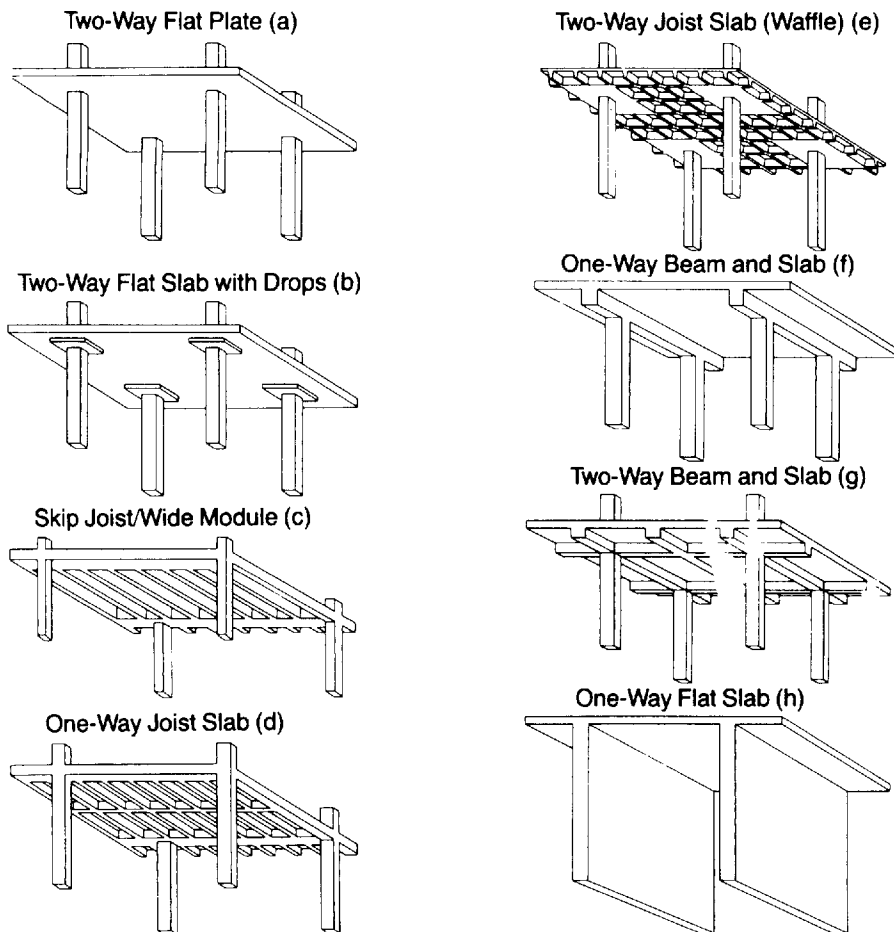


Fig. 7 — Slab systems.

right angles to the beams transfer the loads to the columns. This system generally affords the opportunity to span longer distances than two-way slabs by designing deeper beams and girders.

One-way slab supported by beams or bearing walls. This modification of the slab, beam, and girder system eliminates the secondary beams (Fig. 7h). Reinforcing steel is relatively simple, and the existence of openings is generally not a critical concern.

One-way joist (ribbed) slabs. One-way joist slabs are a monolithic combination of uniformly spaced beams or joists and a thin cast-in-place slab to form an integral unit. When the joists are parallel, this is referred to as one-way joist construction (Fig. 7d). Joists are very attractive to architectural layout and mechanical requirements.

Building design: building shape

Special buildings such as industrial buildings and power plants usually have extensive electrical and mechanical requirements that do not lend themselves to any formwork system. As a result, they should be constructed using the traditional formwork method (stick forms).

The feasibility of using a formwork system or traditional formwork methods is influenced by several design features such as variation of size, shape, and location for various structural elements (columns, walls, beams, cantilevers), existence of blockouts and openings for windows and doors, and HVAC requirements.

A building's structural layout is either uniform modular or irregular. Uniform modular design is characterized by regular spacing between columns and walls, equal story heights, and regular spacing of

cantilevers and openings. Irregular design is characterized by irregular positions of the different structural elements and broken lines or irregular curves in architectural plans.

Speed of construction

The most important advantage of using a formwork system is the speed of construction. The speed of construction affects cost because it determines the time when the building will be available for use and also influences the financing charges. In recent years, casting two floors per week in high-rise buildings has been achieved, especially in metropolitan areas.¹⁵ This fast floor cycle can only be achieved by using sophisticated formwork techniques such as flying forms, which are capable of forming one story every two days.

Area practice

In areas where the labor force is expensive and unskilled, the use of formwork systems can substantially reduce the cost. In areas where the labor force is inexpensive and skilled, a conventional formwork system is an economical alternative even if the building features lend themselves to a formwork system. As a result, preassembled formwork systems are used in some areas because of the lack of inexpensive skilled labor.

Site characteristics

The building site influences the selection of a suitable formwork system, because of site limitations and accessibility for construction operations. The feasibility of using flying forms, for instance, is influenced by site characteristics such as accessibility, existence of surrounding area restrictions, and availability of a make-up area to the site.

In open and unrestricted suburban sites, all formwork systems are viable and some other considerations should be evaluated to determine the most efficient and cost effective system. In downtown restricted sites, the only possible system may be ganged units that can be transferred from floor to floor.

Table 1 — Factors affecting the selection of horizontal formwork systems.

Influence factor			Formwork system	Conventional wood system	Conventional metal system	Flying truss system	Column-mounted shoring system	Tunnel form
Building design	Slab type	Slab type	All slab systems Most suited for two-way slab supported by beams or one-way slab, beam, girder			Two-way: flat plat and flat slab One-way: slab supported by beams or walls and joist slab (standard or skip-joist)		One-way slab supported by walls
	Lateral support	Compatibility with lateral load supporting system	Compatible with all lateral load supporting systems			Generally not suitable for framed tube and tube-in-tube because of the close distance between columns characteristic of tube systems		Bearing wall
	Building shape	Horizontal uniformity/irregularity	System can handle variations in size, shape, and location of beams and cantilevers			Beams and cantilevers should be of the same size and location or within 10% difference from floor to floor		Beams and cantilevers should be of the same size and location
		Vertical uniformity/irregularity	System can handle variations of column/wall size and location System can handle variations in story height within one floor or from floor to floor			Column/wall should be of the same size and location or within 10% difference from floor to floor Can handle limited variation (10%) in story height		Walls should be of the same size, location, and height from floor to floor
	Miscellaneous	High stories (> 14 ft high)	Not suitable for high stories	More suitable for high stories	Limited by truss depth (up to 20 ft)	Height independent system	Limited height system (up to 10 ft)	
		HVAC	Can accommodate extensive HVAC	Cannot accommodate extensive HVAC	HVAC should be minimal and identical from floor to floor			
		Dimension limitations	Used for small building size (less than 100,000 sq. ft.)	Used for medium building size (100,000 to 200,000 sq. ft.)	Used for large size buildings (more than 200,000 sq. ft.)			
Job specification	Speed of construction	Floor cycle (number of floors/day)	Typically floor every 5 working days Faster cycle can be accommodated at additional cost (more stories to be shored and reshored)			Floor every 3-4 days		Floor every 1-2 days
		Rate of placement	Generally not a major factor in horizontal concrete work, average rate between 25-30 cy/hr					
	Construction sequence	Pouring columns, then beams and slabs Slab on grade need not be in place, but cost can be reduced if slab on grade is in place			Pouring columns, then beams and slabs Slab on grade needed for form to be used in first floor	Pouring columns, then beams and slabs Slab on grade need not be in place	Pouring slabs and walls together 3 in. starter wall is necessary	
Supporting organizations	Available capital	Initial make-up cost	Average cost range from \$1 to \$3 per sq. ft. of contact area			Average cost range from \$10 to \$15 per sq. ft. of contact area		Average cost ranges from \$20 to \$50 per sq. ft. of contact area
		Potential reuse	Up to 15 reuses	Up to 20 reuses	Minimum of 12-15 reuses should be available	Minimum of 15-20 reuses should be available	Minimum of 50 reuses should be available	
		Stripping cost	High stripping cost (approximately 1/3 of the makeup cost)			Low stripping cost (approximately 1/2 of the hand set systems)		Low stripping cost
		Average labor productivity	12 sq. ft. per contact area	18 sq. ft. per contact area	36 sq. ft. per contact area	45 sq. ft. per contact area	50 sq. ft. per contact area	
	Hoisting equipment	Availability of crane and crane time	Can be hand-set Less expensive if crane is available	Can be hand-set Crane is necessary if made into panels	Adequate hoisting equipment must be available			
		Adjacent building, traffic, and other constructions	Generally not a factor	Generally not a factor May be a factor if system panelized	A major factor, there must be open space at least 1.5 the length of the large panel from the face of the building			
		Adequate crane capacity	Generally not a factor	May be a factor if system panelized	Crane should have adequate carrying capacity at maximum and minimum radii.			
	Home office support	Safety	Normal safety precautions are required			Special safety in dealing with crane operation.		
		Supervision Trouble shooting experience	Minimum engineering supervision	Requires skilled crew Requires moderate engineering supervision	Requires high engineering supervision		Requires high degree of engineering supervision	
		Supporting yard facility	Minimum yard is required	Requires local yard if made into panels	Requires enough supporting local or regional yard facility		System should be available nearby No yard is required	
Local conditions	Area practice		Work best in areas of high quality, low cost labor force	Work best in areas of high quality, high cost labor force	Generally work in areas of high cost, low quality labor force			
	Site characteristics	Available storage and make-up area	Require minimum storage and make-up area	Small make-up area is required if system is panelized	Site must have adequate storage and make-up area		System preassembled Minimum storage area is required.	
		Access to site	Generally not a factor for hand-set systems			Job must be accessible for large form units May not be a factor if forms are assembled on site		Job must be accessible for large preassembled steel forms