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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Contents

Construction Live Load Caused by Powered Buggies

by Hui-Ming Lee, Wai-Fah Cheh, 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

$$I = \frac{50}{L + 125} \leqslant 0.3 \qquad (1)$$

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

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

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 x 10^6 psi (3.51 x 10^4 MPa); and the elastic modulus of wooden shores is 1.6 x 10^6 psi (1.10 x 10^4 MPa).

Calculation model

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

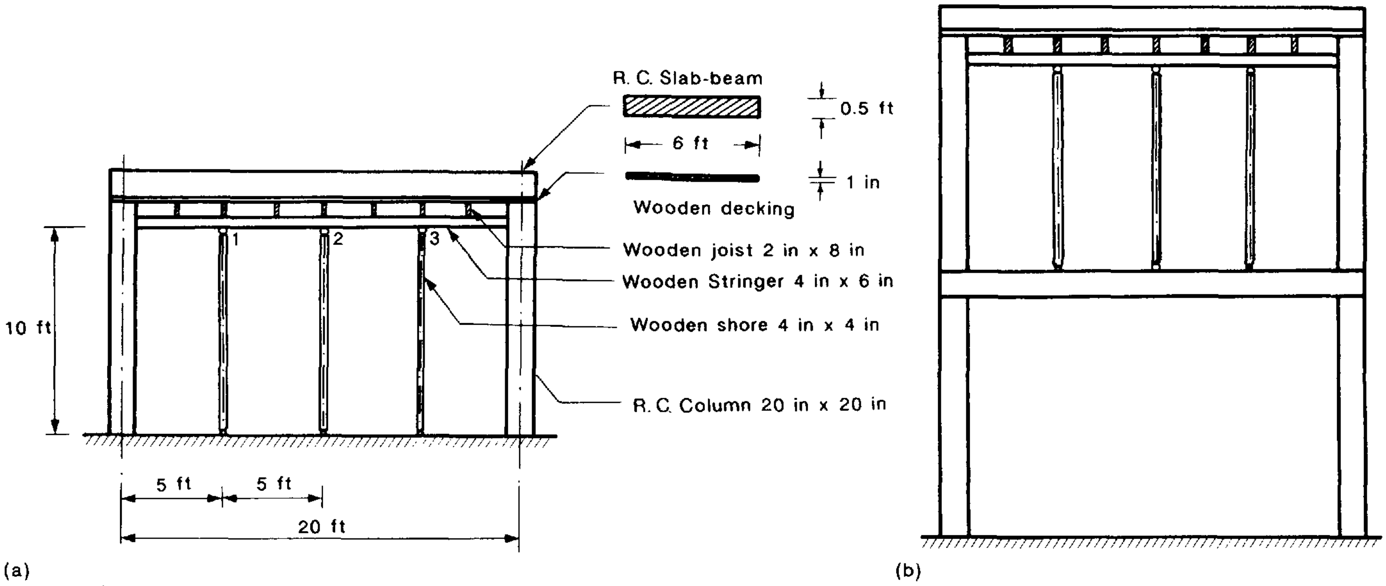

Fig. 1—Calculation model for determining: (a) maximum shore load; (b) maximum slab moment.

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

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

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

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 maximum 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 (Mosallam and Chen, 1990)

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

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

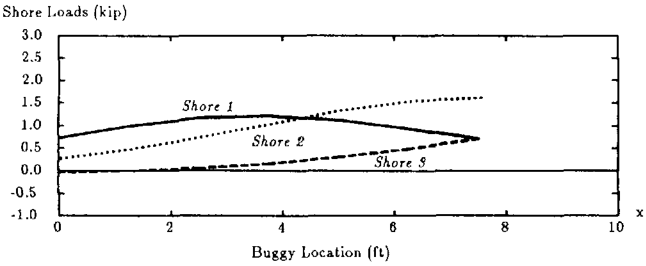

Fig. 2—Shore loads with one buggy.

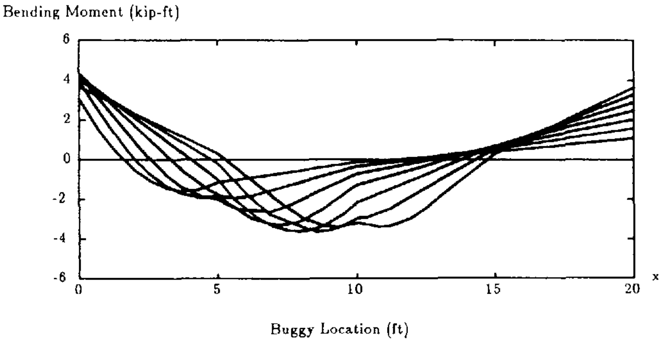

Fig. 3—Bending moments with one buggy.

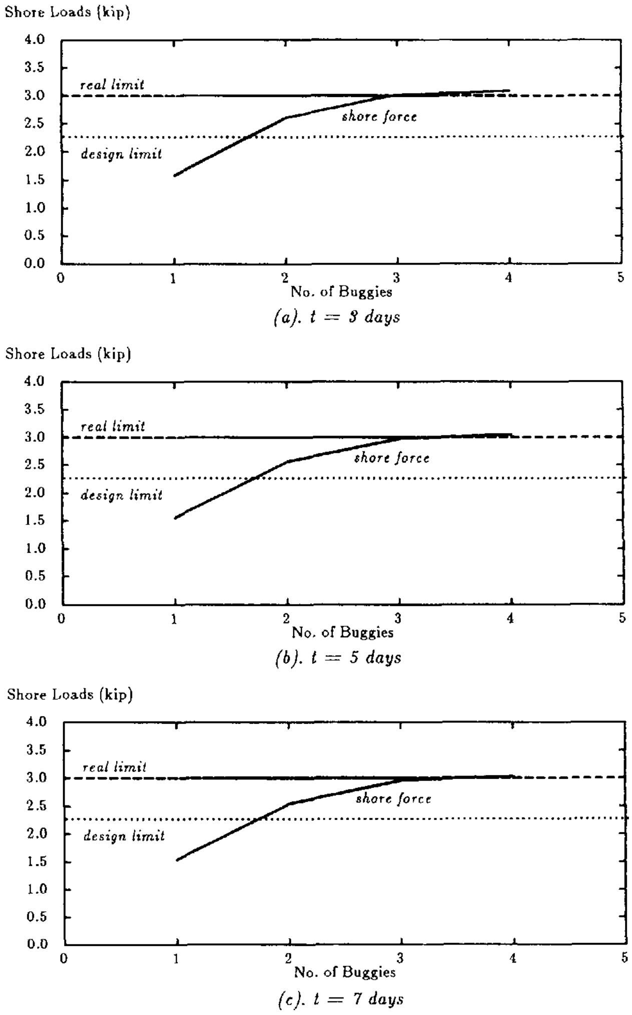

Fig. 4—Maximum shore loads versus number of buggies.

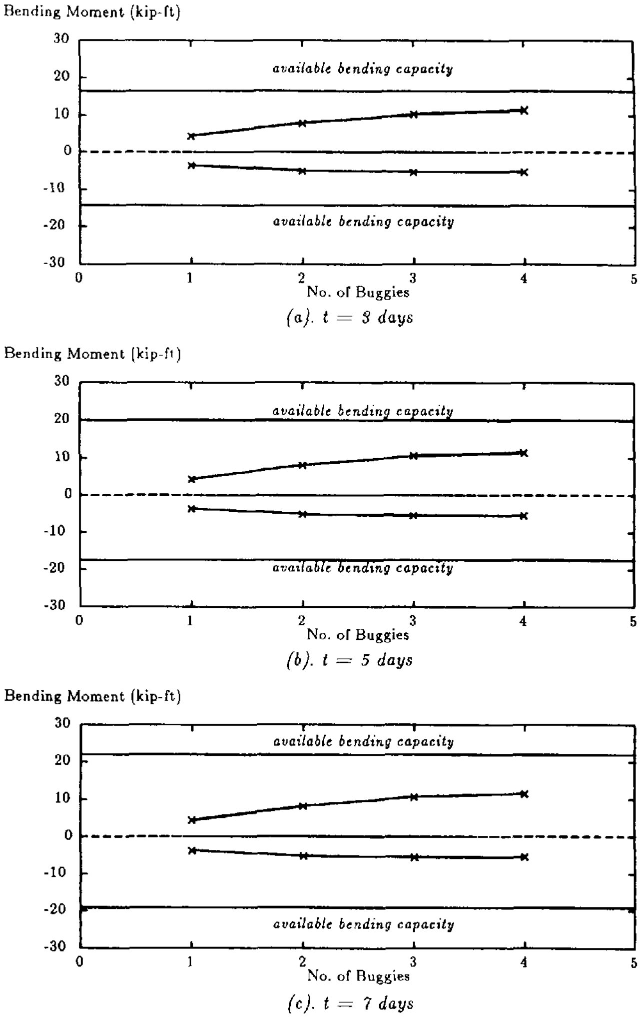

Fig. 5—Maximum bending moment versus number of buggies.

Table 1 — Maximum shore loads, kips

No. of Buggies	Concrete age			
	3 days (1)	5 days (2)	7 days (3)	(1)/(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			
		3 days (1)	5 days (2)	7 days (3)	(1)/(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.

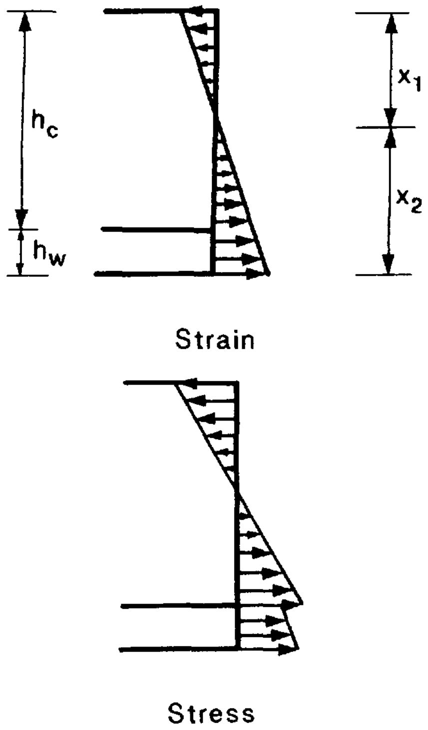

Fig. 6—Strain and stress distributions at slab-beam intersection.

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

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

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 73 F (22.8 C)	Type I cement 55 F (12.8 C)	Type I cement 40 F (4.4 C)	Type II cement 73 F (22.8 C)	Type II cement 55 F (12.8 C)	Type II cement 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

$$A^e_w = \frac{E_w}{E_c} A_w \qquad (5)$$

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

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

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

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

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 Mosallom 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 systematically 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.

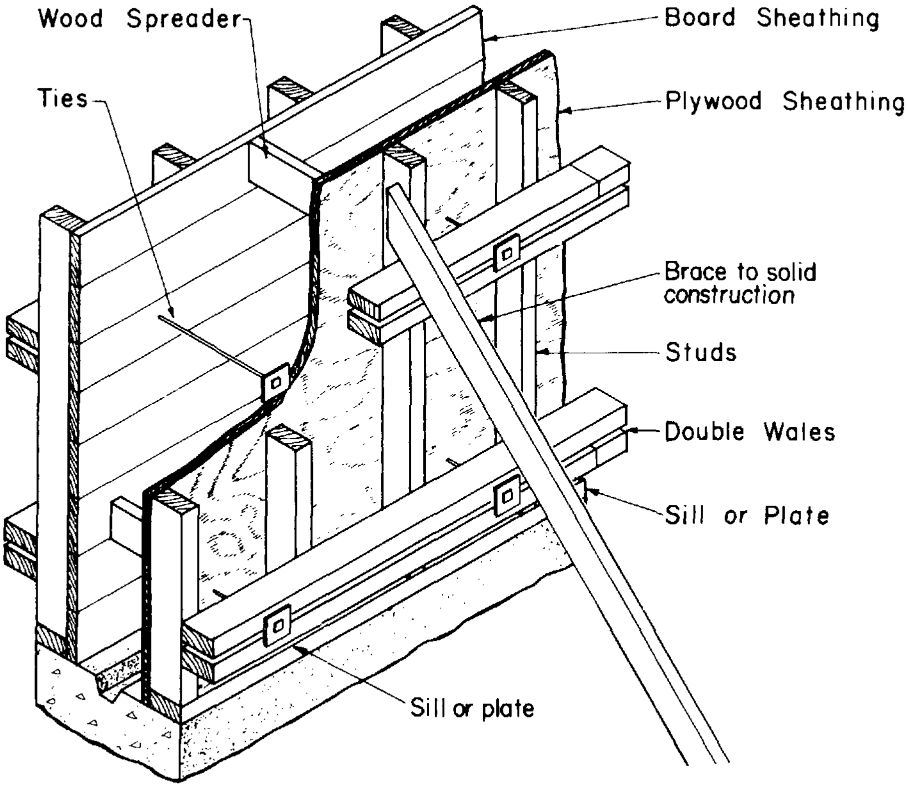

Fig. 1 — Conventional formwork.

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 study[1] 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