Design Optimization of Concrete-Slab Forms

By Awad S. Hanna,[1] Member, ASCE, and Ahmed B. Senouci,[2] Associate Member, ASCE

Abstract: This paper presents a design optimization method for all-wood concrete-slab forms. This procedure was formulated to provide for a safe slab-form design with minimum cost. It considers in its design process the cost of each slab-form component (sheathing, joist, stringer, and wood shore) and all available combinations of slab-form components. The performance of the optimum design method is compared to that of the traditional design method, which uses design charts/tables. The optimum design method was found to have a potential cost savings over the traditional design method. A study was conducted to confirm these cost savings. The results of the study show that cost savings as high as 9.9% were achieved by using the design optimization method.

INTRODUCTION

Formwork consists of temporary structures whose purpose is to provide support and containment for fresh concrete until it can support itself. Concrete forms are engineered structures that are required to support loads composed of the fresh concrete, construction materials, equipment, workers, impact of various kinds, and sometimes wind. The forms must support all the applied loads without collapse or excessive deflection. ACI 347R-88 ("Guide" 1988) defines those applied loads and gives a number of guidelines for safety and serviceability. Based on these guidelines, a number of charts and tables have been developed for the design of concrete formwork (Hurd 1987; Sommers 1984). These charts and tables are very useful design tools. However, they do not guarantee a design of minimum cost.

Formwork costs are significant, generally amounting to anywhere from 40% to 60% of the cost of a concrete structure. Fig. 1 illustrates the overall relative costs for concrete slabs. Formwork material and labor costs are important cost items. A reduction of formwork material and labor costs can produce a real cost savings, thus emphasizing the importance of formwork design optimization. Formwork design optimization produces not only safe and reliable designs but also economical ones.

To date, design optimization of concrete forms has not been addressed in the literature. The present paper provides a design optimization procedure for all-wood concrete-slab forms. This procedure was formulated to provide for a safe and reliable slab-form design whose cost is minimum.

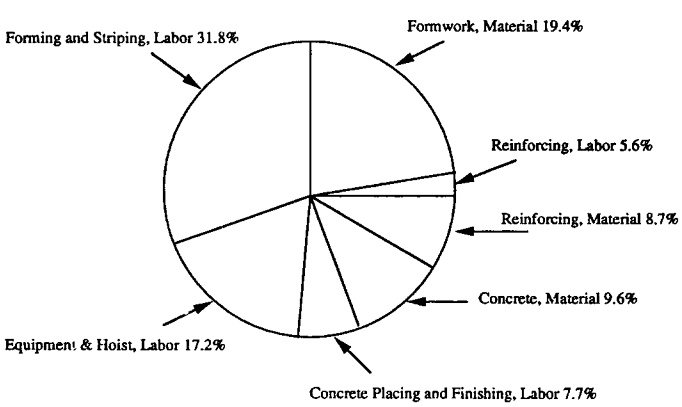

FIG. 1. Typical Cost Breakdown for Concrete Slabs

SLAB-FORM LOADS

Slab-form design loads are divided into vertical and horizontal loads. Vertical loads can be divided into dead and live loads. Dead loads include the weight of formwork, freshly placed concrete, reinforcing steel, and piping. Live loads include the weight of workers, equipment, and material stored on the slab. ACI 347R-88 recommends that slab forms be designed for a minimum live load of 204 kN/m^2 (50 psf), and if motorized carts are used, 3.59 kN/m^2 (75 psf). ACI 347R-88 also recommends for slabs a minimum horizontal design load of 1.46 kN per lineal meter (100 lb per lineal foot) of floor edge or 2% of the total dead load of the floor, whichever is greater.

TRADITIONAL SLAB-FORM DESIGN

Fig. 2 shows a typical structural system for all-wood slab forms. All-wood slab forms are composed of a sheathing, a number of joists spaced by a distance $S1$, a number of string-

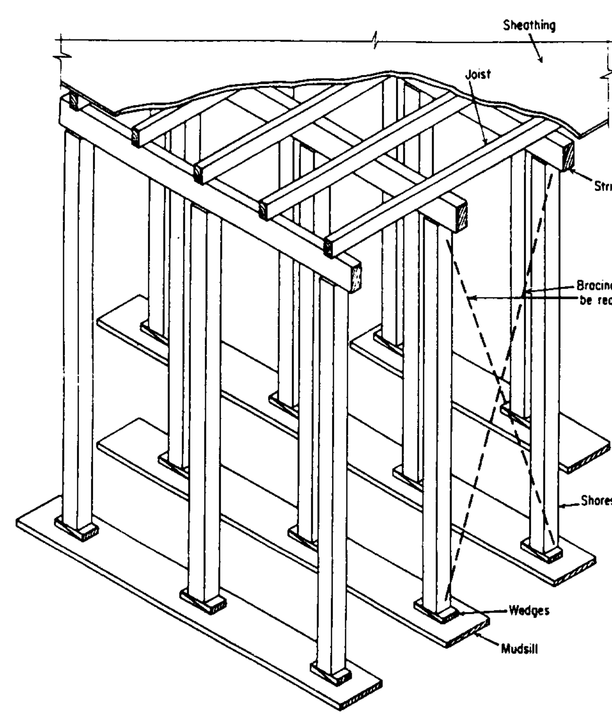

FIG. 2. Typical Structural System for All-Wood Slab Forms (Spiegel and Limbrunner 1991)

[1]Asst. Prof., Univ. of Wisconsin, 460 Henry Mall, Madison, WI 53706.
[2]Assoc. Res. Specialist, Univ. of Wisconsin, 460 Henry Mall, Madison, WI.

Note. Discussion open until November 1, 1995. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on October 18, 1993. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 121, No. 2, June, 1995. ©ASCE, ISSN 0733-9364/95/0002-0215–0221/$2.00 + $.25 per page. Paper No. 7149.

J. Constr. Eng. Manage., 1995, 121(2): 215-221

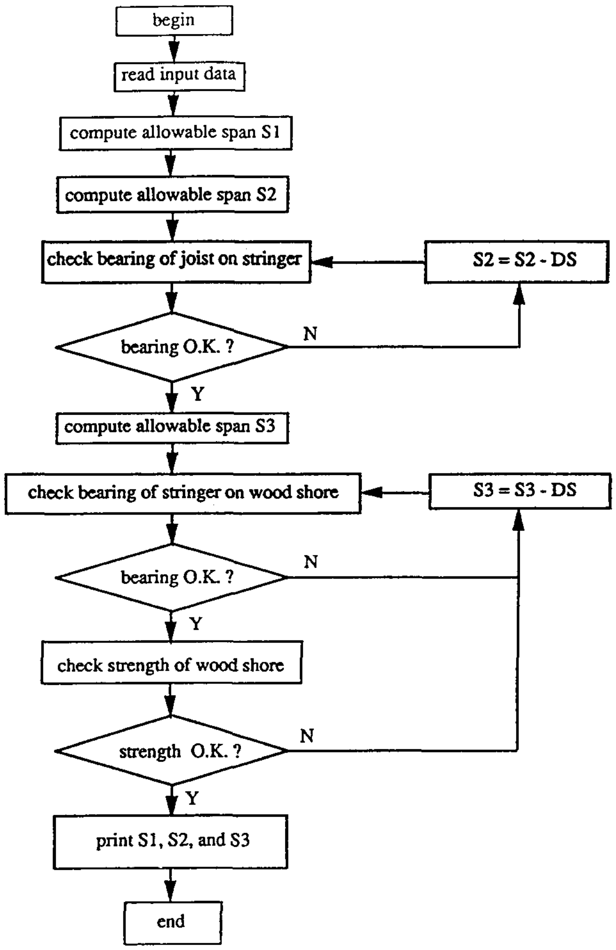

FIG. 3. Algorithm of Traditional Design Method

ers spaced by a distance $S2$, and finally a number of shores spaced by a distance $S3$. Sheathings are defined by three parameters: size, thickness, and type. The size refers to the sheathing's dimensions: 1.22 m $\times$ 2.44 m, 1.22 m $\times$ 3.05 m, and 1.22 m $\times$ 3.66 m (4 ft $\times$ 8 ft, 4 ft $\times$ 10 ft, and 4 ft $\times$ 12 ft). The sheathing thicknesses, which are most widely used thicknesses in formwork, are 0.016 and 0.019 m (5/8 and 3/4 in.). The type refers to the type of plyform used: class I plyform, class II plyform, and structural I plyform. On the other hand, joists, stringers, and shores are defined by their standard dressed sizes (thickness and width), their lumber species, and their lumber grades. Standard lengths of joists, stringers, and shores are available in multiples of 0.61 m (2 ft), with the longer lengths carrying extra costs.

The traditional design method refers to the design method used in the development of the design tables and charts (Hurd) 1987; Sommers 1984). The objective of the traditional design method is to determine the maximum allowable spacings $S1$, $S2$, and $S3$ so that each slab-form component (sheathing, joist, stringer, and wood shore) has adequate strength to resist the applied loads and sufficient stiffness to maintain an allowable deflection. In the analysis of the slab-form components, the traditional stress equations are used (Spiegel and Limbrunner 1991).

Fig. 3 summarizes the design process of the traditional method. A FORTRAN program was written to automate this design process and to compute the total cost of the designed slab forms.

OPTIMUM DESIGN METHOD

The optimum design method, as opposed to the traditional method, considers the form component material and labor

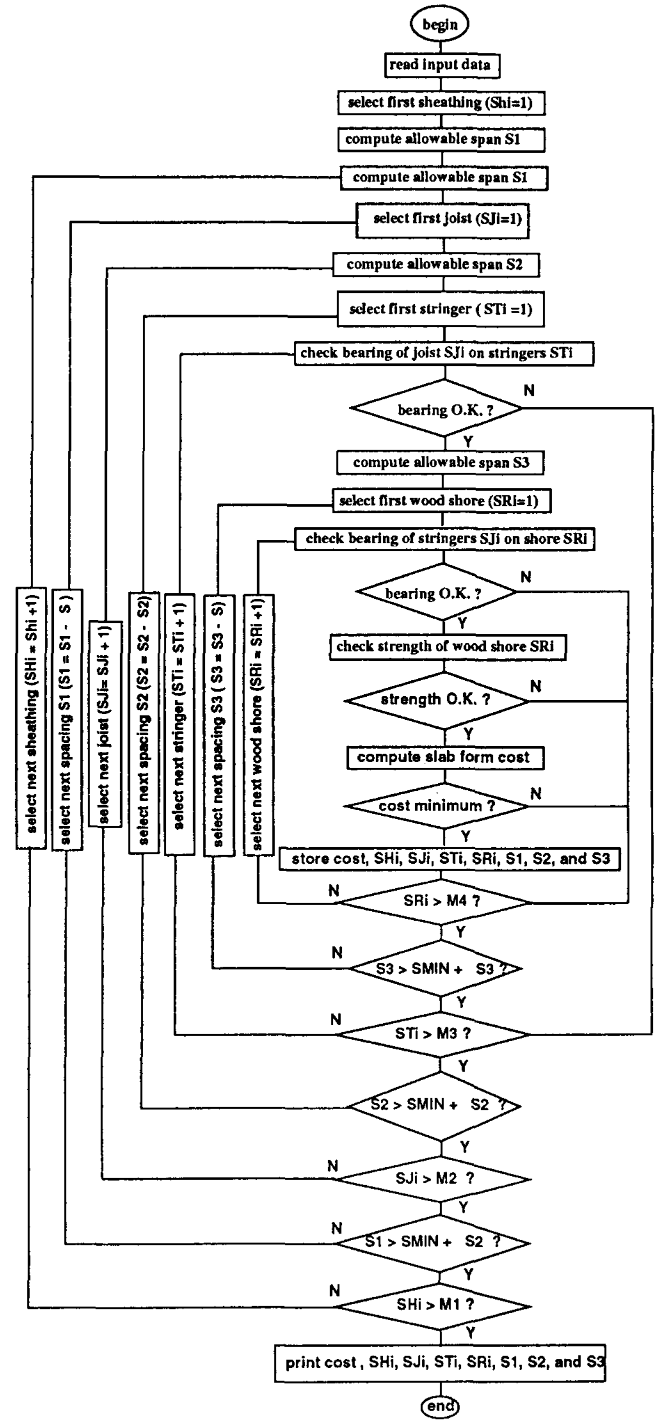

FIG. 4. Algorithm of Optimum Design Method

costs as variables in the design process. Assume that $M1$ sheathings (different in type and/or thickness), $M2$ joists (different in size, lumber species, and/or lumber grade), $M3$ stringers, and $M4$ wood shores are available to the designer to choose from to design a specific concrete-slab form. The objective of the design optimization procedure is to choose a specific sheathing SHi ($SHi = 1, \ldots, M1$), a specific joist JSi ($JSi = 1, \ldots, M2$) with its spacing $S1$, a specific stringer STi ($STi = 1, \ldots, M2$) with its spacing $S2$, and a specific wood shore SRi ($SRi = 1, \ldots, M4$) to minimize the following slab-form cost function:

$$\text{Cost} = CM(SHi) + CM(JSi) + CM(STi) + CM(SRi) + CL(SHi) + CL(JSi) + CL(STi) + CL(SRi) \quad (1)$$

J. Constr. Eng. Manage., 1995, 121(2): 215-221

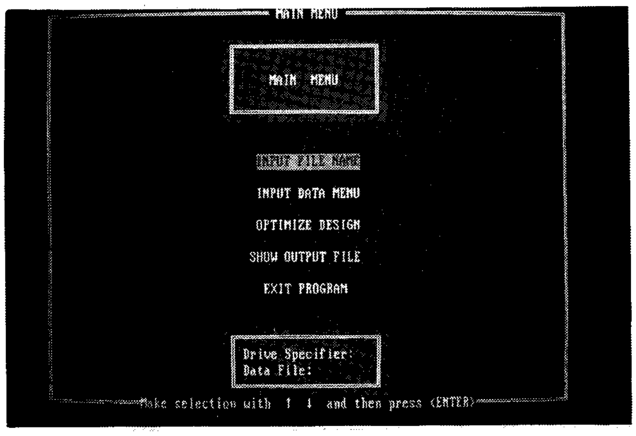

FIG. 5. Main Menu Screen

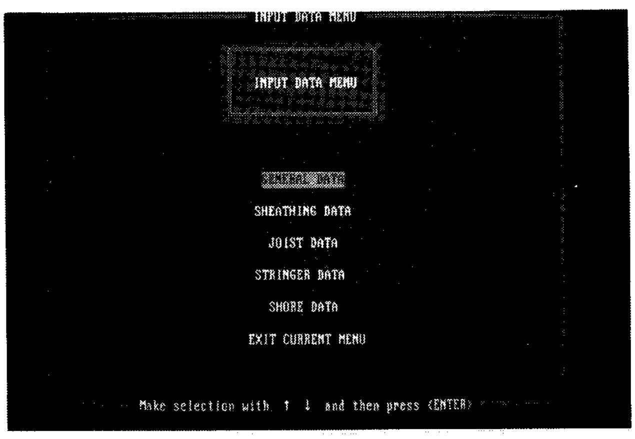

FIG. 6. Input Data Menu Screen

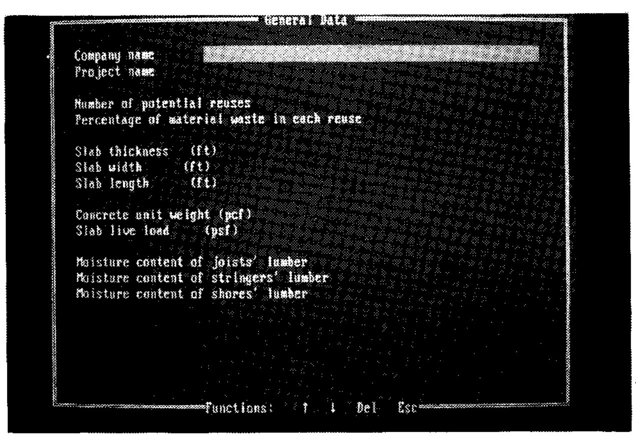

FIG. 7. General Data Input Screen

where $CM(SHi)$ = material cost of all the sheathings; $CM(JSi)$ = material cost of all the joists; $CM(STi)$ = material cost of all the stringers; and $CM(SRi)$ = material cost of all the wood shores. $CL(SHi)$, $CL(JSi)$, $CL(STi)$, and $CL(SRi)$ = labor cost for fabricating, erecting, and stripping all the sheathings, all the joists, all the stringers, and the shores, respectively.

The material cost $CM(SHi)$ of all the sheathings SHi is computed using the following equation:

$$CM(SHi) = NSHi \cdot ASHI \cdot UCSHi \tag{2}$$

where $NSHi$ = number of required sheathing; $ASHI$ = sheathing area; and $UCSHI$ = sheathing material cost per unit area.

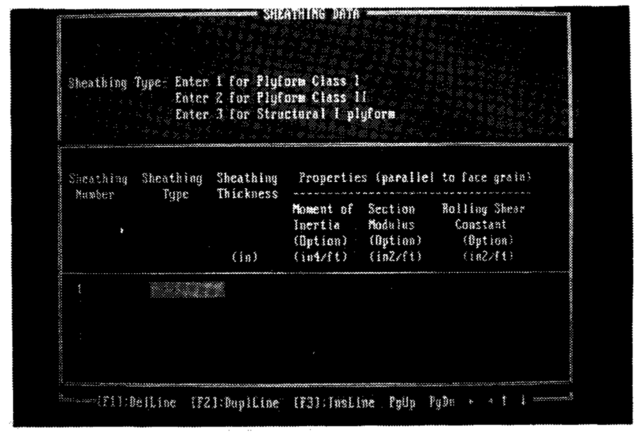

FIG. 8. Sheathing Input Data Screen

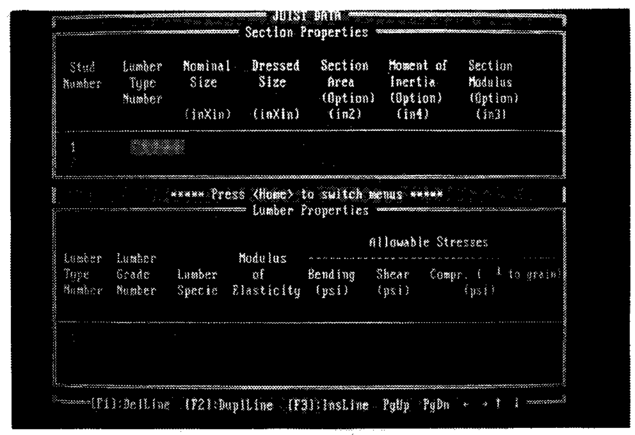

FIG. 9. Joist Input Data Screen

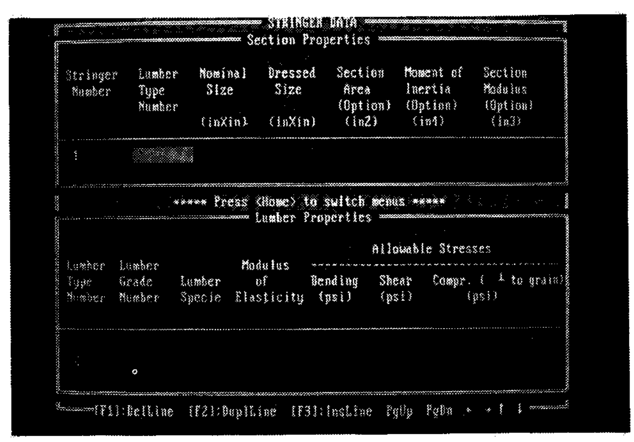

FIG. 10. Stringer Input Data Screen

The material cost of all the joists JSi is computed using the following equation:

$$CM(JSi) = NJSi \cdot NBFJSi \cdot UCJSi \tag{3}$$

where $NJSi$ = number of required joists; $NBFJSi$ = joist number of board feet; and $UCJSi$ = joist unit cost per board foot.

The material costs $CM(STi)$ of all the stringers STi and $CM(SRi)$ of all the shores SRi are computed in the same way $CM(JSi)$ was previously computed.

The labor cost $CL(SHi)$ for fabricating, erecting, and strip-

J. Constr. Eng. Manage., 1995, 121(2): 215-221

TABLE 1. Sheathing Input Data

No. (1)	Type (2)	Thickness (in.) (3)	Dimension (ft × ft) (4)	Moment of inertia (in.^{4}/ft) (5)	Shear constant (sq in./ft) (6)	Elastic modulus (psi) (7)	Allowable bending stress (psi) (8)	Allowable shear stress (psi) (9)
1	Class I	0.625	4 × 8	0.131	6.791	1,650,000	1,930	72
2	Class I	0.750	4 × 8	0.199	8.299	1,650,000	1,930	72

TABLE 2. Joist Input Data

No. (1)	Species/grade (2)	Dimension (in. × in.) (3)	Moment of inertia (in.^{4}) (4)	Section area (sq. in.) (5)	Section modulus (cu. in.) (6)	Modulus of elasticity (psi) (7)	Allowable bending stress (psi) (8)	Allowable shear stress (psi) (9)
1	Spruce/1	2 × 4	5.36	5.25	3.06	1,500,000	1,500	87.5
2	Spruce/1	2 × 6	20.80	8.25	7.56	1,500,000	1,250	87.5
3	Spruce/1	2 × 8	47.63	10.88	13.14	1,500,000	1,250	87.5

TABLE 3. Stringer Input Data

No. (1)	Species/grade (2)	Dimension (in. × in.) (3)	Moment of inertia (in.^{4}) (4)	Section area (sq. in.) (5)	Section modulus (cu. in.) (6)	Elastic modulus (psi) (7)	Allowable bending stress (psi) (8)	Allowable shear stress (psi) (9)
1	Spruce/1	2 × 10	98.93	13.88	21.39	1,500,000	1,250	87.5
2	Spruce/1	2 × 12	178.00	16.88	31.64	1,500,000	1,250	87.5

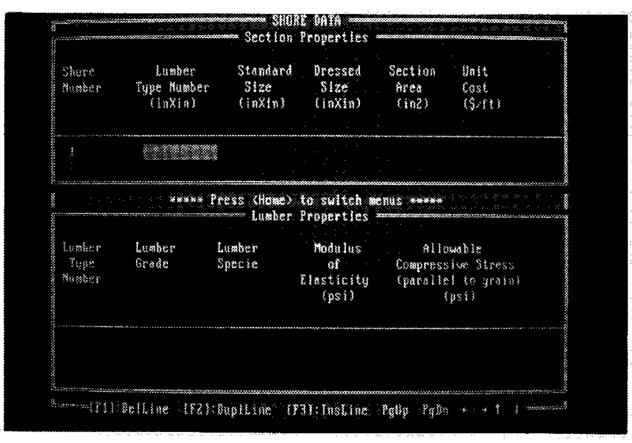

FIG. 11. Shore Input Data Screen

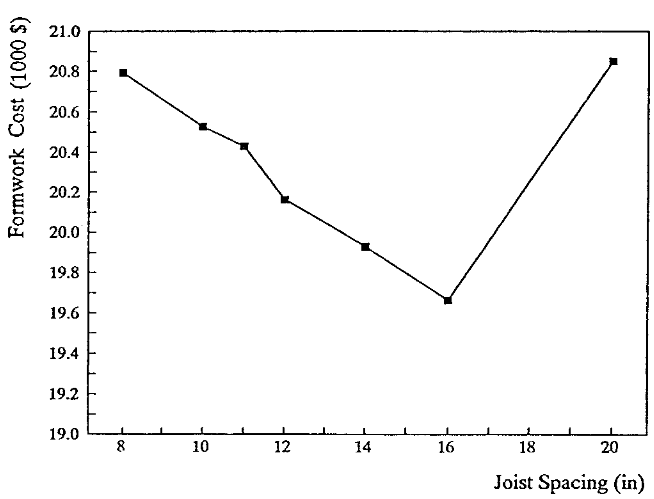

FIG. 12. Slab-Form Cost Savings versus Joist Spacings

TABLE 4. Wood Shore Input Data

No. (1)	Species/grade (2)	Standard dressed dimensions (in. × in.) (3)	Modulus of elasticity (psi) (4)	Allowable compression parallel to grain (psi) (5)
1	Douglas fir-larch	4 × 4	1,800,000	1,563

ping all the sheathings SHi is computed using the following equation:

$$CL(SHi) = NSHi \cdot CLSHi \cdot PRODSHi \tag{4}$$

where $NSHi$ = number of required sheathings; $CLSHi$ = crew total cost per unit time; and $PRODSHi$ = number of sheathings that can be fabricated, erected, and stripped during the same unit time.

The labor costs $CL(JSi)$, $CL(STi)$, and $CL(SRi)$ are computed the same way the labor cost $CL(SHi)$ was previously computed.

In the minimization of the cost function, (1), each selected form component (sheathing SHi, joist JSi, stringer STi, and shore SRi) must have adequate strength to resist failure in either bending, compression, tension, or shear due to the loads applied to it and must have sufficient stiffness so that its deflection does not exceed the allowable.

Fig. 4 presents a schematic diagram for the multistep computational algorithm. The computational steps can be summarized as follows:

1. The input data is read in first. The input data consists of information about dead and live loads, slab dimensions, allowable deflection limits, sheathings, joists, stringers, and shores. Slab dimensions represents the length, width, and height of the slab form. Two deflection parameters are used to control the deflection of sheathings, joists, and stringers. The first parameter is expressed as a fraction of the span length (e.g., $L/320$). The second parameter is independent of the span length

J. Constr. Eng. Manage., 1995, 121(2): 215-221

TABLE 5. Material and Labor Cost Data

No. (1)	Material Cost: Sheathing (dollars/SF) (2)	Joist (dollars/BF) (3)	Stringer (dollars/BF) (4)	Shore (dollars/BF) (5)	Labor Productivity (units/day): Sheathing (6)	Joist (7)	Stringer (8)	Shore (9)	Crew unit total cost (dollars/day) (10)
1	0.625	0.385	0.450	0.675	200	50	30	55	811
2	0.730	0.370	0.460	—	200	50	30	—	811
3	—	0.365	—	—	—	50	—	—	811

Note: SF = sq ft; BF = board foot measure.

TABLE 6. Slab-Form Deflection Limits

Slab-form components (1)	Deflection limit (2)
Sheathings	$L/240$
Joists	$L/360$
Stringers	$L/360$

and represents the maximum allowable deflection [e.g., 0.0064 m (0.25 in.)]. Sheathing input data consists of (1) the number of different sheathings (different in thickness or type); (2) the material cost per square foot of each sheathing; (3) the crew unit total cost and productivity; and (4) the dimensions, the unit weight, the allowable bending stress, the allowable shear stress, and the modulus of elasticity of each sheathing. Joist/stringer input data consists of (1) the number of different joists/stringers available; (2) the material cost per board foot of each joist/stringer; (3) the crew unit total cost and productivity; and (4) the dimensions, the unit weight, the allowable bending stress, the allowable compressive stress perpendicular to grain, the allowable shear stress, and the modulus of elasticity of each joist/stringer. Wood shore input data consists of (1) the number of different wood shore sizes available; (2) the material cost per board foot of each wood shore; (3) the crew unit total cost and productivity; and (4) the dimensions, the allowable compressive stress parallel to grain, and the modulus of elasticity of each wood shore.

2. The first sheathing ($SHi = 1$) is selected and its maximum allowable span is determined. The allowable span $S1$, which is also the allowable joist spacing, is then selected based on practical considerations. The span $S1$ should be rounded down to whole inches and should also be selected as to provide support at edges of all the sheathings.
3. The first joist ($SJi = 1$) is selected and its maximum allowable span is determined. The allowable span $S2$ is then selected based on practical considerations. The span $S2$ should be rounded down to whole inches and should also be selected as to provide support at edges of all the joists.
4. The first stringer ($STi = 1$) is selected. The bearing at the point where each joist rests on the stringer is first checked. Then, the stringer maximum allowable span is determined. The allowable span $S3$ is then selected based on practical considerations. The span $S3$ should be rounded down to whole inches and should also be selected as to provide support at ends of all the stringers.
5. The first wood shore in the list ($SRi = 1$) is selected. The bearing at the point where each stringer rests on the wood shore is first checked. Then, the capacity of the wood shore is checked.
6. If all of the constraints are satisfied, the total cost of the slab form is computed. To compute the total cost, the material and labor costs of sheathing, joists, stringers, and shores are added together. If the total cost is less than previously computed costs, this computed cost as well as the combination SHi, SJI, STi, and SRi with their respective spacings, $S1$, $S2$, and $S3$, are stored in the computer's memory.
7. Steps 2–6 are repeated for each available wood shore SRi, for each span $S3$, for each available stringer STi, for each span $S2$, for each available joist SJi, for each span $S1$, and for each available sheathing.
8. At the end of the computation process, the minimum total cost, SHi, SJi, STi, SRi, $S1$, $S2$, and $S3$ are printed.

PROGRAM DESCRIPTION

The program OPTSLAB was developed for the design optimization of slab forms. OPTSLAB is a public-domain software that was developed for research purposes. It is a user-friendly system that allows the user to enter the required input data, perform the design optimization, and view the optimum design. Fig. 5 shows the main menu screen of OPTSLAB. The first option in the main menu screen allows the user to select the input data file. The second option allows the user to access the input data menu (Fig. 6). Several pop-up input screens, which are accessed through the input data menu, are used for inputting the general data as well as the data for the joists, stringers, and shores. Fig. 7 shows the general data's input screen. The screen is self-explanatory; the user does

TABLE 7. Optimum Design of Each Slab Form

Slab thickness (in.) (1)	Sheathing number (2)	Joist number (3)	Stringer number (4)	Shore number (5)	Joist spacing (in.) (6)	Stringer spacing (in.) (7)	Shore spacing (in.) (8)
6	1	3	2	1	20	64	48
7	1	2	1	1	16	64	39
8	1	3	1	1	16	64	39
9	1	3	2	1	20	48	48
10	1	2	1	1	12	64	32
11	1	2	1	1	11	64	32
12	1	3	1	1	16	48	39
13	1	3	1	1	12	64	28
14	1	3	1	1	11	64	24

TABLE 8. Traditional Design of Each Slab Form

Slab thickness (in.) (1)	Sheathing number (2)	Joist number (3)	Stringer number (4)	Shore number (5)	Joist spacing (in.) (6)	Stringer spacing (in.) (7)	Shore spacing (in.) (8)
6	1	3	2	1	20	64	48
7	1	2	1	1	24	48	48
8	1	2	2	1	20	48	48
9	1	3	2	1	20	48	48
10	2	2	2	1	24	32	64
11	1	2	2	1	20	39	48
12	1	2	2	1	20	39	48
13	1	3	1	1	16	48	32
14	2	2	2	1	20	32	48

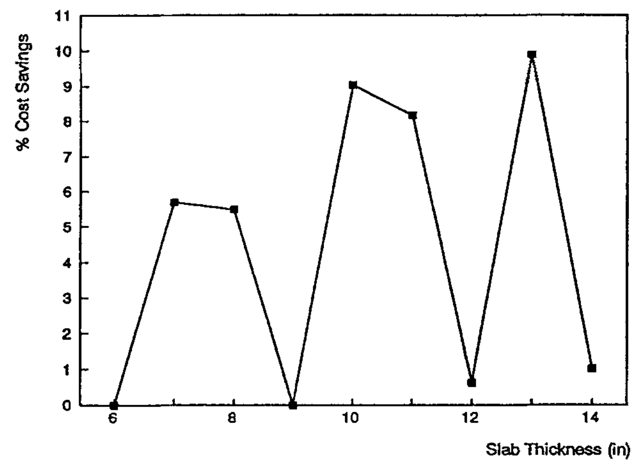

FIG. 13. Slab-Form-Design Cost Savings (All Combinations Are Considered)

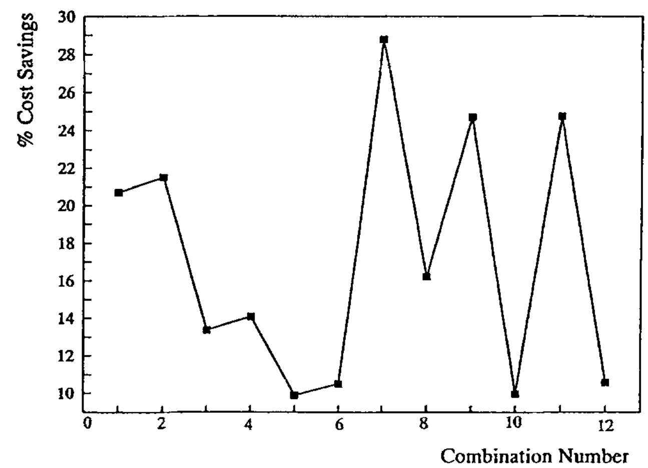

FIG. 14. Slab-Form-Design Cost Savings for each Combination

TABLE 9. Selected Slab-Form Combinations

Combination number (1)	Sheathing number (2)	Joist number (3)	Stringer number (4)	Wood shore number (5)
1	1	1	1	1
2	1	1	2	1
3	1	2	1	1
4	1	2	2	1
5	1	3	1	1
6	1	3	2	1
7	2	1	1	1
8	2	1	2	1
9	2	2	1	1
10	2	2	2	1
11	2	3	1	1
12	2	3	2	1

not have to refer to a user's manual to enter the required data. Fig. 8 shows the spreadsheetlike input screen for the sheathing data. Figs. 9–11 show the spreadsheetlike input screens for the joist, stringer, and shore data, respectively. The top input screen is for inputting the section properties, whereas the bottom one is for the mechanical properties. The home key is used to toggle between the two input screens. Besides the regular keyboard key functions (up, down, left, right, and return function keys), three additional key functions are also available: delete a line, duplicate a line, and insert a line. A database for section properties and a database for mechanical properties of standard lumber were created so that the user does not have to enter the section and mechanical properties of the joists, stringers, and shores. Using the standard dimension and lumber grade and species input by the user, the program searches the two databases for the section and mechanical properties of the specific joist, stringer, or shore and displays them.

The third option in the main menu screen allows the user to perform the slab design optimization. The fourth option allows the user to look at the output of the design optimization without leaving the system. This option is convenient for the user, since it allows him/her to check for possible errors in the input data without leaving the system.

OPTIMUM DESIGN METHOD COST SAVINGS

The traditional design method produces safe and reliable and occasionally optimum slab-form designs. However, the optimum design method guarantees a minimum slab-form cost, whereas the traditional design method does not. Thus, the optimum design method offers a potential cost savings over the traditional design method. The potential cost savings derive from the fact that the material and labor costs of the different slab-form components are not included in the design process of the traditional method. The total cost of the slab form depends on the material and labor costs of its components as well as their spacings. All of these variables are considered together in order to obtain the minimum slab-form cost. Using the maximum allowable spacings, which are based on strength and deflection limits, might not yield a minimum total cost. For example, one may assume that using the maximum allowable spacing between joists will yield the minimum slab-form total cost. However, this assumption may not always be true. Fig. 12 shows the variation of formwork total cost versus joist spacing for a specific concrete slab. The slab-form design gives a maximum allowable joist spacing of 0.5 m (20 in.). However, the joist spacing that yields the minimum slab-form cost is equal to 0.4 m (16 in.). Fig. 12 also shows that reducing the joist spacing by 0.1 m (4 in.) results in a substantial formwork cost savings. This is because reducing the joist spacing has decreased both the number of stringers (lower joist load) and wood shores (fewer stringers).

J. Constr. Eng. Manage., 1995, 121(2): 215-221

A study was conducted to confirm the cost-savings potential of the optimum design method over the traditional design method and to give an order of magnitude of these cost savings. The study was divided into four steps.

In the first step, two sheathings, three joists, two stringers, and one wood shore were selected. The input data of sheathings, joists, stringers, and wood shores is summarized, respectively, in Tables 1, 2, 3, and 4. The material and labor costs of the different sheathings, joists, stringers, and wood shores, which were taken from the Means Building Construction Cost Data (1992), are summarized in Table 5. The information about the deflection limits of the slab form components is summarized in Table 6. In the second step, a number of concrete slabs (different slab thickness) were selected. Slab thicknesses considered in this study are 0.15, 0.175, 0.2, 0.225, 0.25, 0.275, 0.3, 0.325, and 0.35 m (6, 7, 8, 9, 10, 11, 12, 13, and 14 in.). The horizontal dimensions of the slab are 18.3 m and 27.43 m (60 and 90 ft). The height of the slab forms was taken equal to 3.05 m (10 ft). The number of potential reuses was taken equal to 4. The unit weight of concrete was estimated at 23.55 kN/m^3 (150 pcf) and the live load at 2.4 kN/m^2 (50 psf).

In the third step, the forms for each concrete-slab thickness were designed using both the optimum and traditional design methods and their total costs were computed. Tables 7 and 8 summarize, for each concrete-slab thickness, the optimum and traditional slab-form designs, respectively. Fig. 13 summarizes the cost savings, as a percentage of the traditional design cost, for each concrete slab thickness. Cost saving percentages as high as 9.9% were achieved. Based on four potential reuses, the slab form cost saving for the 0.325-m (13-in.) thick concrete slab was equal to $2,940. The variations of slab-form cost savings versus slab thickness did not show a noticeable trend.

In the last step, another source of cost savings was investigated. The cost savings of the optimum design method may be higher when the traditional design of the slab form is performed using the design charts/tables instead of a computer program. When a design aid is used, a limited number of slab-form combinations may be considered; performing the design using all available combinations of slab-form components (12 combinations in the current study) would require substantial time and effort. Usually, a few combinations are selected with the intention that at least one of them will yield the minimum design cost. Because of the large number of variables influencing the variation of the total cost, it is seldom easy to choose firsthand the optimum combination of slab-form components. In the present study, an experiment was conducted to confirm these findings. The forms for the 0.225-m (9-in.) thick concrete slab are designed, using the traditional design method, for each of the 12 available combinations of sheathing, joist, stringer, and shore (Table 9). Fig. 14 summarizes the cost-savings percentages of the optimum design method corresponding to each combination of slab-form components. The minimum cost-savings percentage is equal to 9.9% and corresponds to the combination 1-3-1-1. This combination was already identified when the computerized traditional method was used (Table 8). The maximum cost-savings percentage, which is equal to 29%, corresponds to the combination 2-1-1-1. Based on four potential reuses, the corresponding formwork cost savings is equal to $10,800. One can conclude that the cost savings of the optimum design method may be higher when a limited number of combinations of slab-form components are considered in the traditional design method.

CONCLUSION

A computerized method for the optimum design of concrete-slab forms was developed and its performance compared to that of the traditional design method. From the numerical experiments performed, it can be concluded that substantial cost savings in slab-form material can be achieved by using the optimum design method, which considers in its design process (1) the cost of each slab-form component (sheathing, joist, stringer, and wood shore); and (2) all available combinations of slab-form components. Given the current high cost of formwork material, a potential cost savings as small as a few percent justifies the use of the proposed method in the design of slab forms.

APPENDIX. REFERENCES

Building construction cost data. (1992). R.S. Means Co., Inc., Construction Consultants and Publishers, Kingston, Ma.

"Guide to Formwork for Concrete," (1988). *347R-88*, American Concrete Institute (ACI), Detroit, Mich.

Hurd, M. K. (1987). "Formwork for concrete." *SP-4*, 4th Ed., American Concrete Institute (ACI), Detroit, Mich.

Sommers, P. H. (1984). "Charts aid in design of horizontal formwork." Aberdeen's *Concrete Constr.* 29(4), 648–651.

Spiegel, L., and Limbrunner, G. F. (1991). *Applied statics and strength of materials.* Merill/MacMillan, Columbus, Ohio.

J. Constr. Eng. Manage., 1995, 121(2): 215-221