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OPTIMUM DESIGN OF CONCRETE SLAB FORMS

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ABSTRACT

This paper presents a design optimization method for concrete slab forms. This procedure was formulated to provide a safe slab form design with minimum cost. The proposed method considers in its design process the cost of each slab form component (sheathing, joist, stringer, and steel shore) as well as all available combinations of slab form components. A case study is presented to show the capabilities of the proposed method and also to illustrate its potential cost savings over the slab form design practice in the State of Qatar. The study showed that the proposed design method has a substantial cost saving over the design practice currently used in the State of Qatar.

INTRODUCTION

Concrete slab forms are temporary engineered structures that are designed to support all of the slab applied loads without collapse or excessive deflection. These applied loads include the weight of the fresh concrete, construction materials, equipments, and workers. Since slab forms are structures, they should be carefully and economically designed to support the imposed loads. Safety is a major concern in formwork because a large percentage of the accidents that occur during construction of concrete structures is due to formwork failures. Many of these failures were caused by improper slab form design and too early form stripping.

Economy is also a major concern since formwork costs are significant. Figure 1 shows the overall relative costs for concrete slabs in the State of Qatar [Personal Communication 1996]. As shown in the figure, formwork total cost (material and labor costs) represent about 30% of the total concrete slab cost. Thus, a reduction in formwork material and labor costs will definitely improve the economy of concrete structures.

This paper presents a design optimization procedure for concrete slab forms made of wood. This procedure was formulated to provide a safe slab form design with the minimum total cost. A case study is presented to show the capabilities of the proposed method and also to illustrate the potential cost savings of the proposed design over the current slab form design practice in the State of Qatar.

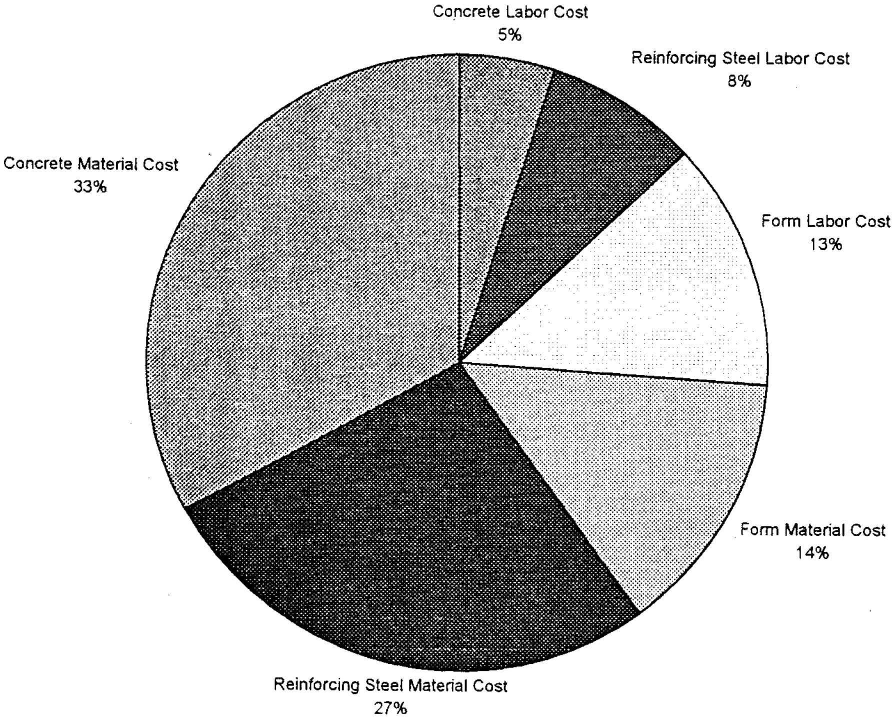

Fig. 1. Typical cost breakdown for concrete slabs

SLAB FORM LOADS

The slab form loads that must be considered by the designer are classified as live and dead loads. Live load is the weight of workmen and equipment such as pipelines and buggies, and other temporary loads that are supported by the form during concrete placing and finishing. Dead load consists of the weight of the form itself plus the weight of the freshly placed concrete. ACI 347R-88 (1988) recommends that slab forms are designed for a minimum live load of 2.4 kN/m^2 and 3.6 kN/m^2 when motorized carts are used.

PROPOSED METHOD

A typical wood slab form, Figure 2, is composed of sheathings, joists spaced by a distance S1, stringers spaced by a distance S2, and finally shores spaced by a distance S3. Marine plywood panels are commonly used as sheathing. The plywood panels have thickness of 12 and 18 millimeters, a length of 2.40 meters, and a width of 1.20 meters. The size of joists and stringers, which is commonly used in the State of Qatar, is 10x10 centimeters. The standard length of joists and stringers is 4 meters.

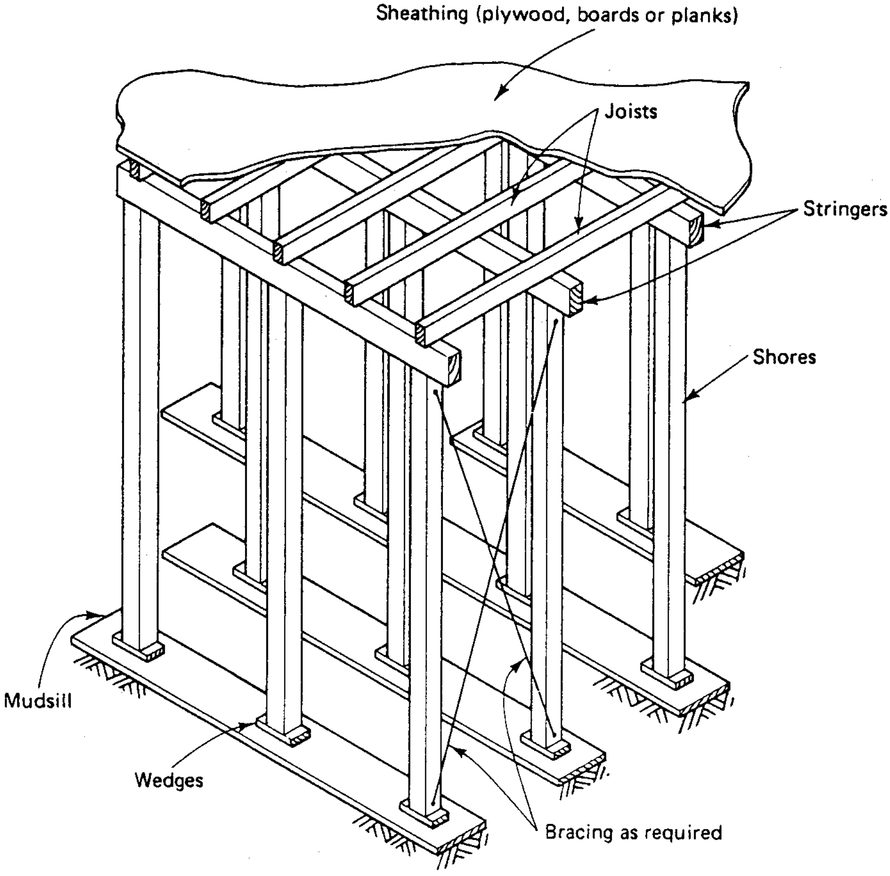

Fig. 2. Typical structural system for concrete slab forms

The form builder has considerable freedom in selecting the size and spacing of joists, stringers, and steel shores [Hurd 1987, McCormac 1993, Peurifoy 1975, Smith and Andes 1993, Sommers 1984, Spiegel and Limbrunner 1993, Wadell and Dobrowoski

1993]. However, in order to obtain a slab form design with a minimum total cost, the proposed design method considers the material costs of the slab form components material costs (sheathings, joists, stringers, and steel shores) as well as the labor cost of the slab form as variables in the design process.

It is assumed that the number of different sheathing types is NSH, the number of different joist types is NJT, the number of different stringer types is NST, and the number of different steel shore types is NSR. The objective of the design optimization procedure is to select the sheathing type SHi (SHi = 1,....,NSH), the joist type JSi (JSi =1,...,NJT), the spacing S1, the stringer type STi (STi=1,..,NST), the spacing S2, and the steel shore type SRi (SRi=1,..,M4), the spacing S3 that will minimize the following cost function:

$$\text{Cost} = CM(SH_i) + CM(JS_i) + CM(ST_i) + CM(SR_i) + CLabor \qquad [1]$$

where $CM(SH_i)$ is the material cost of all the sheathings of type SH_i ; $CM(JS_i)$ is the material cost of all the joists of type Js_i ; $CM(ST_i)$ is the material cost of all the stringers of type St_i ; and $CM(SR_i)$ is the material cost of all the steel shores of type SR_i. CLabor represents the labor cost for fabricating, erecting, and stripping the slab form.

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

$$CM(SH_i) = NSH_i * UCSH_i \qquad [2]$$

where NSH_i is the number of the sheathings of type SH_i while $UCSH_i$ is the unit cost.

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

$$CM(JS_i) = NJS_i * UCJS_i \qquad [3]$$

where NJS_i is the number of the joists of type JS_i while $UCJS_i$ is the unit cost.

The material cost $CM(ST_i)$ of all the stringers of type ST_i and CM(SRi) of all the shores of type SR_i are computed in the same way as $CM(JS_i)$ was previously computed.

The labor cost Clabor for fabricating, erecting, and stripping the slab form is computed using the following equation:

$$CLabor = Area * Thick * ULCost \qquad [4]$$

where Area is the total slab area, Thick is the slab thickness, and ULCost is the labor cost per cubic meter of concrete. In the State of Qatar, carpenters are usually paid per cubic meter of concrete slab to be formed.

In the minimization of the cost function (Eq. 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 applied loads and must have sufficient stiffness to limit the deflection below the allowable one.

SLAB FORM DESIGN PRACTICE IN QATAR

In the State of Qatar, the slab forms are not designed. The following slab form layout is commonly used:

1. Marine plywood sheathings having a thickness of 12 or 18 mm.
2. 10x10 centimeter joists spaced at a distance of 35 centimeters.
3. 10x10 centimeter stringers spaced at a distance of 65 centimeters.

PROGRAM DESCRIPTION

The user-friendly program, OPTSLAB, has been developed for the design optimization of slab forms. OPTSLAB allows the user to enter the required input data, perform the design optimization, and view the optimum design without leaving the program environment. Several pop-up input screens are used for inputting the required data. Figures 3 and 4 show two sample menus of the program OPTSLAB.

The computational algorithm of the program OPTSLAB, which is shown in Figure 5, can be summarized as follows:

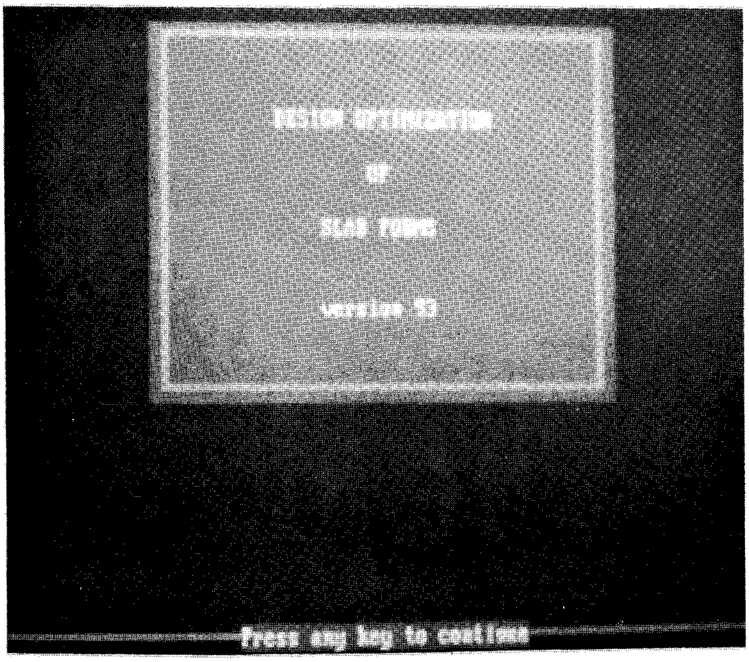

Fig. 3. OPTSLAB menu screen

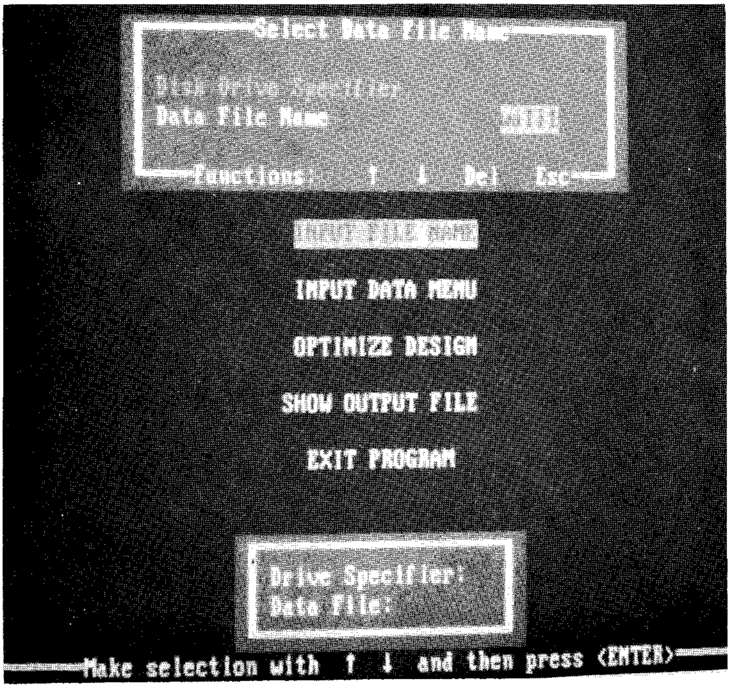

Fig. 4. Main menu screen

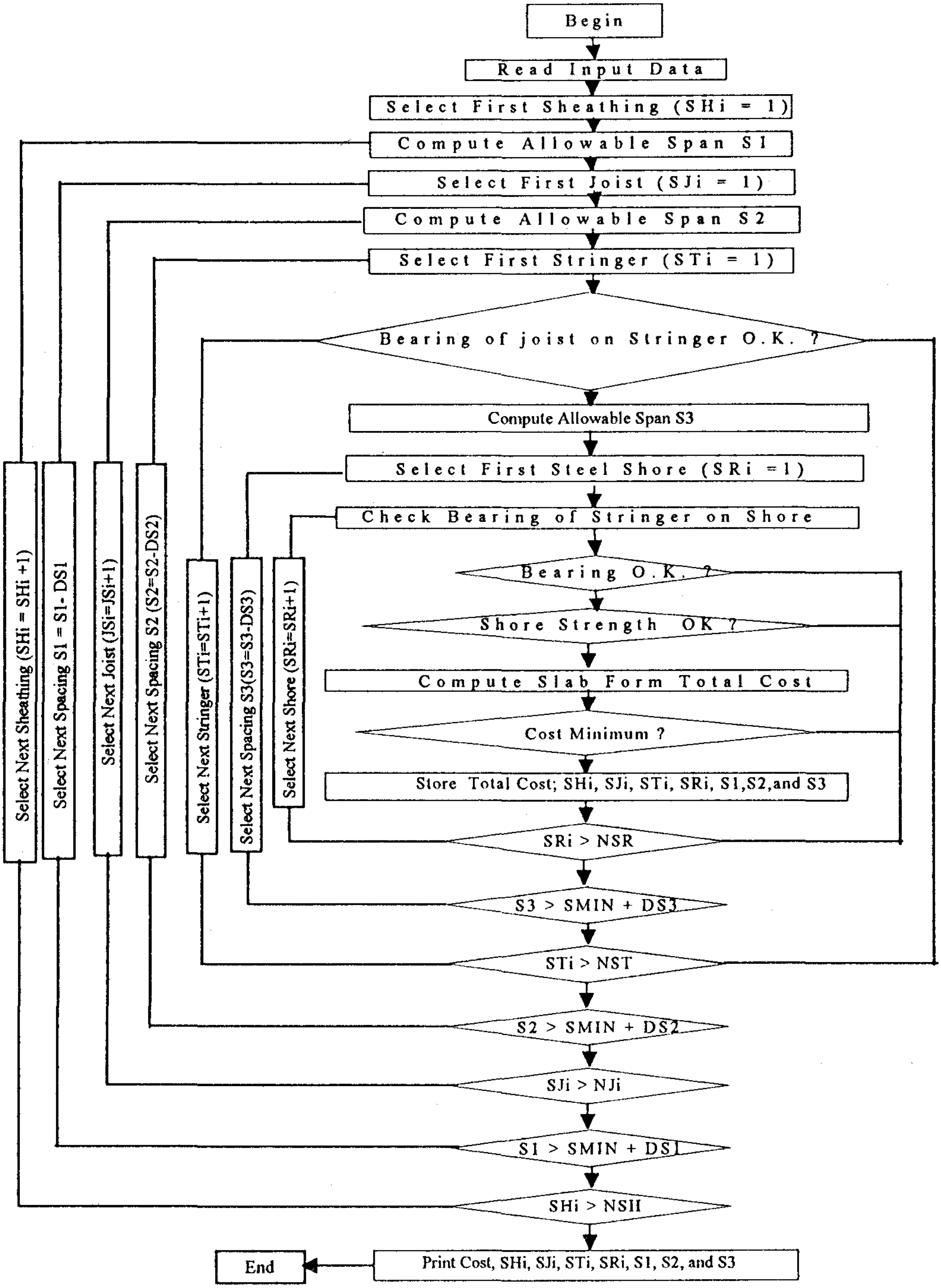

Fig. 5. Proposed design method algorithm

Step 1.

The program starts by reading the following input data:

1. The number of different type of sheathings, joists, stringers, and steel shores available.
2. The concrete slab thickness, the concrete unit weight, and the slab live load.
3. The number of slab bays as well as the length, the width, and the height of each bay.
4. The two deflection parameters which 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., 1/320). The second parameter is independent of the span length and represents the maximum allowable deflection (e.g., 0.6 cm).
5. The number of reuses as well as the percent waste in each reuse for the sheathings, joists, stringers, and steel shores.
6. The material unit costs of the different type of sheathings, joists, stringers, and steel shores.
7. The section and design properties of the sheathings, joists, stringers, and steel shores.

Step 2.

The first sheathing type ($SH_i = 1$) 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 is rounded down to whole centimeter and selected as to provide support at edges of all the sheathings.

Step 3.

The first joist type ($SJ_i = 1$) is selected and its maximum allowable span is determined. The allowable span S2 is then selected based on practical considerations. The span S2 is rounded down to whole centimeters and selected as to provide support at edges of all the joists.

Step 4.

The first stringer type ($ST_i = 1$) 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 is rounded down to whole centimeters and selected as to provide support at edges of all the stringers.

Step 5.

The first steel shore type ($SRi = 1$) is selected. The bearing at the point where each stringer rests on the steel shore is first checked. Then, the capacity of the steel shore is checked.

Step 6.

If all of the constraints are satisfied, the total cost of the slab form is computed by adding the material costs of the form components to the labor costs. If the total cost is less than previously computed costs, the computed cost as well as the combination SH_i, SJ_i, ST_i, and SR_i with their respective spacings S1, S2, and S3 are stored in the computer's memory.

Step 7.

Steps 2 through 6 are repeated for each available steel shore type SR_i, for each shore spacing S3, for each available stringer type ST_i, for each stringer spacing S2, for each available joist type SJ_i, for each joist spacing S1, and for each available sheathing type SHi.

Step 8.

At the end of the computation process, the minimum total cost, SH_i, SJ_i, ST_i, SR_i, S1, S2, and S3 are obtained.

COST SAVINGS

The proposed design method gives a minimum slab form cost and offers a potential cost saving. A study was conducted to confirm the cost savings potential of the optimum design method over the current slab form design practice in the State of Qatar and to give an order of magnitude of these cost savings.

The type of sheathing, joist, stringer, and steel shore most commonly used in the State of Qatar was selected for the study. The sheathing input data is summarized in Table 1 while the joist and stringer input data is summarized in Table 2. The steel shore input data is summarized in Table 3. The unit material costs of the sheathing, joist, stringer, and steel shore as well as the unit labor costs are summarized in Table 4. The number of potential reuses of the slab form components as well as the waste percentage in each reuse are summarized in Table 5. The deflection limit criteria of the slab form components is summarized in Table 6. The unit weight of concrete was estimated at 2400 kg/m^3 and the live load at 2.4 N/m^2. The slab form height is equal to 4 meters. Two concrete slab thickness and ten concrete slab areas were considered in the study.

Table 1. Sheathing Input Data

Thickness (mm)	Dimension (m)	Moment of Inertia (mm^4/m)	Section Modulus (mm^3/m)	Shear Constant (mm^3/m)	Elastic Modulus (GPa)	Bending Stress (MPa)	Shear Stress (MPa)
12	1.2x2.4	11.1x10^4	14.7x10^3	3.3x10^3	9.86	9.17	0.5

Table 2. Joist and Stringer Input Data

Width (cm)	Depth (cm)	Moment of Inertia (cm^4)	Section Modulus (cm^3)	Elastic Modulus (GPa)	Bending Stress (MPa)	Shear Stress (MPa)	Compression ⊥ to Grain (MPa)
10	10	520.5	117.1	11.72	10.0	0.66	4.31

Table 3. Steel Shore Input Data

Height (m)	End Plate Dimension (cm)	Shore Capacity (kN)
4	16x16	22.2

Table 4. Slab Form Material and Labor Cost Data

Material Costs				Labor Costs (QR/m^3 of Concrete)
Sheathing QR/Piece	Joist (QR/Piece)	Stringer (QR/Piece)	Shore (QR/Piece)	
80.00	38.00	38.00	33.00	90.00

Table 5. Slab Form Component Potential Reuses

Slab Form Component	Reuse Number	Percent Waste in Each Use
Sheathing	3	10
Joist	3	10
Stringer	3	10
Shore	25	0

Table 6. Slab Form Component Deflection Criteria

Slab Form Component	Deflection Limit
Sheathing	L/240
Joist	L/360
Stringers	L/360

Twenty slab form designs, i.e. 2 slab thickness x 10 slab areas, were performed using the proposed design method. Table 7 summarizes the optimum slab form designs with their corresponding slab form total cost. Table 8 summarizes the slab form design currently used in the State of Qatar as well as their corresponding slab form total cost.

Figure 6 summarizes the percent cost savings for each slab form design. Cost savings as high as 21% were achieved. The largest slab form cost saving for the 10 centimeter-thick concrete slab was equal to QR 7058 (1 US$ = 3.65 QR). On the other hand, the largest slab form cost saving for the 15 centimeter-thick concrete slab was equal to QR 6560.

Table 7. Optimum Slab Form Design

Slab Length (m)	Slab Width (m)	Slab Thickness (cm)	Joist Spacing (cm)	Stringer Spacing (cm)	Shore Spacing (cm)	Total Form Cost (QR)
10	5	10	41	201	69	1413
		15	41	201	58	1421
15	10	10	41	69	69	3153
		15	41	201	58	3855
20	15	10	41	201	69	5467
		15	41	201	58	5525
25	20	10	41	201	69	8442
		15	41	201	58	8535
30	25	10	41	201	69	11958
		15	41	201	58	12085
35	30	10	41	201	69	16128
		15	41	201	58	19226
40	35	10	41	201	69	20866
		15	41	201	58	21088
45	40	10	41	201	69	26251
		15	41	201	58	26568
50	45	10	41	201	69	32829
		15	41	201	58	33206
55	50	10	41	201	69	39498
		15	41	201	58	39996

Table 8. Slab Form Design Currently Used in Qatar

Slab Length (m)	Slab Width (m)	Slab Thickness (cm)	Joist Spacing (cm)	Stringer Spacing (cm)	Shore Spacing (cm)	Total Form Cost (QR)
10	5	10	36	69	69	1775
		15	36	69	69	1775
15	10	10	36	69	69	3855
		15	36	69	69	3855
20	15	10	36	69	69	6627
		15	36	69	69	6627
25	20	10	36	69	69	10134
		15	36	69	69	10134
30	25	10	36	69	69	14313
		15	36	69	69	14313
35	30	10	36	69	69	19226
		15	36	69	69	19226
40	35	10	36	69	69	24812
		15	36	69	69	24812
45	40	10	36	69	69	31111
		15	36	69	69	31111
50	45	10	36	69	69	38781
		15	36	69	69	38781
55	50	10	36	69	69	46556
		15	36	69	69	46556

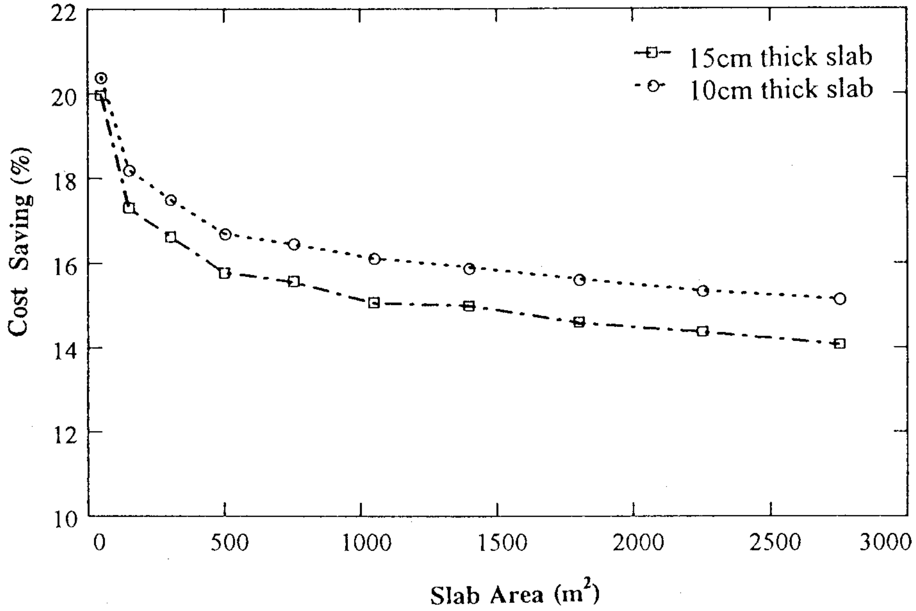

Fig. 6. Slab form design cost savings

CONCLUSION

A computer program for the optimum design of concrete slab forms was developed and its performance compared to that of the slab form design commonly used in the State of Qatar. From the numerical experiments performed, it can be concluded that substantial slab form cost savings can be achieved by using the optimum design method, which considers in its design process the cost of each slab form component (sheathing, joist, stringer, and steel shore) and all available combinations of slab form components.

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