GENETIC ALGORITHM OPTIMAL MODEL FOR SLAB FORMWORK COST AND DESIGN

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ABSTRACT

This paper introduces Genetic Algorithms technique to find an optimum formwork design, using optimum section of joists, stringers and shores along with their spacing, and satisfying minimum cost. Genetic Algorithms technique is based on the principles of natural selection and evolution, and it is used to solve optimization problems. This technique searches from a population of possible solutions that is limited by a set of constraints. The bending moment, shear, maximum deflection, and other imposed ACI code provisions, were used as constraints for the optimization problem. The Genetic Algorithms solution to the formwork design problem provides optimum design parameters such as the optimum cross section for form members, optimum spacing of form members, etc. The cost of material and labor involved in formwork erection are considered in the formulation of the objective function of the optimization problem. The method developed can be applied to the design of formwork for elevated slabs and high rise concrete elements.

KEY WORDS: Optimization, Formwork Design, Genetic Algorithms, Construction Cost.

INTRODUCTION

Slab formwork holds and provides support for freshly placed concrete through a framework of sheathing, joists, stringers and shores (Fig. 1). Sheathing retains both the concrete and applied loads and is placed horizontally on joists, while joists are supported on stringers. Stringers are supported on shores that act vertically. Quality, safety and economy are essential requirements for a reliable formwork (Speigel & Limbrummer 1992). Formwork should be designed accurately, erected,
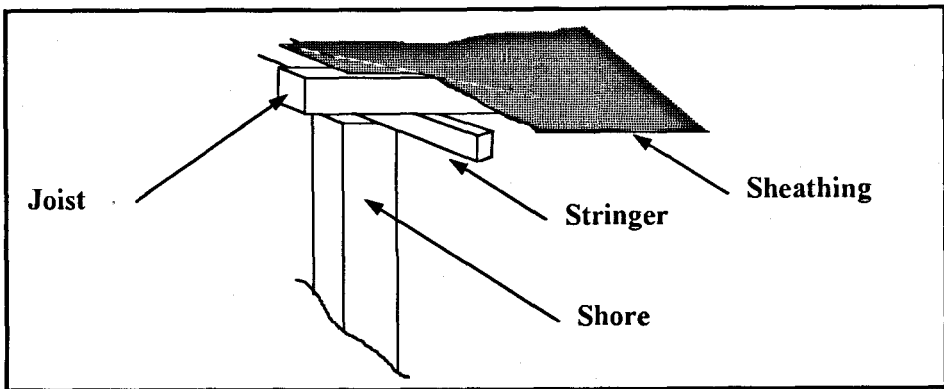
Fig. 1. Typical slab formwork components.

and kept rigid and tightly jointed with proper finish. Economy requires the form to be simple, easy to handle, standardized and reusable. Safety requires the formwork to be strong and sound, as formwork failure is a major cause for accidents during construction.

Traditionally, slab formwork is designed based on developed design tables, taking into consideration the strength and stiffness of the forms to resist failure and to avoid deflection. Christian (1987) proposed an integrated microcomputer package for formwork design based on published data obtained from empirical guidelines and recommendations given in Hover (1981) and Peurifoy (1976). Ringwald (1985) proposed a set of design curves for a specific wood type, for which safe formwork design values namely size and spacing of members can be inferred while Senousi and Al-Ansari (1996) proposed a computer program for the design of slab forms.

These studies undertaken by researchers on the subject of optimum design of slab formwork spacing and cost had shortcomings. In these works, the design process does not evaluate all possible solutions to find an optimum formwork design. Selecting the sizes and spacing of form members empirically can be very unsatisfactory, uneconomic, and even dangerous. Any under-designing can result in ultimate failure of the forms while over-designing can result in excessive cost. Moreover, these published studies applied decision-making models based on quantitative methods using mathematical techniques. In these methods, the relationships between slab formwork design and costs are generally assumed as linear or non-linear. Mathematical design and cost modelling require great deal of computational effort; therefore, they are only suited for small-size design projects. In other words these methods provide good solutions, but do not guarantee

optimality. Selecting one of the near optimum solutions might not give the complete cost advantage required, as there can be a precise optimum design combination (size and spacing) available somewhere in the solution space.

To deal with multiple objectives, this paper introduces Genetic Algorithms technique, an optimization search technique, to find an optimum formwork design, using optimum sections of joists, stringers and shores along with their spacing, and satisfying minimum cost. The cost for each of the formwork component is minimized while maintaining its safety. The cost was considered in the optimization process because material and labor cost is estimated to be approximately 30% of the cost of concrete slab (Senousi & Ansari, 1996), as formwork material cost accounts for about 12% of the total formwork cost (Hanna & Senousi, 1997).

Research in the subject of Genetic Algorithms had potential applications in the selection of optimal solutions. By harnessing the mechanism of evolution, it was established that Genetic Algorithms could solve problems even when they were not appreciated or understood fully. Their was evidence that they had been used successfully to solve complex problems in engineering and their nature in being non-linear, stochastic, and highly dimensional facilitated their application in problems of infinite variety (Holland 1992). The choice of Genetic Algorithms was also complemented by the successful adoption of Genetic Algorithms to solve many science and engineering problems in resource planning, structural design, resource allocation, equipment selection and transportation (Feng et al 1997; Haider et al 1999, and Al-Tabtabai and Alex 1998a and 1998b). Thus, the aim of the research was directed to design a Genetic Algorithms model expressly for the Optimization of slabform formwork and minimization of the cost involved in the erection of the formwork. Minimizing the formwork cost helps in reducing the overall construction cost.

SLAB FORMWORK DESIGN AND COST CONSIDERATIONS

Construction formwork is a temporary support constructed to contain fresh concrete until it holds its own shape and reaches design strengths. The designer has the dilemma of designing the forms and the consideration of minimizing the cost. The cost of forms for slab is considerably greater than for columns and simple shapes because of the extra material and labor costs required building them. Since the major cost of concrete structures frequently results from the cost of forms, the designer of a structure should consider the effect which design of forms and spacing will have on the cost.. The form builder has considerable freedom in selecting the

size of joists and stringers. Joist sizes commonly used are 2 by 2 in ,2 by 4 in, 2 by 6 in and 2 by 8 (1 in = 25.40 mm). Stringer sizes are 2 by 8 in, 2 by 10 in, 4 by 4 in, and 4 by 6 in. The 2-in thick stringers give good economy but the bearing stresses where they rest on the shores may be excessive and should be checked before the final design is selected. The exercise of care in designing forms will result in economical forms, considering the cost of material, and labor.

Loads and Stresses on for Members

Formwork design involves a step-by-step analysis of sheathing and framing members. The design should be such that the formwork should support all the loads applied on it without excessive deflection or collapse. Loads applied on slab formwork include dead load, live load, and wind load and equipment impact load. Dead load includes the weight of the concrete, the reinforcing steel, the forms themselves. Normally, the weight of ordinary concrete including the reinforcement is taken as 150 lb/ft^3 (23.562 kN/m^3). Weight of formwork usually comes to about 3-15 psf (0.143 – 0.718 kN/m^2), which is usually neglected. Live load comprises of the weight of workmen, construction equipment and storage materials comes to about 50 psf (2.394 kN/m^2).

Bending members like sheathing, joists and stringers, are considered as uniformly loaded and supported on three or more spans. They are analysed for bending moment, shear and deflection. Shoring is analysed for compressive loads and also for the bearing stresses developed at supports. These traditional stress equations as are used for the formulation of constraints needed for the genetic algorithms application to slab formwork design/cost optimization.

Design Methodology of Formwork

The design procedure adopted in this paper for slab formwork is based on the standard equations available for structural design contained in the ACI formwork standard, explained further by Hurd (1989). For a beam uniformly loaded and continuous over three or more spans, the following equations summarize the needed formulas when designing slab formwork. These equations (after conversion to SI units) are traditionally used in designing and limiting the spacing of form members and are subject to bending moment, shear, and deflection:

$$\text{Maximum spacing } (l) = 963.6 \sqrt{\frac{fS}{w}} \quad \text{(Subject to Bending Moment)} \quad (1)$$

Maximum spacing $(l) = \left(\dfrac{80 \times Hbh}{w} + h \right)$ (Subject to Shear) (2)

Maximum allowable span $(l) = 98.26 \sqrt[3]{\dfrac{EI}{w}}$ (Subject to Deflection) (3)

where,

l = Spacing of formwork or span (mm)
f = calculated unit stress in bending (MPa),
S = section modulus (mm^3),
w = uniform load (N/m),
H = calculated unit stress in shear (kPa),
b = width of form member (mm),
h = breadth of form member (mm),
E = modulus of elasticity (kPa),
I = moment of inertia (mm^4)

The following items summarizes the procedures and assumptions adopted in this application:

• Based on the computed joist spacing, the joist itself is analysed to determine its maximum allowable span. Joists are assumed to be continuous over three or more spans. Each joist must support the load from the sheathing halfway over to the adjacent joist on either side. Therefore the width of the load carried by the joist is equal to the spacing of the joists. The selected joist span becomes the spacing of the stringers. Based on the obtained stringer spacing, the process is repeated to determine the maximum stringer span which is the distance between the vertical supports (shores). Joist loads will be acting on the stringer as a series of concentrated loads but for the sake of simplicity the load is treated as a uniformly distributed load. Once the distance between the vertical supports (shores) is obtained, the load to be carried by each shore should be less than the safe working load available for the shores which can be calculated as the product of shore spacing, stringer spacing, and design load. A steel shore was assumed for this illustration.

• Based on Equations 1 to 3, the allowable joist spacing based on bending stress, shear, and deflection consideration can be computed. The lowest of the computed values will finally determine the maximum spacing of the joists. Once the spacing is computed, the required quantity of each form member can be obtained. It should be noted that for the joist design, the values of f, S, E, and I in these

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equations are the values that correspond to the sheathing material.

• Deflection is a governing factor where the depth of the member is relatively small compared to its span. Hence for sheathing, deflection will be the governing factor while for joists and stingers the bending and shear are often the governing factors.

• In a beam subjected to a uniformly distributed load, expressions can be derived for the maximum allowable span length by equating the allowable unit stresses to the maximum unit stresses developed. The moment expressions are for maximum positive or negative moment. The limiting deflection is normally taken as $1/360^{th}$ of the Allowable Span (l).

• Extreme fibre bending values were scaled by a factor 0.86, to account for the moisture content and by 1.25 for load duration consideration for this illustration. Douglas Fir Leech Lumber is assumed to be used for the form members and the corresponding extreme fibre bending value was used for the design computation.

• Wood has the property of being able to support excessive loads for short periods of time. So normal allowable stresses can be increased by 25% as formwork is a temporary structure and the loads are of short duration. Partially seasoned wood is normally used for the sheathing and has moisture content of more than 19%. Hence, allowable stresses must be decreased by a factor of 0.86 for bending, 0.97 for horizontal shear and modulus of elasticity.

GENETIC ALGORITHM

Genetic algorithms are recently developed artificial intelligence search techniques inspired by the theory of evolution and biogenesis. They are aimed at imitating the abilities of living organisms of being consummate problem solvers through the apparently undirected mechanism of evolution and natural selection proposed by Holland (1992). Genetic algorithms use random techniques but exploit information from the past experience to evolve solutions to real world problems, once they are appropriately encoded. Genetic Algorithms have been demonstrated to be robust heuristic search techniques that are capable of rapid identification of optimal design options whilst avoiding convergence on local optima (Beasley *et al* 1993). Even though Genetic Algorithms technique does not guarantee to find the global optimum solution to a problem within finite time, they are generally proved valuable at finding near optimal solutions to problems that were previously considered too large or

complicated to solve within reasonable amount of time. This adaptive search technique, which has powerful non-linear processing capabilities, can be used for solving multi-dimensional optimization problems with discrete variables and discontinuous functions.

Genetic Algorithms work with a population of individuals each representing a possible solution to a given problem. Each candidate solution is represented as a string of bits (a set of binary/character strings) analogous to chromosomes and genes in evolution theory. Genetic Algorithms assign a fitness score to each individual based on the quality of the solution it represents and highly fit individuals are reproduced by breeding with other individuals. New populations are continuously evolved over generations. During the evolution process the quality of the population increases, hopefully leading to an optimal solution. Finally the population will converge to an optimal solution to the coded problem.

A fitness function is necessary for each problem to be solved by Genetic Algorithms. Fitness is determined by an objective function, which provides a measure of performance with respect to a particular set of parameters. Fitness function transforms that measure of performance into an allocation of reproductive opportunities. Fitness function is generally used to map individual bit strings into a positive number, which is called the individual's fitness. Probability that an individual in the current population is propagated to the future generation is proportional to its fitness. Survival-of-the fittest method adopted by Genetic Algorithms selects new strings from the old population randomly, but biased by their fitness.

FORMWORK OPTIMIZATION PROCEDURE USING GENETIC ALGORITHM

Optimization of formwork design has not been a simple task. Given the design procedure of slab formwork procedure presented in this paper, the objective can be restated, in heuristic sense as the search for a near optimum slab formwork design that minimizes the total cost of the formwork, while also minimizing the components of the slab formwork. The following major steps describe the formulation and solution procedures adopted for the design/cost of slab formwork optimization (trade-off) problem in this paper:

Step1. Setting the Gene Structure.

The first step in implementing the Genetic Algorithms technique for the problem at hand involved setting the gene structure. The gene structure was set as a string of elements, each corresponding to dimensional entity assigned to formwork components, as shown in Figure 2. As such, each gene represents one possible solution to the problem. To evaluate genes, an objective function can be constructed by eliciting the designer's input regarding dimensions of the formwork components that are represented as a gene structure. The inputs required from the designer namely:

- structural input (length of slab (m), thickness of slab (cm), breadth of slab (m)),

- sheathing input (sheathing thickness (mm), sheathing width (breadth) (m), sheathing length (m), bending stress (MPa), young's modulus (GPa), shear stress (MPa)),

- Joist & stringer inputs (bending stress (MPa), young's modulus (GPa), shear stress (MPa), compression perpendicular to the grain (MPa)), and

- Shore input (bending stress (MPa), young's modulus (GPa), shear stress (MPa), end plate dimensions (cm), and shore capacity (kN)).

Individual cells are designated for the entry of these input variables. Once the input variables are specified in the spreadsheet, a new set of cells are designated for the output variables, namely the breadth of joist, height of joist, breadth of stringer, and height of stringer measured in empirical units. During the Optimization process, Genetic Algorithms technique considers a set of joist and stringer sizes for each iteration. The evolved shore and stringer sizes are used to compute the allowable spacing using Equations (1), (2), and (3). The minimum of this value is then selected as the spacing for members.
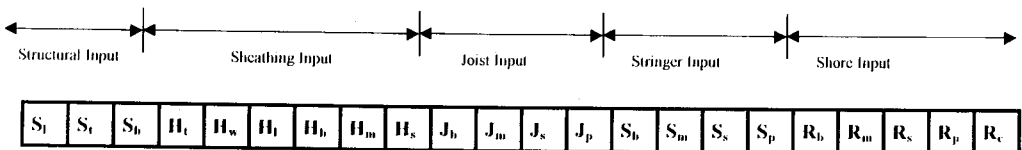

Fig. 2. Gene structure for slab formwork design/cost optimization

Step 2. Define the Objective Function to be Optimised.

The objective function for the optimization problem can be formulated as:

Minimize $\quad C = N_1 \times C_1 + N_2 \times C_2 + N_3 \times C_3 + N_4 \times C_4 + A \times t \times C_5$ $\quad$ (4)

Where; N_1 = No. of sheathing, $\quad C_1$ = Unit cost of sheathing, N_2 = No. of joist, C_2 = Unit cost of joist, N_3 = No. of stringers, C_3 = Unit cost of stringers, N_4 = No. of shores, C_4 = Unit cost of shores, A = Area of slab, $C5$ = Unit labor cost for unit volume of concrete and, t = thickness of slab.

The smaller this fitness value, the less the cost, and accordingly the more fit the gene is. It is noted that this equation considers the minimization of both formwork spacing design and cost of the formwork components.

Step 3. Define The Genetic Algorithms Operators and Stopping Criteria.

Once the gene structure and the fitness function are set, the genetic algorithms evolutionary optimization takes place on a population of parents' genes. The simplest way to generate that population is randomly. Population size (number of genes) is also an important factor affecting the solution and the processing time it consumes. Larger population size (on the order of hundreds) increases the likelihood of obtaining a global optimum; however, it substantially increases processing time.

The first phase in the optimization operation is the selection phase, in which individuals are selected from the population and recombined to generate new offspring. The objective of selection procedure is to give exponentially increasing trials to the fittest individuals; thereby, less fit individuals are eradicated and individuals of higher quality are selected and rewarded by letting them reproduce more often. Once the population is evaluated using the objective function, then its relative merit is calculated as the gene's fitness divided by the total fitness of all genes.

Reproduction operators of Genetic Algorithms provide a mean to weed out the bad and to generate new and better set of solutions during every iteration. Desirable characteristics of the parents are inherited by off-springs during the reproduction phase by combining the best characteristics of both parents. The reproduction process among population takes place by either crossover or mutation, resembling natural evolution. Crossover (marriage) is by far a more common

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process and can be conducted by selecting two parent genes, exchanging their information, and producing an offspring. Each of the two parent genes is randomly selected. Single point crossover is usually performed by swapping the fragments between two parents at a random point along the bit string. Crossover is generally applied to randomly paired strings with a moderate to high probability denoted P_C (usually the value of Pc falls between 0.6 and 1). Figure 3 shows the rearrangement of the genes of two chromosomes as a result of the crossover operation.

As opposed to crossover, mutation is a rare process that resembles the process of the sudden generation of an odd offspring that turns to be genius. This can be done by randomly selecting one gene from the population and then arbitrarily changing some of its information. Mutation is a critical operator that prevents the Genetic Algorithms from being stuck at good but non-optimal solutions. Mutation is done with a low probability denoted by P_m (usually applied with less than 1% probability).

(1) S e l e c t i o n: O r i g i n a l   p a r e n t   s t r i n g s

Parent 1

Parent 2
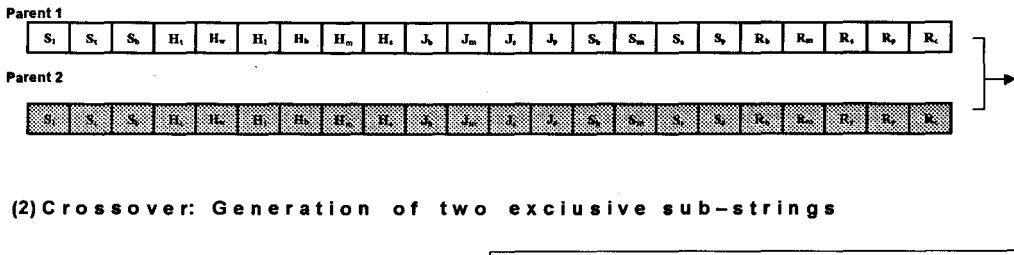
(2) C r o s s o v e r: G e n e r a t i o n   o f   t w o   e x c l u s i v e   s u b – s t r i n g s
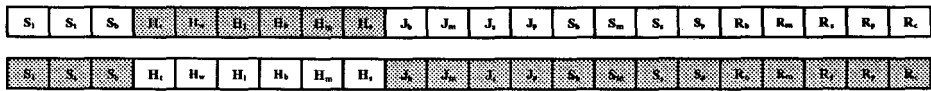
(3) E v a l u a t i o n: S p a c i n g   a n d   C o s t   C a l c u l a t i o n
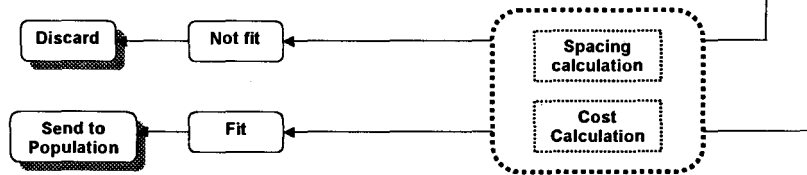
Fig. 3. Operation of slabform/cost optimization

Step 4. Evolve Solutions until the Stopping Criteria are Met.

The values for Genetic Algorithms control parameters, namely probability of crossover (P_c), probability of mutation (P_m) and number of generations (N_{gen}), were selected based on values reported by other researchers in various Optimization problems. The elitist strategy, which always allows the best string in each generation to survive in the next generation, is employed.

Once an offspring is generated by either method, it is evaluated in turn and can be retained only if its fitness is higher than others in the population are. Usually the process is continued for a larger number of offspring generations until an optimum gene is arrived at.

PROCEDURE AUTOMATION AND EXAMPLE APPLICATION

Implementing the proposed Genetic Algorithms procedure on commercial Genetic Algorithms was performed using GeneHunter™, commercially available genetic algorithms add-on software for the Microsoft Excel™ spreadsheet.

As in the case with optimization, the example assumed some constraints' values to work with the objective function. The spacing of shore, stringer, and joist are limited by considering the stringer bearing on shore, joist bearing on stringer, and load carrying capacity of each shore. The load carrying capacity of steel shore is assumed as 22.2KN. The expected reuse was taken as 3 for sheathing, joist and stringer and 25 for the steel shores as practised in the local industry. The number of reuses can be judged based on the care exerted by the form handlers during the dismantling, erecting and storage of formwork. The type of form components, unit material costs, unit labor costs, and the potential reuses of the slab formwork components were selected in this problem are listed in table 1.

During successive evolution, Genetic Algorithms attempts to evolve the optimum dimensions for these members that will eventually result in minimum total cost. For this example, a population of 100 individual solutions has been considered during each evolution. From the initial population the worst solutions, which do not produce minimum cost, were discarded while the best solutions were combined with each other by crossover, thus creating a new population. Table 2 summarizes the genetic algorithms parameters used in example. The probability of crossover used for the problem was 0.9 $(P_c = 0.9)$. A 1-point crossover was used for the current problem. Occasionally a gene will be altered to produce a mutation. The probability

Table 1 Specification and Characteristics of Form Components

Formwork Component	Dimension	Load Specifications	Deflection Limit	Cost (QR/piece)
Sheathing	Thickness=12 mm Size=1.2mx2.4 m	Moment of Inertia = 11.1 X10^4 mm^4/m Section Modulus = 14.7 X 103 mm^3/m Shear Constant = 3.3 X 103 mm^3/m Elastic Modulus = 9.86 GPa Bending Stress = 9.17 MPa Shear Stress = 0.5 MPa	L/240	80.00
Joist & Stringer		Elastic Modulus = 11.72 GPa Bending Stress = 10 MPa Shear Stress = 0.66 MPa Compression + grain = 4.31 MPa	L360	38.00 for both
Shore	End plate = 16 cm x 16 cm	Shore Capacity = 22.32 KN	L/360	33.00

Table 2 Genetic Algorithm Parameters used to Control the Optimization Process

PARAMETER	VALUE
Population	100 Nos, 16 binary encoding
Crossover type	Single Point Crossover
Probability of Crossover (P_c)	0.9
Probability of Mutation (P_m)	0.01
No. of Generation (N_{gen})	2,500
Stopping Criteria	Objective (cost) function unchanged for the last 1,000 generations.

of mutation adopted for the current problem was 0.01 ($P_m = 0.01$). The Genetic Algorithms determined fitness of the current population and the previously mentioned steps were repeated on the current population until the best solution is good enough to become the required solution decided based on the iteration time and the rate of change of objective function. It should be noted that adjusting the values of the parameters outlined in Table 2 could control the Genetic Algorithms implementation for different problems.

The total cost of the formwork was derived from the number and spacing of each individual formwork component used for the construction of the facility. Optimization process using Genetic Algorithms was carried out for various slab sizes. The material properties of each component, the unit cost of each component, deflection limits, and the slab dimensions were required to be input by the user. During the evolution process, the Genetic Algorithms evaluates different dimensions of each formwork component, which will satisfy the design constraints, till the combination that gives the minimum cost is reached. The program to find out the optimum dimensions resulting in overall minimum formwork cost has evaluated different sizes of joists and stringers. The computed formwork design parameters obtained by the proposed optimization method is summerized in Table 3.

For a standard slab carrying standard load with thickness ranging from 10 cm to 15 cm, based on the constrains set, Genetic Algorithms yields an optimum section of 5 cm by 5 cm joist and 5 cm by 20 cm stringer. For a slab thickness of 10 cm, 45 cm spacing is found to be adequate for the joist, while stringer and the shore need to be spaced at 58 cm and 220 cm respectively. With the increase in the thickness of slab to 15 cm, the dead load of slab increases and the spacing becomes 43 cm., 55 cm., and 210 cm, for the joist, stringer and shore respectively. When the slab size increases, the joist size remains the same but the stringer size varied to 5 cm by 20 cm. The spacing for the 10 cm thick slabs are 45 cm for joist, 60 cm for stringer, and 200 cm for shores. For the slab of thickness of 15 cm the joist and stringer spacing remains the same but the shore spacing decreases to 190 cm. The computed formwork design parameters were found to be safe and economical. The above problem was presented as an illustration about the use of Genetic Algorithms for formwork design. However, a comparison between the design options based on traditional methods and use of practical design constraints will provide more confidence in these results.

Table 3. Optimum design variables of Formwork using Genetic Algorithms

Slab Length (m)	Slab Width (m)	Slab Thickness (cm)	Joist Spacing (mm)	Stringer Spacing (mm)	Shore Spacing (mm)	Total Form Cost (Q. Riyal)	Joist Size (inches)	Stringer Size (inches)
10	5	10	474	609	2,235	1,378.84	2×2	2×9
		15	453	564	2,127	1,634.87	2×2	2×9
15	10	10	474	609	1,987	3,964.37	2×2	2×8
		15	453	564	1,890	4,724.78	2×2	2×8
20	15	10	474	609	1,987	7,879.95	2×2	2×8
		15	453	564	1,890	9,400.24	2×2	2×8
25	20	10	474	609	1,987	13,091.54	2×2	2×8
		15	453	564	1,890	15,624.91	2×2	2×8
30	25	10	474	609	1,987	19,599.15	2×2	2×8
		15	453	564	1,890	23,398.77	2×2	2×8
35	30	10	474	609	1,987	27,402.79	2×2	2×8
		15	453	564	1,890	32,721.85	2×2	2×8
40	35	10	474	609	1,987	36,502	2×2	2×8
		15	453	564	1,890	43,594	2×2	2×8
45	40	10	474	609	1,987	46,898	2×2	2×8
		15	453	564	1,890	56,015.6	2×2	2×8
50	45	10	474	609	1,987	58,589.8	2×2	2×8
		15	453	564	1,890	69,986.3	2×2	2×8
55	50	10	474	609	1,987	71,577.55	2×2	2×8
		15	453	564	1,890	85,506.19	2×2	2×8

CONCLUSION

The proposed Genetic Algorithms procedure is a heuristic search algorithm that attempts to optimize the design and minimize cost of the formwork components. This study has been demonstrated to have several interesting characteristics, including the following:

- It attempts to improve on existing slab formwork using the power features of commercial software.

- The Genetic Algorithms approach is an efficient search procedure that arrives at solutions by searching only a small fraction of the total search space.

- It combines both spacing optimization and cost minimization into objective function for the search.

The method can be further useful when incorporated into intelligent formwork design systems that will take into account the shape and load constraints exerted by specific structural design scenarios. Integrating a powerful material management database system can provide information about all locally available formwork components along with the unit rate of material cost, labor cost, dimensions of available formwork materials. Types of available materials, material properties such as Moment of Inertia, section modulus, shear constant, elastic modulus, bending stress and shear stress. Such a system is both feasible and practical for use by structural engineers responsible for design functions and field engineers performing site supervision.

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