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Optimization of Slab and Beam Formwork Using Genetic Algorithm

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Abstract: This paper introduces the use of Genetic Algorithm to identify the best formwork design for slab and beam utilising the best section of joists, stringers, and shores, as well as their spacing, while keeping costs to a minimum. Genetic Algorithms is an approach for solving optimization issues that is based on the ideas of natural selection and evolution. The optimization issue is constrained by the bending moment, shear, maximum deflection, and other required ACI code restrictions. The formwork design problem is solved using Genetic Algorithm, which offers optimum design parameters such as the ideal cross section for form members, optimum spacing of form members. In the design of the optimization problem's objective function, the cost of material and labour involved in formwork erection is taken into account. The established method can be used to design formwork for high-rise concrete structures.
Keywords: Optimization, Formwork Design, Genetic Algorithm, Construction Cost.

I. INTRODUCTION

Concrete formwork serve as a mold for all supporting structures, used for having desired size and configuration and support the concrete until it attains satisfactory strength to carry its own weight. It should be adequately strong to carry all imposed dead; live loads and impact load (if any) apart from its own weight. New materials such as plastics, fiberglass and steel are used in formwork. More attention is being given to the design, fabrication, erection and stripping of formwork. Formwork can be defined as follows: Temporary structure which is designed to hold fresh fluid concrete in place to give required shape and dimensions which helps concrete become self-supporting until it cures. Formwork system is a basic requirement for high-rise cast-in place reinforced concrete buildings. Formwork systems for buildings are divided into two types, i.e. vertical formwork and horizontal formwork. Vertical formwork systems are used to form vertical concrete work like columns, cores and walls, while horizontal formwork systems are those components used to form the horizontal concrete work like slabs or roofs. Sheathing, joists, stringers, and shore materials are the essential components of a horizontal formwork system. While sheathing acts as a mould to shape the concrete, the joists act as a secondary beam, transferring the load to the stringers, which acts as a primary beam, transferring the load to the shores, which then transfer it to the ground. Horizontal formwork can be divided into two categories, according to Hanna (1999) [3]; Hand-set systems and Crane-set systems. Traditional wood, metal, joist-slab, and dome formwork systems are examples of hand-set systems. Crane-set systems include flying formwork, column-mounted shoring, and tunnel forming. The formwork system optimized in this paper is the conventional wood formwork system.

For desired performance, formwork must be sufficiently strong and stiff to carry the loads produced by the concrete, the workers placing and finishing the concrete, and any equipment or materials supported by the forms. For many concrete structures, the largest component of the cost is the formwork. To control this cost, it is required to select and use well suited concrete formwork. Formwork must also be constructed with good quality to produce a finished concrete structure that meets job specification to be economical. The design, construction and use of formwork must be done so that all safety requirements are met.

While formwork expenses can occasionally reach 10%-20% of the entire cost of a concrete construction, the architect and engineer should be the first to save money on formwork. In addition to the typical design requirements, the sizes and shapes of the structure's elements are decided after considering the formwork requirements and formwork expenses. Some of the methods of reducing the formwork cost are keeping floor to floor height constant, using dimensions that match standard material sizes, and avoiding complex shapes for elements. This method allows the previously used formwork to be reused again thereby reducing the formwork cost. The majority of studies published in the field of structural optimization deal with the construction of structures with the minimum design weight and time. Only a few papers examine total cost optimization. Ahmed B. Senouci and Mohammed S. Al-Ansari (2009) [8] adopted genetic algorithms for cost optimization of composite beams. Based on the AISC's load and resistance factor design standards, this work propose genetic algorithm model for cost optimization of composite beams. Concrete, steel beam, and shear stud costs were all factored into the model. The primary aim of this paper was to create a robust optimization model that facilitates composite beam cost minimization. To that purpose, the current model was composed of two primary steps: (1) determining the major decision variables impacting composite beam design; and (2) formulating the objective of composite beam cost optimization in a robust optimization model. Genetic algorithms were search and optimization techniques that aid decision makers in identifying optimal or near-optimal solutions for issues with a vast search space.

V. Rajeshkumar, et.al (2020) [7] analyzed the factors influencing formwork material selection in construction buildings. The study used a structural questionnaire survey from the client, contractor, and consultant, as well as interviews with expert members, to report on the factors that influence the selection of different formwork materials in the construction of high-rise structures. From the literature review carried out by them total of 40 technical elements were discovered and 220 completed questionnaires were obtained from respondents in the state of Tamilnadu. The top ten factors identified as having a significant impact on formwork material selection was the accessibility to work, quality, surface finish, storage of formwork, capital cost, safety, layout of structures, lifespan, exposure to environment and labor cost. The questions were compiled using information from prior research articles as well as input from expert members via a pilot survey and interviews with construction professional. The specialists offered excellent suggestions for phrasing the questionnaire, which helped to refine the criteria in more understandable terms. This paper helped in deciding the factors affecting the formwork design.

Prachi Sohoni, et.al (2020) [9] adopted optimization of shoring and reshoring levels using genetic algorithm in reinforced cement concrete work in high-rise buildings. Time and cost are important issues in multistory structure development. In work carried by them, a genetic algorithm was utilized to discover a time-optimized strategy for quick construction of a multistory building. The distribution of construction loads between slabs, shore, and reshore was calculated using MATLAB software. The five procedures which were detailed are (1) slab casting, (2) removal of the lowest level of reshores, (3) removal of the lowest level of shores, (4) installation of the highest level of reshores, and (5) installation of the highest level of shores. At each stage of construction, this algorithm analyzed the load and strength of each slab of the multistory building. The process of using Genetic Algorithm using MATLAB was well understood using this paper.

Gulbin Ozcan-Deniz, et.al (2012) [6] adopted Genetic Algorithm to optimization of time, cost, and environmental impact analysis on construction operations. The concept of life cycle assessment was used to estimate environmental effect in terms of global warming potential. To find optimal construction processes, the non dominated sorting genetic algorithm II, or NSGA-II, was chosen for implementation in MATLAB. On the basis of various algorithms, such as heuristic methods, mathematical programming, and more recently evolutionary algorithms such as genetic algorithms and ant colony optimization algorithms, multiobjective optimization has been applied to time and cost trade-off analysis of construction projects. A case study was utilized to demonstrate how the framework can be used. The case study demonstrated that using the evolutionary algorithm to search issues, such as the case study, was promising in terms of efficiency discovering ideal solutions.

Changtaek Hyun, et.al (2018) [4] studied on automated optimization of formwork design through spatial analysis in building information modeling. The building of formwork for reinforced cast-in-place concrete work is expensive, time-consuming, and difficult to plan and design. Several parameters that go into formwork design include concrete pressure, bending, deflection, and horizontal shearing. Despite the fact that each of those parameters has equations and calculations in the design of concrete formwork, the procedure of doing the calculations for each concrete formwork application is still time-consuming. As a result, construction managers frequently depend on their prior work experiences and use comparable formwork designs in the majority of cases. In this study, a hospital in Seoul was designed using Revit 2016, a BIM modeling application, and the quantity and cost of formwork were calculated utilizing information from the model's wall objects by converting to an IFC file. The cost of formwork was computed for 96 different scenarios involving the formwork of a BIM model with eight different types of ply forms, eight different stud spacing’s, and twelve different wale spacing’s. The cost of formwork computed by an architectural engineer with five years of expertise in the field was compared to the output of the suggested formwork procedure.

II. ECONOMY OF FORMWORK

Formwork is the most expensive part of a concrete structure's structural frame. Formwork is more expensive than concrete or steel, and in some cases, formwork is more expensive than the concrete and steel combined. Prioritizing the formwork design for a project can save total frame costs by as much as 25% for some projects. This savings covers both direct and indirect savings. Concrete structure economy begins with designers that have a thorough understanding of formwork logic during the design development stage. Frequently, two or more structural solutions will equally well meet the design goal. Formwork economy begins with the structure's design and continues through the selection of form materials, erection, stripping, and formwork care between reuses. Each of the following approaches for decreasing the cost of formwork should be considered when a building is designed:

1. Concurrently prepare structural and architectural designs, which can give maximum possible economy in formwork.
2. Consider the materials and methods that will be necessary to construct, erect, and remove the forms while designing a structure. A computer-aided drafting and design operator may easily sketch sophisticated surfaces, structural connections, and other details; nevertheless, the cost of producing, erecting, and dismantling the formwork may be expensive.
3. Columns should be the same size from the foundation to the roof, or if that is not possible, the same size should be used at least for couple of stories. By following this procedure, beam and column forms can be reused without modification.
4. Specify beams of the same depth and spacing on each level by selecting a depth that allows standard sizes of lumber to be used for beam sides and bottoms, as well as other structural members, without stripping.

III. GENETIC ALGORITHM

The optimization methodology utilized is a genetic algorithm, which is one of the evolutionary algorithm methods. The main principle of the basic algorithm is the survival of the fittest, which is based on natural selection and genetics, to search across the decision space for optimal solutions. The genetic algorithm uses an initial population, which is made up of chromosomes, which are made up of genes, and these genes are the variables in the optimization problem. A fitness value is calculated using these variables, which is the desired outcome of the optimization. Crossover occurs when multiple genes are traded between two chromosomes through a certain cutting point, whereas mutation is merely exchanging values between two chromosomes. The weakest parent (low fitness value) is replaced with the strongest child in the Genetic algorithm, and the process is repeated until a near-optimal solution is found.

a. Population

The process of genetic algorithms begins with a population that is generated at random. Every person in a generation (population) represents one solution and is made up of one chromosome with a number of genes; these genes are the optimization process' variables. The fitness of each chromosome is next assessed (fitness simply implies that it provides a better solution to the goal function). The greater the fitness of the chromosomes, the more likely they are to survive to the following generation.

b. Crossover

The practice of transferring genes between two parents at specific cutting spots in order to produce two offspring is known as crossover. A random location(s) along the strings of two genes are chosen at random and sections to one side of that point are exchanged across the genes to produce a new gene.

c. Mutation

Mutation is a method of introducing new genes (variables) into the gene pool. To generate an offspring, the mutation occurs by exchanging gene values in the parent chromosome. Mutation by itself does not usually advance the search for a solution, but it does provide protection against the formation of a uniform population that is incapable of further evolution; in other words, it prevents the algorithm from being stuck in a local maximum or minimum value in the search space.

d. Elitism

Allowing the best organism(s) from the current generation to pass over to the next generation, unchanged, is a practical version of the basic process of generating a new population. This method is known as elitist selection, and it ensures that the Genetic Algorithm’s solution quality does not deteriorate from generation to generation.

IV. SLAB & BEAM FORMWORK DESIGN

There are six steps that must be followed in order to create a formwork design:

1. Calculate the total unit load on the floor decking, including any impact effects.
2. Decide on the type of floor decking and the thickness of the net decking.
3. Examining the sheathing, joists, and stringers for uniformly distributed load and consider it to be supported on three or more spans.
4. Calculating the slab and beam permissible span from equations 1 to 6 by calculating the lowest span based on the bending, shear, and deflection values.
5. Consider the load when choosing the kind, size, and capacity of joists and stringers, as well as the capacity of shore.
6. Design the sheathing, joists, and stringers to determine the joist, stringer, and shore spacing values.

a. Loads and Design Equations

All live and dead loads applied to and sustained by the formwork are referred to as design loads. The weight of the concrete and reinforcing steel, the weight of the forms, and any construction loads from personnel, equipment, or stored materials are all factors to consider. Usually, the weight of concrete including the reinforcement is taken as 145-150 lb/ft^3. ACI Committee 347 recommends the minimum live load to be used as 50 lb/ft^2 and the formwork load as 5 lb/ft^2.

To account for moisture content, extreme fiber bending results were scaled by a factor of 0.86, and load duration was scaled by a factor of 1.25.Wood has the ability to support heavy loads for brief periods of time. Considering the fact that the formwork is a temporary structure with short-term loads, standard permissible stresses can be increased by 25%. Sheathing is usually made of partially seasoned wood with a moisture content of more than 19 percent [2].As a result, allowable stresses for bending, horizontal shear, and modulus of elasticity must be reduced by a factor of 0.86, 0.97, and 0.9, respectively. For designing of uniformly loaded slab and beam which is supported on three or more span the following design equations are used. Considering the bending, shear and deflection as a parameters for the spacing for joist, stringer and shore for plywood are given by equation 1-3 and whereas for timber given by equation 4-6.

Spacing $(l) = 10.95(\frac{FbKS}{W})^{1/2}$ (Bending) (1)

Spacing $(l) = 20\left(\frac{\frac{Fslb}{Q}}{W}\right) + 2t$ (Shear) (2)

Spacing $(l) = 1.69(\frac{EI}{W})^{\frac{1}{3}}$ (Deflection) (3)

Spacing $(l) = 10.95(\frac{FbS}{W})^{\frac{1}{2}}$ (Bending) (4)

Spacing $(l) = 13.3\left(\frac{FvA}{W}\right) + 2d$ (Shear) (5)

Spacing $(l) = 1.69(\frac{EI}{W})^{\frac{1}{3}}$ (Deflection) (6)

Where,
l = spacing of joist, stringer and shore based on bending, shear and deflection (in),
Fb = allowable bending stress (psi),
Fv (or) Fs = allowable shear stress (psi),
KS (or) S = Section modulus (in^3),
lb/Q = Shear constant (in^2),
E = Modulus of elasticity (psi),
I = Moment of inertia (in^4),
A = Cross sectional area (in^2),
d = lumber depth (in)

V. FORMWORK OPTIMIZATION PROCEDURE

Given the slab formwork design approach provided in this study, the goal can be reformulated, in a heuristic sense, as the search for a near-optimal slab formwork design that reduces the total cost of the formwork while also reducing the cost of the slab formwork components. The steps used for design of slab and beam formwork optimization are as follows.

Step 1: Formation of Gene structure

The initial step in Genetic Algorithm is formation of gene structure where, each gene corresponds to dimensional entity of formwork component as shown in Figure 1 and 2. For forming gene structures following inputs are used.

Structural Input			Sheathing Input						Joist Input			Stringer Input			Shore
S_l	S_t	S_w	H_l	H_t	H_w	H_b	H_m	H_s	J_b	J_m	J_s	S_b	S_m	S_s	R_c

Figure 1: Gene structure for slab formwork design/cost optimization

Structural Input			Sheathing Input						Lumber Input		
Bl	Bw	Bd	Hl	Hw	Ht	Hb	Hm	Hs	Lb	Lm	Ls

Figure 2: Gene structure for beam formwork design/cost optimization

- Structural input

1. Length of slab = Sl (ft)
2. Thickness of slab = St (in)
3. Breadth of slab = Sw (ft)

- Sheathing input

1. Sheathing thickness = Ht (in)
2. Sheathing width (breadth) = Hw (ft)
3. Sheathing length = Hl (ft)
4. Bending stress = Hb (psi)
5. Young's modulus = Hm (psi)
6. Shear stress = Hs(psi)),

- Joist & stringer inputs

1. Bending stress = Jb, Sb and Lb (psi)
2. Young's modulus = Jm, Sm and Lb (psi)
3. Shear stress = Js, Ss and Ls (psi)), and

- Shore input

1. Shore capacity = Rc (lb).

After the formation of gene structure a new gene structure is formed using different input variables such as sheathing thickness, width, length, etc. For each iteration a set of sizes of joist and stringer is considered and are used in equation 1-6 to calculate the allowable spacing. The minimum of the values of bending, shear and deflection is chosen for spacing of joist, stringer and shore.

Step 2: Objective function

For optimization of formwork for slab considering different factors affecting cost of formwork the objective function for optimization is

$$Cs = N_1 * C_1 + N_2 * C_2 + N_3 * C_3 + N_4 * C_4 + A * t * C_5 \quad (7)$$

Where; Cs = Cost slab formwork, N_1= No. of sheathing, 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, C_5= Unit labor cost for unit volume of concrete and t =thickness of slab.

Similarly, the objective function for the beam for optimization will be

$$Cb = N_1 * C_1 + N_2 * C_2 + N_3 * C_3 + C_4 * A * t \quad (8)$$

Where; Cb = Cost of beam formwork, N_1 = No. of plywood, C_1 = Unit cost of sheathing, N_2 = No. of lumber, C_2= Unit cost of lumber, N_3 =No. of shore, C_3 =Unit cost of shore, C_4= Unit labor cost for unit volume of concrete, A = Area of beam and t =thickness of beam.

Step 3: Genetic Algorithm operators and stopping criteria

The genetic algorithm is activated once the gene structure and fitness function have been determined as shown in Figure 3. A population of parents' genes undergoes evolutionary optimization. Random generation is the simplest technique to create such population. The selection phase is the initial step in the optimization process, in which individuals are chosen from the population and recombined to produce new offspring. The goal of the selection technique is to provide the fittest people, thereby eliminating less fit individuals. Normalized fitness value is calculated by dividing the fitness value with sum of all the fitness value after the objective function has been applied. During each iteration, the reproduction operators give a means to screen out the undesirable and generate a new and better collection of solutions. Crossover, mutation and elitism are the evolutionary operators used in the population reproduction process, which is similar to natural evolution. Mostly one point and two point crossover is used which can be symbolized as Pc. Mutation is a method of introducing new genes (variables) into the gene pool. To generate an offspring, the mutation occurs by exchanging gene values in the parent chromosome. The probability of mutation is symbolized by Pm. However, elitism is method of allowing the best organism(s) from the current generation to pass over to the next generation, unchanged, is a practical version of the basic process of generating a new population. The elitism ratio is symbolized by Er.

Step 4: Evolve solutions until the stopping criteria are met

The choices for the control parameters of Genetic Algorithms, such as probability of crossover (Pc), probability of mutation (Pm), elitism ratio (Er) and number of generations (Ngen), were chosen based on values given by other researchers in various optimization problems.

a. Optimization Problem

For the optimization problem, sheathing (Class I ply form) of 1 in. thickness having the size of 8 ft x 4 ft is selected. The sheathing has the following the cross-sectional and material properties. The moment of inertia = 0.27 in^4, section modulus= 0.634 in^3, shear constant= 7.014 in^2, elastic modulus=1.5 x 10^6 psi, bending stress= 1545 psi, shear stress= 57 psi. A joist of 2 x 3 in, stringer of 4 x 4 in and lumber in beam of 2 x 12 in. is used of Douglas- fir larch type. The material properties for joist, stringer and lumber are elastic modulus = 1.6 x 10^6 psi,

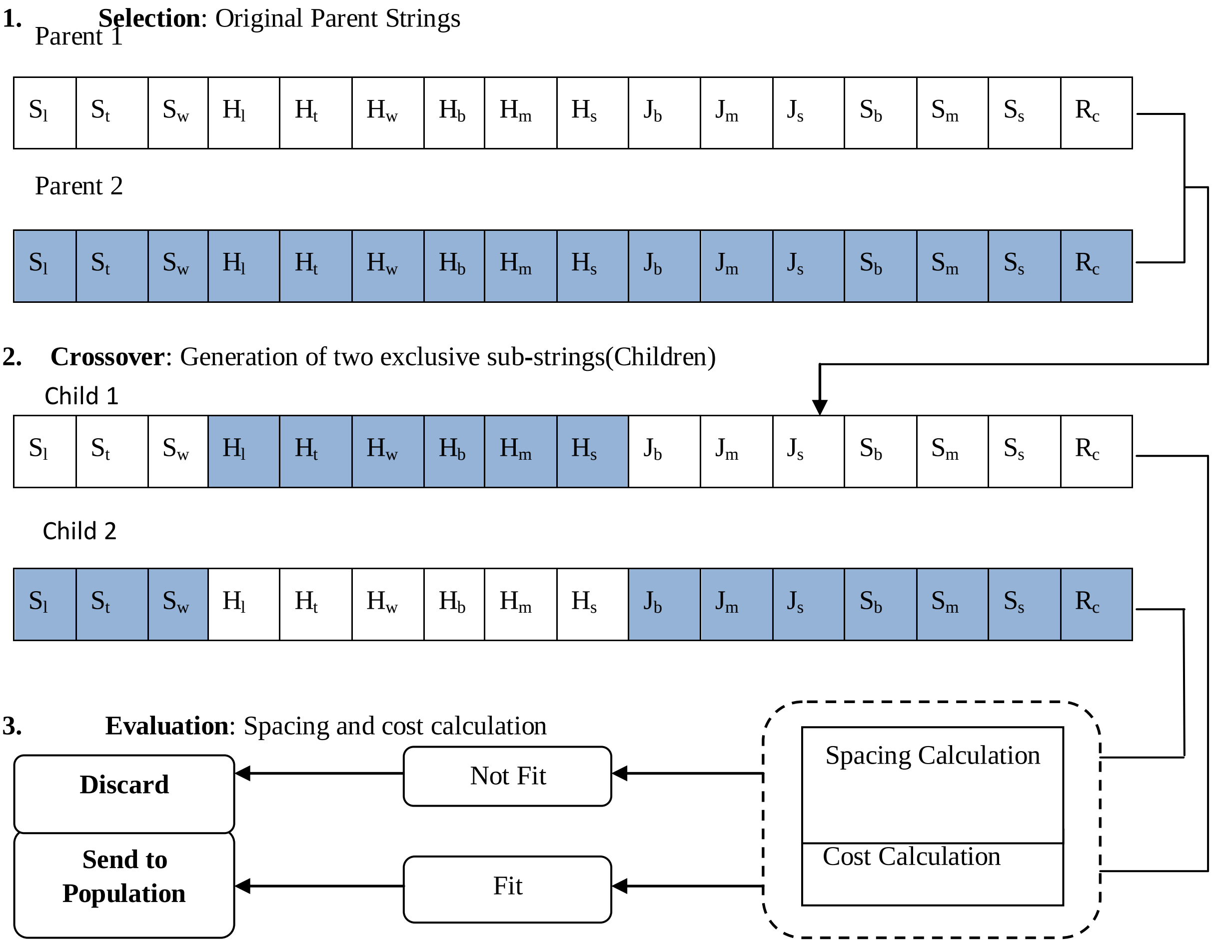

Figure 3: Operation of slab formwork cost optimization [1]

bending stress= 900 psi, shear stress= 180 psi. For both beam and slab the load carrying capacity of shore is assumed to be 4000 lb.

For this problem, a population of 100 individual is considered with single point crossover having probability of crossover (P_c) as 0.9. The probability of mutation (P_m) is taken as 0.01 with elitism ratio as (E_r) as 0.1. The number of generation (N_{gen}) considered is 100.

From this and using the number and spacing of formwork components, the total cost of slab and beam formwork is derived. For various slab and beam sizes, an optimization process utilising Genetic Algorithm is carried out. The user is asked to input the material attributes of each component, the unit cost of each component, deflection limits, and slab dimensions.

VI. RESULTS

In this results are taken for slab and beam formwork using Genetic Algorithm in MATLAB R2020b [5]. To obtain optimized cost as well as spacing for slab formwork as well as beam formwork MATLAB program was generated.

a. Results for slab formwork

Genetic Algorithm produces an optimum section of 2in by 3in joist and 4in by 4in stringer for a typical slab (floor area) carrying standard load with thickness ranging from 0.328 ft to 0.492 ft as shown in Table 1, based on the constraints set. The joist spacing for a slab thickness of 0.328 ft is found to be adequate at 20.60 in, whereas the stringer and the shore need to be spaced at 6.83 in and 25.36 in, respectively. The best formwork price was found to be Rs.99911. The dead load of the slab increases as the thickness of the slab is increased to 0.492 ft, and thereby the joist, stringer, and shore spacing becomes 17.96 in, 5.94 in and 22.09 in, respectively. The best formwork price was found to be Rs.127757. The same process is used for different slab dimensions and varied joist and stringer diameters.

b. Results for beam formwork

Genetic Algorithm produces an optimum section of 2 in. by 12 in. lumber for a standard beam bearing a standard weight with a depth ranging from 0.98 ft to 1.14 ft as shown in Table 2, based on the constraints set. For a 0.98 ft beam depth, 12.79 in. spacing is found to be sufficient for the lumber, whereas the shore requires 88.56 in. spacing. The best formwork price was found to be Rs.1339. The dead weight of the slab increases as the depth of the beam is increased to 1.14 ft, and thereby lumber and shore spacing becomes 12.14 in. and 81.64 in., respectively. The best formwork price was found to be Rs.1526. For varied dimensions of beams and different sizes of lumber, the same technique is followed.

VII. CONCLUSION

The proposed Genetic Algorithm technique is a heuristic search algorithm that aims to optimize the design of formwork components while lowering costs. Following are the conclusion drawn from results.

- For the slab of 32.8 ft x 16.4 ft having thickness 0.328 ft gives the spacing for joist, stringer and shore as 20.60 in, 6.83 in and 25.36 in respectively, with the optimum cost of Rs. 99911.
- For the beam of 4.92 ft x 0.98 ft having thickness 0.98 ft gives the spacing for lumber and shore as 48 in and 117.46 in respectively, with the optimum cost of Rs. 1194.
- As the dimension of structure increases, spacing decreases which leads to increase in the cost of the formwork.

This research has been shown to have a number of intriguing qualities, including the following:

- It attempts to improve on existing slab and beam formwork by utilizing commercial software's powerful features.
- The Genetic Algorithm technique is a fast search method that only searches a small portion of the overall search space to find solutions.

Table 1: Optimum design variables of Formwork

Sr. No.	Slab Length (ft)	Slab Width (ft)	Slab Thickness (ft)	Joist Spacing (in)	Stringer Spacing (in)	Shore Spacing (in)	Cost of Slab Formwork (Rupees)
1	32.8	16.4	0.328	20.60	6.83	25.36	99911
			0.492	17.96	5.94	22.09	127757
2	49.21	32.8	0.328	14.51	4.78	17.82	375092
			0.492	11.69	4.26	13.37	486364
3	65.61	49.21	0.328	8.99	4.25	10.26	965213
			0.492	5.84	4.23	6.62	1304442
4	82.02	65.61	0.328	5.57	4.23	6.32	1995763
			0.492	3.61	4.19	4.06	2783270

Table 2: Optimum design variables of Beam Formwork

Sr. No.	Beam Length (ft)	Beam Width (ft)	Beam Depth (ft)	Spacing of Lumber (in.)	Spacing of Shore (in.)	Cost of Beam Formwork (Rs.)
1	4.921	0.98	0.98	48.08	117.46	1194
			1.14	44.69	113.32	1378
2	4.921	1.14	0.98	44.72	113.28	1365
			1.14	41.57	109.23	1577
3	6.561	0.98	0.98	42.50	110.44	1562
			1.14	39.48	106.48	1775

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