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Design optimization of two-way post-tensioned concrete slab using simulated annealing algorithm

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ABSTRACT

This paper presents advances in design optimization of two-way post-tensioned (P/T) concrete slab using metaheuristic-based simulated annealing algorithm for solving nonlinear constrained optimization problem. Prototype slab is a 4-span P/T flat plate that takes into account the slab band as an alternative solution for design improvement. The objective is to obtain the slab that complies with ACI 318-14 requirements and other practical design recommendations while minimizing the amount of concrete, formwork, and P/T work. The shape design optimization scheme allows the program to decide whether to use the slab band for the exterior or long interior spans, if this can lead to better design results.

1. INTRODUCTION

In common P/T slab design practice, it is sometimes a judicious decision to use slab band whenever slab is not thick enough to accommodate the required tendon sag. This is especially when the span is longer than 10 m or when heavy loads are occupied. Not only slab band can cut down the amount of tendons used by allowing tendon drape at larger value, but also eliminate the cost of punching shear reinforcement at column support (Fig. 1).

Metaheuristic algorithms emerge as general and powerful techniques in structural design optimization and nearly all engineering design disciplines. Although, with more computation cost than the gradient-based methods, the algorithms are simple and robust, so it can be applied to solve most nonlinear constrained optimization problems without requirement to compute function derivatives. Many previous researches attempted to apply metaheuristic algorithms, for example genetic algorithm and harmony search algorithm, to solve existing structural design optimization problems. Coello et al. (1997) developed a genetic algorithm-based approach for reinforced concrete (RC) beams. Rafiq and Soutcombe (1998) optimized biaxial RC columns using genetic algorithm. Koumousis and Arsenis (1998) investigated different types of RC structural members. Camp et al. (2003) investigated the optimum design of RC frames using genetic algorithm. Bekdas et al. (2016) used harmony search algorithm to solve various reinforced concrete design members, such as RC slender columns, RC shear walls and post-tensioned RC axially symmetric cylindrical walls.

Fig. 1 Slab band system (Courtesy of Posteck Prestressing 2015)

This paper presents advances in design optimization of two-way P/T concrete slab using metaheuristic-based SA algorithm for solving nonlinear constrained optimization problem.

2. SIMULATED ANNEALING ALGORITHM

SA is a metaheuristic-based algorithm developed by Kirkpatrick et al. (1983). The overview process of SA can be briefly explained as (Yang 2010):

(i) Starting from initial solution point probably far from optimal solution, the algorithm generates trial random point. The temperature at this initial stage should be high value to increase possibility of point acceptance.

(ii) For each iteration, randomly generated the new point i.e., $x_{t+1} = x_t + s \times \mathrm{rand}(x)$, where s is random walk scaling factor, rand(x) is random function of x. The distance from the current point is based on probability distribution with scaled to the current temperature.

(iii) If the new point gives lower value of objective function, the algorithm keeps that point as starting point for the newly generated point. Otherwise, the algorithm keeps the point with certain probability based on current temperature specified by $p = e^{-\frac{\Delta}{kT}} > \mathrm{rand}(0,1)$ where $\Delta =$ new objective – old objective function value, $T =$ current temperature, and $k =$ Boltzman's constant = 1.0 in this study.

(iv) The algorithm systematically decreases the temperature, i.e. $T_{t+1} = \propto^n T_t$, where $\propto$ is called cooling factor and *n* > 0 is an acceleration exponent. Then the process can be repeated until the temperature or searching space is small. The lower temperature is, the lower acceptance rate for the point the does not lower objective function.

(v) The algorithm terminates when the average change in objective function is smaller than tolerance.

3. OPTIMUM DESIGN OF TWO-WAY P/T SLAB

In this study, cost optimization of two-way P/T slab is presented. Fig. 2 shows a typical model of 4-span P/T plate that takes into account the slab band.

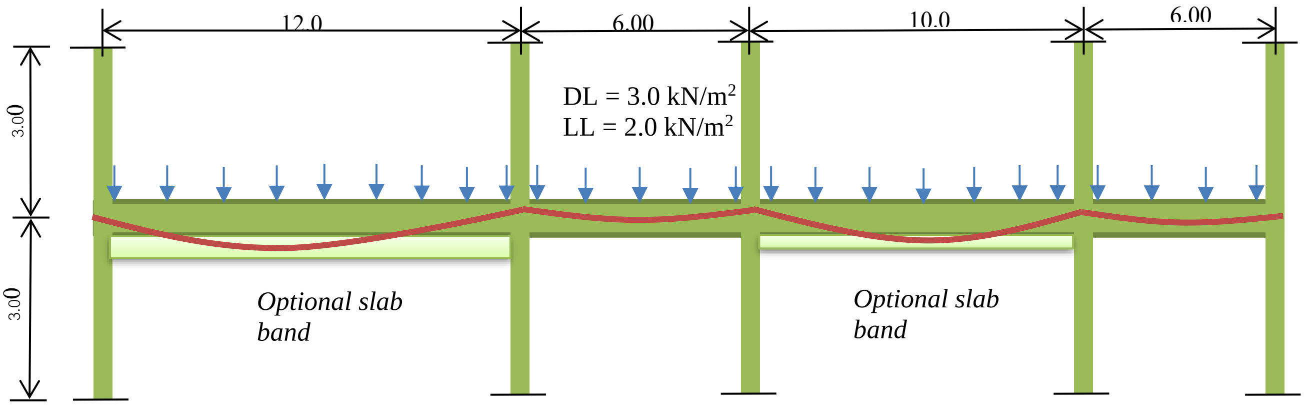

Fig. 2 Model of slab used in optimization process

The total cost of the slab as objective function of process is calculated as,

$$\text{Min f(x)} = 6000 \times 10^{-6} A_g \sum L_i + 80.0\, W_s + 300\, FW \tag{1}$$

where A_g = gross sectional area of slab-beam (mm^2), FW = total area of formwork (m^2), W_s = total strand weight (kg), such as

$$W_s = \sum_{i=1}^{nspan} N_i L_i \times 0.777 \tag{2}$$

N_i = number of strand for beam i, and L_i = span length for beam i (m).

The design variables, parameters and constraints are summarized in Tables 1-3, respectively.

Table 1 Design variables

Design variables	Solution	Definition
t_f	x(1)	Slab thickness (mm)
h_1, h_2, h_3,h_4	x(2)-x(5)	Depth of stem (mm)
N_1,N_2,N_3,N_4	x(6)- x(9)	Number of strand
a_1,a_2,a_3, a_4	x(10)- x(13)	Drape value (m)

Table 2 Design parameters

Design parameters	Values
Design compressive strength of concrete	fc' = 32 MPa fc_i' = 24 MPa at transfer
Unit weight of concrete	24.0 kN/m^3
Elastic modulus of concrete	$4.7\sqrt{fc'}$ = 26.58 GPa
Effective force (after all losses)	110 kN/strand
Strand unit weight	0.777 kg/m

Table 3 Design constraints

Inequality constraints	Assignments
Flexural stress	fct $\leq$ $0.25\sqrt{fci'}$ (1.22 MPa) at transfer (ACI 318-11) fc $\leq$ $0.6fci'$ (14.4 MPa) at transfer (ACI 318-11) fct $\leq$ $0.5\sqrt{fc'}$ = 2.88 MPa at service (ACI 318-11) fc $\leq$ $0.45fc'$ = 14.4 MPa at service (ACI 318-11)
Tendon arrangements	$N_2 \leq N_1$ and $N_3 \leq N_4$
Average pre-compression	[1.0 - 2.0] MPa
% Balance Load	[0.7-1.50] of slab self weight
Drape control	$a_i \leq \frac{C_b+tf+hw-y_c}{2} - y_c$ (m) for exterior span and $a_i \leq t_f + h_w - 2y_c$ (m) for interior span, where C_b = distance from CGC to bottom fiber and y_c = distance from the closest beam face to CG of tendon.
Deflection control	Limit total deflection $\leq$ L/800
Flexural strength	$\emptyset M_n \geq M_u$
Punching shear strength	Not considered in this study
Slab band assignment	Whenever span $\geq$ 10.0 m Stem depth $\leq$ 200 mm only for 1st and 3rd span. Stem are not allowed for other spans. Stem depth $\leq$ 300 mm

Two-way slab system is simplified as equivalent frames in two orthogonal directions. It is common practice to consider different design strips in band tendon direction and another typical design strips in uniform tendon direction separately. Although the system is one-way load transfer in the design calculation, the behavior is still completely two-way load transfer system. The slab band connected to column shall be modeled as non-prismatic beam whose stiffness within column rigid zone is modified by factor $\frac{1}{(1-(c_2/L_2)^2)}$, where c_2 and L_2 are column width and span length perpendicular to the analysis direction. The non-prismatic beam element is shown in Fig. 3. This element has 2 degrees of freedom per node which can be directly incorporated to any frame analysis software using displacement method.

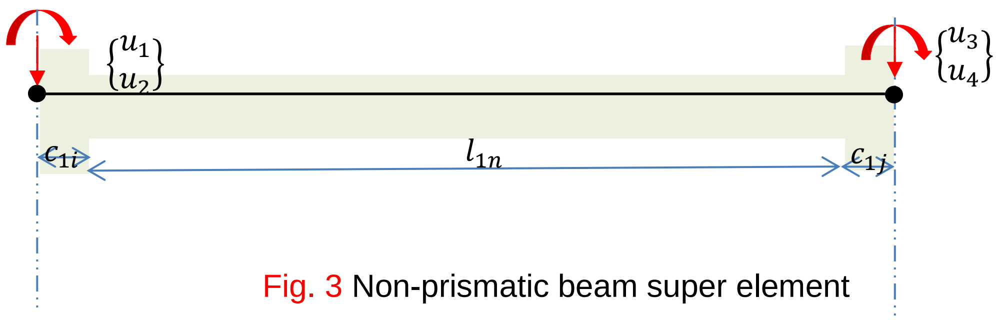

Fig. 3 Non-prismatic beam super element

In the solution process, the initial solution is given as x = [200, 300, 0, 300, 0, 50, 50, 50, 50, 0, 0, 0, 0]. Table 4 shows the comparison of optimal solution for this study case. The optimal solution of P/T slab band system gets significantly improved by 28% over flat plate system.

Table 4 Optimal solution of P/T slab

Design variables	P/T flat plate	P/T slab band
Slab thickness (mm)	303.11	200.00
Stem depth (mm)	-	[268.07, 0, 186.44, 0]
No. of tendons	[33.02, 23.00, 23.90, 32.54]	[20.87, 11.23, 13.69, 14.00]
Drape vale (m)	[0.152, 0.120, 0.181, 0.092]	[0.319, 0.075, 0.278, 0.063]
Cost (THB)	435,410	313,297

4. CONCLUSIONS

In this study, we implemented shape design optimization on P/T slab with slab band using SA algorithm. For the given 4-span P/T slab, the optimal solution of P/T slab band system was significantly improved by 28% compared to the flat plate system.

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