Engineering Structures 111 (2016) 1–10

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Designing construction processes in buildings by heuristic optimization

Manuel Buitrago [a], José M. Adam [a,*], Yezid A. Alvarado [b], Juan J. Moragues [a], Isabel Gasch [a], Pedro A. Calderón [a]

[a] ICITECH, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain
[b] Pontificia Universidad Javeriana, Calle 40 # 5-50 Ed. José Gabriel Maldonado, Bogotá, Colombia

ARTICLE INFO

Article history:
Received 23 July 2015
Revised 25 October 2015
Accepted 11 December 2015
Available online 5 January 2016

Keywords:
Shoring
Building structures
Optimization
Heuristic methods
Reinforced concrete

ABSTRACT

This paper describes a computer tool for calculating and validating loads on floor slabs and shores in the construction of multistorey buildings with *in situ* casting. Its chief novelty lies in its optimization unit, designed to produce appropriate and optimum construction processes, which was created by applying exact and heuristic methods: Random Walk (RW), Descent Local Search (DLS) and Simulated Annealing (SA). The system has shown that it can improve three of the most important aspects involved in construction: time, cost and safety. In some cases the optimal solutions were achieved while reducing up to 53% of the cost of the shoring system, in shorter construction time, and meeting all the usual requirements for the construction of this type of building.

1. Introduction

Reducing building times, saving on costs and improving safety are three important aspects of efficient construction processes. At the present time savings in time and costs are achieved mainly by recovering all or part of the building construction components in the shortest possible time. Although striking time depends on many factors (building process, work requirements, weather, etc.), the financial aspect is always subject to structural safety considerations.

It should be remembered that a high proportion of building collapses take place during construction [1–3], so that an understanding of how loads are transmitted between shores and slabs under construction is required to ensure the safety of the structure and reduce building times and costs. Knowing how these loads are transmitted makes it possible to calculate the loads the slab must support.

Numerous authors have proposed a multitude of theoretical models to estimate shore/slab load transmission, including complex models such as those based on the finite element method [4–10] and simple calculation methods. Among others, Grundy and Kabaila [11], Duan and Chen [12], Fang et al. [13] and Calderón et al. [14] developed simplified methods to estimate load transmission between slabs and shores in multistorey buildings.

In order to develop a computer tool for the present study, a simplified calculation method to avoid having to resort to advanced software is used, but even when simplified methods are used it is by no means a simple or rapid task to calculate construction processes. Therefore, the first objective of this study was to develop and validate a software tool that would provide users with a quick and simple calculation method. The computer tool can be used to check the construction process defined and entered by the user.

Since the design of the optimal construction process is intimately related to the structural designer's experience, he has to follow a strategy of trial and error and continually redefine the process until he finds a better solution than the original. This strategy is not automatic, and as it usually leads to construction processes in which safety is given the highest weight, times are longer and costs are higher than those of the optimal solution. It is therefore advisable to apply optimization techniques to obtain the best construction processes; this is, in fact, the second objective of the study and involves two of the most important aspects of building works, construction time and costs.

Automatic methods of obtaining optimal solutions are generally either exact or heuristic. Even though the former are efficient for dealing with small numbers of variables, they still need long computation times and because of this may be limited when dealing with higher numbers of variables. A review of non-heuristic optimization studies can be found in Sarma and Adeli [15]. Heuristic search methods can also be used intelligently to obtain optimal solutions in a reasonable computation time [16]. Their first application to reinforced concrete in 1997 were by Coello et al. [17] in

* Corresponding author. Tel.: +34 963877562; fax: +34 963877568.
E-mail address: joadmar@upv.es (J.M. Adam).

http://dx.doi.org/10.1016/j.engstruct.2015.12.009
0141-0296/

a simply supported beam, and by studies on pre-tensed concrete beams by Leite and Topping [18], who used genetic algorithms (GA). Other studies also emerged that used both GA and Simulated Annealing (SA) [19], threshold accepting (TA) [20], ant colony optimization (ACO) [21] and particle swarm optimization (PSO) [22], applied to frames, beams, columns and slabs in RC buildings [16,23–25]. Furthermore, Paya [16] applied heuristic search methods as Random Walk (RW) and Descent Local Search (DLS) in search of optimal solutions. Nowadays, many heuristic search methods are used [26,27], being more efficient when they are combined as hybrid optimization [28–30]. In this paper, single optimization algorithms are used as a first approach to building construction processes.

The principal novelty of this paper is that it applies three optimization strategies (RW, DLS and SA) by means of a specially developed computer tool programmed in FORTRAN language to obtain, for the first time, optimal construction processes in multistorey buildings.

2. Development and validation of computer-based tool for estimating and verifying loads on slabs and shores

The chosen calculation method was the new simplified procedure defined by Calderón et al. [14], which is the latest and most complete and has better goodness of fit than the previous simplified methods [14,31–33]. It assumes that the mean deformation of the slabs coincides with the mean deformation of the shores that support them. Also, various boundary conditions are considered (internal, end and corner spans). Deformability is estimated by Scanlon and Murray's method [34]. It should be clearly understood that in this method the analysis of the loads transmitted between slabs and shores is for mean loads, which was the practice used in similar studies. The software was also programmed with the stiffness matrix method to calculate the required bending moments. In order to determine the resistant capacity of the floor slabs to the loads they had to bear during construction, the Calavera [35] and Fernández [36] condition was considered (see Eq. (1)), which is based on the critical evolution of the concrete tensile strength in relation to its other mechanical characteristics:

$$\beta = \alpha \cdot \frac{\gamma'}{\gamma} \leqslant \frac{f_{ckt,j}}{f_{ckt,28}} \quad (1)$$

where, on one hand, α is the proportion of loads received by the slabs under construction compared to the design loads, γ' is the construction safety factor, γ is the service safety factor, and therefore β is the proportion of the load measured on the slab weighted by the safety coefficients. On the other hand, $f_{ckt,j}$ is the tensile strength of the concrete at the age of the concrete under study, and $f_{ckt,28}$ is the concrete's tensile strength in service.

Thus, following Calderón et al.'s simplified procedure [14], the computer tool calculates the loads on both slabs and shores and verifies that the above condition has been satisfied for each slab and building operation, i.e. that β is equal to or lower than the proportion of the acquired tensile strength.

The next task was to choose suitable buildings to verify the computer tool. The first considered was the building studied by Alvarado [37] and Alvarado et al. [38], which was built purely for research purposes. This experimental building contains three storeys with 0.25 m thick reinforced concrete slabs, 2.75 m height between floors and a 6.00 m clear span between columns. The second was the building studied by Gasch [31] in the Fine Arts Faculty of the Universitat Politècnica de València; this has six storeys and a basement with waffle slabs 0.40 m thick, 0.15 m rib and 0.80 × 0.80 m waffle. The spans were 5.50 × 8.00 m and 5.50 × 8.80 m. Height between floors ranged from 2.90 m to 4.00 m. The estimation and verification of loads for each building can be seen in Tables 1 and 2. Figs. 1 and 2 give for each building the comparison between the results of the computer tool ($\overline{Q}_{NSP}$) and the results obtained from the simplified methods of Duan and Chen ($\overline{Q}_{D\&C}$) and Fang et al. ($\overline{Q}_{F}$), with respect to experimental measurements. As can be seen in Figs 1 and 2, the results obtained from the computer tool calculated show a better fit than those obtained from the other methods.

3. Definition of the optimization problem

3.1. Definition of problem

The problem of obtaining optimal construction processes consists of minimizing an objective function F (cost of the shoring system) defined according to Eq. (2) which must comply with the different constraints g_k considered in the Eq. (3).

Table 1
Estimation and verification of loads on slabs and shores in the experimental building.

Stage of construction	Level	$\overline{Q}_{slab}$ [kN/m2]	$\overline{Q}_{shores}$ [kN/m^2]	β	$\frac{f_{ckt,j}}{f_{ckt,28}}$
Casting Level 1	1	0.00	5.64	–	–
Clearing Level 1	1	1.75	3.89	0.14	0.60
Casting Level 2	2	0.00	5.64	–	–
	1	3.76	7.52	0.29	0.78
Clearing Level 2	2	2.43	3.21	0.19	0.75
	1	2.94	5.90	0.23	0.89
Striking Level 1	2	4.51	1.13	0.35	0.78
	1	6.77	–	0.52	0.90
Casting Level 3	3	0.00	5.64	–	–
	2	7.78	3.50	0.60	0.84
	1	9.13	–	0.71	0.93
Clearing Level 3	3	2.44	3.20	0.19	0.60
	2	6.38	2.45	0.49	0.89
	1	8.09	–	0.63	0.96
Striking Level 2	3	3.29	2.35	0.25	0.78
	2	7.99	–	0.62	0.93
Striking Level 3	3	5.64	–	0.44	0.93

Table 2
Estimation and verification of loads on slabs and shores in the fine arts building.

Stage of construction	Level	$\overline{Q}_{slab}$ [kN/m2]	$\overline{Q}_{shores}$ [kN/m^2]	β	$\frac{f_{ckt,j}}{f_{ckt,28}}$
Casting Level 1	1	0.00	5.76	–	–
Clearing Level 1	1	1.58	4.18	0.12	0.60
Casting Level 2	2	0.00	5.76	–	–
	1	3.23	8.29	0.25	0.78
Clearing Level 2	2	2.33	3.43	0.18	0.60
	1	2.58	6.61	0.20	0.84
Striking Level 1	2	4.70	1.06	0.36	0.66
	1	6.82	–	0.53	0.86
Casting Level 3	3	0.00	5.76	–	–
	2	8.03	3.49	0.62	0.78
	1	9.25	–	0.72	0.90
Clearing Level 3	3	2.73	3.03	0.21	0.60
	2	6.48	2.31	0.50	0.84
	1	8.07	–	0.63	0.93
Striking Level 2	3	3.61	2.15	0.28	0.66
	2	7.91	–	0.61	0.86
Casting Level 4	4	0.00	5.76	–	–
	3	6.95	4.57	0.54	0.78
	2	10.33	–	0.80	0.90