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Original Research Article

Heuristics in optimal detailed design of precast road bridges

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ABSTRACT

This paper deals with the cost optimization of road bridges consisting of concrete slabs prepared in situ and two precast-prestressed U-shaped beams of self-compacting concrete. It shows the efficiency of four heuristic algorithms applied to a problem of 59 discrete variables. The four algorithms are the Descent Local Search (DLS), a threshold accepting algorithm with mutation operation (TAMO), the Genetic Algorithm (GA), and the Memetic Algorithm (MA). The heuristic optimization algorithms are applied to a bridge with a span length of 35 m and a width of 12 m. A performance analysis is run for the different heuristics, based on a study of Pareto optimal solutions between execution time and efficiency. The best results were obtained with TAMO for a minimum cost of 104 184€. Among the key findings of the study, the practical use of these heuristics in real cases stands out. Furthermore, the knowledge gained from the investigation of the algorithms allows a range of values for the design optimization of such structures and pre-dimensioning of the variables to be recommended.

1. Introduction

Precast-prestressed concrete (PPC), that is, pretensioned concrete beams with cast-in situ slabs, has been commonly used by designers when building road bridges [1]. In this context, structural engineers have taken advantage of precast technology by specifying designs that utilize standard beams of comparatively short spans, typically ranging from 10 to over 40 m. Moreover, reducing the material weight through prestressing is decisive due to transportation and elevation costs. This is where structural optimization of this type of large and repetitive structure becomes especially relevant.

The basic goal of structural optimization is to find a design having lowest cost, and ensuring predicted constraints. Additionally, in most structural optimization problems, the main drawback appears to be related to the constructability of the proposed design such as reinforcement placement, rules of good design practice, construction management plan, and so on [2]. The decisions taken in such a complex environment require the development of new decisional tools and methods that provide more effective and realistic solutions [3,4]. Among the available computational methods that can be used to solve optimization problems, heuristics and metaheuristics are approximate methods that are considered as particularly useful algorithms in structural engineering [5].

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The earliest studies into structural reinforced concrete (RC) optimization date back to the late 1990s [6,7]. However, Cohn and Dinovitzer [8] identified a great gap between theoretical work and the practical application of structural optimization. Recent research has been conducted with regard to heuristics and metaheuristics [9], such as Descent Local Search (DLS) [10], Genetic Algorithms (GAs) [11,12], evolutionary algorithms [13,14], Simulated Annealing (SA) [15,16], Variable Neighborhood Search (VNS) [17], Harmony Search (HS) [18,19], Ant Colony Optimization (ACO) [20], Glowworm Swarm Algorithm (GSA) [21], Eagle Strategy (ES) [22], and the Big Bang–Big Crunch algorithm (BB-BC) [23], among others.

Despite the aforementioned research works, there is still limited knowledge on the optimization of prestressed concrete (PC) bridge structures. Hassanain and Loov [24] reviewed research on cost optimization of concrete bridge structures; nevertheless, as Hernandez et al. [25] have noted, most approaches for PC bridges found in the literature are not suitable for application in real-life engineering. Ohkubo et al. [26] studied PC box girder bridges and proposed a multi-criteria fuzzy optimization of the total construction cost and esthetic feeling. Sirca and Adeli [27] and Ahsan et al. [28] focused on the optimal-cost design of concrete I-girder bridges. Both used PPC for the beams; the latter also used post-tensioned tendons. García-Segura et al. [29] proposed a hybrid HS for the design of post-tensioned concrete box-girder pedestrian bridges. Martí et al. [30] used a hybrid SA to minimize the cost of PC precast U-beam road bridges.

In this line of work, this paper focuses on the cost optimization of PPC road bridges. The PPC bridge system studied consists of two PC U-beams with a span length of 35 m and a top slab formed by a 0.06 m precast RC slab used as formwork for the cast-in-place RC slab (Fig. 1). Beams are made of self-compacting concrete. The top slab allows vehicle traffic and has a width of 12 m (Fig. 2). The optimization searches for the geometric variables, concrete, and steel that minimize the cost. A module evaluating all relevant limit states has been implemented, and subsequently metaheuristics that are capable of finding cost-optimized solutions have been developed specifically for this work.

2. Definition of the problem

The mathematical problem is comprised of economical optimization of the structure, represented by the objective function f in Eq. (1) while satisfying the constraints in Eq. (2).

$$C = f(x_1, x_2, \ldots, x_n) \tag{1}$$

$$g_j(x_1, x_2, \ldots x_n) \leq 0 \tag{2}$$

$$x_i \in (d_{i1}, d_{i2}, \ldots, d_{iq_i}) \tag{3}$$

Note that x_1, x_2,..., x_n are the design variables whose combination is to be optimized. Each variable can take on the discrete values listed in Eq. (3).

The objective function considered is the cost function defined in Eq. (4), where p_i are the unit prices; m_i are the measurements of the units in which the construction of the PCC bridge is split, and r is the total number of construction units.

$$C = \sum_{i=1,r} p_i \times m_i \tag{4}$$

The cost of the bridge depends on the material volumes used as well as the labor, machinery, and resources necessary for the construction. The cost function is obtained by adding the price of each unit multiplied by the respective measurements (Table 1). As discrete values are used to guarantee the constructability, this is a combinatorial optimization problem.

The analysis includes 59 design variables. Fig. 3 shows the main geometric variables considered in this analysis. The

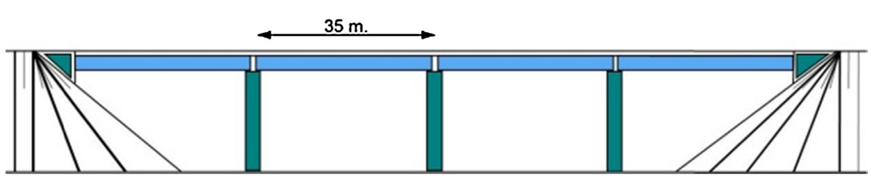

Fig. 1 – Longitudinal profile of the bridge.

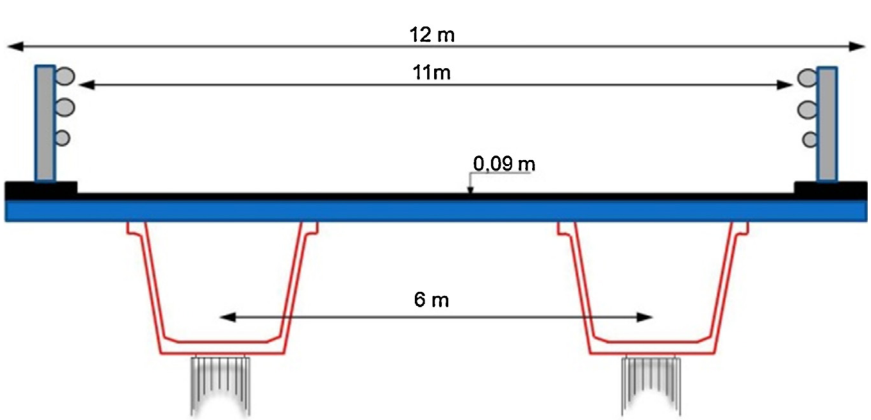

Fig. 2 – Cross section of the beam-slab deck.