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Hybrid harmony search for sustainable design of post-tensioned concrete box-girder pedestrian bridges

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ABSTRACT

This paper aims to find sustainable designs of post-tensioned concrete box-girder pedestrian bridges. A hybrid harmony search algorithm combining threshold optimization is used to find the geometry and the materials for which the sum of the costs or the emissions are the lowest, yet satisfying the requirements for structural safety and durability. An experimental design method was used to adjust the algorithm parameters. The parametric study was applied to three-span deck bridges ranging from 90 m to 130 m. The findings indicated that both objectives lead to similar cost results. However, the variables presented some differences. Such deviations suggested greater depths, more strands and a lower concrete strength for CO_2 target functions. Carbonation captured less than 1% of the deck emissions over 100 years. This methodology leads to a precise analysis of the practical rules to achieve an environmental design approach.

1. Introduction

The construction industry has become one of the most carbon-intensive sectors [1]. Besides, construction requires large amounts of natural resources and therefore, resource depletion and damage to flora and fauna are unavoidable consequences. Concrete production emits large amounts of carbon dioxide, mainly due to high energy demands and limestone calcination during cement manufacture [2]. In 2007, clinker production reached around 55 million tons in Spain. This number dropped to 16.7 million tons in 2012 as a consequence of the financial crisis [3].

The World Commission on Environment and Development (WCED) reported on "Our Common Future", the long-term environmental strategies for achieving sustainable development [4]. The construction sector, an obstacle in advancing toward this goal, has sought new strategies for improving sustainability. Research activities have focused on comparing the emissions for different materials in construction activity [1,5,6], evaluating the life cycle emissions of concrete structures [2,7,8] and identifying optimal maintenance planning [9–11]. However, these approaches quantify the environmental effect once the design is completed. This study tackles the environmental challenge from the choice of the form and the materials involved in structural design.

Traditionally, technical guides and recommendations have provided a starting point for the design process. There are strict codes to assure an appropriate reliability and safety level. Concrete bridge loads and design codes has been developed by Fomento [12,13], the European Committee for Standardization (CEN) [14,15] and American Association of State Highway and Transportation Officials (AASHTO) [16]. Besides, several authors have provided guidance to achieve a proper box-girder bridge design [17,18]. The emergence of optimization methods to minimize the structural weight [19,20] and the economic cost [21–23] has enabled designers to explore new design forms. Both objectives lead to a reduction in material consumption and, therefore, their optimization is a good approach to achieve efficient designs. In this context, some authors have moved in this direction [24–27], proposing environmental emissions minimization. Similarly, the CO_2 emission as single-objective optimization is the focus in this research. Alternatively, Camp and Assadollahi [28] studied the CO_2 and cost optimization of RC footings as biobjectives by a multi-objective optimization method. They reported that more sustainable designs are less economical, while more economical designs are less sustainable.

This research differs from others in that it demonstrates the potential of a hybrid harmony search (HSTA) to find ecological and economic sustainable designs of continuous post-tensioned concrete box-girder pedestrian bridges. In addition, this study extends previous ones considering concrete carbonation as a negative emission. Carbonation during use stage decreases the total

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emissions by 22% [2]. If carbon capture is ignored, emission rates may be overestimated by as much as 13–48% [7]. Carbonation rate depends on concrete strength and the geometry of the structure. Besides, the amount of carbonation will increase over time. This study evaluates carbonation during service life and checks whether the carbonation is notable for this structure. However, the calcium oxide that did not carbonate during the use stage can be carbonated after demolition [2].

Box-girder bridges have numerous advantages from the structural and constructive points of view, as the geometry is characterized by its strength to positive and negative bending moments and torsional stresses. Furthermore, the construction techniques can be cast in situ or precast in segments and then prestressed. Since several authors have advanced our understanding of the structural behavior [17,18,29–31] and codes present well-defined formulas to guarantee structural strength and serviceability [12–16], this paper presents a guide for designing more sustainable post-tensioned concrete box-girder pedestrian bridges.

To this end, a structural optimization tool was developed using a hybrid harmony search algorithm, which combines harmony search (HS) and threshold accepting (TA). Medeiros and Kripka used HS to optimize the monetary and environmental costs associated with pieces of rectangular reinforced concrete columns [32]. Kaveh and Shakouri Mahmud Abadi [33] improved HS by changing dynamically the pitch adjusting rate (PAR) with the generation number. They used the algorithm to optimize a composite floor system. Martí and González-Vidosa [34] proved the efficiency of TA for the pedestrian bridge optimization, although the SA appeared more efficient. A variant of TA improved the best results of reinforced concrete vaults in the study of Carbonell et al. [35]. Yepes et al. [27] proposed a hybrid multistart optimization strategic method based on a variable neighborhood search threshold acceptance strategy (VNS-MTAR) algorithm to design reinforced concrete cantilever retaining walls. Similarly, Martí et al. [36] employed the neighborhood structure of GA with the convergence properties of SA. In this line, Alia and Mandava [37] provided an overview of the variants of HS hybridization. This paper employs the hybridization strategy to combine the strengths of individual algorithms. The HS method is based on searching for perfect harmony by combining the musical notes of each instrument. It means finding the best dimensions of the box-girder, the concrete strength, the number of strands, the tendon layout and the reinforcing steel bars that together constitute a safe and sustainable pedestrian bridge. The economic cost and the CO_2 emissions are used as objective functions to compare the design alternatives. Carbonation is taken into account for emission evaluation as long as this process absorbs atmospheric carbon dioxide. This paper evaluates the importance of carbon capture.

2. Optimization problem definition

The problem proposed for this study involves a single-objective optimization of structural concrete. To this end, a program that determines the optimum values of the pedestrian bridge variables was created. This optimization aims to minimize the objective function associated with the cost (Eq. (1)) or the CO_2 emissions (Eq. (2)) while satisfying the constraints G represented by Eq. (3).

$$C(\vec{x}) = \sum_{i=1,rc} p_i \cdot m_i(\vec{x}) \tag{1}$$

$$E(\vec{x}) = \left(\sum_{i=1,re} e_i \cdot m_i(\vec{x}) \right) - C_{CO_2}(\vec{x}) \tag{2}$$

$$G_j(\vec{x}) \leq 0 \tag{3}$$

Note that the vector x contains the discrete design variables. The values are discrete to adapt to real cases. The objective function is either the cost or the CO_2 emission. Optimization of one objective and evaluation of the other were undertaken simultaneously.

The total cost included the cost of materials for production, transport and placement. The cost during usage was not taken into account since the structure was designed to withstand the duration of its designed service life and, therefore, this study considered that there was no need for maintenance during this stage. The cost for the total number of construction units is given by Eq. (1), where p_i are the unit prices and m_i the measurements which depend on the design variables. The construction units associated with the cost (rc) are the volume of concrete, the amount of post-tensioned steel, the amount of reinforcement steel, the volume of lighting, the area of the formwork, the volume of scaffolding, and the CO_2 cost.

The unit prices and emissions (Table 1) were obtained from the 2013 BEDEC ITEC database of the Institute of Construction Technology of Catalonia [38]. Concrete unit price was determined for each compressive strength grade according to every component cost, including the cost of raw materials extraction, manufacture and transportation. This paper assumes a construction site in Valencia and distances were doubled after considering the return trip. The transport distances for cement, plasticizer, aggregate and silica fume were 32 km, 724 km, 12 km and 1420 km, respectively. Once the concrete was made, a mixer transported it from the concrete plant to the building site. This distance was considered as 40 km. The last construction unit is the cost of the CO_2 emissions given in SendeCO_2 [39].

Likewise, the CO_2 emissions were assessed as defined in Eq. (2), where e_i are the unit emissions. The construction units associated with the emissions (rc) are those of the cost, with the exception of the CO_2 cost. The plasticizer emission was obtained from the European Federation of Concrete Admixtures Associations [40] and the silica fume was considered not to have unit emissions since it is a waste product. During use stage, concrete carbonation absorbs CO_2 and, therefore, this capture (C_{CO2}) was deducted from the emissions (see Eq. (2)). The amount of CO_2 captured was estimated according to Eq. (4) [2,41] based on the predictive models of Fick's first law of diffusion [42].

$$C_{CO_2}(\vec{x}) = k(\vec{x}) \cdot \sqrt{t(\vec{x})} \cdot c(\vec{x}) \cdot \text{CaO} \cdot r \cdot A(\vec{x}) \cdot M \tag{4}$$

where k is the carbonation rate coefficient (Table 2), t is the structure service life (100 years), c is the quantity of Portland cement per cubic meter of concrete (Table 2), CaO is the amount of CaO

Table 1
Basic prices and CO_2 emissions.

Unit measurements	Cost (€)	Emission (kg CO_2)
m^3 of scaffolding	10.02	6.92
m^2 of formwork	33.81	2.08
m^3 of lighting	104.57	604.42
kg of steel (B-500-S)	1.16	3.03
kg of active steel (Y1860-S7)	3.40	5.64
m^3 of concrete HP-35	104.57	321.92
m^3 of concrete HP-40	109.33	338.90
m^3 of concrete HP-45	114.10	355.88
m^3 of concrete HP-50	118.87	372.86
m^3 of concrete HP-55	123.64	389.84
m^3 of concrete HP-60	128.41	406.82
m^3 of concrete HP-70	137.95	440.78
m^3 of concrete HP-80	147.49	474.74
m^3 of concrete HP-90	157.02	508.70
m^3 of concrete HP-100	166.56	542.66
t CO_2 emission	5.00	