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Optimization of under-deck cable-stayed concrete bridges

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Abstract

This paper presents an optimization-based procedure for the design of under-deck cable-stayed concrete bridges. The proposed optimization strategy comprises a convex optimization algorithm combined with a multi-start procedure to generate local optimum solutions and the best of which is selected as the optimum design. The finite element method is used for the three-dimensional analysis of the structure under dead and road traffic live loads including concrete time-dependent effects. The optimum design of under-deck cable-stayed concrete bridges is posed as a multi-criteria optimization problem with objectives of minimum cost, deflections and stresses considering service and strength criteria defined according to the Eurocodes provisions. This minimax optimization problem, which is discontinuous and non-differentiable, is solved indirectly via the minimization of a convex scalar function from which a Pareto solution is obtained. This function is obtained following entropy principles and creates an inside convex approximation of the original nonconvex domain. The analytical discrete direct method is used to obtain the structural response to changes in the design variables, these derivatives are needed in the optimization algorithm used. The design variables considered are: the depth and width of the longitudinal beams of the deck beam-and-slab cross-section, cross-sectional sizes of the struts, under-deck cables cross-sectional area and prestressing force. The geometric design variable representing the strut length was fixed defining three different values corresponding to strut length-to-main span length ratios of 1/8, 1/10 and 1/12. The optimization of a single-span real-sized under-deck cable-stayed concrete bridge illustrates the features and applicability of the proposed method. The optimization-based procedure proposed allows finding minimum cost solutions that balance the deck flexure and the suspension effect provided by the under-deck cable-staying system. For the analysed example, the optimum design is governed by the cable stresses and the deck normal stresses for service conditions. The optimum solution features a deck slenderness of 1/37 and a strut length-to-main span length ratio of 1/10.

Keywords: under-deck, cable-stayed, bridges, optimization, concrete, prestressing.

1 Introduction

Under-deck cable-stayed bridges (UDCSB) can be considered an innovative solution regarding the traditional use of prestressing in bridges. In these structures, the cables define a polygonal layout under the bridge deck being anchored in the deck at the support sections and deflected by struts that, working under compression, introduce vertical forces in the deck contributing to support the acting vertical loads. In the last 30 years, this structural solution was adopted by several designers for road bridges and footbridges, with spans up to 200 m and using concrete, steel, steel-concrete composite and timber solutions for the deck [1, 2, 3].

The literature review shows some extensive research concerning this innovative bridge typology. Previous works addressed the structural behaviour and design criteria of UDCSB in single-span bridges [4], multi-span bridges [5], composite bridges [6], subjected to seismic action [7]. The serviceability limit state of vibrations considering vehicle-structure interaction [8] and the non-linear stability of the deck [9] were also reported.

The design of UDCSB is a challenging task seeking an appropriate balance between the stiffness of the deck and the under-deck cables suspension effect, depending on the cross-sectional dimensions and the prestressing forces. Moreover, concrete time-dependent effects and several load cases need to be considered. Although structural optimization is not usually employed in civil engineering practice, due to the complexity and the large amount of information involved, the design of these structures may be favoured by the use of optimization techniques. These techniques are particularly suited to help designers achieving structurally efficient, economic and sustainable solutions.

To the best of the authors' knowledge the optimization of UDCSB was not yet reported. Moreover, the work reported in this paper follows previous research works by the authors concerning the optimization of cable-supported bridges [10, 11].

Therefore, the main goal of this work is the development of an optimization-based computational method to assist in the design of UDCSB under dead load and road traffic live load. To this aim, a computer program previously developed for the optimization of concrete cable-stayed bridges [10] and extradosed bridges [11] was adapted for the optimization of UDCSB. A convex optimization strategy with multiple starting points is proposed to solve the original nonconvex optimization problem. Local optimum solutions are obtained using a multi-start approach and the minimum cost solution is selected as the optimum design. The flowchart of this procedure is depicted in Figure 1.

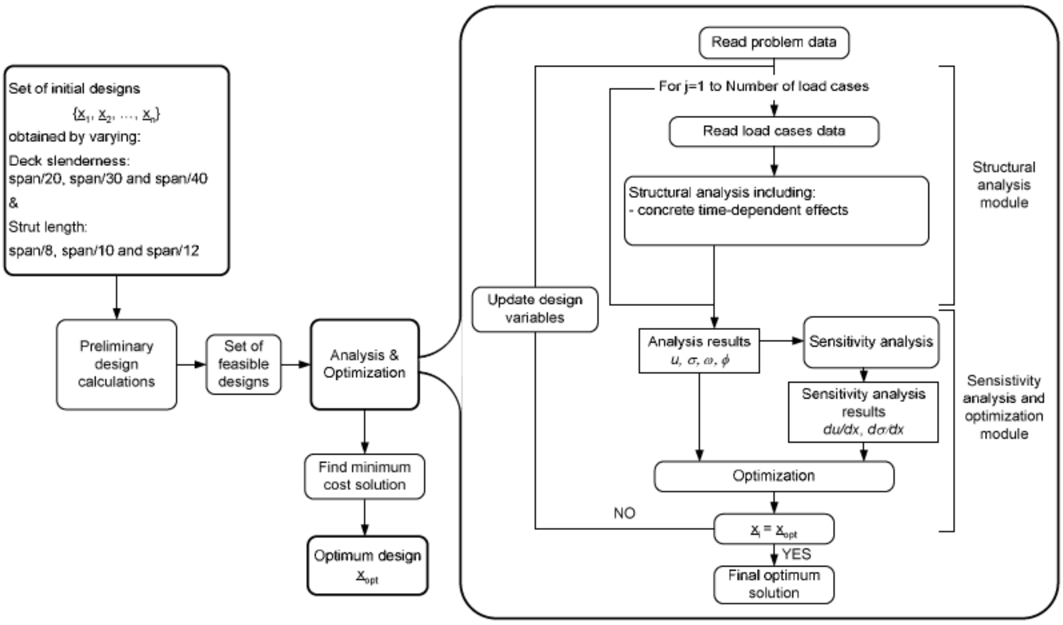


Figure 1: Flowchart of the optimization strategy.

2 Methods

The proposed computational method was developed in MATLAB environment and comprises two modules: a structural analysis module and a sensitivity analysis and optimization module.

The finite element method is used in the first module for the three-dimensional analysis under static loading (dead load and road traffic live load) and concrete time-dependent effects. The deck was modelled with 2-node and 12-degrees of freedom Euler-Bernoulli beam elements, and 2-node bar elements were used to model the under-deck cables.

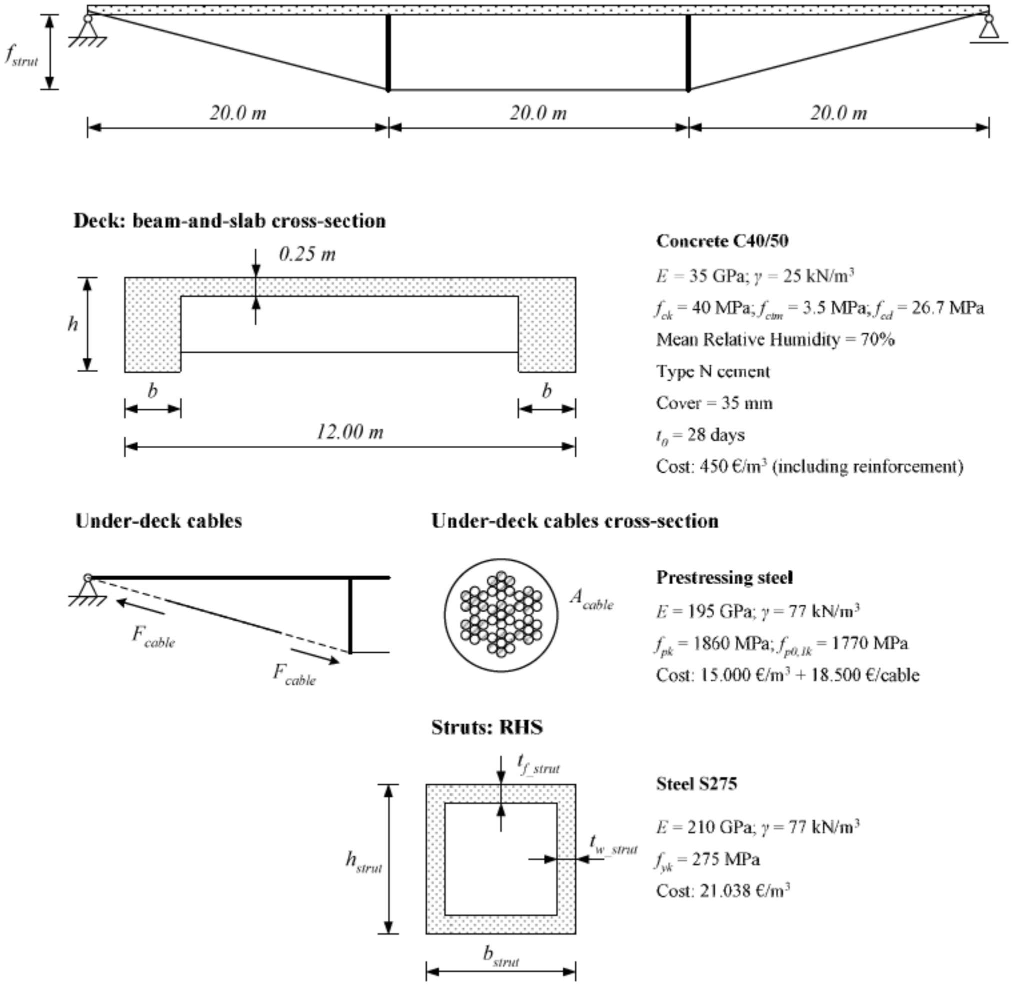
Concrete was modelled as a linear viscoelastic material and the time-dependent effects of ageing, shrinkage and creep were computed according to NP EN 1992-1-1 [12] formulation. Detailed information concerning the time-dependent effects' modelling can be found in a previous work by the authors [13]. Structural concrete was considered with an elastic behaviour in the analysis and the material nonlinearities were considered in members' design. Homogeneous concrete cross-sections were considered and the steel reinforcement was considered only for design purposes.

In the second module, the design of UDCSB is formulated as a multi-criteria optimization problem from which an optimum solution in the Pareto sense is obtained. The solution of the minimax optimization problem is solved indirectly by the minimization of an unconstrained convex scalar function obtained through an entropy-based approach [14]. Considering that the design objectives, $g_j(\underline{x})$, do not have an explicit algebraic form, the problem is solved using an explicit approximation given by the Taylor series expansion of all the objectives, around the current design variable vector, truncated after the linear term

$$\min F(\underline{x}) = \min \frac{1}{\rho} \ln \left[\sum_{j=1}^{M} e^{\rho \left(g_j(\underline{x}) + \sum_{i=1}^{N} \frac{dg_j(\underline{x})}{dx_i} \Delta x_i \right)} \right] \tag{1}$$

where $\underline{x}$ is the vector of design variables, M is the number of objectives, N is the number of design variables, $g_j(\underline{x})$ is the *j-th* design objective, $dg_j(\underline{x})/dx_i$ is the sensitivity of the *j-th* design objective with respect to *i-th* design variable and ρ is a control parameter which must not be decreased through optimization process. Bound constraints with move limits were used to ensure the accuracy of the explicit approximation. The optimization problem is solved with the MATLAB function *fmincon*, which minimizes a scalar function of several variables subjected to bound constraints using a sequence of quadratic problems.

Figure 2 presents the design variables considered. Design objectives of minimum cost, deflections and stresses related to strength and service criteria defined according to NP EN 1992-1-1 [12] provisions were considered.



Concrete C40/50

$E = 35$ GPa; $\gamma = 25$ kN/m^3

$f_{ck} = 40$ MPa; $f_{ctm} = 3.5$ MPa; $f_{cd} = 26.7$ MPa

Mean Relative Humidity = 70%

Type N cement

Cover = 35 mm

$t_0 = 28$ days

Cost: 450 €/m^3 (including reinforcement)

Prestressing steel

$E = 195$ GPa; $\gamma = 77$ kN/m^3

$f_{pk} = 1860$ MPa; $f_{p0,1k} = 1770$ MPa

Cost: 15.000 €/m^3 + 18.500 €/cable

Steel S275

$E = 210$ GPa; $\gamma = 77$ kN/m^3

$f_{yk} = 275$ MPa

Cost: 21.038 €/m^3

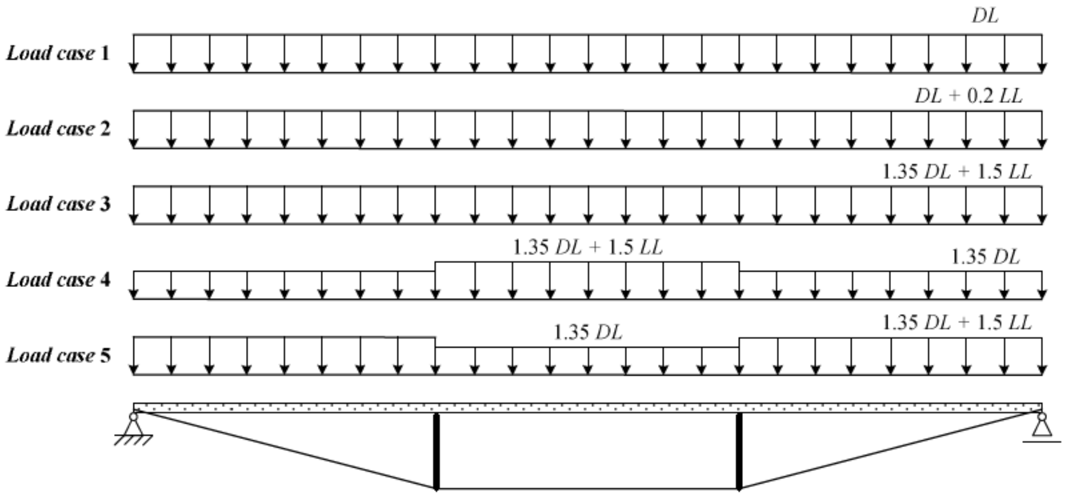
Figure 2: UDCSB example, material properties and design variables.

The analytical discrete direct method is used for sensitivity analysis. This approach was selected due to the computational efficiency, accuracy, availability of the source code and because the number of objectives is far larger than the number of design variables.

3 Results

To illustrate the features and applicability of the proposed method, the optimization of a real-sized UDCSB is presented (Figure 2). The deck is simply supported at the abutments featuring a beam-and-slab cross-section. The under-deck cables are anchored at the deck ends and deviated in two struts located at thirds of the span. The deck was modelled with longitudinal and transverse beams. The bridge finite element model has a total of 30 nodes and 49 finite elements.

Five load cases (Figure 3) were defined to check the relevant service and strength design goals. The current paper focuses in the static response of the complete bridge and thus, the erection stages were not directly considered.



Dead load (*DL*): Self-weight + additional dead load of 2.5 kN/m^2 corresponding to flooring, walkways, safety barriers and guardrails

Live load (*LL*): 4 kN/m^2 corresponding to road traffic load

Load case 1: Bridge under permanent load

Load case 2: Quasi-permanent load combination and long-term analysis (18250 days)

Load cases 3, 4 *and* 5: Fundamental load combination with the *LL* placed to produce the most unfavorable effects

Figure 3: Load cases.

The longitudinal reinforcement and the shear reinforcement were considered constant design parameters with usual practical values. The geometric design variable f_{strut} was considered by solving the optimization problem for three different values of f_{strut}/main span (1/8, 1/10 and 1/12). A total of 9 design variables and almost 350 design objectives for the 5 load cases were considered.

Considering the multi-start approach used, the results presented correspond only to the initial and final values of the optimum solution. Figure 4 shows the bridge cost throughout the optimization process. The optimum solutions are obtained after a relatively small number of iterations. The optimum solution presents a cost reduction of 39.5% compared with the initial solution due to a reduction in the sizing design variables (Table 1).

Design variable	Initial value	Final vale
h [m]	2.00	1.63
b [m]	1.00	0.60
F_{cable} [kN]	8643.88	7279.44
A_{cable} [m^2]	9.30×10^{-03}	6.81×10^{-3}
h_{strut} [m]	0.300	0.156
b_{strut} [m]	0.300	0.140
t_{w_strut} [m]	0.050	0.024
t_{f_strut} [m]	0.050	0.025
f_{strut} [m]	6.00	6.00
Cost	Initial value	Final vale
Deck	130,464 €	75,267 €
Struts	36,351 €	8,759 €
Cables	54,629 €	49,911 €
Total cost	221,444 €	133,938 €

Table 1: Initial and final values of the cost and design variables.

The optimum solution presents a maximum value of 6,76 cm for the deck vertical displacements considering the time-dependent effects (Figure 4). The active design goals at the optimum are the cable stresses and the deck normal stresses for service conditions and the strut normal stresses for load case 3.

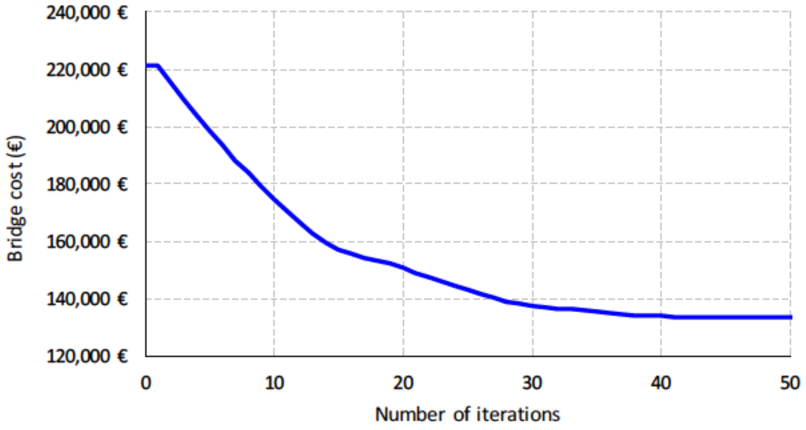


Figure 4: Bridge cost *vs.* number of iterations.

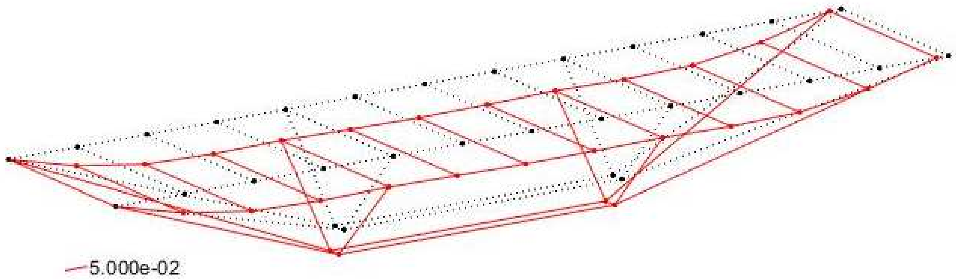


Figure 4: Deformed configuration of the bridge for load case 2 – optimum solution.

4 Conclusions and Contributions

This paper describes the development and application of an optimization-based computational method for the design of UDCSB. The following conclusions can be drawn:

- The design of under-deck cable-stayed concrete bridges can be formulated and solved as a multi-objective optimization problem with objectives of minimum cost, and service and strength criteria.
- A multi-start convex optimization strategy is used to solve the original nonconvex optimization problem. Local optimum solutions are obtained and the minimum cost solution is chosen as the optimum design. This is an efficient procedure to obtain optimised solutions for the design of UDCSB subjected to static loading and considering the most relevant service and strength design objectives.
- The optimization algorithm finds solutions that balance the suspension provided by the under-deck cables and the deck bending stiffness to improve the structural behaviour and reduce the overall cost. The optimum solutions satisfy all the design objectives and present cost reduction due to a decrease in the values of the sizing design variables.
- The use of an optimization-based procedure for the design of UDCSB allows finding structural efficient, cost effective and sustainable solutions.
- In the optimum solution the deck, cables and struts represent 56.2%, 37.3% and 6.5% of the total cost, respectively.
- The design is governed by the cable stresses and the deck normal stresses for service conditions.
- The optimum solution features a deck slenderness of 1/37 and a strut length-to-main span length ratio of 1/10.
- Future developments should consider additional geometrical (eccentricity) and topological (number of struts) design variables describing the polygonal layout of the under-deck cables. It would be relevant to consider the deck internal bonded prestressing and different types of cross-sections and solutions for the bridge deck.
- The optimization considering the seismic action and the vibrations induced by pedestrians in under-deck cable-stayed footbridges should be also considered in upcoming research.

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