Steel-concrete composite bridge optimization through threshold accepting

D. Martínez-Muñoz, J.V. Martí & V. Yepes
ICITECH. Department of Construction Engineering and Civil Engineering Projects
Universitat Politècnica de València, València, Spain.

ABSTRACT: The complexity of bridge optimization is due to the fact that the design of this type of structures evolve a large number of variables. These, generate a space of solutions with too many possibilities to be evaluated in their totality. Because of this, in this work, the optimization of a steel-concrete composite box girder bridge has been performed considering cost as objective function by using heuristic methods. To achieve this objective, a Threshold Accepting with a Mutation Operator (TAMO) has been chosen for the structural optimization of a steel concrete composite bridge. It is observed that the addition of cells on the connections between webs and flanges improves the cross section structural behaviour. The proposed double composite-action design allows to reduce the number of stiffeners for this study case. This method automatize the optimization process of an initial design of a composite bridge, allowing to reach optimum designs without a great expertise in bridge structural design.

1 INTRODUCTION

Any resolution of a problem translates into the search for a solution that allows satisfying the needs posed with the minimum possible investment of resources. In addition, the proposed solution must contemplate and comply with all the restrictions imposed, both by the nature of the problem itself and by any other type of external conditioning factors. In the case of structural problems, the needs of the problem are diverse and the restrictions imposed are related to the resistance of the sections and the compatibility of the deformations with the use to be given to the element to be designed. The proposed solution is required to use as few resources as possible, generally in terms of cost. Therefore, a structural problem is basically an optimization problem, in which a solution is sought that meets certain constraints while minimizing, in this case, the costs of the solution. To arrive at this optimal solution, technicians carry out an iterative process in which solutions are proposed, checked for compliance with the constraints and the costs of each are compared. New solutions are generated by slightly modifying the structural element variables. As expected, the greater the experience of the technician, the faster the optimal solution is reached, since these problems usually have a large number of variables making them stand out for their complexity (Payá-Zaforteza, Yepes, González-Vidosa, & Hospitaler 2010).

The current trend in the field of structural optimization research tries to break this dependence between the quality of the solution and the experience of the technician by taking advantage of the computational capacity of computer equipment. Due to the complexity of structural optimization problems, the exploration of the entire solution space is impossible and, therefore, recourse is made to heuristic and metaheuristic techniques which, although they do not ensure finding the best solution, have been shown to obtain good results (Sarma & Adeli 1998, Hare, Nutini, & Tesfamariam 2013). These methods have been applied to various types of concrete structures such as buttress walls (Martínez-Muñoz, Martí, García, & Yepes 2021, Molina-Moreno, García-Segura, Martí, & Yepes 2017, Molina-Moreno, Martí, & Yepes 2017), building beams (Payá-Zaforteza, Yepes, González-Vidosa, & Hospitaler 2010), bridges (García-Segura, Yepes, & Frangopol 2017, Penadés-Plà, García-Segura, & Yepes 2019, Penadés-Plà, García-Segura, Martí, & Yepes 2018) or even to transfer length prediction in prestressing strands (Martí-Vargas, Ferri, & Yepes 2013). However, the application of these methods to composite structures has not been performed as extensively as indicated in a recent review (Martínez-Muñoz, Martí, & Yepes 2020). In this study, moreover, the lack of study on topics such as life cycle analysis of composite bridges (Martínez-Muñoz, Martí, & Yepes 2021) is emphasized, as has been done extensively for concrete bridges (Penadés-Plà, Martínez-Muñoz, García-Segura, Navarro, & Yepes 2020). This highlights the field of composite structures as a field with potential for exploitation.

The complexity of composite structures, especially composite bridges, can exceed that of concrete structures due to the large number of variables that define their geometry. In addition, the arrangement of the cross-section elements is more sensitive to the predominant stresses of the deck, giving rise to three basic cross-section geometries: box girder, I-beam and composite slab (Vayas & Iliopoulos 2017). This additional condition opens a wide range of possibilities for the application of heuristic techniques to this type of structures, whose behavior and results to optimization problems are not trivial. Current research in this field has applied techniques such as the Excel solver (Musa & Diaz 2007) or the Matlab® fmincom function (Lv & Fan 2014) to solve simplified problems. There are isolated studies applying metaheuristic techniques on pedestrian bridges (Yepes, Dasi-Gil, Martínez-Muñoz, López-Desfilis, & Martí 2019). For more complex problems, most of the algorithms applied to this type of problems have been swarm algorithms (Kaveh, Bakhshpoori, & Barkhori 2014, Kaveh & Zarandi 2019), noting a lack of study of the behavior of trajectory-based algorithms applied to this type of structures.

In this paper, the optimization problem of the deck of a box girder bridge with cost as the objective function is presented. A hybrid Threshold Accepting (TA) modified with a mutation operator algorithm is used to solve this problem. This metaheuristic is framed within the algorithms based on trajectories that perform the search for the optimum by varying the initial solution to solutions close to it, the description of the heuristic is made in section 2.3. The objective of this work is to obtain an optimal design in order to compare it with other research works and traditional designs and to add knowledge to the field of the optimization of composite structures, focusing the study both in the design aspects and in the behavior of the algorithm in this type of problems.

2 OPTIMIZATION PROBLEM DEFINITION

Optimization consist in varying the problem variables in order to maximize or minimize a objective function. In this case, the optimization objectives is the structure cost. In equation 1, the cost objective function is defined by multiplying the unit cost of every material in the bridge by its measurement. The data of prices that are shown in Table 1 have been obtained from the Construction Technology Institute from Catalonia by the BEDEC database (BEDEC 2021). The optimization expressions need to complain the constraints imposed by the regulations or recommendations represented by equation 2.

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

Table 1: Cost values

Unit	Cost (€)
m^3 of concrete C25/30	88.86
m^3 of concrete C30/37	97.80
m^3 of concrete C35/45	101.03
m^3 of concrete C40/50	104.08
m^2 of precast pre-slab	27.10
kg of steel B400S	1.40
kg of steel B500S	1.42
kg of rolled steel S275	1.72
kg of rolled steel S355	1.85
kg of rolled steel S460	2.01
kg of shear-connector steel	1.70

$$G(\vec{x}) \leq 0 \tag{2}$$

2.1 *Parameters and variables definition*

2.1.1 *Variables*

A steel-concrete composite box-girder 60-100-60 meters three-span bridge is proposed for optimization. The problem variables correspond to geometry, reinforcement, and concrete and steel grades from each bridge element. To reach a buildable solution, all of these variables have been discretized, which configures a discrete optimization problem. The variables discretization has been defined in Table 2. Considering this variable discretization, the number of combinations for the optimization problem corresponds to $1.38 \cdot 10^{46}$. Due to this large number of possible combinations, the use of metaheuristic techniques is justified to obtain the optimum. In total, 34 variables are considered for the global definition of this bridge optimization problem. These bridge variables have been represented in Figure 1. According to the nature of the variables, they can be grouped into six categories. The first correspond to transverse section geometric variables, which are: upper distance between wings (b), wings and cells angle (α_w), top slab thickness (h_s), beam depth (h_b), floor beam minimum high (h_{fb}), top flange thickness (t_{f_1}), top flange width (b_{f_1}), top cells high (h_{c_1}) and thickness (t_{c_1}), wing thickness (t_w), bottom cells high (h_{c_2}), thickness (t_{c_2}), and width (b_{c_2}) and bottom slab thickness (h_{s_2}). Beam depth bounds correspond to L/40 and L/25, being L, the largest span length.

SCCB can take advantage of materials to a greater extent because each material that makes it up is subjected to the stresses that best resist. This would be true in an SCCB working as an isostatic girder. In this case, the upper concrete slab would be compressed along the entire length of the bridge. This upper slab is connected to the top flanges by shear connectors. This would also stiffen the flanges plate, which avoids buckling. Moreover, in the isostatics case, the lower flanges would be subjected to tensile stress, which also avoids buckling instability phenomena. However, in the present case and with the usual loads to which the bridges are subjected (which are mostly gravitational in nature), negative bending stresses will occur

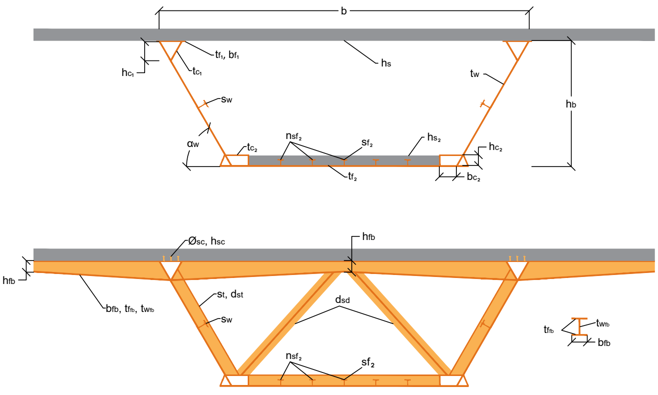

Figure 1: Transverse section variables for SCC bridge

in supported areas. This will result in a reversal of the forces, and therefore tensile stresses in the upper concrete slab and the compression in the lower flange. In this case, to improve the behavior of the bridge transverse section, it has been decided to materialize a concrete bottom slab in these areas in addition to the usual increasing of the top slab reinforcement. To optimize the top slab reinforcement, it has been divided into a base reinforcement that is the minimum required by regulations (CEN 2013a, CEN 2013b, CEN 2013c) and two more areas, in negative bending sections, where the reinforcement is increased. The bottom slab and reinforcement increasing area lengths have been described in section 2.1.2. Accordingly, the second group of variables corresponds to base reinforcement, first reinforcement and second reinforcement bar diameters (ϕ_{base}, ϕ_{r_1}, ϕ_{r_2}), and the corresponding bar number of the reinforcement areas (n_{r_1}, n_{r_2}).

The next variable group correspond to stiffeners. The elements considered in these work as stiffeners are half IPE profiles for wings (s_w), bottom flange(s_{f_2}) and the transverse ones (s_t). For bottom flange stiffeners, the number of stiffeners ($n_{s_{f_2}}$) has also been considered as a variable. As can been seen in Figure 1, there are two more variables that define the distance between diaphragms (d_{sd}) and transverse stiffeners (d_{st}).

The last categories correspond to floor beam variables geometry, the shear connector's characteristics and the materials' grades. Floor beam variables are defined by the floor beam width (b_{fb}), and the flanges ($t_{f_{fb}}$) and wing ($t_{w_{fb}}$) thicknesses. The shear connectors have been defined by their height(h_{sc}) and diameter (ϕ_{sc}). Finally, the yield stress from rolled steel (f_{yk}), concrete strength (f_{ck}) and reinforcement steel bars yield stress (f_{sk}) complete the variable definition. The variables are the same for all the spans of the bridge.

Table 2: Design variables and boundaries

Variables	Unit	Lower Bound	Increment	Upper Bound	Values number
b	m	7	0.01	10	301
α_w	deg	45	1	90	46
h_s	mm	200	10	400	21
h_b	cm	250 (L/40)	1	400 (L/25)	151
h_{fb}	mm	400	100	700	31
t_{f_1}	mm	25	1	80	56
b_{f_1}	mm	300	10	1000	71
h_{c_1}	mm	0	1	1000	101
t_{c_1}	mm	16	1	25	10
t_w	mm	16	1	25	10
h_{c_2}	mm	0	10	1000	101
t_{c_2}	mm	16	1	25	10
b_{c_2}	mm	300	10	1000	71
t_{f_2}	mm	25	1	80	56
h_{s_2}	mm	150	10	400	26
$n_{s_{f_2}}$	u	0	1	10	11
d_{st}	m	1	0.1	5	41
d_{sd}	m	4	0.1	10	61
b_{fb}	mm	200	100	1000	9
$t_{f_{fb}}$	mm	25	1	35	11
$t_{w_{fb}}$	mm	25	1	35	11
n_{r_1}	u	200	1	500	301
n_{r_2}	u	200	1	500	301
ϕ_{base}	mm	6, 8, 10, 12, 16, 20, 25, 32			8
ϕ_{r_1}	mm	6, 8, 10, 12, 16, 20, 25, 32			8
ϕ_{r_2}	mm	6, 8, 10, 12, 16, 20, 25, 32			8
s_{f_2}	mm	From IPE 200 to IPE 600*			12
s_w	mm	From IPE 200 to IPE 600*			12
s_t	mm	From IPE 200 to IPE 600*			12
h_{sc}	mm	100, 150, 175, 200			4
ϕ_{sc}	mm	16, 19, 22			3
f_{ck}	MPa	25, 30, 35, 40			4
f_{yk}	MPa	275, 355, 460			3
f_{sk}	MPa	400, 500			2

*Following the standard series of IPE profiles (CEN 2017).

2.1.2 *Parameters*

In every optimization problem, some variables or properties need to be fixed to narrow down the problem. These fixed variables are named parameters and they remain invariant during the whole optimization process. In this case, these parameters correspond to boundaries that are defined to some bridge elements, including dimension, thicknesses, reinforcement distributions, external ambient conditions, or density (among others). The values of these parameters are summarized in Table 3.

Table 3: Optimization problem main parameters

Geometrical parameters		
Bridge deck width (W)	16	m
Span number	3	
Central span length	100	m
External span length	60	m
Minimum web thickness ($t_{w_{min}}$)	15	mm
Minimum flange thickness ($t_{f_2 min}$)	25	mm
Reinforcement cover	45	mm
Material parameters		
Maximum aggregate size	20	mm
Concrete longitudinal strain modulus (E_{cm})	$22 \cdot ((f_{ck}+8)/10)^3$	MPa
Concrete transverse strain modulus (G_{cm})	$E_{cm}/(2 \cdot (1+0.2))$	MPa
Steel longitudinal strain modulus (E_s)	210000	MPa
Steel transverse strain modulus (G_s)	80769	MPa
Regulation requirement parameters		
Regulations	Eurocodes, IAP-11	
Exposure environment	XD2	
Structural class	S5	
Service life	100	years
Loading parameters		
Reinforced concrete density	25	kN/m^3
Steel density	78.5	kN/m^3
Asphalt density	24	kN/m^3
Asphalt layer thickness	100	mm
Bridge traffic protections	5.6	kN/m
Traffic, thermal and wind load	According to Eurocode 1 (CEN 2019)	

As mentioned earlier, this optimization problem corresponds to a 60-100-60 meters three-span box-girder steel-concrete composite bridge with a deck width (B) of 16 meters without depth variation. In the transverse section, it has been defined by four cells: two on the upper side of the wings and two more on the bottom; as can be seen in Figure 1. These cells allow these parts of the wing to be stiffened, creating a sheet of class one to three that does not need to be reduced according to Eurocodes (CEN 2013a, CEN 2013c). To allow the optimization process to define if these cells improve the structural behavior of the transverse section (and consequently are relevant to obtain a minimum of the objective function), the minimum height of these cells is fixed to zero. The boundaries of all of the variables, including the cells heights (h_{c1}, h_{c2}), can be seen in Table 2. The variable's boundaries have been defined following Monleón bridge design publication (Monleón 2017). The cell height(h_{c1}, h_{c2}) defines the floor beam depth in the zone of contact with the wings. If the cell height is smaller than the floor beam minimum depth (h_{fb}), then it takes that minimum value for beam depth in that zone. Profiles placed to materialize the diaphragm sections are 2L 150x15. Furthermore, precast pre-slabs have been considered for use as a formwork. It should be noted that this element is designed to be part of the resistant section. Therefore, the measurement module of the software subtracts it from the total amount of concrete.

Base reinforcement for both the upper and the lower concrete slabs is obtained according to the minimum need for reinforcement defined in Eurocode 2 (CEN 2013c). The connection between the steel beam and concrete slab is dimensioned to resist the hole tension of the concrete slab considering the effective width that is given by Eurocode 4 (CEN 2013a) due to shear lag. Because the only width considered as resistant (both in the concrete slab and in the lower flange) is effective, the defined steel bar reinforcement is placed only in that width.

To optimize some material in SCCB, it is usual to modify the thicknesses of webs and flanges to reduce its amount. In this work, the variation of thicknesses has been programmed by considering a theoretical bending and shear law for a distributed load over the entire surface of the bridge. In Figure 1, the lower flange thickness is modified along the bridge, varying from a minimum value $t_{f_2 min}$ to the one defined as t_{f_2}. This variation corresponds to the bending theoretical law. In contrast, the wing's thickness varies according to the shear law from $t_{w_{min}}$ to t_w. The minimum value of these thicknesses is been defined according to recommendations in Monleón (Monleón 2017).

Finally, steel bar reinforcements and lower slab areas are defined. The lower slab is placed in negative bending sections to mobilize the composite dual action in these sections. To define lengths where negative bending can be produced, we have considered the distance defined by Eurocode 4 (CEN 2013a) for shear lag stresses that correspond with one-third of the span length. As stated earlier, it is neces-

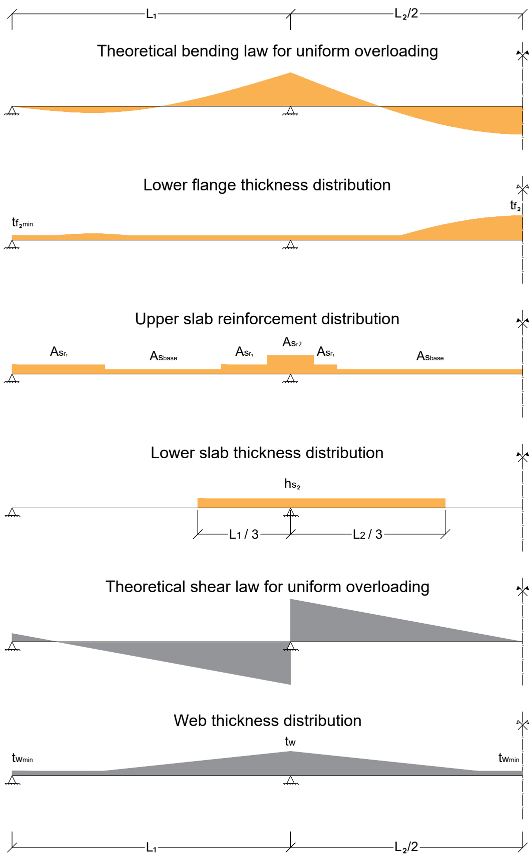

Figure 2: Longitudinal distribution of thicknesses and steel bar reinforcements

sary to increase the upper slab reinforcement to resist the tension stresses produced. In this case study, we have considered two reinforcement areas. The first is placed in zones where the section can be subjected to negative bending and base reinforcement cannot resist the stresses. The second is placed on top of supports, corresponding to one-third of the distance between the support and the point of change of sign of the bending of the theoretical law. This decision is related to the position of the center of gravity of the parabola, which is at one-third of its total length. Figure 2 shows the top slab's reinforcement distributions.

2.2 *Structural Analysis*

As mentioned in section 2, optimization procedures must complain about the constraints imposed on the problem. In bridge optimization, these constraints are imposed by the regulations (CEN 2013a, CEN 2013b, CEN 2013c) and recommendations (Vayas & Iliopoulos 2017, Monleón 2017).

Constraints imposed by regulations can be divided into two main groups: the Ultimate Limit States (ULS) and Serviceability Limit States (SLS). The first group is related to the structural resistance of bridge elements subjected to the stresses caused by the acting loads. Moreover, SLS is related to restrictions that ensure the serviceability of the structure during its service life. All of the loads applied and their combination are defined in regulations (CEN 2019). Table 3 summarizes the load cases that we have considered.

To check ULS for all bridge elements, we have considered both global and local analysis. The checks considered for global analysis include flexure, shear, torsion, and flexure-shear interaction. A linear elastic analysis has been used considering the complete section to obtain the dead weights and stresses. To get section resistance, the effective section has been considered by applying both reductions due to shear lag (CEN 2013a) and section reduction of the steel plates classified as class 4 (CEN 2013b). To attain this, a precision of 10^{-6} meters has been imposed for the iterative process. To obtain the value of the mechanical characteristics of the homogenized section, the relationship (n) between the modulus of longitudinal deformation of concrete (E_{cm}) and steel (E_s) has been obtained according to equation 3. Concrete creep and shrinkage has been considered according to regulations (CEN 2013c, CEN 2013a). Furthermore, a local model has been considered to check ULS in floor beams, stiffeners, and diaphragms by considering flexure, shear, buckling, and minimum mechanical characteristics checks.

$$n = \frac{E_s}{E_{cm}} \tag{3}$$

The SLS considered for the analysis is the tension limit for materials, fatigue, and deflection. There is no clear limit for deflection in Eurocodes but the IAP-11 Spanish regulation (MFOM 2011) gives a maximum of $L/1000$ for the frequent combination of live loads deflection value, with L representing the span length. This has been considered as the maximum value of the deflection. In addition, we have considered geometrical and constructibility requirements.

A numerical model has been implemented in the Python (Van Rossum & Drake 2009) programming language to get the stresses and carry out all ULS, SLS, and geometrical and constructibility checks defined in regulations (CEN 2019, CEN 2013c, CEN 2013b, CEN 2013a) and recommendations (Monleón 2017, Vayas & Iliopoulos 2017). To get the deflections and stresses, this software applies the perfect embedding forces method considering the vertical displacements (U_z) and the rotations between y and x (θ_y, θ_x) axes, taking as input data the 34 bridge variables defined in section 2.1.1 and the loads defined in regulations. To obtain the effects due to the moving loads, each bridge span has been loaded separately and all possible combinations between them have been carried out to obtain their envelope. This software divides every bridge span into a defined number of bars. In this case, the total number of bars is 44, distributed in 12-20-12 corresponding to the three spans of the bridge; thus, discretizing the bridge into 5-meter length bars. Once the stresses have been obtained, the program performs structural checks and returns the results of measurements, cost, CO_2 emissions, and checking coefficients. This checking coefficients correspond to the quotient between the design values of the effects of actions (E_d) and its corresponding resistance value (R_d), as shown in equation 4. If these coefficient values are greater or equal than one, then the section complies with the imposed restriction.

$$\frac{R_d}{E_d} \geq 1 \tag{4}$$

2.3 *Threshold Accepting with a Mutation Operator (TAMO2)*

Threshold Accepting (TA) was developed by Duec and Scheuer (Dueck & Scheuer 1990) as an alternative to Kirpatricks' Simulated Annealing (SA) (Kirkpatrick, Gelatt, & Vecchi 1983). both metaheuristics are within the group of trajectory based. These algorithms vary the problem variables and compare the objective functions obtained, the reject or acceptance of the new solution depend in the criteria chosen. SA applies an acceptation criteria formula that gives the new solution a probability to be chosen even worsening the objective function value. TA applies a simpler criterion applying directly a threshold where the solution is directly accepted if its objective function value is inside. This acceptance of bad solutions adds exploration to the optimization process and allow to avoid local optimums. While the optimization process is being performed the threshold is reduced in order to exploit the optimum neighborhood. In this study it have been applied Threshold Accepting with a Mutaton Operator (TAMO) (Luz, Yepes, González-Vidosa, & Martí 2015). This algorithm, as the original TA, starts with a random solution and an initial threshold. The difference lies in the fact that in each iteration the solution new solution have a possibility to be modified simulating the mutations of genetic algorithms. This modification allow to add exploration to the optimization process.

TAMO algorithm has certain parameters that allow to adjust it to the problem being solved. This parameters are: Variables Number (VN), Chain Length (CL), Standard Deviation for mutation operator (SD), Cooling Coefficient (CC) and Unimproved Chains (UC). VN limit the number of variables changed in each iteration. CL define the number of iterations run for each threshold. SD is related with the probability of mutation of the solution by the mutation operator. CC define the threshold reduction when the CL is reached. Finally, the UC define the number of chains without improvement allowed before the optimization process is ended. In addition to UC, if the threshold arrives to 0.05% of the initial, then the optimization process is also finished. The parameters chosen for this optimization problem have been those described in table 4

CL	SD	VN	CC	UC
1000	0.3	1	0.95	1

Table 4: Parameters chosen for the optimization with TAMO algorithm

3 RESULTS

Results obtained for the optimization will be shown in this section. To get this results, TAMO algorithm have been run 9 times in order to study the differences between the solutions reached. In average, one solution obtaining have a computational cost of 23958 seconds. The TA algorithm parameters chosen for the optimization have been described in section 2.3.

Variable results will be divided in three main categories, in line with the three types of defined variables. This three groups will those related with geometrical, reinforcement and materials resistance variables.

In figure 3 the main geometrical parameters obtained for cross section have been shown. It can be seen that an optimal design for this case study takes depth values for the steel beam (h_b) between 2.9 and 3.4 m with a web angle (α_w) range between 63 and 73 decimal degrees. regarding the distance between transverse stiffeners and diaphragms the values obtained form the optimization process range between 2.6 and 4.2 for transverse stiffeners and 6.3 and 8.7 m for diaphragms. The following parameters define the webs and flanges thicknesses. The algorithm gives clear results of these element thicknesses being 25 mm for upper (t_{f_1}) and lower (t_{f_2}) flanges and 16 for the web. This values correspond with the lower bound given to the algorithm. The same occurs with the upper flange width b_{f_1} that takes the a value of 300 mm also corresponding with the lower bound.

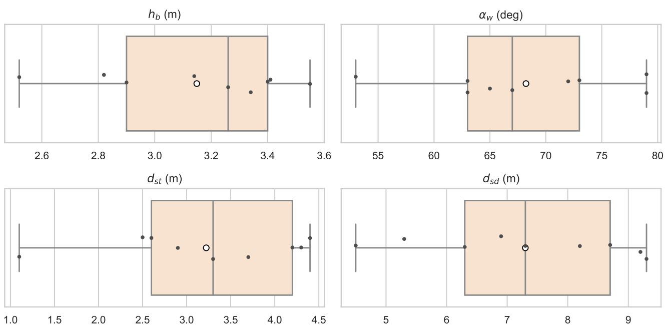

Figure 3: Cross section geometrical variables for cost TAMO optimization

The following geometrical variables are those that define the upper and lower cells geometry. This cells have been added in order to reduce the distance of web plates to improve its bending behavior. The distance between stiffened parts is reduced with this elements and as a consequence increases the area which can be considered according the section reduction method of Eurocode 2 (CEN 2013c). As it can be seen in figure 4, both cells heights (h_{c_1}, h_{c_2}) values are different to zero which means that the optimization process has taken as a result an improvement in adding the cells. Regarding these elements thicknesses the upper cell thickness (t_{c_1}) takes the lower bound value of 16 mm in all cases, while the lower cell (t_{c_2}) ranges between 20 to 23 mm. Regarding bottom flange stiffeners the algorithm removes them by adding the concrete slab on supports.

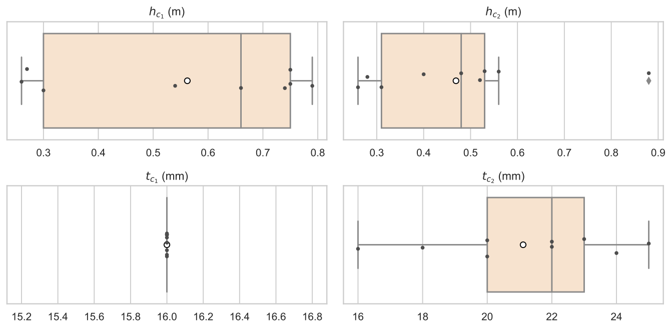

Figure 4: Cell variables results for cost TAMO optimization

The last results related with sections geometry are related with floor beams that controls the transversal bending behaviour. In this case study, the optimum geometry for these elements considers heights from 0.45 to 0.56 m with thicknesses of its elements rounding 30 mm.

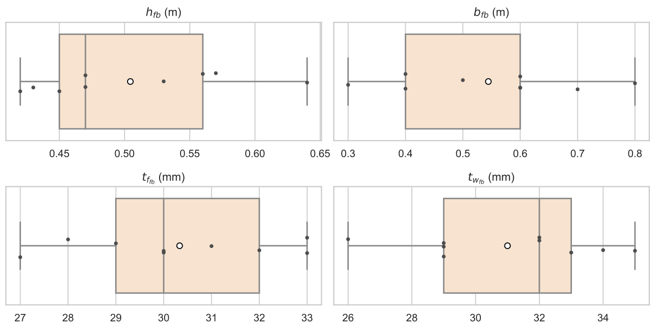

Figure 5: Floor beam variables results for cost TAMO optimization

Following variables are related with reinforcement of the upper slab. The areas where the lower slab has been placed to mobilize the double composite action contains the base reinforcement needed according regulations (CEN 2013b), since are basically going to be compressed. Regarding the reinforcement the optimization procedure takes as a result low diameter bars with a higher amount in order to reduce the reinforcement to the minimum. As a consequence the software add a third layer of reinforcement in the upper slab. The resistance of materials given by the optimization procedure takes 25 MPa for concrete, 275 MPa for rolled steel and 500 MPa for reinforcement bar steel.

4 CONCLUSIONS

In bridge design, there is a clear trend to consider new techniques to obtain new structural design alternatives. Consequently, optimization of concrete bridges

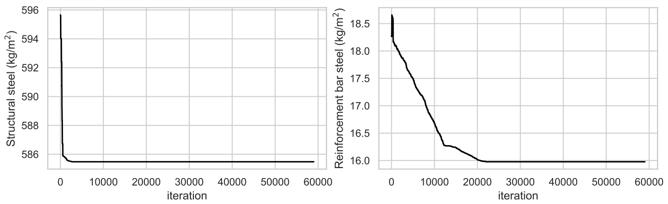

Figure 6: Reinforcement bars and structural steel amounts for cost TAMO optimization

using algorithms has been developed to a large extent. In contrast, optimization studies of composite steel-concrete bridges are few and the performance of these techniques for this type of structure is not known. Threshold Accepting (TA), which belongs to the trajectory-based algorithms, has been proposed as an algorithm to carry out the optimization of the structure.

This study shows the optimization of a steel-concrete composite box-girder bridge by using heuristic techniques. In conclusion, it has been observed that the algorithm eliminates the stiffeners of the lower wings due to the double composite action of the concrete slabs on the supports. In addition, the use of interior cells in the bridge section has been considered. As a result for these elements variables the optimization process gives positive values confirming that these cells allow improving the stress resistances of the section and reducing the distance between unstiffened zones in the web steel plates. This work allows the structural researcher to broaden his knowledge on the optimization of composite bridges by considering new techniques to obtain an optimal design, and opens a door to the use of these elements to obtain new design criteria to obtain more sustainable and efficient composite bridge alternatives.

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REFERENCES

BEDEC (accessed on January 2021). BEDEC ITEC *Materials Database https://metabase.itec.cat/vide/es/bedec*. Catalonia Institute of Construction Technology.

CEN (2013a). *Eurocode 2: Design of concrete structures*. Brussels, Belgium: European Committee for Standardization.

CEN (2013b). *Eurocode 3: Design of steel structures*. Brussels, Belgium: European Committee for Standardization.

CEN (2013c). *Eurocode 4: Design of composite steel and concrete structures*. Brussels, Belgium: European Committee for Standardization.

CEN (2017). *EN 10365:2017: Hot rolled steel channels, I and H sections. Dimensions and masses*. Brussels, Belgium: European Committee for Standardization.

CEN (2019). *Eurocode 1: Actions on structures*. Brussels, Belgium: European Committee for Standardization.

Dueck, G. & T. Scheuer (1990). Threshold accepting: A general purpose optimization algorithm appearing superior to simulated annealing. *Journal of Computational Physics 90*(1), 161–175.

García-Segura, T., V. Yepes, & D. M. Frangopol (2017). Multi-objective design of post-tensioned concrete road bridges using artificial neural networks. *Structural and Multidisciplinary Optimization 56*, 139–150.

Hare, W., J. Nutini, & S. Tesfamariam (2013). A survey of non-gradient optimization methods in structural engineering. *Advances in Engineering Software 59*, 19–28.

Kaveh, A., T. Bakhshpoori, & M. Barkhori (2014). Optimum design of multi-span composite box girder bridges using cuckoo search algorithm. *Steel and Composite Structures 17*(5), 703–717.

Kaveh, A. & M. M. M. Zarandi (2019). Optimal design of steel-concrete composite i-girder bridges using three meta-heuristic algorithms. *Periodica Polytechnica Civil Engineering 63*(2), 317–337.

Kirkpatrick, S., C. D. J. Gelatt, & M. P. Vecchi (1983). Optimization by simulated annealing. *Science 220*(4598), 671–680.

Luz, A., V. Yepes, F. González-Vidosa, & J. V. Martí (2015, dic.). Diseño de estribos abiertos en puentes de carretera obtenidos mediante optimización híbrida de escalada estocástica. *Informes de la Construcción 67*(540), e114.

Lv, N. & L. Fan (2014). Optimization of quickly assembled steel-concrete composite bridge used in temporary. *Modern Applied Science 8*(4), 134–143.

Martí-Vargas, J. R., F. J. Ferri, & V. Yepes (2013). Prediction of the transfer length of prestressing strands with neural networks. *Computers and Concrete 12*(2), 187–209.

Martínez-Muñoz, D., J. V. Martí, J. García, & V. Yepes (2021). Embodied energy optimization of buttressed earth-retaining walls with hybrid simulated annealing. *Applied Sciences 11*(4), 1800.

Martínez-Muñoz, D., J. V. Martí, & V. Yepes (2020). Steel-concrete composite bridges: Design, life cycle assessment, maintenance, and decision-making. *Advances in Civil Engineering 2020*, 8823370.

Martínez-Muñoz, D., J. V. Martí, & V. Yepes (2021). Comparative life cycle analysis of concrete and composite bridges varying steel recycling ratio. *Materials 14*(15), 4218.

MFOM (2011). *IAP-11: Code on the actions for the design of road bridges*. Madrid: Ministerio de Fomento.

Molina-Moreno, F., T. García-Segura, J. V. Martí, & V. Yepes (2017). Optimization of buttressed earth-retaining walls using hybrid harmony search algorithms. *Engineering Structures 134*, 205–216.

Molina-Moreno, F., J. V. Martí, & V. Yepes (2017). Carbon embodied optimization for buttressed earth-retaining walls: Implications for low-carbon conceptual designs. *Journal of Cleaner Production 164*, 872–884.

Monleón, S. (2017). *Diseño estructural de puentes (in Spanish)*. València: Universitat Politècnica de València.

Musa, Y. I. & M. A. Diaz (2007). Design optimization of composite steel box girder in flexure. *Practice Periodical on Structural Design and Construction 12*(3), 146–152.

Payá-Zaforteza, I., V. Yepes, F. González-Vidosa, & A. Hospitaler (2010). On the weibull cost estimation of building frames designed by simulated annealing. *Meccanica 45*(5), 693–704.

Penadés-Plà, V., T. García-Segura, J. V. Martí, & V. Yepes (2018). An optimization-lca of a prestressed concrete precast bridge. *Sustainability 10*(3), 685.

Penadés-Plà, V., T. García-Segura, & V. Yepes (2019). Accelerated optimization method for low-embodied energy concrete box-girder bridge design. *Engineering Structures 179*, 556–565.

Penadés-Plà, V., D. Martínez-Muñoz, T. García-Segura, I. J.

Navarro, & V. Yepes (2020). Environmental and social impact assessment of optimized post-tensioned concrete road bridges. *Sustainability 12*(10), 4265.

Sarma, K. C. & H. Adeli (1998). Cost optimization of concrete structures. *Journal of Structural Engineering 124*(5), 570–578.

Van Rossum, G. & F. L. Drake (2009). *Python 3 Reference Manual*. Scotts Valley, CA: CreateSpace.

Vayas, I. & A. Iliopoulos (2017). *Design of steel-concrete composite bridges to Eurocodes*. Boca Raton: CRC Press.

Yepes, V., M. Dasi-Gil, D. Martínez-Muñoz, V. J. López-Desfilis, & J. V. Martí (2019). Heuristic techniques for the design of steel-concrete composite pedestrian bridges. *Applied Sciences 9*(16), 3253.