International Journal of Bridge Engineering (IJBE), Vol. 5, No. 2, (2017), pp. 1-20

COMPOSITE BRIDGES: STUDY OF PARAMETERS TO OPTIMIZED DESIGN

Ricardo Fabeane[1], Moacir Kripka[2] and Zacarias M. Chamberlain Pravia[3]

[1,2,3] University of Passo Fundo, Civil and Environmental Engineering
Graduate Program, Brazil
e-mail: ricardo.fabeane@gmail.com, mkripka@upf.br, zacarias@upf.br

ABSTRACT: The present study aimed to supply parameters that lead to optimized design in composite bridges. To achieve the proposed objectives has been formulated an optimization problem which aims to reduce the cost of bridge cross section by varying the dimensions of the steel girders. The implementation of the proposed formulation has been done by creating a design routine in MS Excel and using the Solver to find the optimized sections to the girders. The specification used in the analysis and design of the girders has been the AASHTO (2012), and the cases studied are of simple span bridges with different spans and a variable number of steel girders in its cross section. The results obtained enabled identification of parameters aimed at the optimized design of composite bridges, showing that the use of criteria based on optimization techniques can lead to a significant reduction in the cost of the structures.

KEYWORDS: Bridges; Composite bridges; Composite structures; Design; Optimization.

1 INTRODUCTION

It’s known by all the high financial value that is associated to a bridge construction. The need to construct this kind of structure minimizing the necessary time and the cost is an antique question to the society. In the last years, to these goals has been added the need to develop projects that have a minimum environmental cost.

A structural system that has a large potential to achieve this goals is the steel-concrete composite system, which works taking advantage of the main characteristics of both materials: the high industrialization, the geometry flexibility, the precision and the high tension resistance of steel elements; combined with the good compression resistance, economic cost lower, high mass and stability of concrete.

Based on this, one can see that is extremely important that the structural engineer knows in the design phase the characteristics of the composite bridges with minimized cost, so that it can replicate these parameters to always obtain gains in construction time, natural resources and financial costs. The main gains associated to these goals can be attributed to the simplicity of the bridge geometry and the minimization of the material consumed on its construction.

Regarding optimization, it can be understood like an exploratory action done to obtain the best possible solution about a problem under specific circumstances. The main objective of any optimization work is related to the minimization or maximization of a predefined function that can represent a geometric property, a cost value, among a lot of other possibilities of application.

On general, the optimization problems are presented in this manner: Find $X = \{X_1, X_2, \ldots, X_n\}^T$ that minimize (or maximize) the function $f(X)$ under the following constraints:

$$g_j(X) \leq 0, \qquad j = 1, 2, \ldots, m \tag{1}$$

$$l_j(X) = 0, \qquad j = 1, 2, \ldots, p \tag{2}$$

$$X_i^l \leq X_i \leq X_i^u \tag{3}$$

The *f(X)* represents the objective function of the problem, i.e., the criterion on which the problem in optimized when expressed based on the project variables, which can represent situation of cost or weight minimization, or efficiency maximization, for example. The Eq. (1)-(3) represent constraints that shall be respected in the project so that the obtained optimum solution can be possible and adequate for use. The Eq. (1)-(2) are called inequality and equality constraints, respectively, while the Eq. (3) is called lateral restriction.

In Engineering, the classical examples of optimization studies are related to minimization of airplanes weight, the efficiency maximization of heat transfer systems and turbines, the minimization of building costs, and others. To the present study the optimization will be applied to minimize the weight of the girder sets present in the bridge cross section.

The interest by definition of parameters that conduce optimized projects of composite multi-girders highway bridges is an antique question although the number of studies associated to this theme is still small. The main studies that apply optimization techniques in search of the best results are the works of Memari, West and Cavalier [1], Toma and Maeda [2], and Salman *et al.* [3]. Furthermore, some of the works do not apply optimization techniques to search the optimum solution, basing their results in practice experiences or treating as optimization the result of the comparison of two (or more) situations evaluated, like is the case of the works of Knight [4], Bhatti and Al-Gahtani [5] e Gocál and Dursová [6], for example. Other interesting works related to optimization of different bridges models are Ghasemi and Dizangian [7]; Mohammadzadeh and Nouri [8]; Xie *et al.* [9]; Kaveh, Bakhshpoori and Barkhori [10]; and Kutylowski and Rasiak [11].

This study is structured in the following way: the item 1 (current item) presents a brief introduction about the theme; in item 2 is presented the formulation for the optimization problem; in item 3 are presented the characteristic of the used bridge model and the realized studies; ultimately, in item 4 the conclusions obtained from the studies are presented.

2 FORMULATION OF THE OPTIMIZATION PROBLEM

The search by minimization of the cost per meter of bridge superstructures shall be done taking into account the unit costs and the quantities of materials composing its structural system. To the specific case of composite bridges, the superstructure cost is obtained summing the parts referred to the steel used in the girders, the reinforcement and the concrete used in the deck.

Among to the materials previously cited, the steel girders represent the major part of the cost function because of the elevated cost of its raw material and its fabrication, the transportation of the elements, the need to use heavy equipment and specialized teams during its construction phase, and other reasons.

Taking into account the importance of the steel girders in the cost, it is understood that search the optimum section for these elements are equivalent to obtain a solution with optimized cost for the system. Based on this, the actual study exclusively deals with to minimize of the weight per meter of the steel girders sets.

The search by the optimum sections has been done by the use of a spreadsheet implemented in MS Excel for structural design of simple span composite bridges. The optimization method used in the study was the Generalized Reduced Gradient (GRG) Nonlinear available in the Solver of MS Excel.

2.1 Design variables

In the Fig. 1 it is showing the cross section dimensions for the exterior and interior girders of composite bridges. Because the weight per meter of the girders is directly related with its cross section dimensions, these dimensions will be taken as variables of the optimization problem.

The variables in Fig. 1 are:

- d: total depth of steel girders. This parameter constitutes a variable just for the girders in major number in the bridge cross section (external girders for bridges with 3 girders and internal girders for the other cases – for bridges with 4 girders, after some previous studies, it was realized that the best results were obtained when the girder’s depth was varied for the internal girders). The depth used for the girders in minor number is the same obtained for the girders in major number, not being an optimization variable in this case.
- b_f ($b_{f,se}$; $b_{f,ie}$; $b_{f,si}$; $b_{f,ii}$): Width of top and bottom flanges of exterior and

interior girders;

- t_f ($t_{f,se}$; $t_{f,ie}$; $t_{f,si}$; $t_{f,ii}$): Thickness of top and bottom flanges of exterior and interior girders;
- t_w ($t_{w,e}$; $t_{w,i}$): Web thickness of exterior and interior girders;

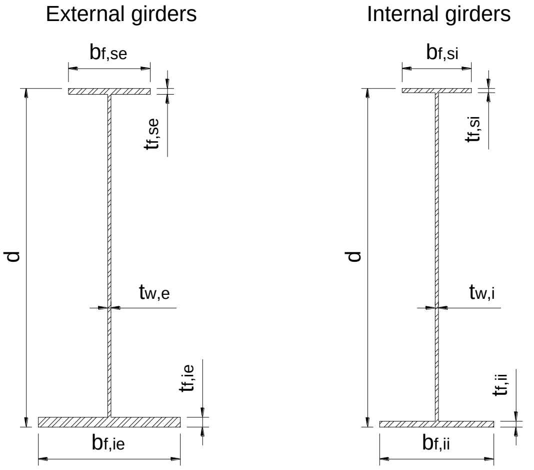

Figure 1. Dimensions of girder cross section

2.2 Objective function

The objective function treated in this study is shown in Eq. (4):
Minimize:

$$P(X)=\left\{\begin{matrix}2\times\left[(d-t_{f,se}-t_{f,ie})\times t_{w,e}+(b_{f,se}\times t_{f,se})+(b_{f,ie}\times t_{f,ie})\right]\\+(N_g-2)\times\left[(d-t_{f,si}-t_{f,ii})\times t_{w,i}+(b_{f,si}\times t_{f,si})+(b_{f,ii}\times t_{f,ii})\right]\end{matrix}\right\}\times\gamma_{steel} \qquad (4)$$

From Eq. (4) it follows that *P(X)* represents the weight per meter of the girder sets in the bridge cross section (in kgf/m), N_g is the number of girders and γ_{steel} represent the steel specific weight [$7.85\text{x}10^{-3}$ (kgf/mm^3.mm/m)]. The other variables are referred to the girder dimensions, like previously shown in Fig. 1, used in Eq. (4) with the unit of millimeters (mm).

2.3 Design constraints

Once that already know the variables and the objective function of the optimization problem remain only formulate the restrictions, which define the intervals of values that the variables can assume for which the obtained solutions can be applied in practical cases.

For the girder's depth is used like minimum value (d_{min}) the limits indicated by the AASHTO [12] specification to guarantee that this dimension is above values that demonstrated undesirable behavior in the past. Like upper limit will be used the depth of 3200mm taking into account that above this dimension the transport of the girders become more expensive, requiring the monitoring of scouts. Thus, the lateral restrictions for the girder's depth are those shown in Eq. (5).

$$d_{\min} \le d \le 3200mm \tag{5}$$

For the thickness of the elements, the limits are presented in Eqs. (6)-(11). The lower limit (8mm) is referred to an exigency of AASHTO [12] specification that does not permit the use of thicknesses below the cited in principal members of the structures (except for hot rolled sections). The upper limit (37.5mm) is used because thicknesses above the mentioned are slightly more difficult to be find and are more expensive.

$$8mm \le t_{f,se} \le 37.5mm \tag{6}$$

$$8mm \le t_{w,e} \le 37.5mm \tag{7}$$

$$8mm \le t_{f,ie} \le 37.5mm \tag{8}$$

$$8mm \le t_{f,si} \le 37.5mm \tag{9}$$

$$8mm \le t_{w,i} \le 37.5mm \tag{10}$$

$$8mm \le t_{f,ii} \le 37.5mm \tag{11}$$

The limits for flanges width are presented in Eqs. (12)-(15). The use of 200mm like lower limit is based on the fact that below this value the assembly of deck pre-slab (or forms) turns more difficult. For other hand, the upper limit (900mm) is due a limitation of AASHTO [12] specification about the local slender of the section flanges, where the relation bf/(2tf) shall be equal or inferior to 12, and the value of 900mm is the upper limit for the maximum plate thickness used in this study.

$$200mm \le b_{f,se} \le 900mm \tag{12}$$

$$200mm \le b_{f,ie} \le 900mm \tag{13}$$

$$200mm \le b_{f,si} \le 900mm \tag{14}$$

$$200mm \le b_{f,ii} \le 900mm \tag{15}$$

It's necessary to highlight that the number of girders in the bridge cross section (N_g) will not be a variable altered by the optimization method, being this value adjusted before starting the optimization process.

The sets of checks done during the design process, whose maximum value represent the value of $R_{máx}$ [Eq. (16)] is composed by the following checks:

- Cross section proportion limits of the girders according with item 6.10.2 of AASHTO specification: web depth to thickness ratio, flanges width to thickness ratio, depth of web to width of flanges, thickness of flanges and thickness of web, ratio between the moments of inertia of the compression flange to tension flange of the steel section about the vertical axis in the plane of the web;

- Ductility check of the girder’s cross section according to the item 6.10.7.3 of the AASHTO specification;
- Flexure resistance of the composite girders (compact and noncompact steel sections) according to the item 6.10.7 of AASHTO specification;
- Shear resistance of the girder's web according to the item 6.10.9 of the AASHTO specification
- Fatigue check of the girders (in the region of the toe of fillet welds in transverse stiffener, in the base metal and weld metal in the weld between the web and tension flange, region of bolted splices between the parts that compose the girders and according to the special fatigue requirement for the web of girders). The special fatigue requirement for the web of the girders is checked according to the 6.10.5.3 of the AASHTO specification, while the other checks are made according to the item 6.6.1 of the same specification;
- Check of the girders during the construction phase (considered after the launching and positioning of the girders) when only the girders (in the noncomposite condition) resists to all efforts from dead load of the elements and deck slab after concrete pouring until concrete curing. The guidelines used in the verifications are based on the item 6.10.8 of the AASHTO specification.

$$R_{máx} \leq 1.0 \tag{16}$$

3 NUMERICAL SIMULATIONS

3.1 Characteristics of the studied bridges

As the design of any bridge involves a multitude of parameters that can be changed, is big the potential to obtain a lot of structural models for this type of building.

When working with the study of improving this system, an issue to keep in mind is that simulate all variation possibilities of that is extremely costly in time and effort, losing practicality.

Aimed to obtain results that can be applied to the major amount possible of composite bridges with multi girders in its cross sections, it was predefined the bridge models used in the studies. The studies realized consider the variation of few parameters of these models, like will be described later.

The characteristics of the studied bridge models are:

- Number of girders varying from 3 to 7;
- The cross section of the girders are constant along the entire span;
- Possibility to study bridges with exterior and interior girders different or with all the girders equals. Independent of the cases the depth of the girders is held the same.
- Studied spans of 24m, 30m, 36m, 42m and 48m;

- Spacing between the cross frames of the girders to each 6m;
- The girders have only transverse stiffeners spaced to each 3m, except for the extreme 3m where the spacing between the transverse stiffeners is of 1.5m.
- The total width of the bridge deck is of 9.80m (9.0m of roadway and 0.80m of barrier width);
- The lateral overhang of the concrete deck have length of 37.5% of the transversal spacing between the girders, and in its external face supporting the lateral barriers which are considered with the weight of 5.80 kN/m;
- The composite girders don't consider the reinforcement contribution in its flexural strength;
- The steel used for the girder have yielding stress of 345MPa and rupture stress of 450MPa, and the concrete used in the deck have compression strength of 30MPa;
- The deck slab thickness is of 30cm for both the region of overhanging as for the roadway;
- It’s considered that the pavement used in the bridge are done with concrete of 30 MPa and will have thickness of 7cm. It’s yet considered a resurfacing load of 2.0kN/m²;
- It’s considered that the constructive methodology used in the concrete deck will be through the use of pre-slabs with 6cm of thickness as stay-in-place forms;
- It’s considered that during the constructive phase the deck lateral overhangs will have its braces attached directly to the inferior flange of the external girders;
- It’s considered a constructions live load of 1.0kN/m²; It’s considered a miscellaneous load of 0.25kN/m²;
- For the wind load determination it’s considered that the bridge is higher 10m from the ground and is situated in a region classified like *open country;*
- The design vehicle used is the Brazilian design vehicle TB-450 (450kN of vertical load) defined by the Brazilian standard ABNT NBR 7188:2013 [13];
- The traffic characteristics for the fatigue checks of the girders are: Highway class equivalent to *other rurals* of the AASHTO specification and number of lanes available to trucks equal to 3;
- Fatigue check of the elements to a finite fatigue life (by using the load combination *Fatigue II).*

In general the characteristics used on the studied models have been defined based on literature recommendation for condition of lower cost of the system, in standards guidelines and observations done in some executive projects.

3.2 Study of the number of girders in bridge cross section

A study has been done aimed to identify what is the ideal number of girders in the cross section of composite bridges. For this purpose have been done examples for the two extreme spans treated in this study (24m and 48m), with the number of girders in the cross section varying from 3 to 7. Another question covered is the design condition of the girder system, where was evaluate the condition when the exterior and interior girders are different with those in which all the bridge's girders are equal.

The obtained results of this study are presented in Table 1 (for bridges with exterior and interior girders different) and in Table 2 (for bridges with all girders equals). In the Fig. 2 is presented a graphic relating the two evaluated conditions for the span of 24m, while in Fig. 3 is presented the same comparison for the span of 48m.

Table 1. Optimized sections obtained for the condition with exterior and interior girders different

Span (m)	Ng	Exterior girders	Interior girders	Total weight of the girder sets (kgf/m)
		PS x "d" x "tw,e" x "bf,se" x "tf,se" x "bf,ie" x "tf,ie"	PS x "d" x "tw,i" x "bf,si" x "tf,si" x "bf,ii" x "tf,ii"	
24	3	PS 1944 x 12.5 x 331 x 22.4 x 599 x 37.5	PS 1944 x 12.5 x 316 x 16 x 497 x 37.5	1210.3
24	4	PS 1624 x 12.5 x 317 x 22.4 x 550 x 37.5	PS 1624 x 12.5 x 268 x 16 x 442 x 22.4	1276.2
24	5	PS 1384 x 12.5 x 324 x 19 x 540 x 31.5	PS 1384 x 12.5 x 270 x 16 x 418 x 25.4	1372.4
24	6	PS 1238 x 12.5 x 340 x 16 x 470 x 37.5	PS 1238 x 12.5 x 266 x 16 x 346 x 31.5	1537.8
24	7	PS 1151 x 12.5 x 301 x 19 x 440 x 37.5	PS 1151 x 9.5 x 262 x 16 x 458 x 25.4	1598.6
48	3	PS 2649 x 19 x 443 x 31.5 x 866 x 37.5	PS 2649 x 22.4 x 433 x 25.4 x 755 x 31.5	2227.4
48	4	PS 2102 x 19 x 537 x 25.4 x 892 x 37.5	PS 2102 x 16 x 339 x 37.5 x 408 x 31.5	2259.6
48	5	PS 2037 x 16 x 474 x 25.4 x 756 x 31.5	PS 2037 x 16 x 408 x 22.4 x 329 x 37.5	2311.1
48	6	PS 2036 x 16 x 351 x 37.5 x 644 x 31.5	PS 2036 x 16 x 396 x 19 x 333 x 25.4	2521.6
48	7	PS 1878 x 12.5 x 375 x 37.5 x 576 x 37.5	PS 1878 x 12.5 x 391 x 22.4 x 303 x 37.5	2595.8

Table 2. Optimized sections obtained for the condition with all the girders equals

Span (m)	Ng	Exterior and Interior girders	Total weight of the girder sets (kgf/m)
		PS x "d" x "tw" x "bfs" x "tfs" x "bfi" x "tfi"	
24	3	PS 2133 x 16 x 346 x 19 x 456 x 37.5	1339.8
24	4	PS 1825 x 12.5 x 315 x 19 x 535 x 31.5	1413.6
24	5	PS 1499 x 12.5 x 304 x 19 x 410 x 37.5	1538.0
24	6	PS 1210 x 12.5 x 328 x 16 x 484 x 37.5	1783.2
24	7	PS 1516 x 12.5 x 246 x 25.4 x 400 x 25.4	1908.2
48	3	PS 2680 x 19 x 443 x 31.5 x 847 x 37.5	2244.9
48	4	PS 2452 x 19 x 410 x 25.4 x 674 x 37.5	2546.0
48	5	PS 2316 x 16 x 394 x 25.4 x 596 x 31.5	2548.5
48	6	PS 2076 x 16 x 341 x 31.5 x 532 x 37.5	2958.0
48	7	PS 1915 x 12.5 x 400 x 31.5 x 552 x 37.5	3097.5

In addition to the obtained sections, the critical limit states of the girders have been also evaluated, and in most cases the optimized sections presented like critical the combination of fatigue check (in the region of the toe of fillet welds in transverse stiffener) with the resistance of the girders during the construction phase (noncomposite condition).

Like can be observed from Figs. 2-3, the sets of girders with the lower weight per meter are those which have 3 girders, and the most significant growth in the weight of the sets occurs when the number of girders is changed of 5 to 6. It's also possible to observe than the weight of the sets is major as the number of girders increase.

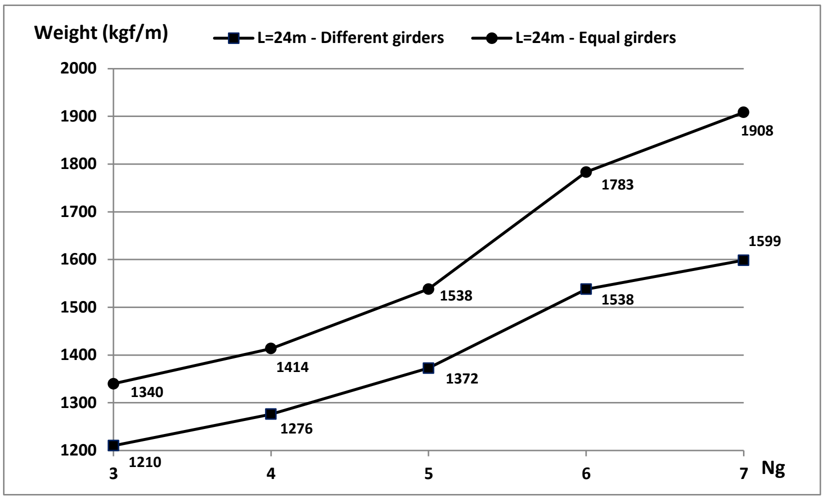

Figure 2. Comparison between the weights of the evaluated conditions for span of 24m

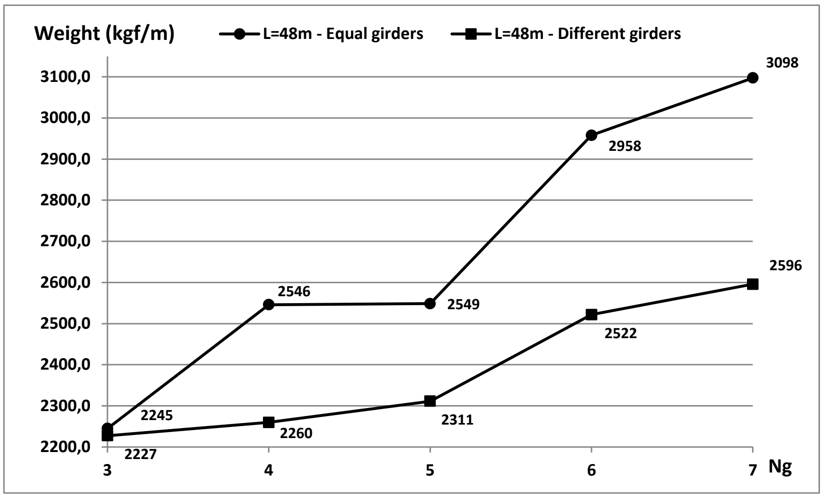

Figure 3. Comparison between the weights of the evaluated conditions for span of 48m

Other important conclusion is related to the economy that can be obtained when working with the condition where the external and internal girders are different in comparison with those in which all the girders are equal. The difference in weight for the conditions was between 10.7% and 19.4% for bridges with span of 24m; and between 10.3% and 19.3% for bridges with span of 48m which uses 4 or more girders. For bridges with span of 48m and with 3 girders the results for both conditions have been practically the same.

3.3 Study of bridge's span variation

To the realization of this study have been utilized bridges with 3 and 4 girders in its cross sections. The choice to use these numbers of girder is because they presented the lowers weights per meter for the sets of girders, like shown previously.

The bridge span has been varied on each 6m between 24m and 48m. Again in this study is evaluated the difference obtained between the condition where the exterior and interior girders are different and those where all the girders are equal.

The results obtained for the studied cases are presented in Table 3 (for bridges with exterior and interior girders different) and in Table 4 (for bridges with all the girders equals). In the Fig. 4 is shown a graphing relating the two evaluated conditions for bridges with number of girders (N_g) equal to 3, while in Fig. 5 is presented the same comparison for bridges with 4 girders.

Table 3. Optimized sections obtained for the condition with exterior and interior girders different

Span (m)	**Ng**	**Exterior girders**	**Interior girders**	**Total weight of the girder sets (kgf/m)**
		PS x "d" x "tw,e" x "bf,se" x "tf,se" x "bf,ie" x "tf,ie"	**PS x "d" x "tw,i" x "bf,si" x "tf,si" x "bf,ii" x "tf,ii"**	
24	3	PS 1944 x 12.5 x 331 x 22.4 x 599 x 37.5	PS 1944 x 12.5 x 316 x 16 x 497 x 37.5	1210.3
30	3	PS 2193 x 16 x 364 x 22.4 x 624 x 37.5	PS 2193 x 16 x 358 x 19 x 600 x 31.5	1502.1
36	3	PS 2453 x 19 x 399 x 22.4 x 624 x 37.5	PS 2453 x 16 x 420 x 19 x 554 x 37.5	1748.3
42	3	PS 2591 x 19 x 422 x 25.4 x 727 x 37.5	PS 2591 x 19 x 422 x 22.4 x 583 x 37.5	1973.7
48	3	PS 2649 x 19 x 443 x 31.5 x 866 x 37.5	PS 2649 x 22.4 x 433 x 25.4 x 755 x 31.5	2227.4
24	4	PS 1624 x 12.5 x 317 x 22.4 x 550 x 37.5	PS 1624 x 12.5 x 268 x 16 x 442 x 22.4	1276.2
30	4	PS 1715 x 12.5 x 436 x 19 x 673 x 37.5	PS 1715 x 12.5 x 278 x 22.4 x 384 x 31.5	1465.4
36	4	PS 1817 x 16 x 430 x 22.4 x 772 x 37.5	PS 1817 x 12.5 x 294 x 25.4 x 374 x 37.5	1728.8
42	4	PS 1935 x 16 x 476 x 25.4 x 868 x 37.5	PS 1935 x 12.5 x 344 x 31.5 x 398 x 37.5	1941.8
48	4	PS 2102 x 19 x 537 x 25.4 x 892 x 37.5	PS 2102 x 16 x 339 x 37.5 x 408 x 31.5	2259.6

Table 4. Optimized sections obtained for the condition with all the girders equals

Span (m)	**Ng**	**Exterior and Interior girders**	**Total weight of the girder sets (kgf/m)**
		PS x "d" x "tw" x "bfs" x "tfs" x "bfi" x "tfi"	
24	3	PS 2133 x 16 x 346 x 19 x 456 x 37.5	1339.8
30	3	PS 2219 x 16 x 360 x 22.4 x 610 x 37.5	1542.3
36	3	PS 2460 x 19 x 400 x 22.4 x 620 x 37.5	1832.4
42	3	PS 2549 x 19 x 415 x 25.4 x 758 x 37.5	2030.1
48	3	PS 2680 x 19 x 443 x 31.5 x 847 x 37.5	2244.9
24	4	PS 1825 x 12.5 x 315 x 19 x 535 x 31.5	1413.6
30	4	PS 2026 x 16 x 347 x 19 x 580 x 31.5	1773.2
36	4	PS 2211 x 16 x 382 x 19 x 656 x 31.5	1962.0
42	4	PS 2303 x 16 x 388 x 25.4 x 661 x 37.5	2213.2
48	4	PS 2452 x 19 x 410 x 25.4 x 674 x 37.5	2546.0

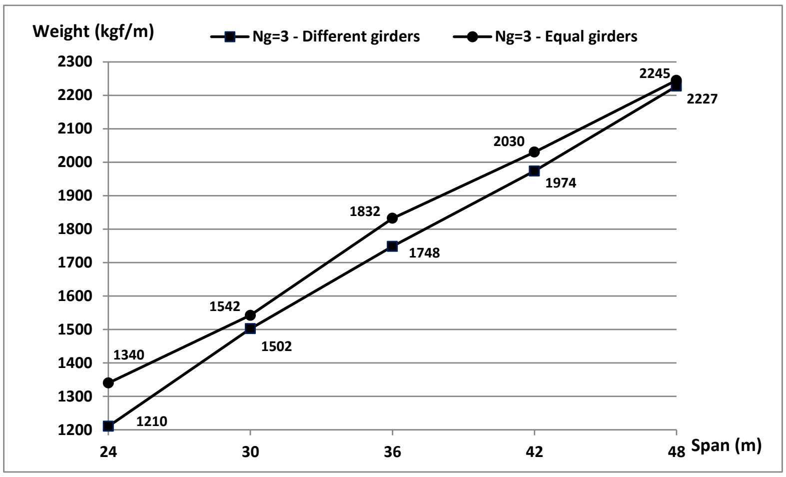

Figure 4. Comparison between the weights of the girder sets with Ng=3

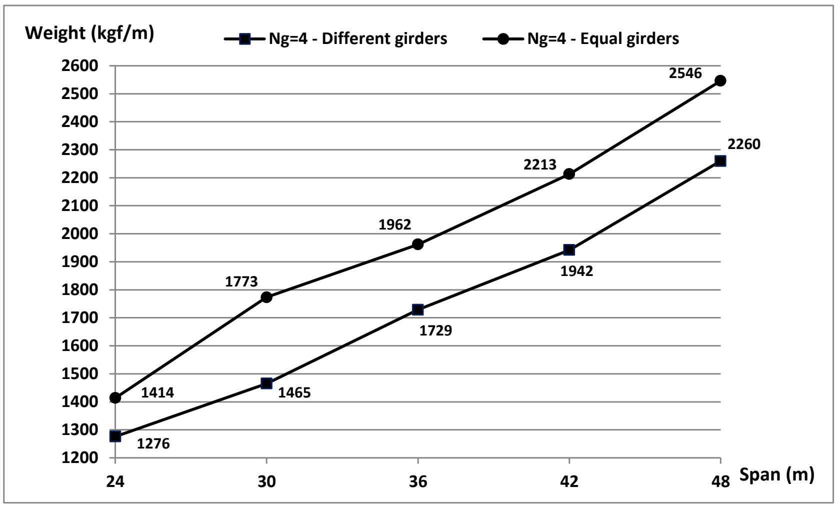

Figure 5. Comparison between the weights of the girder sets with Ng=4

Through the analysis of the results has been noticed again that the critical limit states of the majority of the girders has been the combination between the fatigue check (in the region of the toe of fillet welds in transverse stiffener) with the resistance of the girders during the construction phase (noncomposite condition).

For bridges with Ng=3 it can be noticed from Fig. 4 that the most significant difference in the weight of the girder sets occurs to the lower span (difference of 10.7%) whereas for the other spans the weight of the girders sets is practically the same (difference between 0.8% and 4.8%).

On the other hand, for bridges with Ng=4 (Fig. 5) it can be noted that when the exterior and interior girders are different, the weight growth of the girder sets presents a behavior slightly parabolic. For the condition where all the girders are equal it can be noticed that the major growth in the weight of the girder sets occurs when the bridge span changes from 24m to 30m, whereas from this value the growth tax turns minor but yet with a behavior slightly parabolic. Even through the analysis of this figure it is noted that the lower difference between the weight of the girder sets occurs to the lower span (about 10.8%) and the major difference occur to the span of 30m (21.0%). From 36m to 48m the weight difference becomes approximately constant, varying between 12.7% and 14%.

3.4 Comparison of the results for bridges with 3 and 4 girders

Aimed to facilitate the direct comparison between the weight of the girder sets for the cases with 3 and 4 girders is presented the graphic in Fig. 6 that shows the superposition of the obtained results.

How can be observed from this graphic, for the condition where the interior and exterior girders are different the weight growth projection for bridges with 3 and 4 girders presents with near values, with a slightly variation in the results (between 1.1% and 5.4%). Based on this, it’s possible consider that the solution with minimized weight for both cases are equivalent and optimum.

Still analyzing the graphic of the Fig.6 it can be noticed that the results obtained for the condition with 3 equal girders and those with the exterior and interior girders different are near, with a difference between 1.4% and 10.7%. When is compared the weight for 3 and 4 girders for the condition where all the girders are equal the difference increases, keeping in the interval between 5.5% and 15.0%.

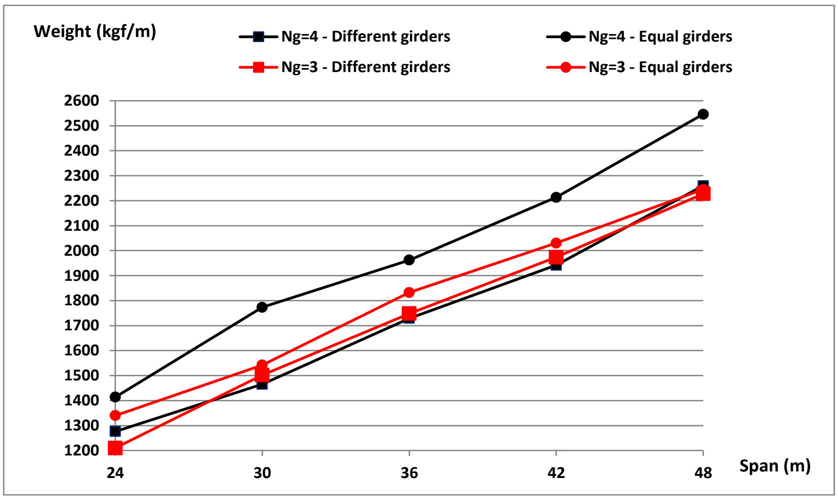

Figure 6. Comparison between the weights of the girder sets with Ng=3 and Ng=4

3.5 Parameter analysis of the optimized girders

A traditional parameter used to estimate the initial height of bridge girders is the depth/span ratio. This ratio is largely used because it is a parameter with easy application and by lead to consistent results in most cases.

In the Fig. 7 is presented a graphic that shows the variation of the d/L parameter like a function of the span for bridges with exterior and interior girders different while in Fig. 8 is presented a graphic that shows this same parameter for the case where all the girders in the bridge are equal. These two graphics show the results obtained for bridges with 3 and 4 girders, that have been the cases with variable span covered in this study.

Comparing the obtained results for the evaluated conditions it can be noted that for both cases the d/L ratio presents with near values, suggesting that there is a depth around which it can be obtained the girders with minimum weight, indifferent of the adopted condition.

It is also noted that when working with all girders equal the ratio d/L for bridges with 3 and 4 girders presented near values for this parameter for all the analyzed spans.

On the other hand, for bridges with exterior and interior girders different the values of this ratio present more distant tending to increase the difference as the bridge span increase.

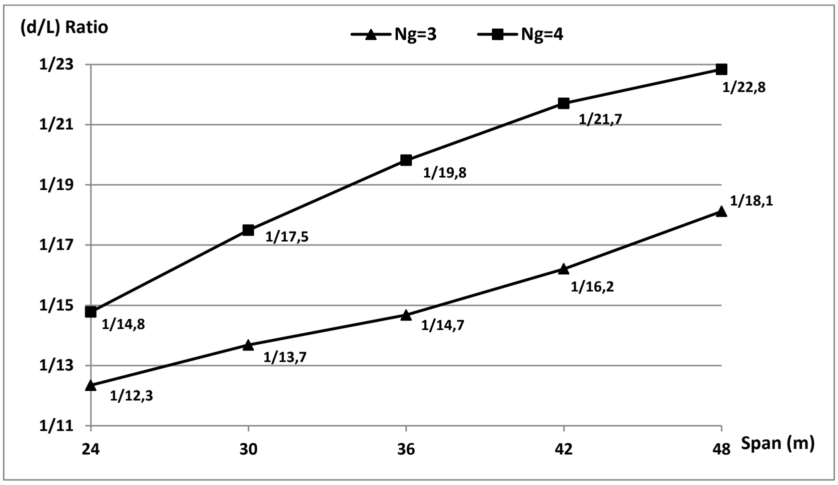

Figure 7. Depth/span ratio (d/L) for bridges with N_g=3 and N_g=4 and with different exterior and interior girders

The ratio between the moment of inertia of the compression flange to tension flange about the vertical axis in the plane of the web (I_{yc}/I_{yt}) is indicated by the AASHTO specification like a parameter to prevent the use of extremely monosymmetric sections. As indicated by the referred specification, the value of this ratio shall be between 0.1 and 10; like is shown in Eq. (17).

$$0.1 \le I_{yc}/I_{yt} \le 10 \tag{17}$$

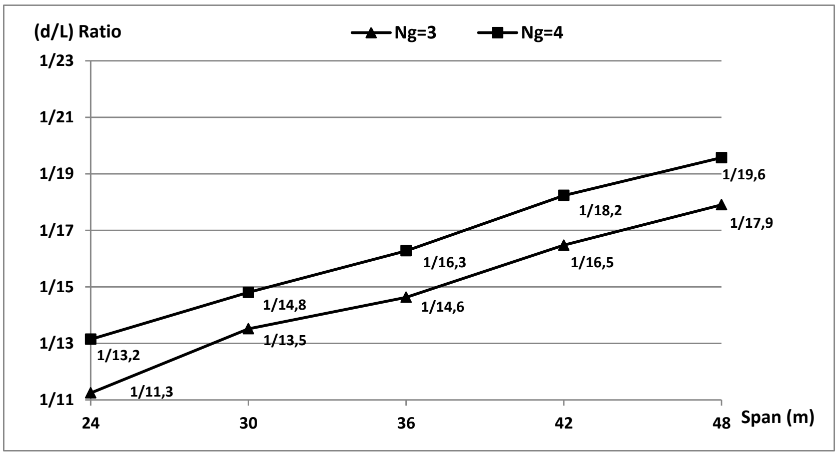

Figure 8. Depth/span ratio (d/L) for bridges with N_g=3 and N_g=4 and with all girders equal

In the Figs. 9-10 are presented two graphics that show the ration I_{yc}/I_{yt} like a function of the number of girders in the bridge cross section for both the analyzed conditions.

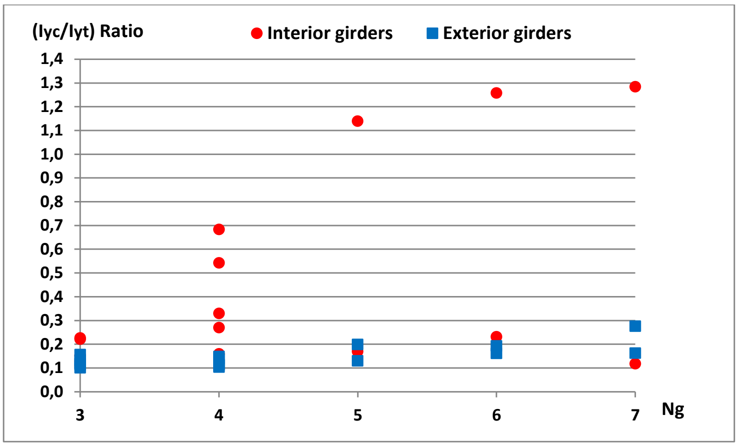

Figure 9. Values of ratio I_{yc}/I_{yt} for bridges with exterior and interior girders different

As can be observed from Fig. 9, for the condition on which the exterior and interior girders are different the majority of the values for the ratio I_{yc}/I_{yt} for the internal girders are below 0.70, with only three of these values upper 1.0

(between 1.0 and 1.30). For the exterior girders all the values of the evaluated ratio were lower than 0.30.

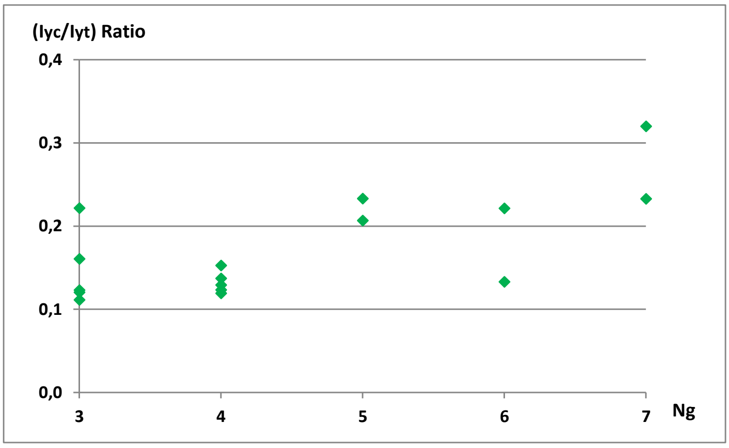

Figure 10. Values of ratio I_{yc}/I_{yt} for bridges with all girders equal

Doing the same analysis for the condition where all the girders are equal it can be noted from Fig. 10 that all obtained values for this ratio are lesser than 0.40, with the majority near the minimum allowed by the AASHTO specification.

Based on the lower values obtained for the ratio I_{yc}/I_{yt} it is noted that the sections which compose the minimum weight girder sets tend to be monosymmetric, suggesting that the tensioned flange (bottom flange) is always greater than the compressed flange (upper flange).

As indicated in the commentary of AASHTO specification, the cross section aspect ratio (D/bf) is a parameter that affect the resistance and characteristics of I girders. Based on this, the AASHTO specification defines that the value of this ratio shall be equal to or lower than 6, like shown in Eq. (18).

$$D/b_f \leq 6 \tag{18}$$

The ratio D/b_f for the girder's sections obtained in this study are presented on Figs. 11-13.

As can be observed from Fig. 11 the majority of the D/b_f ratio values for the upper flange of the interior girders are between 4.5 and 6, while for the bottom flange the majority of the values of this ratio is between 3 and 5.

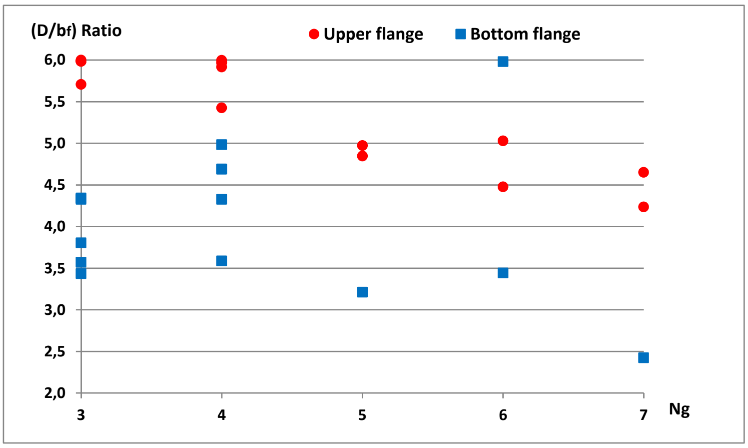

Figure 11. Values of ratio D/b_f for interior girders in bridges with exterior and interior girders different

With regard to the results of the exterior girders it is noticed from Fig. 12 that the majority of the D/b_f ratio for the upper flange is between 3.5 and 6. For the bottom flange the obtained results are between 2 and 4.

For the condition where all the girders are equal the graphic of Fig. 13 shows that the majority of the values for the D/b_f ratio are situated between 4.5 and 6 for the upper flange and between 3 and 4.5 for the bottom flange.

From a general comparison between the presented results it is noticed that the majority of the results for the D/b_f ratio are situated between 4 and 6 for the upper flange and between 2 and 4.5 for the bottom flange.

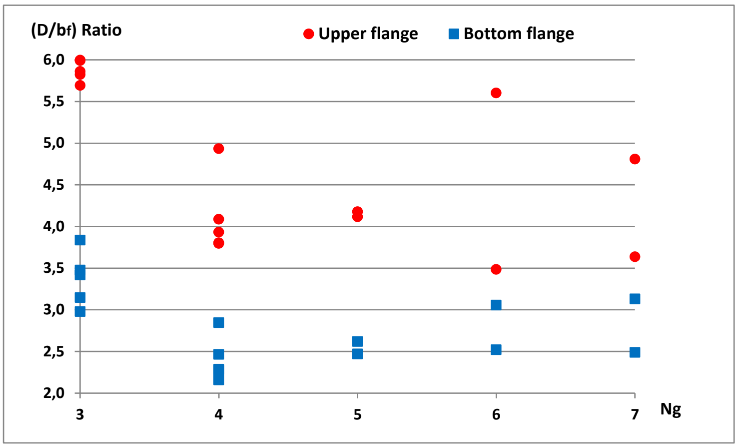

Figure 12. Values of ratio D/b_f for exterior girders in bridges with exterior and interior girders different

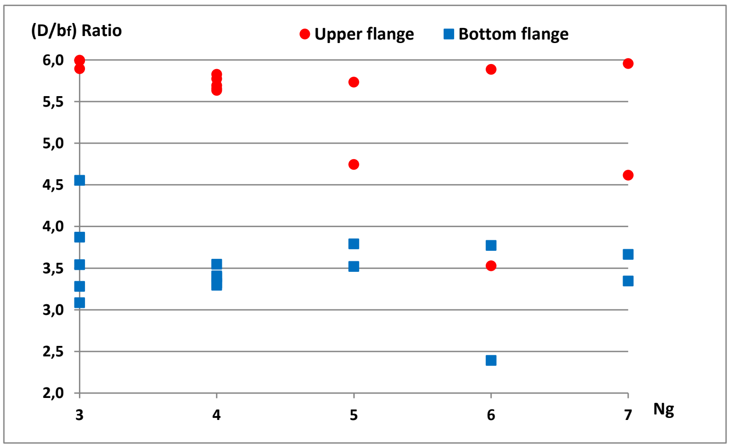

Figure 13. Values of ratio D/b_f for girders in bridges with all girders equal

According to AASHTO the web slenderness ratio for girders without longitudinal stiffeners is limited to the value of 150 as shown in Eq. (19), where D and t_w refers to the height and thickness of the web, respectively.

$$D/t_w \leq 150 \tag{19}$$

The web slenderness ratio for the optimized sections are presented graphically in Fig. 14 for the condition with exterior and interior girders different, and in Fig. 15 for the condition where all the girders are equal.

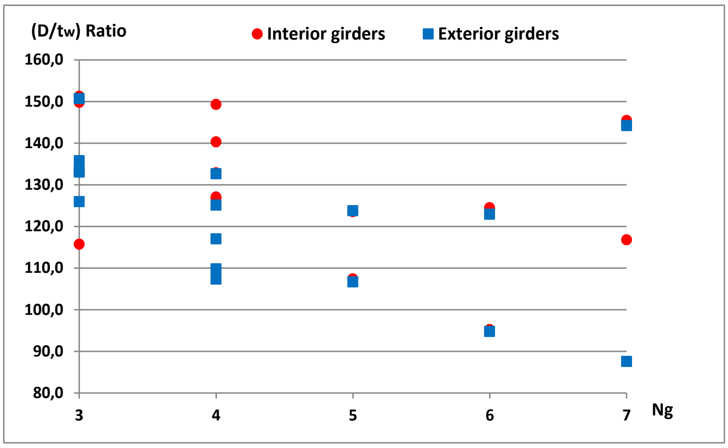

Figure 14. Values of ratio D/t_w for girders in bridges with exterior and interior girders different

As can be observed from Fig. 14 the majority of the values of D/t_w ratio are between 120 and 150 for the interior girders, and between 100 and 140 for the exterior girders. It's important to mention that for the case where the bridge have 3 girders and span of 24m the values of D/t_w ratio were slightly larger than the value defined by the AASHTO specification, with a maximum difference of 0.8%, what is considered an tolerable value.

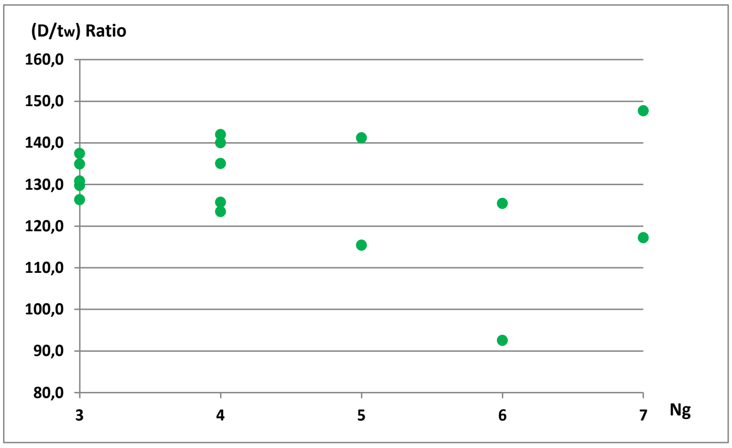

Figure 15. Values of ratio D/t_w for girders in bridges with all girders equal

For the case where all the girders of the bridge are equal, as is shown in Fig. 15 the majority of the values for the analyzed ratio are between 110 and 150.

4. CONCLUSIONS

The main objective of this study was to identify parameters and characteristics that influence the design of composite bridges with multiple plate girders in its cross section, seeking to provide indicatives to design these structures with cost minimization. The search by the minimum cost has realized by the optimization of the weight per meter of the girder sets taking into account that this is the most influential parameter in the cost per meter of the composite bridge cross section.

The stresses determination and the girders verifications have been based on the AASHTO specification, except for the design truck that has been used the Brazilian design vehicle TB-450. It is important highlight that though it has been used a Brazilian vehicle in the study, It's believed that the obtained results are valid for the application with other design vehicles.

The studied cases have been yet verified for two design conditions, where in one the exterior and interior girders are different and in the other all the girders in the bridge cross section are equal.

In order to develop the presented studies a spreadsheet for the design of the steel girders was implemented in the MS Excel software. The search by the section with minimum weight has been done through the use of the optimization method of Generalized Reduced Gradient (GRG) Nonlinear taking as variables the dimensions of the girder's cross section (except the depth of the girders in minor number in the bridge cross section when the exterior and interior girders were different, that has been maintained with the same depth of the girders in major number).

Based on the obtained results the following conclusions can be set out for this research:

- For bridges with the same span the weight of the girder sets has been higher as increased the number of girders in the bridge cross section (independently of the used condition), and the most significant weight increase occurred when the number of girders was changed from 5 to 6;
- For the condition with exterior and interior girders different the obtained results for the cases with 3 and 4 girders in the bridge cross section have been practically equal, indicating that both lead to the minimized weight of the girder sets. For the condition where all girders in bridge cross section are equal only the case with 3 girders presented the minimum weight for the girder sets;
- For both the evaluated conditions in this study the majority of the girders in the minimum weight girder sets presented like critical limit states the fatigue check (in the region of the toe of fillet welds in transverse stiffener at the central region of the span) and the girder check during the construction phase (noncomposite situation), highlighting the importance of these limit states during the girder design.
- For bridges with 3 and 4 girders in its cross section it is noted that the most significant difference between the sets with exterior and interior girders different and those with all the girders equal occurred for the lower span;
- The ratio between the girders depth and the bridge span (d/L) has been variable as the number of girders in the bridge cross section was changed, wherein for a same span as major the number of girder in the bridge cross section as lower was the value of this ratio. The reference values for this ratio were previously presented in the graphics.
- Still regarding to the d/L ratio, for both the analyzed conditions it could be noted from the graphics that the values presented for this ratio were close, suggesting that have a girder depth through that it can be obtained the minimum weight solution for both conditions;
- It is noted that the sections which compose the minimum weight girder sets tends to be monosymmetric, especially in the exterior girders, where the I_{yc}/I_{yt} ratio was close from the minimum value permitted by the AASHTO specification, suggesting that the tension flange (bottom flange) be always greater than the compression flange (upper flange);
- In general it is noted that the girders which compose the minimum weight girder sets presents values for the D/b_f ratio between 4 and 6 for the upper flange and between 2 and 4.5 for the bottom flange;
- For both the analyzed conditions, the majority of the girders which compose

the minimum weight girder sets present the web slenderness ratio (D/t_w) between 100 and 150.

ACKNOWLEDGEMENTS

The first author acknowledges the University of Passo Fundo by the partial scholarship during this research.

REFERENCES

[1] Memari, A. M.; West, H. H. and Cavalier, T. M. “Optimization of continuous steel plate girder bridges”, Structural Optimization, 3, 1991.

[2] Toma, S. and Maeda, J. “Optimum girder height and minimum sectional area of highway composite girder bridge”, Hokuga, 2011.

[3] Salman, F. I.; Said, A. M. I.; Bunnori, N. M. and Johari, I. B. “Effect of concrete cost on optimum design of I-steel girder bridges”, Paripex – Indian Journal of Research, **3(5),** 99-104, 2014.

[4] Knight, R.P. “Economical steel plate girder bridges”, In: National Bridge Conference, 1983. Available in<http://www.ence.umd.edu/~ccfu/ref/EconomicDesign_PlateGirder_Bridge.pd>. Last access in March 2, 2015.

[5] Bhatti, M. A. and Al-Gahtani, A. S. “Optimum design of welded plate girders subjected to highway bridge loading”, *Transactions on the Built Environment* , 13, 1995.

[6] Gocál, J. and Dursová, A. “Optimization of transversal disposition of steel and concrete composite road bridges”, Procedia Engineering, 40, 125-130, 2012..

[7] Ghasemi, M.R. and Dizangian, B., “Size, shape and topology optimization of composite steel box girders using PSO method”, Asian Journal of Civil Engineering (Building and Housing), 11(6), 699-715, 2010.

[8] Mohammadzadeh, S. and Nouri, M. “An improved algorithm in railway truss bridge optimization under stress, displacement and buckling constraints imposed on moving load”, Structural Engineering and Mechanics, 46(4), 571-594, 2013.

[9] Xie, M. Y. M.; Zuo, Z. H.; Huang, X.; Black, T. and Felicetti, P., “Application of topological optimization technology to bridge design”, Structural Engineering International, **2**,185-191, 2014.

[10] Kaveh, A.; Bakhshpoori, T. and Barkhori, M. “Optimum design of multi-span composite box girder bridges using cuckoo search algorithm”, Steel and Composite Structures, **17(5),** 705-719, 2014.

[11] Kutylowski, R. and Rasiak, B., “Application of topology optimization to bridge girder design”, Structural Engineering and Mechanics, 51(1), 39-66, 2014.

[12] AASHTO, AASHTO LRFD Bridge Design Specifications – Customary U.S. units, American Association of State Highway and Transportations Officials, Washington, 2012.

[13] ABNT NBR 7188, Road and pedestrian live load on bridges, viaducts, footbridges and other structures, Brazilian Association of Technical Standards, Rio de Janeiro, 2013.