Acta Scientiarum
http://periodicos.uem.br/ojs
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v46i1.64764

CIVIL ENGINEERING

Effective width of steel-concrete composite box girder bridges: a review and method comparison

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ABSTRACT. Steel-concrete composite girders have non-uniform stress distribution on the slab, presenting maximum stresses next to the webs of the girder. This phenomenon is known as shear lag effect. To understand this effect, there is the effective width concept, in which only a portion of the slab width is considered effective in contributing to the composite element's resistant capacity. However, in the technical standards, there is no recommendation for calculating the effective width in steel-concrete composite box girder bridges. In view of this situation, the purpose of this paper is to carry out a systematic review on effective width and/or the shear lag effect in steel-concrete composite bridges, in order to raise the main existing recommendations and compare them. Through a bibliometric scan with carefully chosen keywords, it was found that of all research on shear lag or effective width in steel-concrete composite structures, only 31.19 are on bridges and 14.97% are on bridges with box girders. Among the papers, those that have a method for calculating the effective width of steel-concrete composite girder bridges have been compared quantitatively and qualitatively with the procedures of AASHTO and EN 1994-2-2. In these procedures were also identified that the, for the boundary conditions of the present paper, the parameters that most influencing the effective width are, in that order, the span length, the distance between girders, the concrete slab height, the longitudinal position and the type of load.

Keywords: shear lag effect; normal stresses; literature review.

Received on August 24, 2022.
Accepted on March 3, 2023.

Introduction

Steel-concrete composite bridges are constituted by the association of a concrete deck and one or more steel beams, using shear connectors. Through this arrangement, the composite behavior of the materials is developed to resist bending stresses, with a predominance of compressive stresses in concrete and tensile stresses in steel, optimizing the materials' use.

A structural typology of steel-concrete composite bridges widely used is that with box girders. It is characterized by forming the closed section in which the sides (webs) and the lower part (bottom flange) are composed of steel, forming a closed section through the connection of the top flange with the concrete deck using shear connectors. It has a number of advantages, such as greater torsional rigidity, durability, construction and maintenance, aesthetic as well as economic advantages (Su, Yang, & Wu, 2012; Zhou, Jiang, & Yu, 2013; Fatemi, Ali, & Sheikh, 2016; 2018; Soto, Caldentey, Peiretti, & Benítez, 2020). In addition, steel-concrete composite box girder bridges are a structural system that offers economic, constructive and lower environmental impact advantages, since it optimizes the use of steel and concrete materials, allocating tensile stresses to steel and compressive stresses to concrete (Nicoletti, Rossi, Souza, & Martins, 2021a; 2021b).

Steel-concrete composite box girder bridges' cross section commonly have two box girders, however they may contain merely one box girder or multiple box girders, depending on the transversal width, longitudinal span and loads. Figure 1 indicates the elements of steel-concrete bridges, with double box configuration.

The distributed stresses contained in the concrete slab are not uniform in bridges with steel-concrete composite girders. They have maximum stresses next to the webs of the girder. This phenomenon is known as shear lag effect. To understand this effect, the concept of effective width must be studied, in which only a portion of the slab width is considered effective in contributing to the composite element's resistant capacity.

Otherwise, it is evident that only a portion of the concrete slab is considered effective in contributing to the composite element's resistant capacity. Figure 2 presents the concept of effective width (b_{eff}), demonstrating that it is determined when the ABCDEFG stress area is equal to the abcd area (rectangle highlighted in gray in Figure 2), delimiting a width in which the stresses are maximum and uniform.

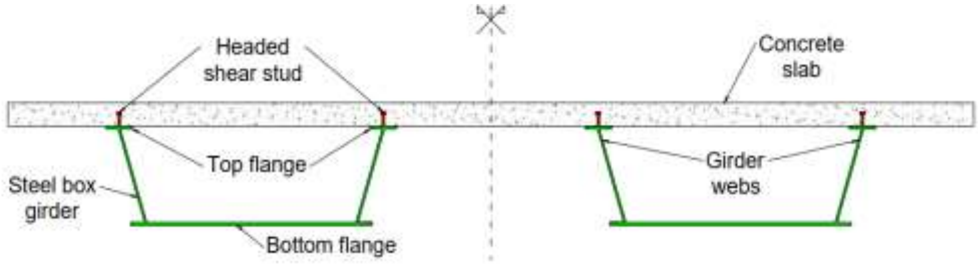

Figure 1. Typical configurations of steel-concrete composite box girder bridges with double box configuration. Source: Nicoletti et al. (2021b).

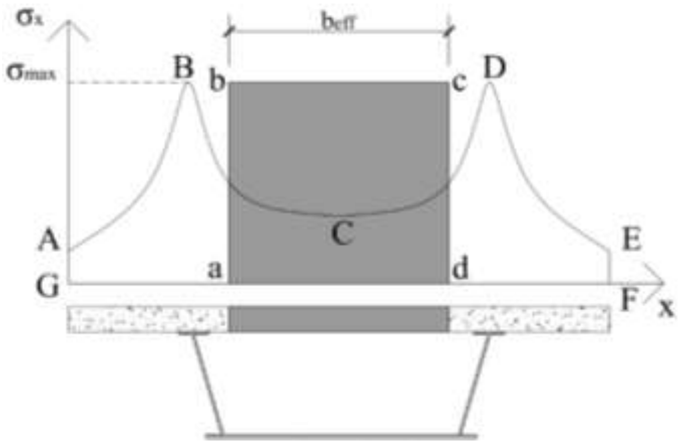

Figure 2. Effective width concept. Adapted from Nicoletti et al. (2021b).

In the context of steel-concrete composite bridges, the effective width is a widely studied topic (Dezi, Gara, & Leoni, 2003; Amadio, Fedrigo, Fragiacomo, & Macorini, 2004; Chiewanichakorn, Aref, Chen, & Ahn, 2004; Macorini, Fragiacomo, Amadio, & Izzuddin, 2006; Gara, Leoni, & Dezi, 2009; Gara, Ranzi, & Leoni, 2011; Salama & Nassif, 2011; Wang & Nie, 2015; Zhu, Nie, Li, & Ji, 2015a; Galuppi & Royer-Carfagni, 2016; Yuan, Deng, Yang, Weijian, & Zhenggeng, 2016a; Reginato, Tamayo, & Morsch, 2018; Lasheen, Shaat, & Khalil, 2018; Silva, & Dias, 2018; Nicoletti et al., 2021a; 2021b). One of the justifications for the high number of researches is the fact that the effective width is a parameter that directly influences the design of these structures. However, in the technical standards, there is no recommendation for calculating the effective width in steel-concrete composite box girder bridges. As an alternative, the existing recommendations for I-girders are adopted, such as, for example, the American standard American Association of State Highway and Transportation Officials (AASHTO, 2017) and the European standard EN 1994-2-2 (European Committee for Standardization [CEN], 2005b). Another alternative is to employ methods from the literature. Although, there is a considerable divergence between the recommendations, which may result in more costly solutions, or even unsafe to use.

The purpose of this paper is to carry out a systematic review of research on effective width and/or the shear lag effect in steel-concrete composite bridges, in order to raise the main existing recommendations and compare them. In addition, it aims to determine the main knowledge gaps in the area and propose future work.

Material and methods

Systematic review

The first stage aimed to identify articles published in the international literature on the effective width in steel-concrete composite box girder bridges. In april/2021, a systematic review of articles published in all years available in the Web of Science (WoS) and Scopus databases was carried out. The review was carried out with three different searches. The following strings were used:

Search 1:

Web of Science: (Steel and Concrete) and (Effective width or Shear lag);

Scopus: (title-abs-key (‘steel’) and title-abs-key (‘concrete’) and title-abs-key (‘shear lag’ or ‘effective width’) and doctype (ar) and pubyear > 1900;

Search 2:

Web of Science: (Steel and Concrete) and (Effective width or Shear lag) and (Bridges or Bridge);

Scopus: (title-abs-key (‘steel’) and title-abs-key (‘concrete’) and title-abs-key (‘shear lag’ or ‘effective width’) and title-abs-key (‘bridge*’) and doctype (ar) and pubyear > 1900;

Search 3

Web of Science: (Steel and Concrete) and (Effective width or Shear lag) and (Bridges or Bridge) and (Box or Tubular);

Scopus: (title-abs-key (‘steel’) and title-abs-key (‘concrete’) and title-abs-key (‘shear lag’ or ‘effective width’) and title-abs-key (‘bridge*’) and title-abs-key (‘box’ or ‘tubular’) and doctype (ar) and pubyear > 1900.

All articles were exported to a file with extension ‘.bib’ and the two generated files, one for each base, were imported into R Studio to be combined, excluding repetitions, using the ‘mergeDbSources’ tool in the Bibliometrix package of R (Aria & Cuccurullo, 2017). Thus, statistical data from the searches were obtained. Figure 3 shows the number of documents for each search and illustrates the results.

For Figure 3, of all research on shear lag or effective width in steel-concrete composite structures, only 31.19 are on bridges and 14.97% are on bridges with box girders. This fact justifies the lack of studies on this topic and, possibly, the absence of specific procedures for the calculation of the effective width in steel-concrete composite box girder bridges. Considering all articles (Search 1), there was also an annual growth rate of 8.20% between 1970 and 2021 with a practically exponential growth in the last two decades. This fact corroborates the existence of gaps in the researched topic.

Finally, the articles with the highest number of citations were identified considering the collection of articles selected in each search - called ‘local citation’ in this document. Local citations were considered instead of global citations due to the fact that this practice allows to further filter and refine the search objective of the strings. Table 1 presents the four documents with the highest number of local citations in each search.

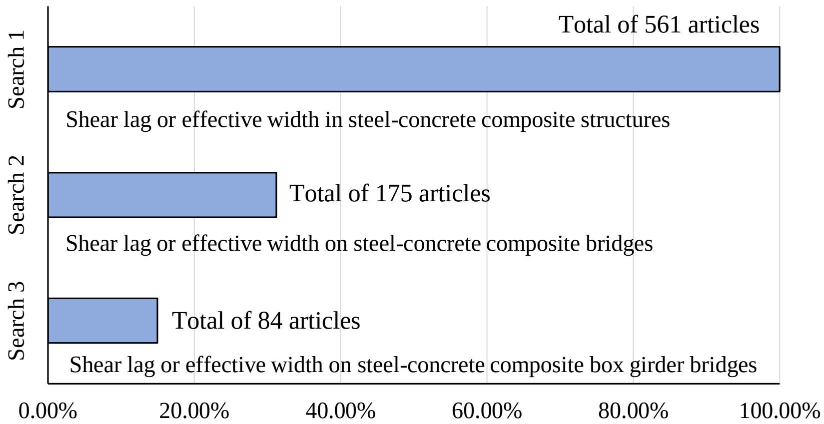

Figure 3. Accumulated production of each search in relation to search 1.

Table 1. Documents with more local citations in searches.

Search	Authors	Year	Local citations
1	Gara et al.	2009	25
	Amadio and Fragiacomo	2002	19
	Chiewanichakorn et al.	2004	17
	Amadio et al.	2004	17
2	Gara et al.	2009	25
	Amadio and Fragiacomo	2002	19
	Dezi et al.	2003	9
	Macorini et al.	2006	9
3	Zhu et al.	2015	3
	Gara et al.	2011	2
	Su et al.	2012	1
	Zhou et al.	2013	1

Regarding the bases, still considering the broader string (Search 1), the three journals with the greatest number of documents were Engineering Structures (56 papers), Journal of Constructional Steel Research (29) and ACI Structural Journal (24). As for the geographical distribution of the research authors, considering Search 1, Figure 4 shows the countries of the authors with the largest number of documents. China is the country with the most publications (214), followed by the USA (53).

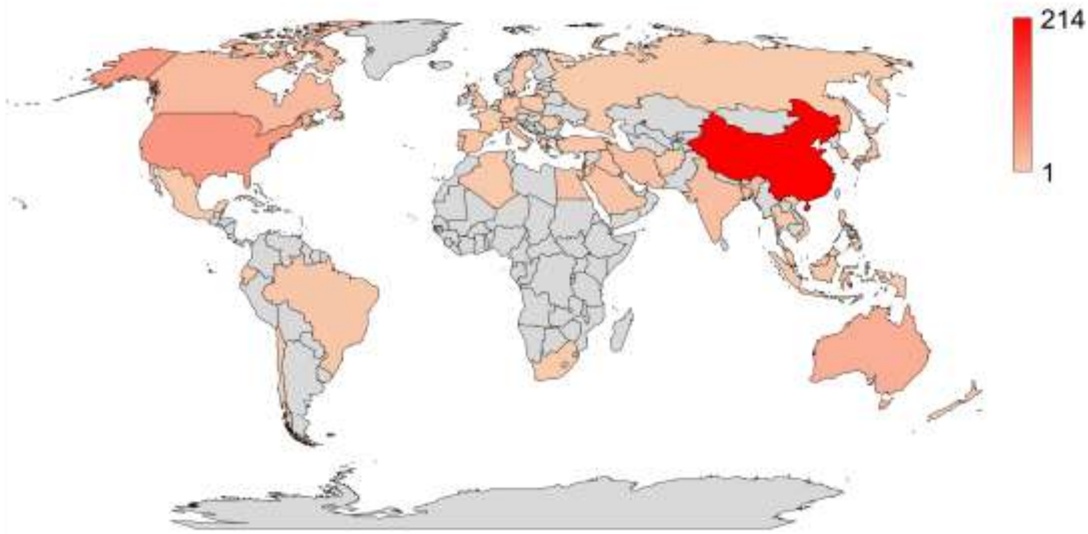

Figure 4. Countries with the largest number of publications.

Gara et al. (2009) developed a finite beam element for long-term analysis of steel-concrete composite beams, which captures the shear lag effect on the slab and the shear interaction at the slab-beam interface. This paper is a continuation of Gara, Ranzi, and Leoni (2006) and was the reference of the work of Gara et al. (2011), which recommends a method for calculating the effective width of slabs in steel-concrete composite beams.

Amadio and Fragiacomo (2002) performed parametric studies on composite beams with type 'I' profiles. The authors verified that there is no variation in the effective width in regions of positive and negative bendings and also found that in the plastic analysis, the redistribution of stresses causes an increase in the effective width when compared to the elastic analysis.

Chiewanichakorn et al. (2004) noted that the normal stresses to the cross section vary with slab thickness and need to be considered to produce a more viable representation of the effective width criteria. As a main result, Chiewanichakorn et al. (2004) propose a different method to define the effective width that considers such variation.

Amadio et al. (2004) in order to study the effective width behavior in the elastic and plastic phases of steel-concrete composite beams, conducted experimental tests on four specimens for positive and negative bending moments. The researchers observed that the effective width increases with the load until it approaches the actual width (that is, the geometric width) close to collapse.

Dezi et al. (2003) proposed an analytical solution to consider shear lag in bridge decks with two steel-composite beams subjected to static actions, support settlement and concrete shrinkage, which are the main actions of interest in the design of composite bridges. Dezi et al. (2003) method's is recommended for three different width-length ratios on the deck. During a literature review, it was possible to access only the abstract of this article.

Macorini et al. (2006), based on analyzes using the finite element method, studied the behavior of steel-concrete composite bridges with I-girders subjected to short and long-term loads, evaluating phenomena such as creep, tension and mechanical non-linearity. It was observed that the effective width remained practically constant with time and equal to the value assumed immediately after the application of the external load for a linear viscoelastic analysis without retraction. However, the retraction caused a significant variation in the effective width over time, both in linear and non-linear viscoelastic analysis.

Zhu et al. (2015) performed static tests on steel-concrete composite bridges in sections composed of two I-girders and with simple box girder subjected to vertical flexing loads and compression loads by means of prestressing. Afterwards, several numerical analyzes were calibrated with the tests performed and the shear lag effect was studied and, as a result, some equations were formulated to calculate the effective width.

Gara et al. (2011) performed parametric studies with numerical simulations based on the finite element method. They developed a simplified analysis method for calculating the effective width of steel-concrete composite bridges with I-girders and box girders, which considers the effective width variation along the longitudinal length, different loading conditions, in addition to support settlement and concrete shrinkage. However, it is worth mentioning that he proposes a unique method for box and I-girders.

Su et al. (2012) carried out an experimental investigation on the inelastic behavior of steel-concrete composite bridge beams under negative moment. It was found that the occurrence of the shear lag effect was verified, however, it was not the focus. Instead, the authors focused on studying the effect of the reinforcement rate on concrete cracking.

Zhou et al. (2013) conducted studies on the free vibration of steel-concrete composite box girders considering the shear lag effect and sliding. Specifically, regarding the shear lag effect, it was observed that the effective width of the beam increases when the frequency order increases and also when the relationship between the longitudinal span and the width of the cross section decreases.

In view of the most relevant research cited, it can be observed that studies on the shear lag effect have a very varied focus. For the purposes of this work, papers that present a method for calculating the effective width of steel-concrete composite girder bridges were selected: Gara et al. (2011), Zhu et al. (2015), Yuan et al. (2016) and Nicoletti et al. (2021b), in addition to the standard recommendations of AASHTO (2017) and EN 1994-2-2 (CEN, 2005b). In section 3, these methods were explained and, in section 4, they were compared and discussed.

Methods for calculating the effective width of steel-concrete composite box girder bridges

EN 1994-2-2 (CEN, 2005b)

EN 1994-2-2 (CEN, 2005b) establishes, in its topic 6.1.2, that the effective width for verification of the cross section in the ultimate limit state must be determined through the recommendations of its topic 5.4.1.2. The effective width is considered to be varied along the beam span. In the middle of the span or on an internal support, it is recommended that the effective width (b_{eff}) be calculated using Equation (1).

$$b_{eff} = b_0 + \sum b_{ei} \quad (1)$$

where: b_0 is the distance between the shear connector centers; and b_{ei} are the values of the effective widths of the board for each side of the beam center, admitted as $L_e/8$, where L_e is an equivalent span corresponding to the approximate distance between two points of null bending. It is also established that b_{ei} is not greater than the geometric width b_i. The distance b_i is the distance between the center of the shear connector (or the group of connectors) and the central point between two adjacent girders, except for a free end, where b_i is the distance between the shear connector and the edge of the concrete slab.

Figure 5 presents the recommendations of EN 1994-2-2 (CEN, 2005b) for L_e calculation. It can also be noted that topic 5.4.1.2 of EN 1994-2-2 refers to topic 5.2.1 of EN 1993-1-1 (European Committee for Standardization [CEN], 2005a), which deals with the design of steel structures, to explain the shear lag effect.

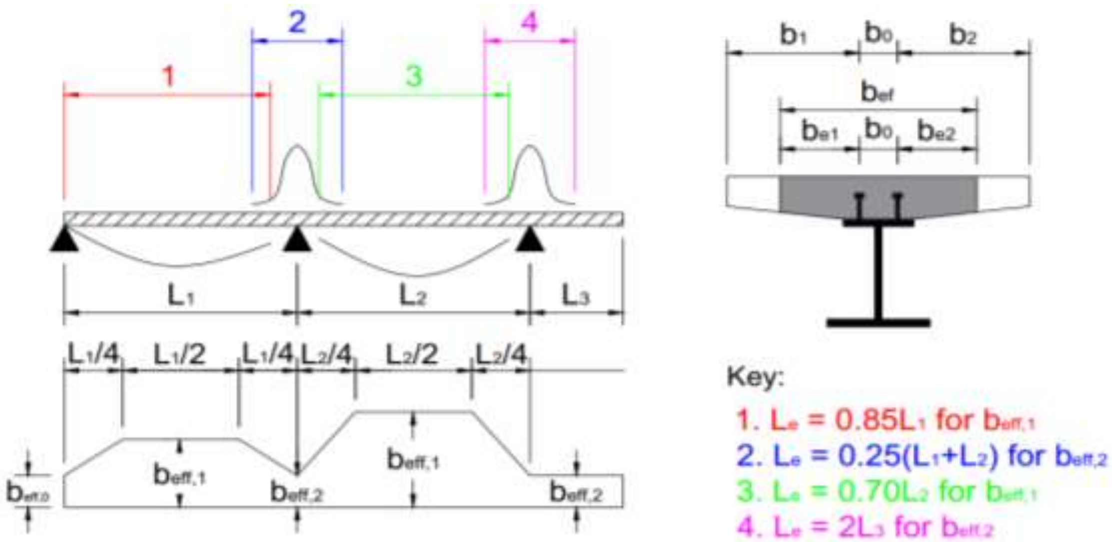

Figure 5. Equivalent span length to determine effective width according to EN 1994-2-2 (CEN, 2005b). Adapted from EN 1994-2-2 EN 1994-2-2 (CEN, 2005b).

AASHTO (2017)

The American standard American Association of State Highway and Transportation Officials (AASHTO, 2017) defines, in its topic 6.10.1.1.1e, for steel-concrete composite bridges with I-girders, that the effective width of the concrete slab must not exceed: one-fourth of the girder span length; the distance center to center of girders; twelve times the slab least thickness.

For girders located at the ends of the cross section, with concrete slab only on one side, the effective width is limited to: half the girder span length; half the distance center to center of girders; six times the slab least thickness.

The topic 6.11 of AASHTO (2017) deals with steel-concrete composite girders with box girders, however there is no recommendation for the effective width.

Gara et al. (2011)

Gara et al. (2011) developed a simplified analysis method for calculating the effective width of steel-concrete composite bridges with I-girders and box girders. However, there is no differentiation between the methods. In the formulations, Gara et al. (2011) consider different loading conditions, in addition to support settlement and concrete shrinkage. The method formulation can be summarized as follows:

Equation (2) allows to calculate the effective width in the cross sections at the longitudinal ends of the concrete deck ($B_{eff,0}$):

$$B_{eff,0} = B \cdot (C_1 \cdot \frac{B}{L_0} + C_2) \cdot (C_3 \cdot (\frac{B_1}{B})^2 + C_4 \cdot \frac{B_1}{B} + C_5) \quad (2)$$

Equation (3) determines the effective width in the regions of positive bending ($B_{eff,1}$):

$$B_{eff,1} = B \cdot (D_1 \cdot \frac{B}{L_0} + D_2) \cdot (D_3 \cdot (\frac{B_1}{B})^2 + D_4 \cdot \frac{B_1}{B} + D_5) \quad (3)$$

Equation (4) is used to calculate the effective width on the internal supports ($B_{eff,2}$):

$$B_{eff,2} = B \cdot (E_1 \cdot \frac{B}{L_{2tot}} + E_2 \cdot \frac{B}{L_{2tot}} + E_3) \cdot (E_4 \cdot (\frac{B_1}{B})^2 + E_5 \cdot \frac{B_1}{B} + E_6) + (E_7 \cdot \frac{L_2}{L_{2tot}} + E_8) \quad (4)$$

The coefficients C_i, D_i and E_i of the equations are shown in Table 2 as a function of loading (UDL = Uniformly distributed loading; TLE = Traffic loading envelope) or for the effective width arising from the support settlement (SS) or concrete shrinkage (CS). L_2 and L_{2Tot} are calculated by Equation (5-6), respectively.

$$L_2 = mín(L_{2L}, L_{R2}) \quad (5)$$

$$L_{2tot} = L_{2L} + L_{2R} \quad (6)$$

Figure 6 shows the variation of the effective width along the span, while Figure 7 illustrates the geometric quantities of the method.

Table 2. Coefficients required in the analytical expressions to calculate the effective width. Adapted from Gara et al. (2011)

	C_1	C_2	C_3	C_4	C_5	D_1	D_2	D_3	D_4	D_5
UDL	-0.75	0.97	-1.45	1.20	0.76	-0.67	1.05	-0.66	0.72	0.81
TLE	-0.75	0.87	-1.45	1.20	0.76	-0.67	0.95	-0.66	0.72	0.81
SS	0	1	0	0	1	0	1	0	0	1
CS	0	0.5	-4.80	2.80	0.80	0	1	0	0	1
	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8		
UDL	0	0	1	0	0	1	0	1		
TLE	6	-3.75	0.95	-2.81	2.07	0.67	-0.35	1.17		
SS	6	-3.75	0.95	-2.81	2.07	0.67	-0.35	1.17		
CS	0	-0.83	0.97	-1.24	1	0.81	0	1		

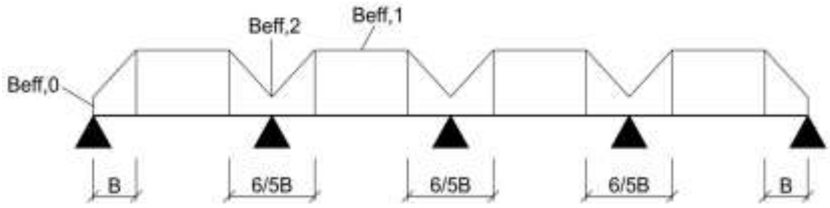

Figure 6. Longitudinal variation of the effective width according to the Gara et al. (2011) method. Adapted from Gara et al. (2011).

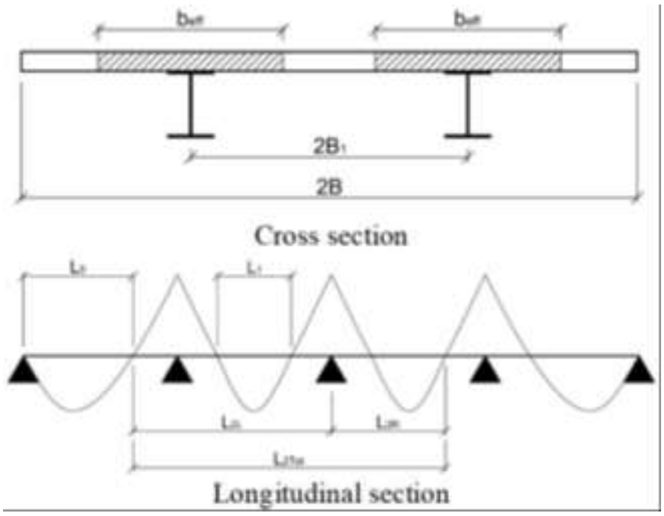

Figure 7. Geometric quantities of the analytical expressions of the Gara et al. (2011) method in (a) cross section and (b) longitudinal. Adapted from Gara et al. (2011).

Zhu et al. (2015)

The method developed by Zhu et al. (2015) considers the type of loading to determine the effective width, as well as its variability over the span. The method is divided into two criteria: for loads perpendicular to the longitudinal axis and for axial loads to the longitudinal axis of the composite girder. In both methods, the shear lag effect is applied using an effective width dimensionless coefficient (λ) calculated according to Equation (7). Figure 8 shows the Zhu et al. (2015) geometric parameters.

$$\lambda = \frac{b_{eff}}{b} \tag{7}$$

The method for vertical flexural loads segments the span length of the steel-concrete composite girders at points of inflection - points of support and/or application of point loads - in order to obtain several equivalent spans. Specifically, the region of the supports is considered to be that which extends from the end to 1/3 of the length of the equivalent span (l_e). Thus, the effective width distribution is approximated through a linear pattern that considers three representative effective widths:

1. The effective width in the middle of the span for uniformly distributed loads ($b_{eff,u}$), associated with the coefficient λ_u;
2. The effective width in the middle of the span for concentrated loads ($b_{eff,c}$), associated with the coefficient λ_c;
3. The effective width in the region of the supports ($b_{eff,s}$) associated with the coefficient λ_s.

In addition, two loading cases are considered: the one that does not have concentrated loads, (Figure 9a; and he one with concentrated loads, in which the equivalent span is initially divided into two parts at the point where the concentrated load is applied (Figure 9b).

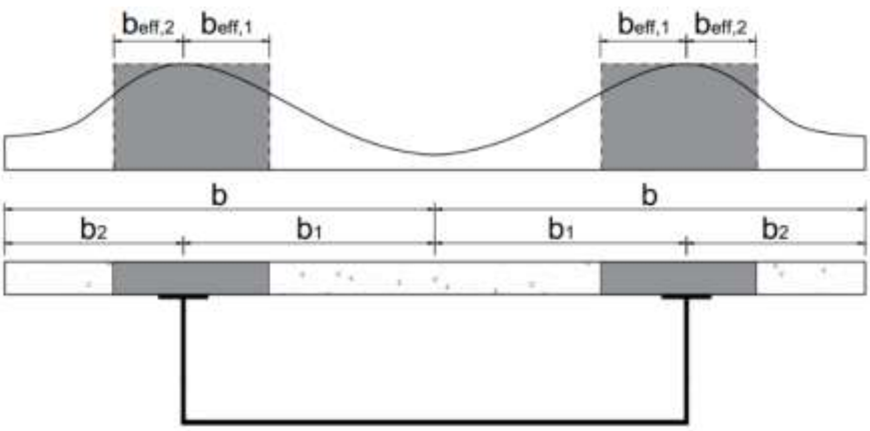

Figure 8. Variables of the Zhu et al. (2015) method. Adapted from Zhu et al. (2015).

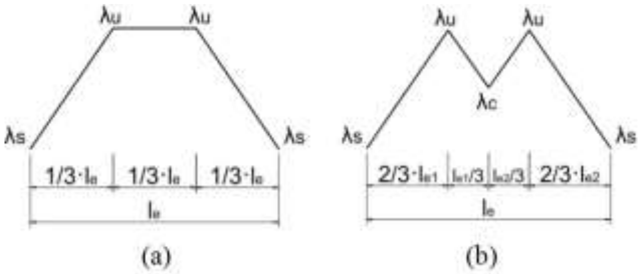

Figure 9. Distribution patterns of the effective width coefficient of the method by Zhu et al. (2015): (a) In which case there are no concentrated loads. (b) In which case there are concentrated loads. Adapted from Zhu et al. (2015).

Equation (8-10), respectively, are used to calculate the effective width coefficients in the following cases: loads distributed in the middle of the equivalent span; load concentrated in the middle of the equivalent span; and in the support region in both cases.

$$\lambda_u = \frac{b_{i,ef,u}}{b_i} = 1 - e^{-0.212(\frac{b_i}{L})^{-0.1284}} (i = 1 \wedge 2) \quad (8)$$

$$\lambda_c = \frac{b_{i,ef,c}}{b_i} = \frac{1}{3.294 \cdot (\frac{b_i}{L})^2 + 2.487 \cdot (\frac{b_i}{L})^2 + 1} (i = 1 \wedge 2) \quad (9)$$

$$\lambda_s = \frac{b_{i,ef,s}}{b_i} = 1 - e^{-0.0652(\frac{b_i}{L})^{-0.313}} (i = 1 \wedge 2) \quad (10)$$

In turn, the method for axial compression loads is used to calculate the effective width in steel-concrete composite girders with external prestressing. This paper does not aim to analyze prestressed composite bridges and, therefore, this method will not be detailed.

Yuan et al. (2016)

Yuan et al. (2016) method is intended for the calculation of the effective width of steel-concree composite I-girders. It is based on the service limit state and is directly associated to the steel-concrete composite element deflection. Figure 10 shows the main method variables.

The effective width is calculated using Equation (11).

$$b_{eff} = \eta_1 \cdot b \quad (11)$$

The η_1 coefficient is called by the author 'effective width coefficient'. It is calculated using two other dimensionless variables, x_1 and x_2, which are calculated by Equation (12-13).

$$x_1 = \frac{L}{b} \quad (12)$$

$$x_2 = \frac{h_{slab}}{b} \quad (13)$$

where:
b is the width of the concrete slab measured from the center of the girder to the end or half the distance from center to center of girders;
L the span length of the composite girder; and;
h_{slab} the height of the concrete slab.

Based on a large amount of theoretical data from the parametric analysis performed, Yuan et al. proposed Equation (14) to calculate the effective width coefficient.

$$\eta_1 = mín\begin{cases} 1 - e^{-0.65 \cdot x_1} \\ \frac{2.83 \cdot 10^{-4} + x_2^2}{0.001 + x_2^2} \end{cases} \quad (14)$$

Nicoletti et al. (2021b)

Nicoletti et al. (2021b) numerically determined in the Abaqus® software, in a qualitative and quantitative way, the parameters that exert the greatest influence on the effective width of steel-concrete composite box girder bridges. For this purpose, 260 simply supported models were evaluated, in which the study variables were the configuration of the cross section, the height of the slab, the length of the span, the arrangement of elements in the cross section and the degree of steel-concrete interaction.

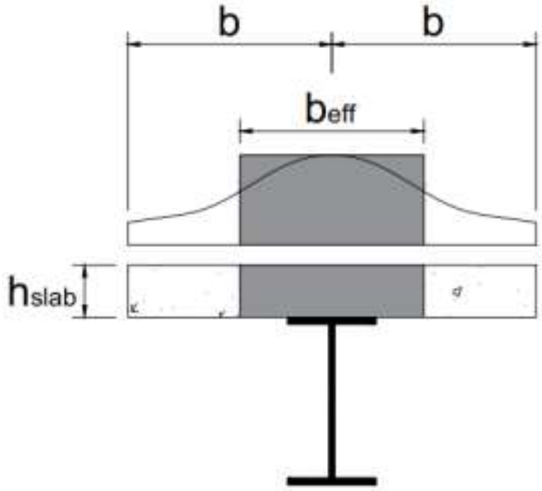

Figure 10. Variables from Yuan et al. (2016) method. Adapted from Yuan et al. (2016).

Based on the results found in the numerical analyzes, for models with a single box girder in the cross section, it is recommended that the effective slab width calculation does not exceed: 20.25 times the least thickness of the slab; 18.1% of the girder span length; 71.5% of the distance between webs.

In turn, for models with two box girders in cross section, it is recommended that the effective width of the slab calculation be limited to: 11.82 times the least thickness of the slab; 8.5% of the girder span length; 34.3% of the distance between box girders.

Results and discussion

From a qualitative point of view, Table 3 points out and compares the existing variables in the methods mentioned in Section 2.

From Table 3, it is noted that:

All methods consider the length of the longitudinal span and the distance between girders and/or the girders arrangement in the cross section;

EN 1994-2-2 (CEN, 2005b) and the methods of Gara et al. (2011) and Zhu et al. (2015) consider the effective width variation along the longitudinal length;

AASHTO (2017) and the methods of Yuan et al. (2016) and Nicoletti et al. (2021b) are the only ones that consider the slab height influencing the effective width;

The type of load is a parameter considered only by the methods of Gara et al. (2011) and Zhu et al. (2015);

The parameters considered by a single method are the effects of retraction and repression by that of Gara et al. (2011), and prestressing by Zhu et al. (2015).

Table 3. Variables of the methods for calculating the effective width.

Parameter /method	Longitudinal position	Longitudinal span	Girders distance	Slab height	Loading type	Support settlement and/or concrete shrinkage	Prestressing
EN 1994-2-2 (CEN, 2005b)	x	x	x	-	-	-	-
AASHTO (2017)	-	x	x	x	-	-	-
Gara et al. (2011)	x	x	x	-	x	x	-
Zhu et al. (2015)	x	x	x	-	x	-	x
Yuan et al. (2016)	-	x	x	x	-	-	-
Nicoletti et al. (2021b)	-	x	x	x	-	-	-

There is a great variability between the methods just considering their variables. In order to quantitatively and statistically evaluate the influence of the effective width variability between the methods, a parametric analysis was performed, whose variables are the slab height, the length of the longitudinal span and the distance between girders. Such variables were chosen because they were the most frequent among the methods. The variation in the effective width along the longitudinal length was disregarded because the analysis of the present paper will be in the middle of the span of simply supported girders (the most critical situation). In all models, the following admissions were made: the load will be considered distributed on the concrete slab; steel-concrete composite bridges with two box girders in the cross section (double box configuration); width of the cross section of the board equal to 12.80 m. Table 4 presents the variation of values of the parametric analysis and the default values of each variable. Figure 11 illustrates the variables slab height (h_{slab}) and distance between girders ($D_{girders}$). It is noteworthy that the longitudinal span (L) consists of the longitudinal distance between the supports.

Figure 12, 13 and 14 show the results of the parametric analysis of the slab height, the length of the longitudinal span and the distance between girders, respectively.

Table 4. Parametric analysis variables and values.

Parameter	Values	Default Values
Slab height [m]	0.14, 0.17, 0.20, 0.23, 0.26, 0.29, 0.32, 0.35, 0.38, 0.41, 0.44, 0.47, 0.50	0.32
Longitudinal span [m]	10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70	40
Distance between girders [m]	2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3.5, 3.75, 4.0, 4.25, 4.50, 4.75, 5.0	3.5

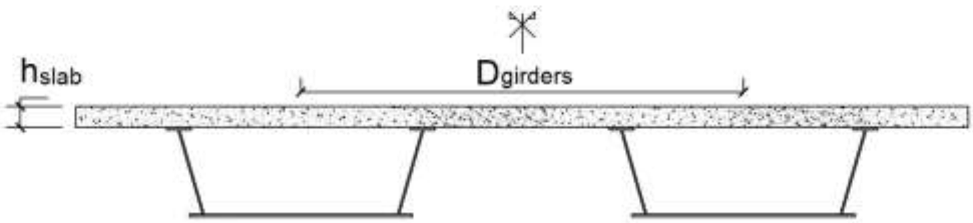

Figure 11. Parametric variables 'h_{slab}'and '$D_{girders}$'.

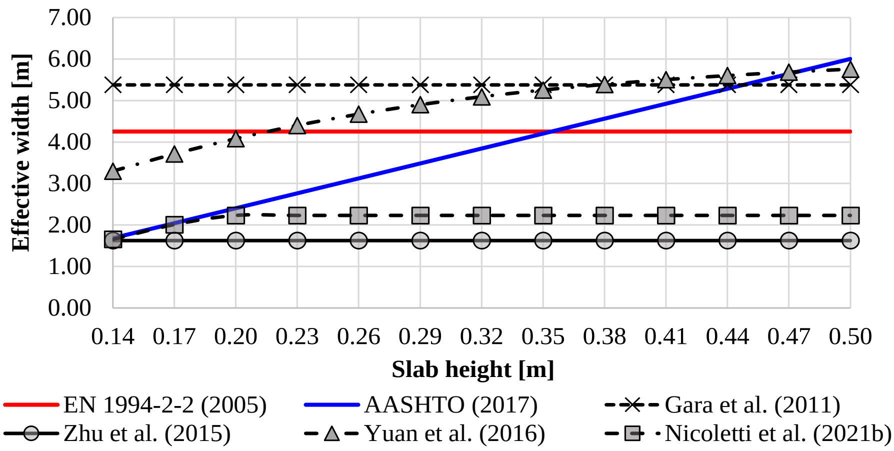

Figure 12. Results of the slab height parametric analysis.

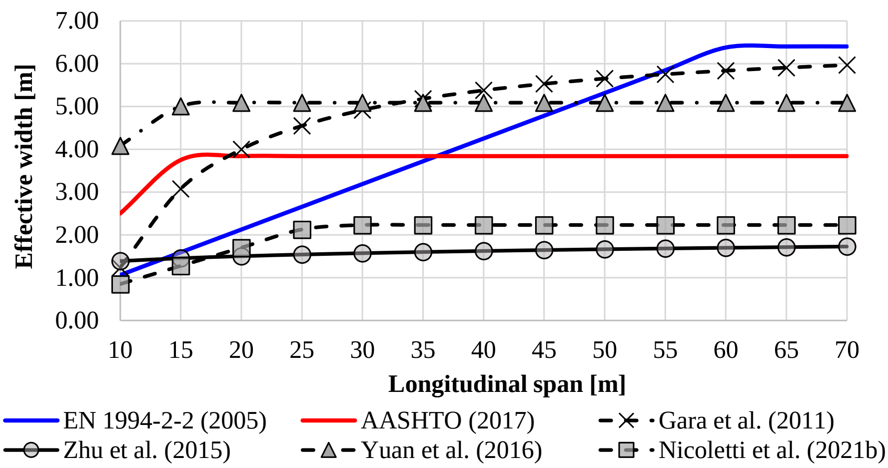

Figure 13. Results of the longitudinal span parametric analysis.

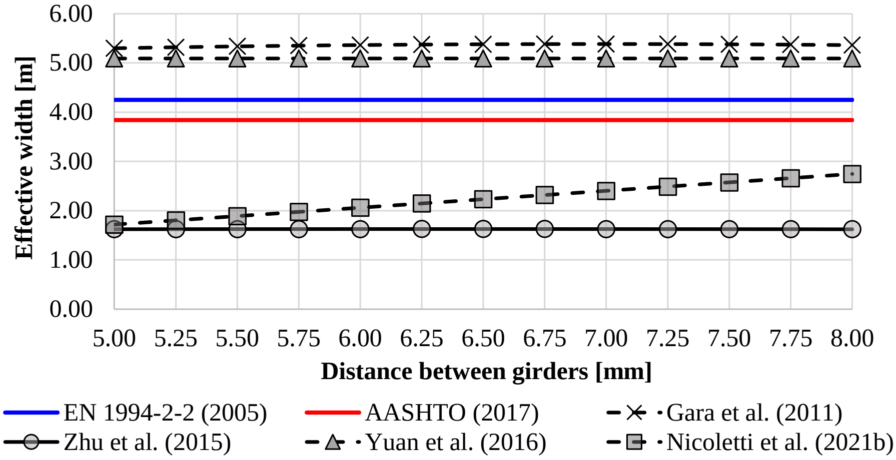

Figure 14. Results of the distance between girders parametric analysis.

By comparing the methods, the following general observations can be made:

There are significant divergences in the effective width between the methods;

With the exception of 2 of the 37 models, the Zhu et al. (2015) method is the largest conservator, followed by the Nicoletti et al. (2021b) method;

Although the longitudinal span and the distance between girders are variable according to the method of Zhu et al. (2015), the variation of such parameters resulted in small changes in the effective width;

In 29 of the 37 cases, the Gara et al. (2011) and Yuan et al. (2016) methods were the ones that resulted in the highest effective width values;

The method most sensitive to the variation of the slab height and longitudinal span is that of AASHTO (2017);

The method with the greatest sensitivity to variation in distance between beams is that of Nicoletti et al. (2021b).

Aiming to verify and order the methods based on conservatism, the sum of the effective width of the 37 models was compared between the methods. Table 5 shows the results. The greener the color, the 'more positive'is the relationship between the methods. In turn, red colors are associated with negative relationships. Yellow colors denote a middle ground between the cases mentioned above.

Based on the value of the deviations sum, expressed by the column 'Sum', it is possible to order the methods from the most conservative (those with the lowest 'Sum' value) to the least conservative (with the highest 'Sum' value). Table 6 presents the methods order.

In order to verify the empirical distribution of the data, boxplots were created. Figure 15 presents boxplots for seven different models: the two extreme models of each parameterization interval (totaling six), in addition to the model with default values.

Table 5. Comparison of methods conservatism.

	EN 1994-2-2 (CEN, 2005b)	AASHTO (2017)	Gara et al. (2011)	Zhu et al. (2015)	Yuan et al. (2016)	Nicoletti et al. (2021b)	Sum [%]
EN 1994-2-2 (CEN, 2005b)	0.0%	10.7%	-18.9%	160.2%	-15.6%	97.4%	233.8
AASHTO (2017)	-9.7%	0.0%	-26.8%	135.0%	-23.7%	78.3%	153.1
Gara et al. (2011)	23.3%	36.5%	0.0%	220.9%	4.1%	143.5%	428.4
Zhu et al. (2015)	-61.6%	-57.5%	-68.8%	0.0%	-67.6%	-24.1%	-279.5
Yuan et al. (2016)	18.5%	31.1%	-4.0%	208.2%	0.0%	133.8%	387.7
Nicoletti et al. (2021b)	-49.3%	-43.9%	-58.9%	31.8%	-57.2%	0.0%	-177.6

Method 1 was considered as the first line, while Method 2 appears in the first column.

Table 6. order of methods from the most conservative to the least conservative.

Order	Analytical Methods	Standard Methods	All Methods
1	Zhu et al. (2015)	EN 1994-2-2 (CEN, 2005b)	Zhu et al. (2015)
2	Nicoletti et al. (2021b)	AASHTO (2017)	Nicoletti et al. (2021b)
3	Yuan et al. (2016)	-	EN 1994-2-2 (CEN, 2005b)
4	Gara et al. (2011)	-	AASHTO (2017)
5	-	-	Yuan et al. (2016)
6	-	-	Gara et al. (2011)

From Figure 15, it can be seen that there was no outlier. However, it is clear that the amplitude and dispersion of the data is high. The EN 1994-2-2 (CEN, 2005b) resulted in a *beff* value outside the Q2 quartiles for the model with L = 70.00 m. This is an indication that the greater the length of the longitudinal span, the greater the divergence of the EN 1994-2-2 (CEN, 2005b) method to the others. In this specific case, the European standard results in an effective width about 71.12% greater than the median of the other methods.

The AASHTO (2017) resulted in a b_{eff} value outside the boxplot for the model with the highest slab height, that is, for h_{slab} = 0.50 m. Analogously to the previous conclusion, this means that the greater the slab height, the greater the divergence from the AASHTO (2017) recommendation in relation to the others. In the model analyzed, the AASHTO (2017) method recommends an effective width 61% greater than the median of the others.

In general, there is a lack of experimental research on effect width or the shear lag effect in steel-concrete composite bridges with box girders. In the literature review, only Zhu et al. (2015) and Ryu, Shim, and Chang (2004) papers were found. However, only the first proposed a method and both are not focused on composite bridges with box girders. In addition, both experimental works cited are cross sections with a single box girder, which is not the most common situation in bridges, as they have two or more box girders.

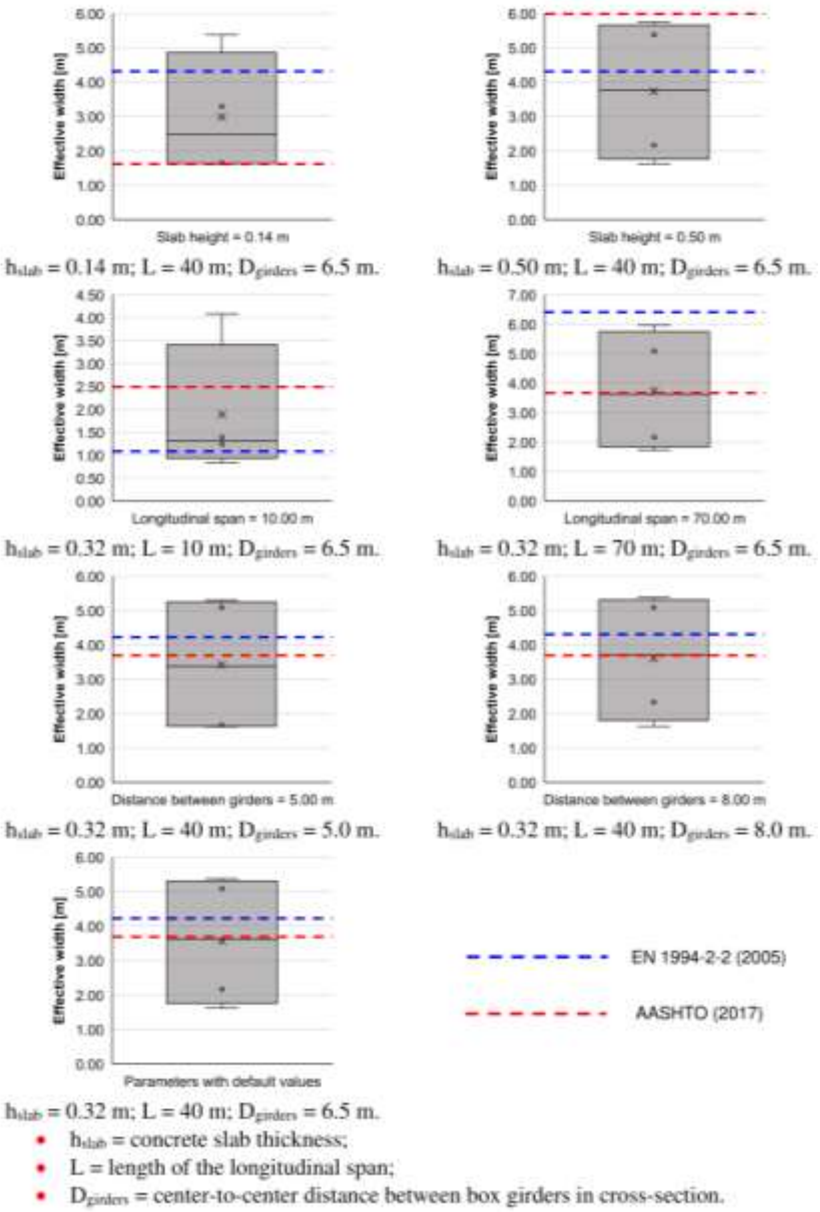

Figure 15. Boxplots of seven parameterization models.

Conclusion

Based on the systematic review, it was noted that out of all research on shear lag or effective width in steel-concrete concrete structures, only 31.19 are on bridges and 14.97% are on bridges with box girders, confirming the lack of studies on the subject. In addition, among the technical standards and articles, no specific method was found for calculating the effective width of steel-concrete composite box girder bridges.

Selecting the articles that present methods to calculate the effective width of steel-concrete composite bridges and the standard recommendations of EN 1994-2-2 (CEN, 2005b) and AASHTO (2017), it was observed that the parameters that most influencing the effective width are, in that order: the span length, the distance between girders, the concrete slab height, the longitudinal position and the type of load. Quantitatively, the order from the most conservative to the least conservative method is Zhu et al. (2015); Nicoletti et al. (2021b), EN 1994-2-2 (CEN, 2005b), AASHTO (2017), Yuan et al. (2016) and Gara et al. (2011).

Finally, about future researches, there is a shortage of experimental research on effect width or the shear lag effect in steel-concrete composite bridges with box girders. In the literature review, only Zhu et al. (2015) and Ryu et al. (2004) papers were found. However, only the first proposed a method. In addition, both experimental works cited are cross sections with a single box girder, which is not the most common situation in bridges, as they have two or more box girders.

In view of these gaps and the variables not studied in the present paper, the following topics are proposed for future work on steel-concrete composite bridges with box girders:

- Analysis of the influence of prestressing on the slab and external prestressing in the effective width;
- Sensitive analyses of the effective width in relation to the loading type;
- Study the variation of the effective width along the entire slab height;
- Conducting experimental studies on steel-concrete composite bridges with two or more box girders;
- Analyze the variation of the effective width along the longitudinal span and also for continuous bridges, investigating their behavior in the region of the supports.

Acknowledgments

This study was financed by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (Capes) - Finance Code 001.

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