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EFFECT OF DESIGN PARAMETERS ON SHEAR LAG IN ORTHOTROPIC DECK OF STEEL ROAD BRIDGES

BY

CĂTĂLIN MOGA, CLAUDIA PONDICHI-ALB* and MIRCEA SUCIU

Technical University of Cluj-Napoca, Faculty of Civil Engineering, Cluj-Napoca, Romania

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Abstract. The phenomenon of shear lag refers to the increases of the bending stresses near the flange-to-web junctions, and the corresponding decreases in the flange stresses away from these junctions.

In the plated structures with wide flanges, such as in the orthotropic deck of the steel road bridges, shear lag caused by shear strains, may be taken into account by a reduced flange width concentrated along the webs of the steel plate girders.

In the norm EN 1993-1-5, the concept of taking shear lag into account is based on effective[s] width of the flange which is defined in order to have the same total normal force in the gross flange subjected to the real transverse stress distribution as the effective flange subjected to a uniform stress equal to the maximum stress of the real transverse distribution.

This paper presents some aspects concerning the shear lag phenomenon and a design analysis taking into account the geometrical parameters such as the stiffeners thickness, flange width and the girder span for a steel deck of a road bridge.

Keywords: shear lag, road bridge, orthotropic steel deck, geometrical parameters influence, EN 1993-1-5, EN 1993-2.

*Corresponding author: *e-mail*: claudia.alb@infra.utcluj.ro
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1. Introduction

In the classical theory of bending, shear strains are neglected so that it can be assumed that plane sections remain plane after loading.

The phenomenon of shear lag is related to the discrepancies between the approximate theory of the bending of beams and their real behaviour, and in particular, it refers to the increases of the bending stresses near the flange-to-web junctions, and the corresponding decreases in the flange stresses away from these junctions (Trahair N.S. *et al.*, 2008).

In case of wide flanges of plated structures, shear lag may be taken into account by a reduced flange width concentrated along the webs and it has to be taken into account for the verification of stresses.

Shear lag effects may be significant in stiffened box girders and generally in structures with large width of the flange, Figure 1, especially for short spans, since it causes the longitudinal stresses at a flange/web intersection to exceed the average stresses in the flange.

An approximate method of dealing with shear lag is to use an effective width concept, in which the actual width b of a flange is replaced by a reduced width b_{eff} Figure 1.

This approach is similar to that used to allow for the redistribution of stresses which takes place in a thin compression flange after local buckling but, the two effects of shear lag and local buckling are quite distinct, and should not be confused (Trahair N.S. *et al.*, 2008).

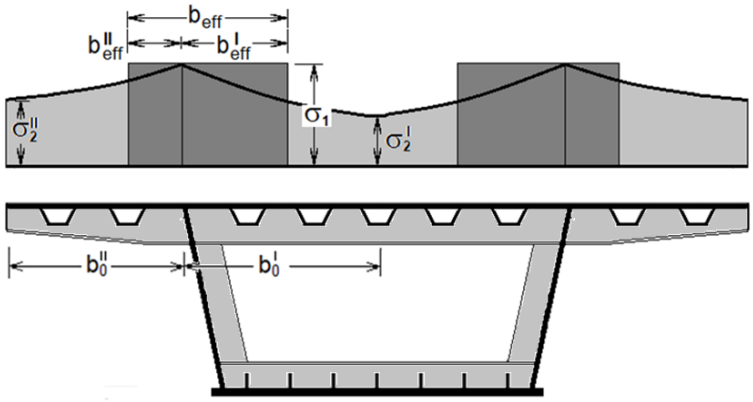


Fig. 1 - Effective width due to shear lag in a steel deck of a box girder

In relation to the effective width method, SR EN 1993-1-5. §3.3 introduces three different designations for three types of effective width (SR EN 1993-1-5:2006. Eurocod 3, Part 1-5, Beg D. *et al*., 2010, Johansson B. *et al.,*2007).

- Effective^{s} width – shear lag effects;
- Effective^{p} width – local buckling of plates;
- Effective width – interaction of shear lag and local buckling.

When designing plated structures, the effects of shear lag, plate buckling and interaction of both effects should be taken into account at the ultimate, serviceability or fatigue limit states.

For simplicity the effective^{s} width may be considered as constant over the length of each span:

$$b_{eff} = \min\left(b_0; \frac{L_i}{8}\right) \tag{1}$$

2. Shear Lag Evaluation According to EN 1993-1-5

Effective^{s} width for elastic shear lag analysis

In EN 1993-1-5, the concept of taking shear lag into account is based on the effectives width of the flange which is defined in order to have the same total normal force in the gross flange subjected to the real transverse stress distribution as the effective flange subjected to a uniform stress equal to the maximum stress of the real transverse distribution:

$$\int_0^b \sigma_x(y) \cdot t_f \cdot dy = b_{eff} \cdot t_f \cdot \sigma_{x.\max} \tag{2}$$

where: $b_{eff} = \beta \cdot b_0$; β is an efficiency factor given in Table 3.1 – EN1993-1-5.

The transverse bending stresses distribution due to shear lag is given in Figure 2 and can be evaluated with the relation given in EN1993-1-5.

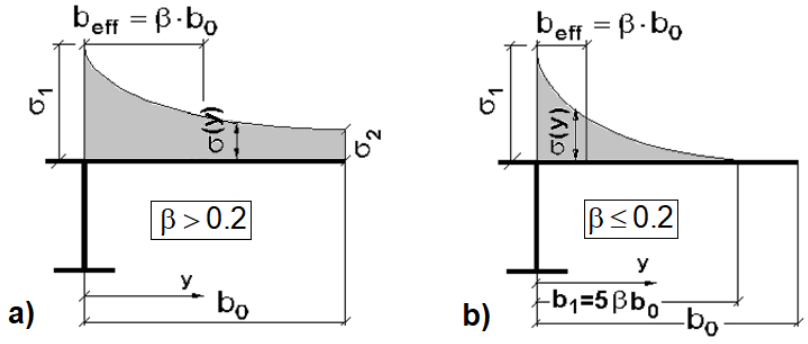


Fig. 2 - Distribution of stresses due to shear lag

According to EN 1993-1-5, the shear lag in the flanges may be neglected if $b_0 < L_e/50$.

Interaction between shear lag and plate buckling at ULS

In case of a flange in compression at ultimate limit state verification, the plate buckling effects which results in an effectivep area of the flange may occur in addition to the shear lag effects.

At the ultimate limit state shear lag effects may be determined as follows (SR EN 1993-1-5:2006. Eurocod 3, Part 1-5):

a) elastic shear lag effects as determined by serviceability and fatigue limit states;

b) combined effects of shear lag and of plate buckling;

c) elastic-plastic shear lag effects allowing for limited plastic strains.

EN 1993-1-5 proposes two models of steps for interaction between shear lag and plate buckling (SR EN 1993-1-5:2006. Eurocod 3, Part 1-5, Beg D. *et al*., 2010, Johansson B. *et al.,*2007).

Method b (effect of shear lag and of plate buckling):

- Calculate the effecivep area to plate buckling;
- Define an effectivep stiffening ratio α_0^* to be used instead of the stiffened ratio α_0 and calculating the reduction factor β_{ult} instead of β, where:

$$\alpha_0^* = \sqrt{\frac{A_{c.eff}}{b_0 t}} \tag{3}$$

- Calculate the effective area A_{eff} for taking shear lag and plate buckling effects into account as follows:

$$A_{eff} = \beta_{ult} \cdot A_{c.eff} \tag{4}$$

Method **c** *(elastic-plastic shear lag effects - recommended in EN 1993-1-5):*

- An elastoplastic reduction factor $\beta^k \geq \beta$ is directly applied to the effective[p] area of the compression flange, where k is based on α_0:

$$A_{eff} = \beta^k \cdot A_{c.eff} \geq A_{c.eff} \cdot \beta \tag{5}$$

It is recommended to apply the reduction factor of the area to the thickness of the plate, and not to the width (Beg D. *et al*., 2010, Johansson B. *et al.,*2007), especially for unstiffened flange.

3. Design Analysis

In the papers (Moga C., Feneşan C., Suciu M., 2020, Moga C., Drăgan D., Nerişanu R., 2020) and in the handbook (Moga P., 2018) some structures from the shear lag point of view are analyzed, respectively the evaluation of effectives width of the compression and of the tension flanges and the shear lag at the ultimate limit state.

This is a working example of the shear lag phenomenon in a steel deck of a road bridge girder. The steel grade used in structure is S355.

The bridge superstructure is a steel box girder, simple supported analyzed for three spans, respectively equal to 20.00 m; 40.00 m and 60.00 m.

The steel deck is analyzed in the hypothesis of three flange wide dimensions corresponding to the following structure types:

Case 1: One carriage lane road bridge:
B= carriage way (3500 mm) + 2 footpaths (2x1700 mm) = 6900 mm, Figure 3.

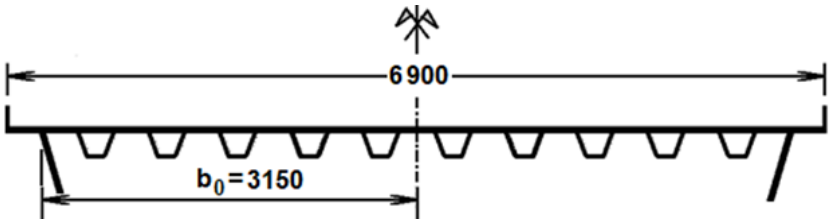


Fig. 3 - One lane steel deck

Case 2: Two carriage lanes road bridge:
B= carriage way (2x3500 mm) + 2 footpaths (2x1750 mm) = 10 500 mm, Figure 4.

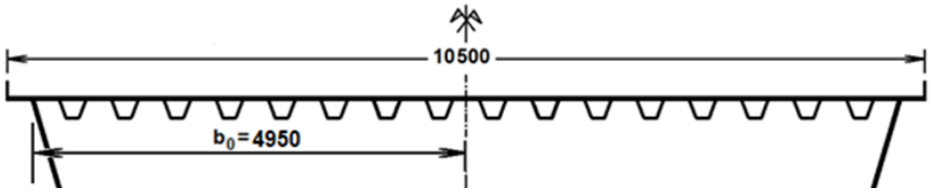


Fig. 4 - Two lanes steel deck

Case 3: Four carriage lanes road bridge:
B= carriage way (4x3500 mm) + 2 footpaths (2x1850 mm) = 17 700 mm, Figure 5.

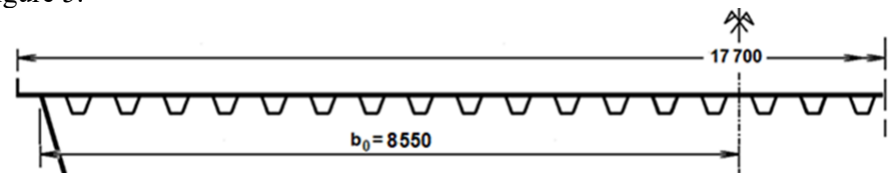


Fig. 5 - Four lanes steel deck

Each case presented above is also analyzed for two longitudinal stiffener thickness, respectively 8 mm and 10 mm, so a total of 18 deck types are in discussion and compared from the shear lag point of view (effective width). In all cases the top flange thickness is taken equal to 14 mm, and the interaxle between longitudinal stiffeners is 600 mm.

It can be mentioned that the deck dimensions are in accordance with some of the recommendations of EN1993-2 - Annex C (SR EN 1993-2:2007, Part 2):

- the deck plate thickness in the carriage way in the heavy vehicle lane is $t_f \geq 14$ mm for asphalt layer $g \geq 70$ mm;
- spacing of the supports of the deck plate by webs of stiffeners in the carriage way $e \leq$ 300 mm ;
- for hollow section stiffeners: 6 mm $\leq t_{stiff} \leq$ 10 mm.

The geometrical characteristics of the steel deck for these two longitudinal stiffener thicknesses are presented in Figure 6.

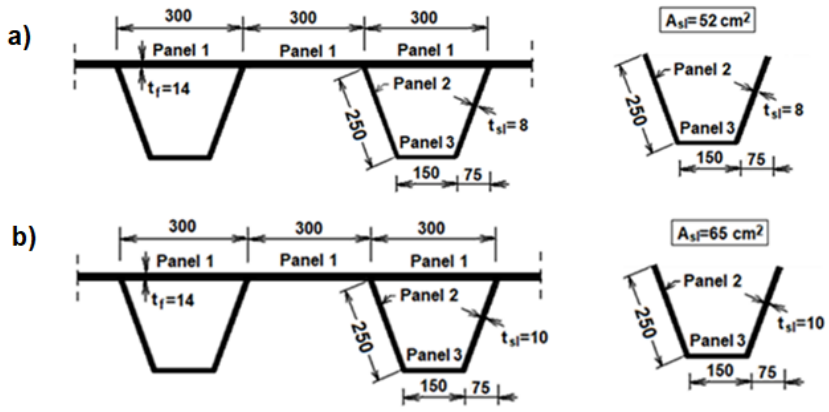


Fig. 6 - Geometrical characteristics of the stiffened steel deck: stiffeners thickness = 8 mm (*a*) and stiffeners thickness = 10 mm (*b*)

Effective[s] width and the shear lag at serviceability limit state (SLS)

The evaluation of the effective[s] widths for the analyzed structures is centralized in the tables 1.a; 1.b and 1.c,

where: $\alpha_0 = \sqrt{1 + \frac{\sum A_{sl}}{b_0 \cdot t_f}}$; $k = \frac{\alpha_0 \cdot b_0}{L_e}$; $\beta = \beta_1 = \frac{1}{1 + 6.4 \cdot k^2}$ and $b_{eff} = \beta \cdot b_0$.

Table 1.a

Evaluation of effective[s] widths for L=20 m

GIRDER SPAN *L*=20.00 m						
	$b_0 = 3150$ mm		$b_0 = 4950$ mm		$b_0 = 8550$ mm	
t_{sl} [mm]	**8**	**10**	**8**	**10**	**8**	**10**
α_0	1.26	1.32	1.27	1.32	1.27	1.33
k	0.198	0.208	0.314	0.327	0.543	0.568
β	0.799	0.783	0.613	0.594	0.346	0.326
b_{eff} [mm]	2517	2466	3034	2940	2958	2787

Table 1.b

Evaluation of effective[s] widths for L=40 m

GIRDER SPAN *L*=40.00 m						
	$b_0 = 3150$ mm		$b_0 = 4950$ mm		$b_0 = 8550$ mm	
t_{sl} [mm]	**8**	**10**	**8**	**10**	**8**	**10**
α_0	1.26	1.32	1.27	1.32	1.27	1.33
k	0.099	0.104	0.157	0.163	0.271	0.284
β	0.941	0.935	0.864	0.855	0.680	0.660
b_{eff} [mm]	2964	2945	4277	4232	5814	5643

Table 1.c

Evaluation of effective[s] widths for L=60 m

GIRDER SPAN *L*=60.00 m						
	$b_0 = 3150$ mm		$b_0 = 4950$ mm		$b_0 = 8550$ mm	
t_{sl} [mm]	**8**	**10**	**8**	**10**	**8**	**10**
α_0	1.26	1.32	1.27	1.32	1.27	1.33
k	0.066	0.069	0.105	0.109	0.181	0.189
β	0.973	0.970	0.934	0.929	0.827	0.814
b_{eff} [mm]	3065	3055	4623	4598	7070	6960

In Figure 7 the obtained results for the effective[s] widths of the steel deck when t_{stiff} = 10 mm are graphically presented.

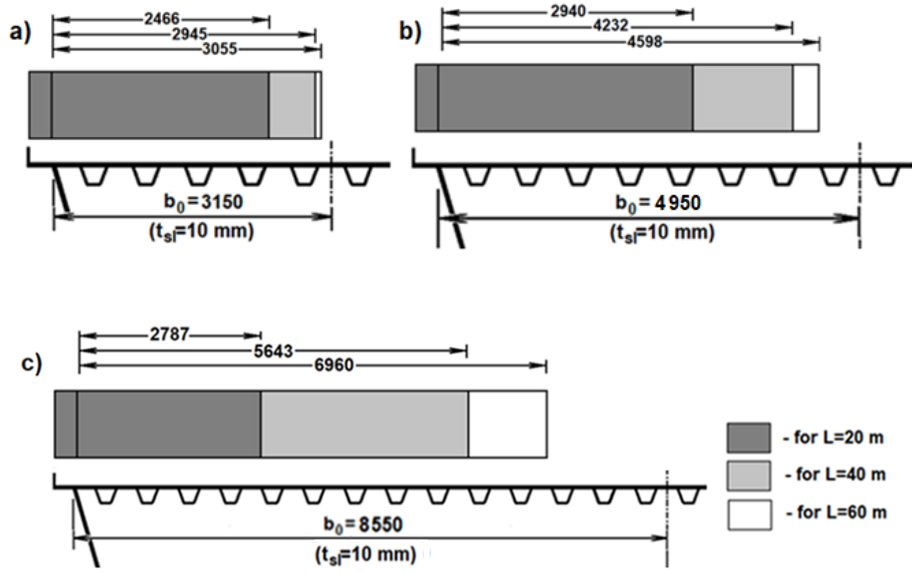


Fig. 7 - Effective[s] widths for the analyzed steel decks:
a) Steel deck - Case 1; b) Steel deck - Case 2; c) Steel deck - Case 3

Effective[s] width and the shear lag at ultimate limit state (ULS)

The effect of plate buckling in the elastic global analysis and ULS may be neglected because the condition $A_{eff} > \rho_{\lim} \cdot A_f = 0.5 \cdot A_f$ is fulfilled (Beg D. *et al.,* 2010).

In these analyzed cases all sub-panels are in section class less than Class 4, so we have $\rho = 1.0 > \rho_{\lim} = 0.5$ and $A_{c.eff} = A_f$.

For a more exact evaluation of the shear lag effect the method *c)* recommended by EN1993-1-5 can be used.

An elastoplastic reduction factor $\beta^k \geq \beta$ should be directly applied to the effective[p] area of the compression flange, where *k* is based on α_0:

$$A_{eff} = \beta^k \cdot A_{c.eff} \geq A_{c.eff} \cdot \beta$$

Example: From Table 2.a for: b_0=8550 mm; t_{sl}=10 mm; β =0.326; k=0.568

It results: $\beta_{e-p} = \max\left(\beta^k; \beta\right) = \max\left(0.326^{0.568}; 0.326\right) = 0.53$

The flange gross and effective areas will result as follows:

$$A_f = A_{c.eff} = 1.4 \cdot 855 + 14 \cdot 65 = 2107 \text{ cm}^2;$$
$$A_{f.eff} = \beta_{e-p} \cdot A_{c.eff} = 0.53 \cdot 2107 = 1327 \text{ cm}^2.$$

4. Conclusions and final remarks

The phenomenon shear lag is related to some of the discrepancies between this approximate theory of the bending of beams and their real behaviour and refers to the increases of the bending stresses near the flange-to-web junctions, and the corresponding decreases in the flange stresses away from these junctions.

In relation to the effective width method, SR EN 1993-1-5. §3.3 introduces three different designations for three types of effective width:

- Effective^s width – shear lag effects;
- Effectivep width – local buckling of plates;
- Effective width – interaction of shear lag and local buckling of plates (method recommended in the norm EN1993-1-5).

According to EN 1993-1-5, the shear lag in the flanges may be neglected if $b_0 < L_e/50$.

When designing plated structures, the effects of shear lag, plate buckling and interaction of both effects should be taken into account at the ultimate, serviceability or fatigue limit states, because the shear lag and plate buckling reduce the stiffness of the plated structures.

The following observations should be noticed:

- the more stiffened the flange is, the smaller its effectives width results (see the influence of the longitudinal stiffeners thickness, respectively the degree of stiffening);
- the flange width strongly influences the size of the effectives width (see β values given in the tables 2.a, 2.b and 2.c);
- the girder span size (effective girder length) has an important influence on the effectives width of the flange, especially when the large flanges are combined with a small girder span (a small effective length).

The design analysis presented in this paper is useful in the design activity and also to illustrate the determination of the shear lag effects according to EC1993-1-5.

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INFLUENŢA PARAMETRILOR DE CALCUL ASUPRA EFECTULUI SHEAR LAG LA PLATELAJELE ORTOTROPE DE PODURI METALICE RUTIERE

(Rezumat)

Fenomenul „shear lag" este legat de discordanța între teoria clasică de încovoiere a grinzii și comportarea reală a acesteia, în particular cea referitoare la creșterea eforturilor unitare din încovoiere la nivelul legăturii talpă-inimă și corespunzător, scăderea acestora în talpă, la o anumită distanță de această zonă de conexiune.

În cazul structurilor cu tălpi dezvoltate, cum este cazul grinzilor de poduri metalice tip cheson cu platelaj ortotrop, efectul shear lag trebuie luat în considerare prin introducerea unei lățimi efectives reduse, pe lățimea căreia eforturile unitare normale din încovoiere se consideră constante și egale cu valoarea maximă a acestora calculată prin teoria clasică de încovoiere.

În lucrare se prezintă câteva aspecte teoretice privind fenomenul shear lag și evaluarea lățimii efectives, precum efectele parametrilor de calcul – gradul de rigidizare, lățimea platelajului și deschiderea grinzii (lățimea efectivă a grinzii) asupra lățimii efective, efecte puse în evidentă prin analiza numerică efectuată în cadrul lucrării.

Analiza numerică de calcul prezentată în această lucrare este utilă în activitatea de proiectare și, de asemenea, pentru a înțelege evaluarea efectelor shear lag în conformitate cu normativul EC1993-1-5.