XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Comparative analysis of composite slab steel formwork design by Direct Strength and Effective Width Methods

Mayane C. Loureiro[1], Élcio C. Alves[1], Adenilcia Fernanda G. Calenzani[1]

[1] *Dept. of Civil Engineering, Federal University of Espírito Santo*
Avenue Fernando Ferrari, 514, 29075-910, Vitória/ES, Brazil
mayane.loureiro@ufes.edu.br, elcio.calves1@gmail.com, adenilcia.calenzani@ufes.br

Abstract. Among the different methods used to analyze the behavior of a cold-formed profile section subjected to bending moment, the Direct Strength Method (DSM) and the Effective Width Method (EWM) have become popular in the design of these structures. Although recently both methods have been approached in the area of optimization for different geometries and applications and, also, in the comparison with experimental results, there is a lack of studies that contemplate the design of composite slab formwork considering the construction phase in which the resistant section is that of profiled steel sheet. Thus, this article aims to compare the Direct Strength and Effective Width methods when used to dimension steel formwork sections for composite slabs. In the application of the DSM, to obtain the critical moments through the analysis of elastic stability, the computational program CUFSM was used, whose methodology used is the finite strip method (FSM). The design process was carried out on the MATLAB® computational platform and the analysis started from 4 different geometries, produced for commercialization in the Brazilian market. EWM has proven to be a more conservative approach for geometries with stiffeners and DSM for geometries without stiffeners.

Keywords: Steel formworks, Design Methods, Direct Strength Method, Effective Width Method, Elastic buckling analysis.

1 Introduction

Composite slab design occurs both during the initial or construction phase (verification of the formwork separately supporting the actions of fresh concrete and the construction overload) and during the final (after the concrete has cured). In both cases, the safety, to the ultimate limit states (ULS), and performance, to the serviceability limit states (SLS), must be verified.

NBR 16421:2015 [1] determine specific requirements for the design of steel forms, such as minimum thickness, steel type, dimensions, and constructive provisions. The structural analysis and design, in turn, are based on the following standards: NBR 8800:2008 [2], which specifies how to proceed in the verification design of steel and composite structures for buildings, and NBR 14762:2010 [3], which addresses the design of cold-formed steel structures.

There is currently no standard methodology for analyzing the behavior of a steel formwork section for composite slabs subjected to bending moments. Existing cold-formed profile dimensioning methods are used, and the Direct Strength Method (DSM) and the Effective Width Method (EWM) have become popular in the design of these structures.

Schafer [4] described the evolution of DSM, noting that in the last ten years, the method is scope of application in cold-formed steel profiles has significantly expanded, making it one of the most advantageous and promising techniques in this field. Despite its greater complexity in methodology, the EWM is a consolidated alternative that is present in several world codes such Eurocode 3 [5] e AISI S100-16 [6].

Although DSM and EWM are addressed in several optimization studies of cold-formed steel structures in various geometries and applications such as beam [7-10], column [11], beam-column [12], and frames [13], studies on steel formwork for composite slabs are lacking. Both methods have recently been compared with experimental results using different sections of steel formwork [14-16].

Therefore, this research aims to compare the DSM e EWM for dimensioning steel formwork sections for composite slabs. The computational program CUFSM, whose methodology is the conventional finite strip method (FSM), was used to obtain the critical moments through the analysis of elastic stability when using the DSM.

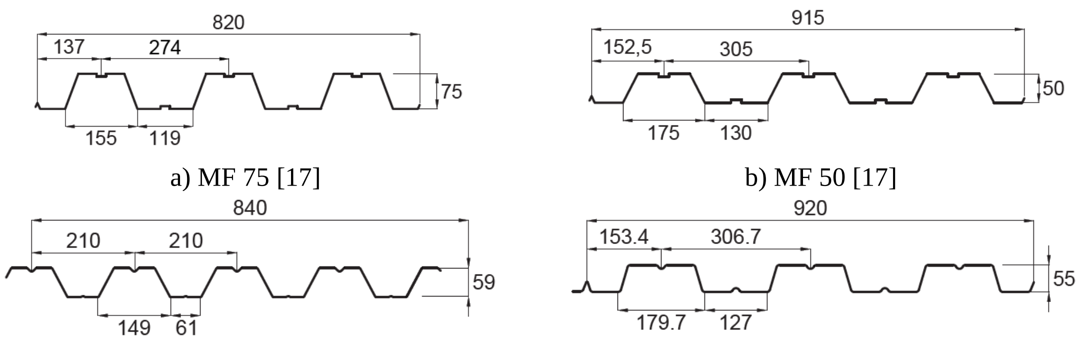
The analysis began with four different geometries with intermediate stiffeners, produced for commercialization in the Brazilian market, and was carried out in the MATLAB® computer program. In addition to the original geometries, four forms without stiffeners are designed, for a total of eight geometries. Furthermore, the study considers spans with three and four supports that are simply supported (positive bending) or continuously supported (positive and negative bending).

2 Problem definition

The research consists of an examination of four different steel form geometries produced for commercialization in the Brazilian market. Modular Sistema Construtivo [16], Metform [17], and ArcelorMittal Perfilor [18] provided the geometries dimensions. Metform is cross-sections are from models with straight corners, so the MF 50 and MF 75 will be analyzed without regard for bend radii.

Four more geometries without stiffeners were designed to compare forms with and without intermediate stiffeners on the tables. Furthermore, the design takes into account three span support conditions: simply supported spans (positive bending) and continuous spans (positive and negative bending) with three and four supports. In numerical applications, its value is given as the calculated maximum span (L_F), having as a reference section without stiffener, since the section with stiffener reach larger spans.

Polydeck 59S [18], Modular Deck MD 55 [16], MF 75 [17], and MF 50 [17] with and without stiffeners are the examples studied. Figure 1 depicts the original prototypes that were used.



a) MF 75 [17]

b) MF 50 [17]

c) Polydeck 59S [18]

d) Modular Deck MD 55 [16]

Figure 1. Cross-section models and its respective dimensions (units in mm)

The following steel properties and formwork thickness were used: f_y = 280 MPa, E = 200 GPa, ν = 0.3 and t = 0.76 mm. The overall depth of the composite slab was considered equal to 130 mm when calculating the loading in the construction phase. For the serviceability limit state, it was taken the most onerous combination with unity load factor for live load.

3 Design method

The EWM is an analytical and traditional method for assessing local instability in cold-formed steel structures. Von Karman *et al.* [19] proposed the concept of effective width, which is now included in the scope of several world codes.

In theory, the EWM simplifies the fact that, instead of using a non-uniform stress distribution in any width plate, it is considered a fictitious width of a smaller plate, called effective width, subjected to a uniformly distributed stress equal to the maximum stress. Despite being a standardized method that is frequently used in several cross-sections of cold-formed steel profiles, it is a time-consuming alternative that is still not used in the evaluation of formwork sections for composite slabs.

The DSM emerged in 1998 from Benjamin W. Schafer doctoral studies with the goal of providing more efficient calculation procedures for geometries with intermediate and edge stiffeners [4]. This method can help with the design of cold formed steel members, which are considered complex in the field of structural engineering.

According to NBR 14762:2010 [3] a general analysis of the elastic stability of the bar is required for the evaluation of the resistant bending moment by the DSM. The method relies on determining the critical buckling moment values for the local, distortional, and global modes.

Because it is used as a parameter to determine the design strengths, the elastic stability analysis is a critical step in the modeling of cold-formed steel profiles. The engineer must seek assistance from computational tools, such as CUFSM [20], a reference in cold-formed cross-section elastic stability analysis.

3.1 Finite strip method (FSM)

The FSM elastic stability analysis requires the interpretation of a generated curve in order to determine the critical (or minimum) loads of the local, distortional, and global buckling modes. According to Li and Schafer [20], the signature curve can have both unique and non-unique minima. In the first case, there are two distinct minima that correspond to local buckling and distortional buckling, respectively. However, in some cases, only one or more than two points on the graph are identified, called indistinct or non-unique minima.

In the cases mentioned above, the calculation with the FSM is difficult because it is impossible to identify the elastic buckling loads. Because of its ability to automatically predict the loads of pure elastic buckling modes, the constrained finite strip method (*c*FSM) is useful in this situation. However, the direct application of *c*FSM has the following limitations [20]: The DSM formulation is adjusted for the FSM is critical loads and can produce small divergence when using the values of the *c*FSM pure modes; however, the *c*FSM cannot handle rounded corners.

When modeling cold-formed steel structures, rounded corners must be considered in order to achieve satisfactory and close-to-real results. In this study, the FSM@*c*FSM-L_{cr} [20] methodology was used to solve the problem of non-unique minima and the impact of rounded corners, which identifies the length of half-wave of the unique minima determined in the *c*FSM and uses them in the FSM to find the elastic buckling loads.

3.2 Direct Resistance Method (DSM)

The assessment of bending moment resistance by DSM is addressed in Annex C of NBR 14762:2010 [3]. The Brazilian standard expresses are represented in the Equations (1) to (3).

The bending moment of design M_{Rd} is given by:

$$M_{Rd} = \frac{M_{Rk}}{\gamma_a}. \tag{1}$$

where γ_a is the strength weighting coefficient assuming the value of 1.1 and M_{Rk} is the characteristic resistant bending moment, taken as the smallest value between the bending moments resistant to lateral torsional buckling (M_{Re}), to local buckling ($M_{R\ell}$) and distortional buckling (M_{Rdist}).

The bending moments resistant to lateral torsional buckling (M_{Re}), local buckling ($M_{R\ell}$) and distortional buckling (M_{Rdist}) are obtained respectively from the critical moments to lateral torsional buckling (M_e), local buckling (M_ℓ) and to distortional buckling (M_{dist}), determined by elastic stability analysis.

In this work, to determine the M_{Rk}, only the critical moment of local buckling was considered, since lateral torsional and distortional buckling are not predominant failure modes due to the wide and flat configuration of the formwork [15]. The FSM via CUFSM was used to calculate the critical moment for local buckling, taking a unitary reference moment, 1 N.m, so the load factor found in CUFSM consists of the critical moment itself (M_ℓ).

The local buckling nominal flexural strength, $M_{R\ell}$, shall be determined as follows:

$$\lambda_\ell = \left(\frac{M_{Re}}{M_\ell}\right)^{0.5}. \tag{2}$$

$$M_{R\ell} = \begin{cases} M_{Re}. & if\ \lambda_\ell \le 0.776 \\ \left(1 - \frac{0.15}{\lambda_\ell^{0.8}}\right)\frac{M_{Re}}{\lambda_\ell^{0.8}}. & if\ \lambda_\ell > 0.776 \end{cases} \quad (3)$$

were λ_ℓ is the slenderness factor of local buckling. For the displacement of bars by the DSM, an effective moment of inertia of the section I_{ef} given by Equation (4) must be considered.

$$I_{ef} = I_g \left(\frac{M_{Rser}}{M_n}\right) \le I_g. \quad (4)$$

where M_n is the requesting bending moment considering the combinations of actions for the SLS, M_{Rser} is the resisting bending moment and I_g is the gross moment of inertia.

3.3 Effective Width Method (EWM)

According to NBR 14762:2010 [3] the design resistant bending moment M_{Rd} by the EWM must be determined based on Equation (5):

$$M_{Rd} = \frac{(W_{ef}\, f_y)}{\gamma}. \quad (5)$$

where W_{ef} is the elastic resistance modulus of the effective section with respect to the extreme fiber that reaches yield, with the stress σ calculated for the effective section yield start ULS, f_y is the yield strength of the formwork steel and γ is the resistance weighting coefficient.

To find the W_{ef} it is necessary to determine the effective width, b_{ef}, according to Equations (6) to (9), considering the two types of boundary conditions for the sheet elements, AA and AL, that is, element with supported-supported edges and element with free-supported edges, respectively.

For $\lambda_p \le 0.673$,

$$b_{ef} = b. \quad (6)$$

For $\lambda_p > 0.673$,

$$b_{ef} = \frac{b\left(1 - \frac{0.22}{\lambda_p}\right)}{\lambda_p}. \quad (7)$$

$$\lambda_p = \left(\frac{\sigma}{\sigma_{cr}}\right)^{0.5}. \quad (8)$$

$$\sigma_{cr} = k\frac{\pi^2 E}{12(1-\nu^2)\,(b/t)^2}. \quad (9)$$

where b is the width of the element, λ_p is the reduced slenderness index of the element, σ_{cr} is the conventional elastic buckling stress of the element, t is the thickness of the steel formwork, k is the local buckling coefficient of the element, calculated according to Table 5 of NBR 14762:2010 [3], ν is the Poisson ratio of steel, adopted the value of 0.3, E is the modulus of elasticity, σ is the normal compressive stress, determined for the effective section. If the maximum stress is tensile, σ can be calculated assuming linear stress distribution. Therefore, the effective section must be determined by successive approximations.

The formulation of the method used by the Brazilian standard presents similarities in relation to the American standard AISI S100-16 [19]. However, NBR 14762:2010 [3] does not have in its scope the determination of the effective width of elements with intermediate stiffeners. The effective width of elements with intermediate stiffeners are determined in accordance with Appendix 1 in AISI S100–16 [6].

Regarding the displacement by the EWM, according to NBR 14762:2010 [3], it must be determined by successive approximations, considering the reduction of its stiffness associated with local buckling, through an effective moment of inertia of the I_{ef} section. The I_{ef} is obtained based on the effective widths b_{ef}, replacing λ_p by λ_{pd} as indicated in Equation (10).

$$\lambda_{pd} = \frac{\left(\frac{b}{t}\right)}{0.95\left(\frac{kE}{\sigma_n}\right)^{0.5}}. \quad (10)$$

where σ_n corresponds to the maximum normal compressive stress, calculated for the effective cross-section and considering the combinations of actions for the SLS.

4 Results and discussions

The estimation of the resistant bending moment M_{Rd} and the moment of inertia I_{ef} obtained by the EWM and DSM for the section of steel forms with stiffener are presented in Table 1.

Table 1. Strength estimation by EWM and DSM for section with stiffener

Span		Modular Deck MD 55			Polydeck 59S			MF 75			MF 50		
		MRD	MLE	R	MRD	MLE	R	MRD	MLE	R	MRD	MLE	R
Simple	L_F	1.50	1.50	--	1.70	1.70	--	2.10	2.10	--	1.40	1.40	--
	$M_{Rd}{}^{+}$	3.87	3.57	0.92	4.75	4.59	0.97	6.12	5.25	0.86	3.51	2.76	0.78
	I_{ef}	56.56	56.48	1.00	59.23	59.13	1.00	116.20	117.42	1.01	47.37	47.29	1.00
Double	L_F	1.80	1.80	--	2.00	2.00	--	2.40	2.40	--	1.60	1.60	--
	$M_{Rd}{}^{+}$	3.87	3.57	0.92	4.75	4.59	0.97	6.12	5.25	0.86	3.51	2.76	0.78
	$M_{Rd}{}^{-}$	3.91	3.57	0.91	4.75	3.96	0.83	6.19	5.25	0.85	3.53	2.76	0.78
	I_{ef}	56.56	56.48	1.00	59.23	59.13	1.00	116.20	117.42	1.01	47.37	47.29	1.00
Triple	L_F	1.80	1.80	--	2.00	2.00	--	2.50	2.50	--	1.70	1.70	--
	$M_{Rd}{}^{+}$	3.87	3.57	0.92	4.75	4.59	0.97	6.12	5.25	0.86	3.51	2.76	0.78
	$M_{Rd}{}^{-}$	3.91	3.57	0.91	4.75	3.96	0.83	6.19	5.25	0.85	3.53	2.76	0.78
	I_{ef}	56.56	56.48	1.00	59.23	59.13	1.00	116.20	117.42	1.01	47.37	47.29	1.00

Note: M_{Rd} in kN.m/m; I_{ef} in cm^4/m; R - Ratio between EWM and DSM

Note that the results obtained by the DSM were higher in all geometries, except the estimated I_{ef} for the MF 75 formwork. The largest percentage difference between the methods was for the MF 50 formwork (double and triple span), 21.88% and 1.05% in strength and inertia, respectively. The smallest for Polydeck 59S (all spans) and Modular Deck MD 55 (all spans), equivalent to 3.31% and 0.15% for M_{Rd} and I_{ef}, respectively.

When comparing the EWM and DSM, agreement between the two methods is observed due to the small divergence in the results found. In addition, the M_{Rd} obtained by the DSM was higher in all forms and the I_{ef} in approximately 75% of the cases, indicating an advantage over the EWM, since its use will lead to more economical forms.

Table 2 presents the results for the section without stiffener considering the three support conditions of the slab span.

Table 2. Strength estimation by EWM and DSM for section without stiffener

Span		Modular Deck MD 55			Polydeck 59S			MF 75			MF 50		
		MRD	MLE	R**	MRD	MLE	R	MRD	MLE	R	MRD	MLE	R
Simple	L_F	1.50	1.50	--	1.70	1.70	--	2.10	2.10	--	1.40	1.40	--
	M_{Rd}^+	2.11	2.44	1.16	2.52	3.39	3.39	3.36	3.82	1.14	1.94	2.00	1.03
	I_{ef}	47.46	57.38	1.21	56.75	59.56	59.56	94.20	113.03	1.20	43.70	46.18	1.06
Double	L_F	1.80	1.80	--	2.00	2.00	--	2.40	2.40	--	1.60	1.60	--
	M_{Rd}^+	2.11	2.44	1.16	2.52	3.39	3.39	3.36	3.82	1.14	1.94	2.00	1.03
	M_{Rd}^-	2.10	2.44	1.16	2.90	3.49	3.49	3.27	3.82	1.17	1.95	2.00	1.02
	I_{ef}	50.94	57.38	1.13	59.38	59.56	59.56	104.26	113.03	1.08	43.29	46.18	1.07
Triple	L_F	1.80	1.80	--	2.00	2.00	--	2.50	2.50	--	1.70	1.70	--
	M_{Rd}^+	2.11	2.44	1.16	2.52	3.39	3.39	3.36	3.82	1.14	1.94	2.00	1.03
	M_{Rd}^-	2.10	2.44	1.16	2.90	3.49	3.49	3.27	3.82	1.17	1.95	2.00	1.02
	I_{ef}	48.76	57.38	1.18	58.95	59.56	59.56	97.27	113.03	1.16	40.24	46.18	1.15

Note: M_{Rd} in kN.m/m; I_{ef} in cm^4/m; R - Ratio between EWM and DSM

When comparing the two methods, it is observed that the EWM presented better results in all cases, with a difference of up to 34.13% for Polydeck 59S (all spans) and 20.91% for Modular Deck MD 55 (simple span), for M_{Rd} and I_{ef}, respectively. The sections with the smallest percentage difference were MF 75 (double and triple span) in M_{Rd} and Polydeck 59S (double span) in I_{ef}. The percentage difference between the two methods for section without stiffener was between 2.31% to 34.13% for M_{Rd} and 0.3% to 20.91% for I_{ef}.

5 Conclusions

This research compared the DSM and EWM in the design of steel formwork sections for composite slabs. The computational program CUFSM, whose technique is the FSM, was utilized to obtain the critical moments through the analysis of elastic stability while using the DSM. Because of the FSM is limitations, the method FSM@cFSM-L_{cr} [20] was chosen as an efficient solution to the problem.

The dimensioning process was carried out in the computer application MATLAB® and the study started from four geometries, produced for commercialization in the Brazilian market. Four further geometries without stiffeners were studied to examine the influence of stiffeners. For the shapes, different boundary conditions were investigated, including a two-supported span, two spans with three supports, and three spans with four supports.

In the examination of stiffened sections, the DSM appears to be a more beneficial approach than the EWM, once the M_{Rd} and I_{ef} was higher in all conditions. The percentage difference between the methods was of 3.31% to 21.88% for the M_{Rd} and 0.15% to 1.05% for the I_{ef}.

With respect to geometries without an intermediate stiffener, the EWM achieves higher strength estimates. The methods showed divergence of up to 34.13% for M_{Rd} and 20.91% for I_{ef}.

In summary, DSM gives higher strength values than EWN for all sections with intermediate stiffeners. Once the forms, in practical, presents intermedial stiffeners, the DSM method shows to be a more interesting methodology from an economic standpoint, as well as being simpler to apply in complex geometries, as is the case with steel forms for composite slabs.

Acknowledgements. The authors acknowledge the Brazilian Federal Government Agency CAPES for the financial support provided during the development of this research. The third author thanks the Brazilian Federal Government Agency CNPq for the productivity research grant number 309741/2020-3.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] NBR 16421. Stell floor deck for composite steel and concrete slab - Requirements and testing. Brazilian Association of Technical Standards, 2015.
[2] NBR 8800. Design of steel and composite structures for buildings. Brazilian Association of Technical Standards, 2008.
[3] NBR 14762. Design of cold-formed steel structures. Brazilian Association of Technical Standards, 2010.
[4] B. W. SCHAFER. "Advances in the Direct Strength Method of cold-formed steel design". *Thin-Walled Structures*, v. 140, n. March, pp. 533–541, 2019.
[5] CEN. Eurocode 3: design of steel structures, part 1.3: general rules—supplementary rules for cold formed members and sheeting. Brussels: European Comittee for Standardization; 2005.
[6] AISI S100-16: North American specification for the design of cold-formed steel structural members. American Iron and Steel Institute, 2016.
[7] S. M. MOJTABAEI, J. YE, and I. HAJIRASOULIHA. "Development of optimum cold-formed steel beams for serviceability and ultimate limit states using Big Bang-Big Crunch optimisation". *Engineering Structures*, v. 195, n. May, pp. 172–181, 2019.
[8] J. YE *et al.* "Optimum design of cold-formed steel beams using Particle Swarm Optimisation method". *Journal of Constructional Steel Research*, v. 122, pp. 80–93, 2016a.
[9] J. YE *et al.* "Development of more efficient cold-formed steel channel sections in bending". *Thin-Walled Structures*, v. 101, pp. 1–13, 2016b.
[10] B. WANG *et al.*, "Unconstrained shape optimisation of singly-symmetric and open cold-formed steel beams and beam-columns". *Thin-Walled Structures*, v. 104, pp. 54–61, 2016b.
[11] B. WANG *et al.*, "Shape optimisation of manufacturable and usable cold-formed steel singly-symmetric and open columns". *Thin-Walled Structures*, v. 109, n. September, pp. 271–284, 2016a.
[12] H. PARASTESH *et al.*, "Shape optimization of cold-formed steel beam-columns with practical and manufacturing constraints". *Journal of Constructional Steel Research*, v. 155, pp. 249–259, 2019.
[13] D. T. PHAN *et al.* "Coupled element and structural level optimisation framework for cold-formed steel frames*". Journal of Constructional Steel Research*, v. 168, pp. 105867, 2020.
[14] C. H. RAEBEL, J. A. SCHULTZ, and B. WHITSELL. "Experimental investigation into acceptable design methods for cold-formed metal deck". *Journal of Constructional Steel Research*, v. 172, pp. 106176, 2020.
[15] R. K. D. SCHULTZ, S. THOMAS, and F. WALTER. Direct Strength Method for Steel Deck. AISI-Specifications for the Design of Cold-Formed Steel Structural Members, 2015. Disponível em: <https://scholarsmine.mst.edu/ccfss-aisi-spec/116>. Acesso em: 22 set. 2020.
[16] MODULAR SISTEMA CONSTRUTIVO. Modular Deck MD 55 – Laje com fôrma de aço incorporada. 2014.
[17] METFORM. Catálogo steel deck. 2019. Disponível em: <http://www.metform.com.br/wordpress/?project=telha-forma>. Acesso em: 04 nov. 2020.
[18] ARCELORMITTAL PERFILOR. Polydeck 59S - Forma-laje "Steel Deck". 2016 Disponível em: <https://brasil.arcelormittal.com/produtos-solucoes/construcao-civil/Polydeck-59s>. Acesso em: 04 nov. 2020
[19] T. VON KARMAN, E. E. SECHLER, and L. H. DONNEL. "The strength of thin plates in compression". *Transactions of the American Society of Mechanical Engineers*, New York, vol. 54, n. 5, pp. 53-57, 1932.
[20] Z. LI and B. W. SCHAFER. "Application of the finite strip method in cold-formed steel member design". *Journal of Constructional Steel Research*, v. 66, n. 8–9, pp. 971–980, 2010.