The Effect of Rounded Corners in the Moment Resistance of Steel Shuttering of Composite Slabs

Mayane C. Loureiro[1], Protáze Mageveske[2], Élcio C. Alves[1], Adenilcia Fernanda G. Calenzani[1]

[1]*Dept. of Civil Engineering, Federal University of Espírito Santo*
514 Fernando Ferrari Avenue, VI Technological Center, 204 Room, Vitória, ES, 29060-970, Brazil
mayane.loureiro@ufes.edu.br, adenilcia.calenzani@ufes.br, elcio.calves1@gmail.com
[2]*Dept. of Civil Engineering, Federal University of Ouro Preto*
Campus Morro do Cruzeiro, 35400-000, Ouro Preto, Minas Gerais, Brazil
protaze.netto@aluno.ufop.edu.br

Abstract. The objective of this paper is to analyze the influence of modeling rounded corners on the bending moment resistance of steel formworks used in composite slabs. The Finite Strip Method (FSM), as well as the constrained Finite Strip Method (cFSM) were implemented via the software CUFSM for trapezoidal cross-sections to predict the bending moment resistance with the Direct Strength Method. The FSM was used to determine the critical loads and the cFSM served to identify distinct buckling modes for signature curves without unique minima. Five different steel sheet geometries were analyzed - four commercially available sections and one extracted from the literature. Based on these, 4 additional geometries with no intermediate stiffeners and 5 with straight-line models were designed. In total, this study investigated 5 and 9 cross-sections with straight-line and rounded corner models, respectively. Results show a slight influence of the corners on the critical moment of local buckling, with straight-line models reducing this value, as well as increasing the distortional critical moment. Overall, the difference between the cFSM and the FSM decreases for the local mode when considering rounded corner models with stiffeners and for the distortional mode when using straight-line models with stiffeners.

Keywords: elastic buckling analysis, steel formwork, finite strip method.

1 Introduction

Due to the small thickness of the steel decking used in composite slabs, these elements are susceptible to local and distortional instabilities. This particularity, along with complex geometry, demands a high level of knowledge from engineers when designing this type of element. According to Schafer [1], the Direct Strength Method (DSM) coupled with computational elastic stability analyses simplifies the design of complex thin-walled cold-formed steel cross-sections, providing a repeatable and efficient framework that enables structural optimization.

The recent scientific literature features some optimization studies conducted on cold-formed steel structures using different techniques, loading conditions, and cross-section geometries, implemented with the Finite Strip Method (FSM) via the software CUFSM to investigate the behavior of beams, columns, and beam-column systems [2]-[4]. Although said studies address the optimization of cold-formed steel structures for different geometries and applications, there is a lack of studies focused on the cross-section modelling during the stability analysis, especially for steel decks. Usually, the studies investigate the effectiveness of the Effective Width (EWM) and Direct Resistance Methods for floors and roofs comprised of steel decking and compare results with data from numerical and experimental tests [5]-[7].

Therefore, this research aims to analyze the influence of modeling rounded corners on the bending moment strength of steel formworks used in composite slabs. The FSM and the constrained Finite Strip Method (cFSM) were explored for steel formwork with trapezoidal cross-sections, via the software CUFSM, to predict the bending moment resistance using the DSM. The FSM can determine the critical loads and the cFSM helps to identify distinct buckling modes when the analysis does not present unique minima.

Moreover, mesh sensibility studies were carried out along with an evaluation of elastic buckling moments obtained with the FSM and cFSM methods, for both straight-line and round corner models, with and without intermediate stiffeners on the flanges. The analysis is based on five different geometries, one reproduced from the literature, and four are currently available in the Brazilian market. In total, 5 geometries with round corners and 9 geometries with straight-line models were analyzed.

2 Finite Strip Method

The conventional, or semi-analytical, FSM provides the most widely used approach for examining instabilities in a thin-walled member under longitudinal stress (axial, bending, and/or warping torsion). In particular, the application of FSM to members with simply supported ends results in an efficient solution and provides a ''signature curve'' for the stability of a member [8]. This curve graphically presents the load factor as a function of the half-wavelength, as illustrated in Fig. 1. It should be noted that the load factor is the ratio between the critical load and the initial applied load.

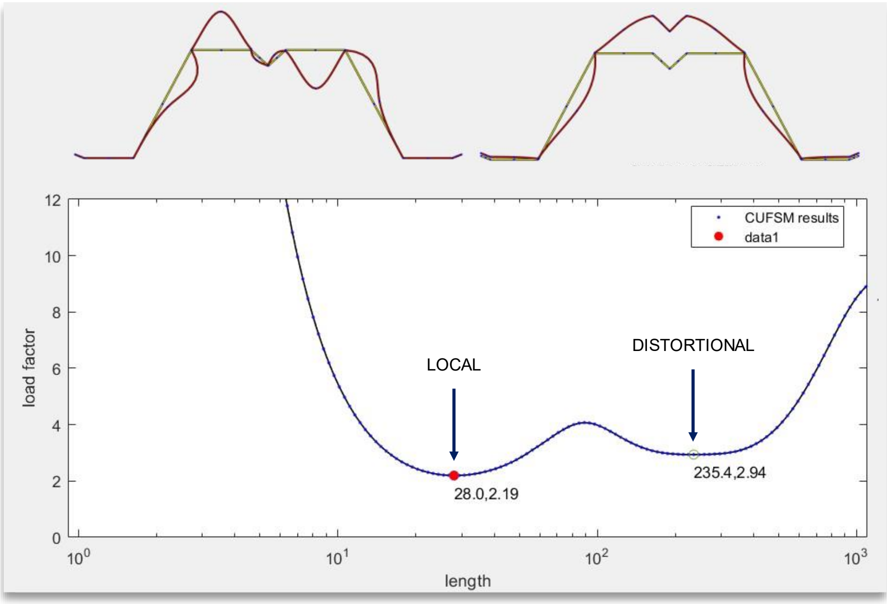

Figure 1. Signature curve – FSM solution

The elastic stability analysis performed by the FSM requires curve interpretation to find the critical/minimum loads of local, distortional, and global buckling modes. The signature curve can contain both unique and non-unique minima [8]. In the first case, there are two minima characterized as distinct, corresponding to local buckling and distortional buckling, respectively. However, in some situations, the signature curve may not have two minima, or may have more than one minimum for local or distortional buckling, called indistinct or non-unique minima. In these cases, the calculation with the FSM is not straightforward, as it makes it impossible to identify the elastic buckling loads. This prompted the development of the cFSM [9], which predicts the loads of pure elastic buckling modes automatically.

Li and Schafer [8] explain that cFSM was originally derived from the semi-analytical FSM and that the method is capable of decomposing the original FSM displacement into pure local (L), distortional (D), global (G), and other (O) buckling modes. Pure buckling modes are isolated ones that do not interact with other modes, unlike the semi-analytical FSM.

According to Li and Schafer [8], cFSM has two main applications: modal decomposition and modal identification. The first presents the stability solution for the selected buckling mode (Fig. 2), while the second classifies the contribution of the buckling modes in the general solution via semi-analytical FSM.

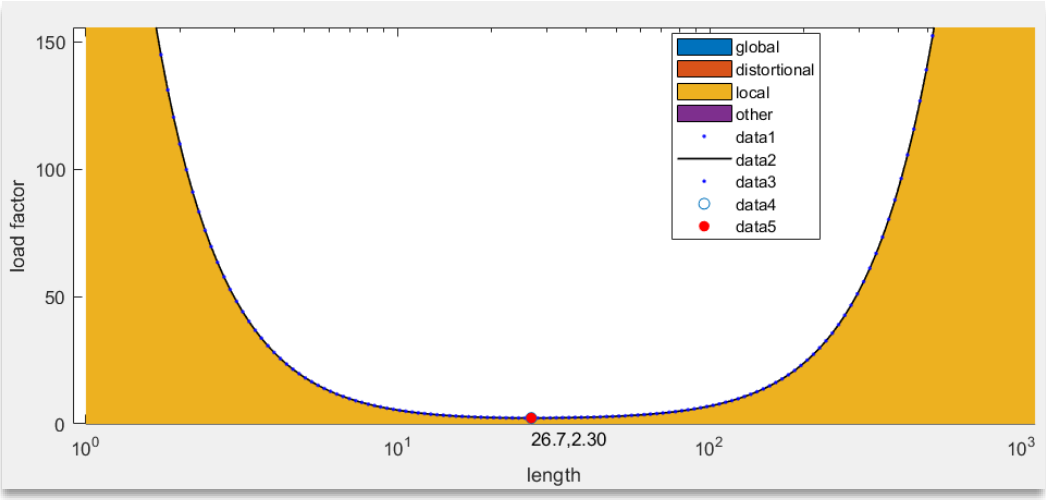

Figure 2. Example of signature curve with pure local mode cFSM solution

3 Problem definition

In addition to the geometry obtained from the literature [6], the companies Modular Sistema Construtivo [10], Metform [11], and ArcelorMittal Perfilor [12] have provided four other steel formwork geometries for this study. The cross-sections supplied by Metform are straight-line models. Therefore, MF 50 and MF 75 will be analyzed without the bend radius.

To compare formworks with and without intermediate stiffeners on the flanges, four additional geometries without stiffeners and five geometries with straight-lines were designed to obtain critical loads with FSM and cFSM methods. The novel designs were based on formwork 1.5B [6], Polydeck 59S [12], Modular Deck MD 55 [10], MF 75 and MF 50 [11]. The originally adopted prototypes are illustrated in Fig. 3.

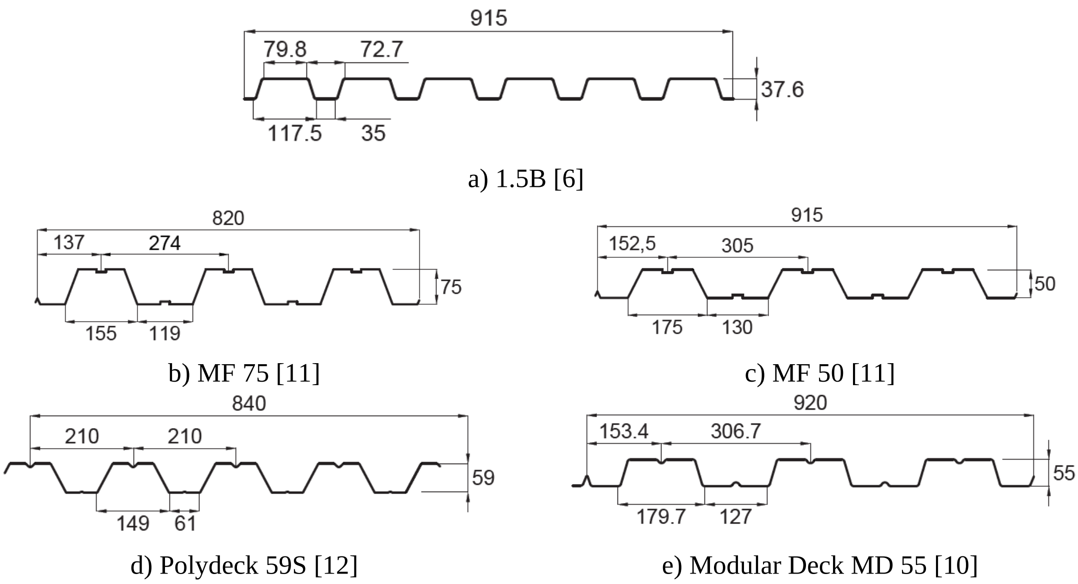

Figure 3. Cross-section models and its respective dimensions (units in mm)

For model 1.5B, the following proprieties are considered: thickness (t) equal to 0.75 mm, yield stress (F_y) equal to 227.53 MPa and modulus of elasticity (E) of 203.4 GPa. For the other models, the values were: t equal to

0.76 mm, F_y equal to 280 MPa, and E of 200 GPa. Moreover, Poisson's ratio v is 0.3.

4 Numerical simulation

4.1 Study of the number of finite strips

The influence of the number of finite strips, adopted for the cross-sections, on the critical moment was investigated. The analysis considered straight-line and round corner models with flat elements discretized in one, two, four, and eight strips. Different meshes were also evaluated for round corner models, such as one strip per flat element and four strips on each curved element, two strips for both flat and curved elements, four strips for both flat and curved elements, and eight strips for both flat and curved elements.

The cFSM was implemented for the straight-line models only, while FSM was applied to both types considering half-wavelengths between 1 and 10000 mm with 200 points, in logarithmic scale. Tables 1 and 2 provide the mean percentage error (MPE), standard deviation (St. dev.), and the critical moment variance (Var.) of local and distortional buckling, for results obtained with the finest mesh (i.e., 8 strips).

Table 1. FSM strip sensitivity analysis

Model	Section type	Number of strips	M_ℓ [%]			M_{dist} [%]		
			MPE	St. dev.	Var.	MPE	St. dev.	Var.
Straight-line	Without stiffeners	1	40.20	1.45	0.02	3.68	0.00	0.00
		2	1.44	0.07	0.00	1.06	0.00	0.00
		4	0.09	0.01	0.00	0.26	0.00	0.00
		8	0.00	0.00	0.00	0.00	0.00	0.00
	With stiffeners	1	39.78	12.85	1.65	2.56	0.49	0.00
		2	1.56	0.30	0.00	0.48	0.10	0.00
		4	0.16	0.05	0.00	0.09	0.03	0.00
		8	0.00	0.00	0.00	0.00	0.00	0.00
Rounded corner	Without stiffeners	1p-4c*	28.87	3.10	0.10	n/d**	n/d	n/d
		2	2.06	0.65	0.00	n/d	n/d	n/d
		4	0.17	0.11	0.00	n/d	n/d	n/d
		8	0.00	0.00	0.00	n/d	n/d	n/d
	With stiffeners	1p-4c	26.51	0.62	0.00	1.56	0.16	0.00
		2	2.95	1.79	0.03	-1.01	1.04	0.01
		4	0.18	0.10	0.00	0.38	0.31	0.00
		8	0.00	0.00	0.00	0.00	0.00	0.00

*1p-4c: 1 strip per flat elements and 4 strips per curved elements; **n/d: no data available.

Table 2. cFSM strip sensitivity analysis

Model	Section type	Number of strips	M_ℓ [%]			M_{dist} [%]		
			MPE	St. dev.	Var.	MPE	St. dev.	Var.
Straight-line	Without stiffeners	1	24.83	9.63	0.93	1133.88	1133.81	12855.26
		2	-3.75	6.14	0.38	1133.88	1133.81	12855.20
		4	-1.51	2.58	0.07	9.01	9.03	0.82
		8	0.00	0.00	0.00	0.00	0.00	0.00
	With stiffeners	1	30.90	17.01	2.89	16.79	16.72	2.80
		2	-2.91	4.31	0.19	16.64	16.66	2.77
		4	-1.43	1.46	0.02	3.40	4.11	0.17

8	0.00	0.00	0.00	0.00	0.00	0.00

When the elements are discretized into 4 ranges, the sensitivity analysis presents satisfactory precision and acceptable variation, also pointed out by Li and Schafer [8] and Chodraui [13]. For the FSM, the MPE and standard deviation reached between 0.18% and 0.11% for M_{ℓ}, and 0.38% and 0.31% for M_{dist}, respectively. The cFSM shows increasing values compared to the FSM, apart from MPE values for M_{ℓ}, with a reduction of 1.51%. The local mode standard deviation and variance correspond to 2.58% and 0.07%, respectively. The highest values found were 9.01%, 9.03%, and 0.82% for the M_{dist}. Therefore, 4 strips will be used in future analyses.

4.2 Elastic buckling moment

To analyze and compare the FSM and cFSM responses, the critical moments obtained by each method are presented in Tab. 3 for models with and without stiffeners. Due to limitations of the method, it is not possible to obtain results for round corner models with cFSM.

Table 3. FSM and cFSM critical moments

Section type	Deck	FSM				cFSM	
		Round corner model		Straight-line model			
		M_{ℓ} [kN.m]	M_{dist} [kN.m]	M_{ℓ} [kN.m]	M_{dist} [kN.m]	M_{ℓ} [kN.m]	M_{dist} [kN.m]
Without stiffeners	1.5B	0.21	n/d*	0.21	n/d	0.23	0.42
	PD 59S**	0.37	n/d	0.37	n/d	0.37	n/d
	MD 55***	0.21	n/d	0.20	n/d	0.23	0.37
	MF 75	--	--	0.42	11.02	0.47	0.76
	MF 50	--	--	0.20	n/d	0.20	30.18
With stiffeners	PD 59S	2.40	2.95	2.39	3.23	2.54	3.55
	MD 55	1.17	1.68	1.09	2.12	1.22	1.92
	MF 75	--	--	2.75	3.71	2.97	3.21
	MF 50	--	--	1.13	1.70	1.14	1.88

*n/d: no data available; **Polydeck 59S; ***Modular Deck MD 55.

The FSM analysis allowed the definition of local and distortional critical moment minima for every geometry with stiffeners and the MF 75 without stiffeners. It was observed that the use of stiffeners considerably increases the critical moment values. Also, there was reasonable agreement between the two methods, especially for M_{ℓ}. Tab. 4 presents the differences between the critical cFSM moments.

Table 4. cFSM relative to FSM solution

Section Type	Deck	Round corner model		Straight-line model	
		M_{ℓ} [%]	M_{dist} [%]	M_{ℓ} [%]	M_{dist} [%]
Without stiffeners	1.5B	7.95	n/d*	9.21	n/d
	PD 59S**	0.63	n/d	0.10	n/d
	MD 55***	10.00	n/d	12.77	n/d
	MF 75	--	--	11.47	-93.07
	MF 50	--	--	0.06	n/d
With stiffeners	PD 59S	5.85	20.43	6.12	10.09
	MD 55	4.27	14.48	12.34	-9.28
	MF 75	--	--	8.05	-13.56
	MF 50	--	--	1.19	10.67

*n/d: no data available; **Polydeck 59S; ***Modular Deck MD 55.

Comparing the critical moments of the cFSM with those from FSM, it is observed that the former leads to larger critical moment values in almost all cases, which contributes to unconservative strength predictions [8]. For models considering round corners only, the highest percentage difference between methods is observed for local moment M_ℓ of Modular Deck MD 55 without stiffeners, equal to 10%. On the other hand, among straight-line models, the highest percentage difference of M_ℓ is up to 12.77%, also for Modular Deck MD 55 without stiffeners.

Moreover, distortional buckling values present a maximum difference between the two methods of up to 20% for Polydeck 59S with rounded corners and stiffeners, and -93% for MF 75 considering straight-line models without stiffeners. Overall, the difference between the cFSM and the FSM decreased for the local mode of rounded corner models with stiffeners and for the distortional mode when straight-line models with stiffeners were adopted.

4.3 Influence of the rounded corner modeling - FSM

Table 5 provides the percentage difference between the rounded corner model results obtained via FSM versus straight-line model results obtained with the same method. The comparison indicates that M_ℓ present lower and approximate values for every geometry, except Polydeck 59S, which has a small increase of 0.53%. Alternatively, M_{dist} presents a minimum increase of 9.39%. This may be a result of the curved corner reducing the flat part of the element and, consequently, the local slenderness. Therefore, straight-line models contribute to a lower critical local moment but increases the distortional critical moment. Thus, there is a small influence of corner geometry on the values of M_ℓ for the geometries studied.

Table 5. FSM rounded corners versus straight-line models

Section type	Deck	M_ℓ [%]	M_{dist} [%]
Without stiffeners	1.5B	-1.15	n/d*
	PD 59S**	0.53	n/d
	MD 55***	-2.45	n/d
	MF 75	--	--
	MF 50	--	--
With stiffeners	PD 59S	-0.25	9.39
	MD 55	-7.19	26.19
	MF 75	--	--
	MF 50	--	--

*n/d: no data available; **Polydeck 59S; ***Modular Deck MD 55.

5 Conclusions

This research analyzed the influence of rounded corners on the bending moment strength of steel formworks used in composite slabs. The FSM and cFSM methods were explored, via the software CUFSM, to obtain the trapezoidal cross-section elastic buckling moments. Five geometries with rounded corners and nine geometries with straight-line corners were adopted, considering models with and without intermediate stiffeners on the flanges.

In order to determine the ideal mesh configuration, a sensitivity study was carried out in relation to the number of strips used in FSM and cFSM. This analysis showed satisfactory precision when discretizing the elements into 4 ranges, which yielded acceptable variations in critical moment values. The highest mean percentage error observed for critical local buckling moments was of 0.18% for the FSM, while the cFSM showed a reduction of 1.51%. For critical distortional buckling moments, the cFSM presented the highest value, of 9.01%.

When evaluating the critical moments found by FSM and cFSM, it was observed that the use of stiffeners considerably increased critical moments. Furthermore, there was reasonable agreement between methods, with differences ranging from 0.53% to 12.77% for the critical moment of local buckling.

The cFSM application resulted in higher critical moment values for almost all cases analyzed in relation to the FSM, except for the determination of distortional buckling, which was lower in three out of five analyzed models. The difference is smaller in local mode when considering rounded corner models with stiffeners and in distortional mode when using straight-line models with stiffeners.

Comparing FSM results for both model types, when the straight-lines corners are adopted, the critical moment of local buckling presents inferior and approximate values for every geometry, while the critical moment of distortional buckling had an increase greater than or equal to 9.39%. Therefore, straight-line models contribute to a lower local critical moment and an increase in the distortional critical moment. Thus, there is slight influence of the corners on the local mode of the studied geometries.

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