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# Steel shuttering optimum geometry in construction stage for steel-concrete composite slabs

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**Abstract.** The use of profiled steel sheeting in steel-concrete composite slabs stands out for its economic and environmental advantages, since they are easy to install, fast in construction and reduce material waste. However, this system is still little used in Brazil and one of the reasons may be associated with the restricted supply of steel formwork geometries available in the national market. Therefore, this article determines the optimal structural solution for steel shuttering geometry of composite slabs focused on the construction phase, considering the minimization of steel consumption in the manufacturing process. The steel formwork design was performed by applying the Effective Width Method (EWM), which is a traditional and analytical method present in several optimization studies of cold formed steel structures. Finally, the optimization process was performed by Particle Swarm Optimization (PSO) in the software MATLAB®. In addition, four different commercial geometries will be analyzed at this stage in order to contribute to the development of new market models of shapes. The solution reduced steel consumption by 34.65% on average for formwork with intermediate stiffeners and 26.16% for sections without stiffeners.

**Keywords:** Steel formwork, Steel formwork geometry, Optimization, Effective Width Method.

## 1 Introduction

In the social context, composite floor system provide security during the assembly stage by acting as a service platform for workers and freeing up more free space between floors for equipment movement. On the environmental front, they can reduce the consumption of concrete, thereby reducing waste generation and pollutant emissions into the atmosphere, both of which are major causes of the greenhouse effect. In terms of economics, they result in significant labor savings as well as reduced use of shoring systems, saving the enterprise is overall budget.

Studies on cold-formed steel profiles, as steel forms are known, have encouraged the use of a wide range of cross-sections with simple to complex geometries. This significant advantage is due to steel is malleability, which allows for greater variety in the fabrication of geometries, motivating researchers and structural engineers to seek solutions to the problem of cross-section optimization.

Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) have recently been used in studies to solve cold-formed steel structure optimization problems. PSO [1] is an efficient method for optimizing cold-formed steel structures because it does not require crossover or mutation operators. This improves computational efficiency in general, especially for highly nonlinear optimization problems [2]. According to Jun Ye *et al.* [3], this results in a faster convergence rate than GA.

PSO was used by Ye *et al.* [4-5] to increase the flexural strength of cold-formed U-section steel beams with intermediate stiffeners in the web and edges. The researchers discovered a new stiffened table U-section with increased bending moment resistance. The optimized sections were created to meet the Effective Width Method (EWM) requirements in Ye *et al.* [4].

Ye *et al.* [6] identified a gap in research on energy dissipation in cold-formed profile structures and presented a cross section with better seismic performance than the geometry on the market. They also used the PSO to validate the cross-section beams used in the 2016 studies.

Mojtabaei, Ye, and Hajirasouliha [7] developed a method for designing cold-formed steel profile beams with maximum bending strength and minimum deflection under maximum load and service conditions. The Big Bang-Big Crunch optimization method was used by the authors, who were based on the EWM and took manufacturing and use constraints into account. The optimized sections had higher effective stiffness and resistance to bending moment when compared to standard U-section beams.

Although research on the optimization of cold-formed steel structural elements can be found, approaches to minimizing steel consumption of steel formwork for composite slabs are lacking. Steel sheets have thin thicknesses, which makes them susceptible to phenomena of local, distortional, and global instability. These peculiarities, combined with the geometry is complexity, necessitate a high level of knowledge for the design of such structures.

It is possible to evaluate the mechanical performance of composite slabs by linking them to optimization methods and techniques, especially during the construction stage, when the steel formwork, which works in isolation, is more requested and conditions the maximum span without shoring.

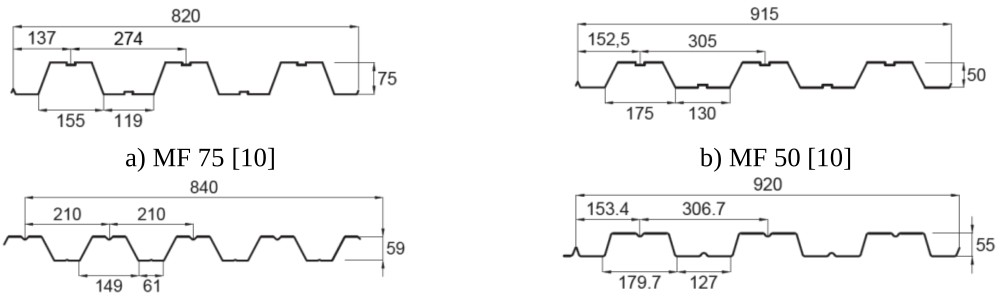
Thus, the goal of this article is to find the best structural solution for steel formwork geometry for composite slabs during the construction phase (before concrete curing), while minimizing steel consumption in the manufacturing process. The process of dimensioning the formwork in the construction phase, in which a cold-formed steel profile is generally considered supporting the acting actions in isolation, will be carried out in the Matlab R2021a program, using the EWM, a traditional and analytical method that has been used in several optimization studies of cold-formed steel profiles. The optimization will be carried out using PSO implemented within the Matlab platform and will take into account four commercial geometries.

# 2 The problem formulation

## 2.1 Problem definition

The formulation was validated in four numerical applications, the first in a manual example developed due to a lack of information and studies in the literature, using the commercial formwork Modular Deck MD 55, and the second in three different geometries of steel forms produced for the Brazilian market. Modular Sistema Construtivo [9], Metform [10], and ArcelorMittal Perfilor [11] 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. The Polydeck 59S [11], Modular Deck MD 55 [9], MF 75 [10], and MF 50 [10] formwork were studied, both with and without stiffeners. Figure 1 depicts the original prototypes that were used.




a) MF 75 [10]

b) MF 50 [10]

c) Polydeck 59S [11]

d) Modular Deck MD 55 [9]

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

The extent and properties of the materials used were: $t$ = 0.76 mm, $f_y$ = 280 MPa, $E$ = 200 GPa e $\nu$ = 0.3.

### 2.2 Choice variables

In general, the decision variables ($x_i$) used are the dimensions referring to the steel formwork is cross section (Figure 2). Two variables were chosen, the data for which are as follows:

$x_1$: The form is thickness ($t$). The values range from 0.5 mm to 1.50 mm in 0.05 mm increments;

$x_2$: Web bending angle (θ). Every 0,01º, a limit of 45º to 80º was adopted.

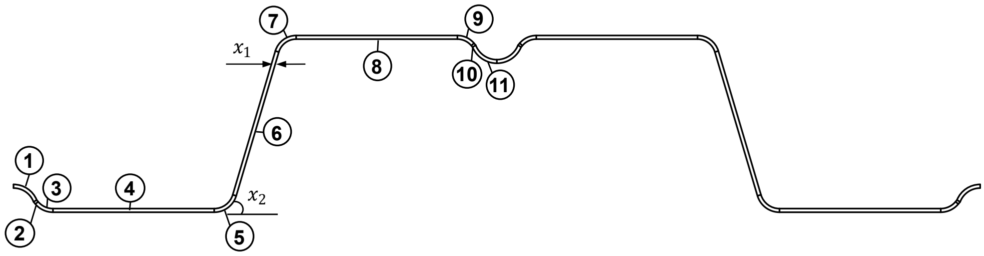



Figure 2. Steel formwork geometry decision variables

### 2.3 Objective function

The objective function is presented in Equation (1) and seeks to minimize steel consumption in the manufacturing process in the following form:

$$Minimize\ kg = \frac{A_F \cdot \lambda_a}{b_n}. \quad (1)$$

where $A_F$ is the cross-sectional area of the formwork in mm$^2$, $\lambda_a$ is the specific weight of the steel in kg/mm$^3$, and $b_n$ is the width between two ribs of the formwork in mm.

### 2.4 Constraints

The restrictions of the proposed problem refer to the requirements imposed by the standard NBR 16421:2015 [12], NBR 8800:2008 [13] and NBR 14762:2010 [14] for the verification of the steel formwork in the construction phase to the Service Limit State (SLS) and Ultimate Limit State (ULS), given by Equation (2):

$$C = \begin{cases} \frac{M_{Sd}}{M_{Rd}} - 1 \leq 0 \\ \frac{V_{Sd}}{V_{Rd}} - 1 \leq 0 \\ \left(\frac{M_{Sd}}{M_{Rd}}\right)^2 + \left(\frac{V_{Sd}}{V_{Rd}}\right)^2 - 1 \leq 0 \\ \frac{\delta_{máx}}{mín\begin{cases}\frac{L_F}{180} \\ 20\end{cases}} - 1 \leq 0 \end{cases} \quad (2)$$

where $M_{Sd}$ (kN.m), $M_{Rd}$ (kN.m), $V_{sd}$ (kN) and $V_{Rd}$ (kN) are the requesting bending moment, resisting bending moment, requesting shearing force and resisting shearing force, respectively, $\delta_{máx}$ (mm) is the closing maximum and $L_F$ (m) is the span width.

## 3 Results and discussions

Table 1 presents the results obtained for the original geometries and the results of the proposed formulation for the sections with intermediate stiffeners.

Table 1. Results for section with intermediate stiffener

| Span Condition | Information | Unit | Exemple 1 | | Exemple 2 | | Exemple 3 | | Exemple 4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | MD 55* | Optim. prog. | PD 59S** | Optim. prog. | MF 50 | Optim. prog. | MF 75 | Optim. prog. |
| Simple | $L_F$ | m | 1.80 | 1.80 | 2.20 | 2.20 | 1.50 | 1.50 | 2.30 | 2.30 |
| | Weight | kg/m$^2$ | **7.68** | **5.41** | **8.09** | **5.65** | **7.62** | **4.99** | **9.00** | **5.60** |
| | $t$ | mm | 0.76 | 0.50 | 0.76 | 0.50 | 0.76 | 0.50 | 0.76 | 0.50 |
| | $\theta$ | degrees | 73.54 | 76.72 | 61.90 | 65.22 | 65.77 | 65.22 | 74.92 | 72.27 |
| | $h_F$ | mm | 55.76 | 69.81 | 59.76 | 69.11 | 50.76 | 49.49 | 75.76 | 63.85 |
| Double | $L_F$ | m | 2.10 | 2.10 | 2.30 | 2.30 | 1.80 | 1.80 | 2.30 | 2.30 |
| | Weight | kg/m$^2$ | **7.68** | **5.43** | **8.09** | **5.08** | **7.62** | **4.99** | **9.00** | **5.34** |
| | $t$ | mm | 0.76 | 0.50 | 0.76 | 0.50 | 0.76 | 0.50 | 0.76 | 0.50 |
| | $\theta$ | degrees | 73.54 | 76.89 | 61.90 | 58.58 | 65.77 | 65.22 | 74.92 | 69.31 |
| | $h_F$ | mm | 55.76 | 70.75 | 59.76 | 52.23 | 50.76 | 49.49 | 75.76 | 54.05 |
| Triple | $L_F$ | m | 2.10 | 2.10 | 2.30 | 2.30 | 1.80 | 1.80 | 2.30 | 2.30 |
| | Weight | kg/m$^2$ | **7.68** | **5.43** | **8.09** | **5.04** | **7.62** | **4.99** | **9.00** | **5.34** |
| | $t$ | mm | 0.76 | 0.50 | 0.76 | 0.50 | 0.76 | 0.50 | 0.76 | 0.50 |
| | $\theta$ | degrees | 73.54 | 76.89 | 61.90 | 57.95 | 65.77 | 65.22 | 74.92 | 69.31 |
| | $h_F$ | mm | 55.76 | 70.75 | 59.76 | 50.96 | 50.76 | 49.49 | 75.76 | 54.05 |

*Modular Deck MD 55; **Polydeck 59S

As shown in Table 1, the steel consumption of the forms is reduced by 34.65% on average for all geometries used with stiffeners when the three support conditions of the span are considered. The MF 75 with four and three supports had the greatest percentage difference, approximately 40.71%. Except for MF 50, MF 75 and Polydeck 59S (with three and four supports), where all variables were optimized, there was only a reduction in thickness in all cases. Figure 3 depicts the verification of the SLS and ULS.

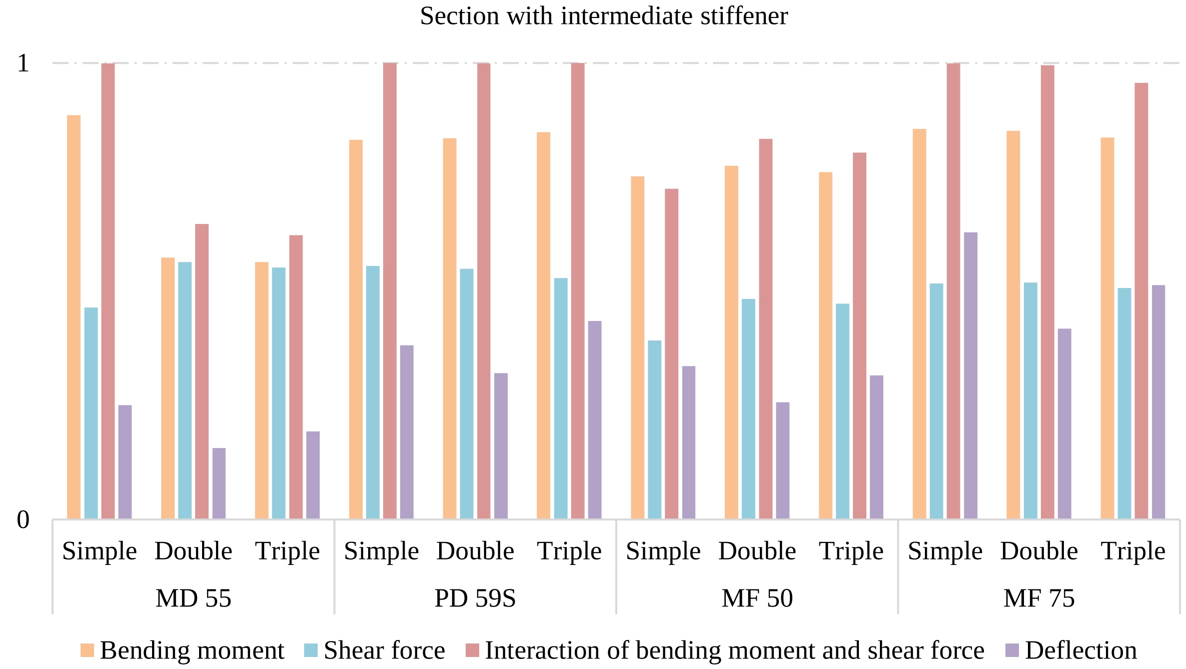



Figure 3. Verification of SLS and ULS for section with intermediate stiffener

It is verified that the analyzed ULS values are relatively high for the interaction between bending moment and shear force and bending moment, that is, the design is close to the allowed limit for the ULS. Table 2 presents the results obtained for the original geometries and the results of the proposed formulation for the sections without an intermediate stiffener.

Table 2. Results for section without intermediate stiffener

| Span Condition | Information | Unit | Exemple 1 | | Exemple 2 | | Exemple 3 | | Exemple 4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | MD 55* | Optim. prog. | PD 59S** | Optim. prog. | MF 50 | Optim. prog. | MF 75 | Optim. prog. |
| Simple | $L_F$ | m | 1.8 | 1.8 | 2.2 | 2.2 | 1.5 | 1.5 | 2.3 | 2.3 |
| | Weight | kg/m$^2$ | **7.46** | **5.30** | **7.92** | **6.83** | **7.23** | **5.04** | **8.56** | **6.23** |
| | $t$ | mm | 0.76 | 0.50 | 0.76 | 0.60 | 0.76 | 0.50 | 0.76 | 0.50 |
| | $h_F$ | mm | 55.76 | 71.20 | 59.76 | 73.66 | 50.76 | 62.26 | 75.76 | 96.95 |
| | $\theta$ | degrees | 73.54 | 76.97 | 61.90 | 66.58 | 65.77 | 69.85 | 74.92 | 78.11 |
| Double | $L_F$ | m | 2.10 | 2.10 | 2.30 | 2.30 | 1.80 | 1.80 | 2.30 | 2.30 |
| | Weight | kg/m$^2$ | **7.46** | **5.39** | **7.92** | **6.44** | **7.23** | **5.17** | **8.56** | **5.94** |
| | $t$ | mm | 0.76 | 0.50 | 0.76 | 0.60 | 0.76 | 0.50 | 0.76 | 0.50 |
| | $h_F$ | mm | 55.76 | 74.88 | 59.76 | 64.13 | 50.76 | 67.61 | 75.76 | 86.42 |
| | $\theta$ | degrees | 73.54 | 77.59 | 61.90 | 63.55 | 65.77 | 71.33 | 74.92 | 76.71 |
| Triple | $L_F$ | m | 2.10 | 2.10 | 2.30 | 2.30 | 1.80 | 1.80 | 2.30 | 2.30 |
| | Weight | kg/m$^2$ | **7.46** | **5.35** | **7.92** | **6.40** | **7.23** | **5.13** | **8.56** | **5.86** |
| | $t$ | mm | 0.76 | 0.50 | 0.76 | 0.60 | 0.76 | 0.50 | 0.76 | 0.50 |
| | $h_F$ | mm | 55.76 | 73.06 | 59.76 | 63.25 | 50.76 | 66.01 | 75.76 | 83.42 |
| | $\theta$ | degrees | 73.54 | 77.29 | 61.90 | 63.23 | 65.77 | 70.91 | 74.92 | 76.25 |

*Modular Deck MD 55; **Polydeck 59S

Similarly, to the previous analysis, when the section without an intermediate stiffener was considered, the weight of the formwork was reduced by 26.16% on average. However, because the variable was reduced while height and bending angle increased, thickness had a greater influence on weight.

Based on the results, it is noted that the sections with stiffener presented better optimization solutions compared to those without stiffener. The percentage difference for the first case ranged from 29.27% (Modular Deck MD 55 with three and four supports) to 40.71% (MF 75 with three and four supports), while sections without stiffener ranged from 13.79% (Polydeck 59S with two supports) to 31.60% (MF 75 with four supports). Figure 4 depicts the SLS as it relates to deflection and the ULS as it relates to shear and shear stresses, as well as the bending moment of the section without an intermediate stiffener.

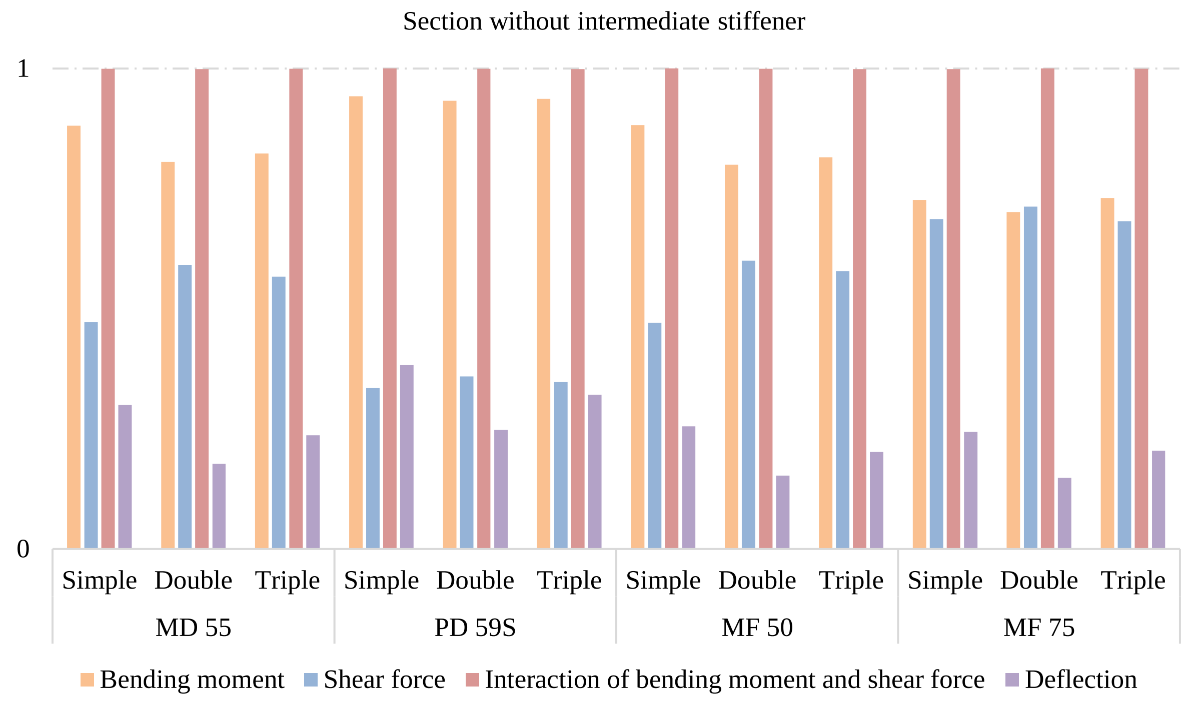



Figure 4. Verification of SLS and ULS for section without intermediate stiffener

Verifying the constraints during the optimization process reveals that the highest relationship is in the interaction of bending and shear force, indicating in the dimensioning a close match to the maximum allowable for the ULS.

## 4 Conclusions

This study proposed to determine the optimal structural solution for steel shuttering geometry of composite slabs focused on the construction phase, considering the minimization of steel consumption in the manufacturing process. To accomplish this, the objective function was implemented, which reduces weight and security measures established by NBR 16421:2015 [12], NBR 8800:2008 [13], and NBR 14762:2010 [14], by utilizing EWM and PSO in the computer program MATLAB®.

The formula was validated in four numerical applications, all of which were produced for commercialization in the Brazilian market, and one of which was performed manually with an Modular Deck MD 55 due to a lack of information and studies in the literature. The main results achieved showed that the elaborated program was successful in the search for efficient solutions for the optimization of the forms.

In general, it was found that thickness had a greater influence on weight, since there was a reduction in the variable and an increase in height and bending angle. Furthermore, the analysis of constraints indicated that the interaction between bending moment and shear force is the governing limit state, as it obtained the values closest to the maximum allowed limit for the ULS in all cases. Finally, the solution reduced an average of 34.65% of steel consumption for forms with intermediate stiffeners and 26.16% for sections without stiffeners.

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