UDC 624.04, 519.853

OPTIMIZATION OF CROSS-SECTIONAL DIMENSIONS FOR COLD-FORMED STEEL LIPPED CHANNEL COLUMNS

A.V. Perelmuter[1,2],
Doctor of Technical Science, Senior Staff Scientist

V. V. Yurchenko[2],
Doctor of Technical Science, Professor

I. D. Peleshko[3],
Candidate of Technical Science, Associate Professor

[1]*SCAD Soft Ltd.*
Osvity str., 3A, of. 2, Kyiv, 03037

[2]*Kyiv National University of Construction and Architecture*
Povitroflotskyj av., 31, Kyiv, 03680

[3]*Lviv Polytechnic National University*
St. Bandery, 12, Lviv, 79013

DOI: 10.32347/2410-2547.2022.108.156-170

A parametric optimization problem of cross-sectional sizes for cold-formed steel lipped channel structural members subjected to central compression has been considered by the paper. An optimization problem is formulated as follow: to define optimum cross-sectional sizes of cold-formed structural member taking into account post-buckling behavior and structural requirements when stripe width and profile thickness as well as type of the cold-formed profile are constant and defined by the designer.

Maximization of load-carrying capacity of the cold-formed structural member has been assumed as purpose function. The latter has been presented in the form of linear convolution of the buckling resistance to the central compression taking into account flexural, torsional and torsional-flexural buckling of the thin-walled structural member determined according to the requirements EN 1993-1-3:2012 and EN 1993-1-5:2012. Searching for the optimum cross-sectional sizes of the cold-formed structural member has been performed taking into account the possibility of it post-critical buckling behavior based on the local buckling of the web and flanges and/or distortional buckling of the edge fold stiffeners.

As optimization results cold-formed steel lipped channel have been obtained. With the same stripe width optimum profiles have higher load-carrying capacity level taking into account buckling resistance under the central compression comparing with the cold-formed steel lipped channel proposed by Ukrainian manufacturers. Besides, torsional-flexural buckling resistance of the cold-formed steel lipped channel is determinative for all optimum cross-sectional decisions.

Key words: cold-formed steel, load-carrying capacity, buckling resistance, local buckling, distortional buckling, parametric optimization, gradient-based methods.

Introduction. Previously, the use of cold-formed thin-walled profiles was limited to cases where reducing the weight of the structure was a priority, such as in the aviation or automotive industries. However, due to the development of production technology, corrosion protection, product availability as well as implementation of the design code the use of thin-walled structural elements, including cold-formed profiles is gradually expanding.

Today, various structural systems made from cold-formed steel (CFS) structural members, which are widely used in the construction industry, are actively imported to the Ukrainian market of steel structures. Implementation of steel structures made from thin-walled cold-formed profiles in building practice is relevant and economically reasonable. There are specific fields of application where their efficiency is the highest [9]. However, the widespread application of the structures made from thin-walled cold-formed profiles of the domestic production is delayed due to the lack of domestic experience in economic and reliable design of such structures.

A high degree of flexibility in the manufacturing of various cross-sectional shapes provides a unique opportunity to further improve the load-carrying capacity of these structural elements through an optimisation process, leading to more efficient and economical structural systems [1].

The paper [2] reviews the existing studies on the structural optimization of CFS sections and the structural and thermal performance of such CFS structures. The methodologies used in the existing literature for optimizing CFS members have been summarized and presented systematically.

In the paper [1] a practical methodology for the optimum design of cold-formed steel beam-column members with different lengths and thicknesses, subject to various combinations of axial compression and bending moment and with constant material use has been proposed by the paper. The optimisation process is carried out using a genetic algorithm and aims to maximise the resistances of CFS members, determined according to the Eurocode 3 design guidelines.

Optimisation technique was employed to enhance the structural performance and to effectively use the given amount of material of CFS members in the paper [3]. Lipped channel, folded-flange, and super-sigma have been optimised using the particle swarm optimisation method. Results showed that the flexural capacity of the optimised sections was improved significantly compared to conventional CFS sections.

The paper [4] presents a procedure to obtain optimized steel channel cross-sections for use in compression or bending. The cross-sections are optimized with respect to their structural capacity, determined according to the EN1993-1-3 using genetic algorithms. The optimization for compression is carried out for different column lengths and includes the effects of the shift of the effective centroid induced by local buckling.

A methodology that would enable the development of optimised CFS beam sections with maximum flexural strength for practical applications has been provided by the paper [5]. The optimised sections are designed to comply with the Eurocode 3 geometrical requirements as well as with a number of manufacturing and practical constraints. The flexural strengths of the sections are determined based on the effective width method adopted in EC3, while the optimisation process is performed using the particle swarm optimisation method.

Papers [6, 7] aim at finding the optimal folding of open cold formed steel cross sections under compression. The design space is searched primarily via a stochastic search algorithm, genetic algorithm. The near-optimal folding of the cross section is then fine-tuned through a few steps of the gradient descent optimization [7]. To arrive at practical designs the optimization problem is augmented with constraints on the geometrical properties of the cross section. The optimal cross sections are found to have compressive capacities that are higher than the original designs [6].

Applied optimum design problems for structures in some cases are formulated as parametric optimization problems, namely as searching problems for unknown structural parameters, which provide an extreme value of the specified purpose function in the feasible region defined by the specified constraints [8]. The mathematical model of the parametric optimization problems includes a set of design variables, an objective function, as well as constraints, which reflect generally non-linear dependences between them. If the purpose function and constraints of the mathematical model are continuously differentiable functions, as well as the search space is smooth, then the parametric optimization problems are successfully solved using gradient projection non-linear methods [9]. The gradient projection methods operate with the first derivatives or gradients only both of the objective function and constraints. The methods are based on the iterative construction of such a sequence of the approximations of design variables that provides convergence to the optimum solution (optimum values of the structural parameters) [10]. Additionally, a sensitivity analysis is a useful optional feature that could be used in scope of the numerical algorithms developed based on the gradients methods [11].

The paper [12] covers optimization problems and algorithms in the design of CFS structural members. A brief review of problem formulation and solution techniques in past research as well as details of optimization algorithms, including gradient-based, stochastic search, artificial neural network, and ant colony optimization, are discussed.

In order to increase the widespread application of the structures made from CFS profiles of the domestic production, effective national ranges of assortments of CFS profiles have to be developed. In this paper, CFS lipped channel structural members subjected to central compression are considered as research object, which investigated for the searching for optimum cross-sectional dimensions. The following research tasks are formulated: to develop a mathematical model and a numerical technique to solve an optimization problem for cross-sectional sizes of CFS structural members; to perform numerical investigations in order to obtain optimal solutions for considered research object; to develop a guide for designers relating to the optimum material distribution in the cross-sections of the CFS structural members

1. Problem formulation. Let formulate *a parametric optimization problem* as follow: to find optimum values of cross-sectional sizes for CFS lipped channel structural members subjected to central compression taking into account structural requirements when the profile perimeter (strip width), profile thickness as well as the type of the CFS cross-section are constant and specified in advance.

The formulated parametric optimization problem can be stated in the following mathematical terms: to find unknown structural parameters:

$$\vec{X} = \{X_\iota\}^T, \ \iota = \overline{1, N_X}\,; \tag{1.1}$$

providing the least value of the determined objective function:

$$f^* = f(\vec{X}^*) = \min_{\vec{X} \in \Im} f(\vec{X})\,; \tag{1.2}$$

in a feasible region (search space) $\Im$ defined by the following system of constraints:

$$\boldsymbol{\varphi}(\vec{X}) = \left\{\varphi_\eta(\vec{X}) \le 0 \mid \eta = \overline{1, N_{IC}}\right\}; \tag{1.3}$$

where $\vec{X}$ is the vector of the design variables (unknown structural parameters); N_X is the total number of the design variables; f, φ_η are the continuous functions of the vector argument; $\vec{X}^*$ is the optimum solution or optimum point (the vector of optimum values of the structural parameters); f^* is the optimum value of the optimum criterion (objective function); N_{IC} is the number of constraints-inequalities $\varphi_\eta(\vec{X})$, which define a feasible region in the design space $\Im$.

Overall cross-section dimensions of a CFS lipped channel, namely web height h, flange width b and single edge fold length c (Fig. 1.1) are considered as *design variables*. Initial data for optimization calculation are profile thickness t, internal bend radius $r = 1{,}5t$; base yield strength f_{yb}, MPa; E – modulus of elasticity, MPa; design lengths of the structural member corresponded to the flexural buckling $l_{ef,y}$, $l_{ef,z}$ as well as to the torsional buckling $l_{ef,T}$.

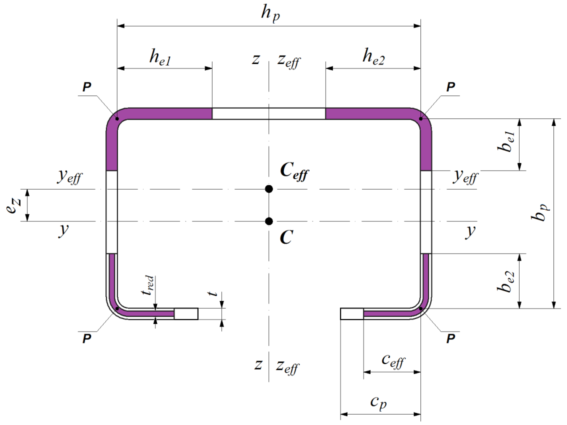

Fig. 1. Cross-section of the CFS lipped channel structural member

Design sizes of plane cross-sectional elements (Fig. 1) for CFS lipped channel structural member are considered as state variables of the optimization problem and calculated according to [13] depending on the design variables h, b and c, internal bend radius $r = 1,5t$ and profile thickness t as presented below:

$$h_p = h - 2,5t\,;$$
$$b_p = b - 2,5t\,;$$
$$c_p = c - 1,25t\,.$$

where h_p is the design web height; b_p is the design flange width; c_p is the design length of a single edge fold.

Geometrical properties of CFS lipped channel cross section are determined depending on the design variables and the state variables as presented below:

$$A_g = t\left(h_p + 2b_p + 2c_p\right);$$
$$z = \frac{1}{A}\left(tb_p^2 \; + \; 2tc_p b_p\right);$$
$$I_y = \frac{th_p^3}{12} + \frac{b_p t^3}{6} + 0,5b_p th_p^2 + \frac{tc_p^3}{6} + 0,5tc_p\left(h_p - c_p\right)^2\,;\; i_y = \sqrt{\frac{I_y}{A}}\,;$$
$$I_z = \frac{h_p t^3}{12} + th_p z^2 + \frac{tb_p^3}{6} + 2tb_p\left(0,5b_p - z\right)^2 + \frac{c_p t^3}{6} + 2c_p t\left(b_p - z\right)^2\,;\; i_z = \sqrt{\frac{I_z}{A}}\,.$$

where A_g is gross cross-sectional area; I_y, I_z are second moment of inertia relative to the main axis of inertia of the cross-section; i_y, i_z are radiuses of inertia of the cross-section; z is the distance which defines the center of mass location.

Relative slenderness $\bar{\lambda}_{ph}$ of the web and relative slenderness $\bar{\lambda}_{pb}$ of the flanges for CFS lipped channel are calculated according to [13, 14] as follow:

$$\bar{\lambda}_{ph} = \frac{h_p}{56,8t}\sqrt{\frac{f_{yb}}{235}}\,;$$
$$\bar{\lambda}_{pb} = \frac{b_p}{56,8t}\sqrt{\frac{f_{yb}}{235}}\,.$$

Relative slenderness $\bar{\lambda}_{pc}$ of the single edge fold is determined according to [13, 14] as follow:

$$\bar{\lambda}_{pc} = \frac{c_p}{28,4t\sqrt{k_{\sigma c}}}\sqrt{\frac{f_{yb}}{235}} = \frac{c_p}{28,4t\sqrt{\tilde{\mathbf{k}}_{\boldsymbol{\sigma}\mathbf{c}}\left(c_p/b_p\right)}}\sqrt{\frac{f_{yb}}{235}}\,;$$

where $k_{\sigma c} = \tilde{\mathbf{k}}_{\boldsymbol{\sigma}\mathbf{c}}\left(b_{pc,j}/b_{pb,j}\right)$ is buckling factor calculated according to the polynomial dependency proposed by the papers [15] taking into account that the formulated parametric optimization task is solved using a gradient-based steepest descent method.

Reduction factors ρ_h and ρ_b corresponded to the local buckling of the profile web and flange respectively are determined according to [13, 14] as presented below:

$$\rho_h = \frac{h_{eff}}{h_p} = \frac{1}{\bar{\lambda}_{ph}}\left(1 - \frac{0,22}{\bar{\lambda}_{ph}}\right) \le 1,0\,;$$

$$\rho_b = \frac{b_{eff}}{b_p} = \frac{1}{\bar{\lambda}_{pb}}\left(1 - \frac{0,22}{\bar{\lambda}_{pb}}\right) \le 1,0\,.$$

Reduction factor ρ_c corresponded to the local buckling of the single edge fold is calculated according to [13, 14] as follow:

$$\rho_c = \frac{c_{eff}}{c_p} = \frac{1}{\bar{\lambda}_{pc}}\left(1 - \frac{0,188}{\bar{\lambda}_{pc}}\right) \le 1,0\,.$$

Cross-section flanges and web of CFS lipped channel structural member are subjected to post-buckling behavior (when local buckling occurs) in the case when its slenderness exceed limit value, namely $\bar{\lambda}_{ph} > 0,673$ and/or flange slenderness $\bar{\lambda}_{pb} > 0,673$. In this case effective widths of the web h_{eff} and flanges b_{eff} are defined according to [13, 14] as presented below:

$$h_{eff} = \frac{h_p}{\bar{\lambda}_{ph}}\left(1 - \frac{0,22}{\bar{\lambda}_{ph}}\right) = 56,8t\sqrt{\frac{235}{f_{yb}}}\left(1 - \frac{12,496t}{h_p}\sqrt{\frac{235}{f_{yb}}}\right);$$

$$b_{eff} = \frac{b_p}{\bar{\lambda}_{pb}}\left(1 - \frac{0,22}{\bar{\lambda}_{pb}}\right) = 56,8t\sqrt{\frac{235}{f_{yb}}}\left(1 - \frac{12,496t}{b_p}\sqrt{\frac{235}{f_{yb}}}\right).$$

Single edge fold of CFS lipped channel cross-section is subjected to post-buckling behavior (when local buckling occurs) in case when it slenderness exceeds limit value ($\bar{\lambda}_{pc} > 0,748$).In this case effective single edge fold width c_{eff} is determined according to [13] as follow:

$$c_{eff} = 28,4t\varepsilon\sqrt{\tilde{\mathbf{k}}_{\boldsymbol{\sigma}\mathbf{c}}\left(b_{pc}/b_{pb}\right)}\left(1 - \frac{5,3392t\varepsilon}{b_{pc}}\sqrt{\tilde{\mathbf{k}}_{\boldsymbol{\sigma}\mathbf{c}}\left(b_{pc}/b_{pb}\right)}\right);$$

where $\tilde{\mathbf{k}}_{\boldsymbol{\sigma}\mathbf{c}}\left(b_{pc}/b_{pb}\right)$ is buckling factor calculated according to the polynomial dependency proposed by the papers [15] taking into account that the formulated parametric optimization task is solved using a gradient-based steepest descent method.

Design cross-section of the stiffener (Fig. 2) consists of single edge fold with effective width c_{eff} together with effective adjacent part of the flange with effective width $0.5b_{eff}$. Geometrical properties of the design cross-section of the stiffener are determined according to [13] as follow:

$$A_s = t\left(c_{eff} + 0,5b_{eff}\right);$$

$$I_s = \frac{tc_{eff}^3}{4}\left(\frac{1}{3} + \frac{0,5b_{eff}}{c_{eff} + 0,5b_{eff}}\right),$$

where A_s and I_s are area and second moment of inertia for the design cross-section of the stiffener (Fig. 1.2).

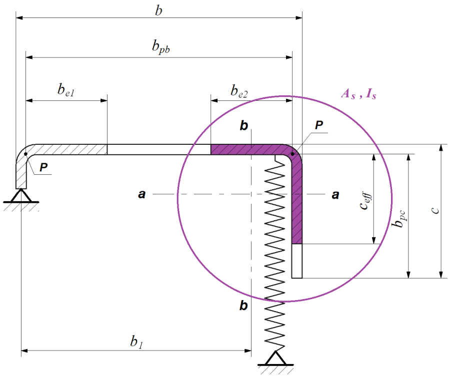

Fig. 2. Flange plane element of the CFS lipped channel stiffened by the single edge fold

Single edge folds in CFS lipped channel structural members ensure partial restraint for plane flanges which can be simulated using a linear spring. In case of the central compression stiffness for such linear spring can be estimated according to [13] as presented below:

$$K = \frac{E}{3,64} \cdot \frac{t^3}{\left(b_p - \frac{0,5\left(0,5b_{eff}\right)^2}{c_{eff} + 0,5b_{eff}}\right)^2 \left(1,5h_p + b_p - \frac{0,5\left(0,5b_{eff}\right)^2}{c_{eff} + 0,5b_{eff}}\right)}.$$

It should be noted that analytical expression for stiffness of the linear spring presented above is restricted by the case of cold-formed structural members with flanges stiffened by single or double edge folds only and cross-section symmetrical relatively to the main axes of inertia which is perpendicular to the web plane.

Then relative slenderness of the stiffener $\bar{\lambda}_d$ corresponded to the flexural buckling of the stiffener is calculated according to [13] as follow:

$$\bar{\lambda}_d = \sqrt{\frac{f_{yb}A_s}{2\sqrt{KEI_s}}}.$$

The reduction factor χ_d for the flexural buckling of the stiffener (or reduction factor for the distortional buckling cross-section resistance) is determined depending on relative slenderness $\bar{\lambda}_d$. Taking into account that the formulated parametric optimization task is solved using a gradient-based steepest descent method, reduction factor for the distortional buckling cross-section resistance χ_d can be calculated depending on $\bar{\lambda}_d$ using polynomial dependency proposed by the paper [15]:

$$\chi_d = \tilde{\Xi}\left(\bar{\lambda}_d\right).$$

We suppose that in the optimum cross-section the compressive stress at the centreline of the stiffener estimated on the basis of the effective cross-section equals to the base yield strength. Therefore, the reduced thickness t_{red} of the design cross-section of the stiffener allowing for reduced stiffener resistance due to flexural buckling of the stiffener is determined according to [13] as follow:

$$t_{red} = t\frac{A_{s,red}}{A_s} = t\frac{\chi_d A_s}{A_s} = \chi_d t ,$$

where $A_{s,red}$ is the reduced effective area of the stiffener allowing for flexural buckling.

Finally, the area of the effective cross-section of CFS lipped channel structural member subjected to central compression is calculated as presented below:

$$A_{eff} = t\left(h_{eff} + b_{eff}\right) + t_{red}\left(b_{eff} + 2c_{eff}\right).$$

The maximization criterion of the overall design buckling resistance represented as a linear convolution of the corresponded design buckling resistances with the same weight factors can be considered as the purpose function (1.2) and can be written as follow:

$$N_{bRd\Sigma} = N_{byRd} + N_{bzRd} + N_{bT,Rd} + N_{bTF,Rd} \rightarrow \max ,$$

where $N_{by,Rd}$,$N_{bz,Rd}$ are the design buckling resistance for flexural buckling of the cold-formed structutal member relative to the main axis of inertia $y-y$ and $z-z$ determined according to [13, 16]; $N_{bT,Rd}$,$N_{bTF,Rd}$ are the design buckling resistance corresponded to the torsional and flexural-torsional buckling of the structural member calculated according to [13, 16].

Then the purpose function can be rewritten as follow:

$$N_{bRd\Sigma} = \frac{A_{eff} f_{yb}}{\gamma_{M1}}\left(\chi_y + \chi_z + \chi_T + \chi_{TF}\right) \rightarrow \max , \tag{1.4}$$

where χ_y ,χ_z,χ_T ,χ_{TF} are buckling factors allowing for the flexural buckling of the CFS structural member relative to the main axis of inertia $y-y$ and $z-z$, as well as for the torsional and flexural-torsional buckling. The buckling factors are determined from the relevant buckling curve b according to:

$$\chi^b = \left(0.466 + 0.17\overline{\lambda} + 0.5\overline{\lambda}^2 + \right.$$
$$\left. + \sqrt{\left(0.466 - 0.83\overline{\lambda} + 0.5\overline{\lambda}^2\right)\left(0.466 + 1.17\overline{\lambda} + 0.5\overline{\lambda}^2\right)}\right)^{-1} \le 1.0$$

with substitution of the relevant non-dimensional slendernesses $\overline{\lambda}_y$, $\overline{\lambda}_z$, $\overline{\lambda}_T$, $\overline{\lambda}_{TF}$ corresponded to the considered buckling modes and calculated taking into account geometrical properties of the effective cross-section of the structural member subjected to the central compression according to [13, 16]:

$$\overline{\lambda}_y = \sqrt{\frac{A_{eff} f_{yb}}{N_{cr,y}}}; \qquad \overline{\lambda}_z = \sqrt{\frac{A_{eff} f_{yb}}{N_{cr,z}}};$$
$$\overline{\lambda}_T = \sqrt{\frac{A_{eff} f_{yb}}{N_{cr,T}}}; \qquad \overline{\lambda}_{TF} = \sqrt{\frac{A_{eff} f_{yb}}{N_{cr,TF}}};$$

where $N_{cr,y,j}$, $N_{cr,z,j}$, $N_{cr,T,j}$ і $N_{cr,TF,j}$ are the elastic critical forces for the relevant buckling mode calculated taking into account gross cross-section geometrical properties of the structural member according to [16].

System of constraints (1.3) for the formulated optimization problem consists of a constraint on the profile perimeter or on a strip width which can be written as presented below:

$$\frac{h + 2b + 2c}{P_{\max}} - 1 \le 0, \tag{1.5}$$

where $P_{\max}$ is the maximum value of the cross-section perimeter for CFS lipped channel.

The constraints reflected design code requirements [13] for the ultimate slenderness of the cross-section elements of the CFS channel with flanges stiffened by single edge folds are also included in the system of constraints (1.3) and presented below:

$$\frac{h}{500t} - 1 \le 0, \tag{1.6}$$

$$\frac{b}{60t} - 1 \le 0, \tag{1.7}$$

$$\frac{c}{50t} - 1 \le 0. \tag{1.8}$$

Additionally, a constraint on the minimum gap between single edge folds ends allowing for providing an access to the internal surface of the CFS lipped channel (for example, in order to organize a bolted connection on the profile flanges) is included to the system of constraints (1.3) as well and written as below:

$$\frac{h - 2c}{d_{\min}} - 1 \le 0, \tag{1.9}$$

where $d_{\min}$ is the minimum gap between single edge folds ends.

Thus, the optimization problem of cross-sectional sizes for CFS lipped channel structural member is formulated as follow: to find optimum values of C-profile cross-sectional sizes (web height h, flange width b and single edge fold length c) providing the maximum value of the determined objective function (1.4) in the feasible region defined by the system of constraints (1.5) – (1.9) when the profile perimeter (strip width) $P_{\max}$, profile thickness t as well as the type of the cold-formed cross-section are constant and specified in advance.

The formulated parametric optimization problem has been solved using the software OptCAD where the modified method of the purpose function gradient projection onto the surface of the active constraints with simultaneous liquidations of the residuals in the violated constraints has been implemented [17].

2. Optimization results. As optimization results the cold-formed C-profiles with optimum cross-sectional dimensions have been obtained. Characteristics of the obtained C-profiles with optimum cross-sectional sizes have been presented by the Table 1.

With the same stripe width C-profile structural members with optimum cross-sectional sizes have higher design buckling resistance under central compression comparing with the cold-formed C-profiles proposed by Ukrainian manufacturers (group of the companies «Blachy Pruszyński», companies BF Zavod and STEELCO) [18]. It should be noted that torsional-flexural buckling resistance of C-profile cold-formed structural members was determinative for all optimum cross-sectional decisions.

Thus, for example, the initial cold-formed C-profile with the strip width 25.8 cm manufactured by the company «Blachy Pruszyński» has the cross-sectional dimensions 100×60×19×1.5cm and the minimum buckling resistance $N_{bRd,\min} = N_{bTF,Rd} = 7.373$ kN corresponded to the torsional-flexural buckling mode. For the same stripe width 25.8 cm cold-formed C-profile with optimum cross-sectional sizes $h = 8.914$ cm, $b = 6.171$ cm, $c = 2.272$ cm or 88×62×23×1.5cm has been obtained. The minimum buckling resistance corresponded to the torsional-flexural buckling mode for the optimum solution is $N_{bRd,\min} = N_{bTF,Rd} = 8.093$ kN which is greater than 9.67% comparing to the one of initial profile (see Table 2).

With the same stripe width CFS lipped channel structural members with optimum cross-sectional dimensions have higher load-carrying capacity taking into account minimum buckling resistance under the central compression comparing with ones proposed by Ukrainian manufacturers.

Conclusion. Searching for optimum cross-sectional sizes of CFS lipped channel structural members taking into account post-buckling behavior and structural requirements has been realized. Presented results of the performed optimization calculation allow developing guides for designers relating to the optimum material distribution in the cross-sections of CFS structural members as well as are base to develop effective national ranges of assortments of cold-formed profiles.

Table 1

C-profile cross-sections with optimum sizes and characteristics

t, cm	Optimum sizes of the C-profile cross-section, cm	A_{eff}, mm^2	$P_{\max}$, cm	$N_{bTF,Rd}$, kN	ρ_h	ρ_b	χ_d	A_{eff}, mm^2
0.1	8.960×9.040×1.480	1.061	30.0	8.652	0.481	0.477	0.379	1.061
0.12	9.548×8.452×1.774	1.575	30.0	10.828	0.535	0.597	0.478	1.575
0.14	10.104×7.896×2.052	2.235	30.0	12.538	0.584	0.721	0.615	2.235
0.15	10.386×7.614×2.193	2.612	30.0	13.119	0.606	0.786	0.685	2.612
0.17	7.848×11.069×2.507	3.182	35.0	21.483	0.845	0.639	0.587	3.182
0.18	11.263×9.237×2.632	3.757	35.0	24.643	0.661	0.779	0.694	3.757
0.20	11.970×8.531×2.985	4.765	35.0	25.827	0.686	0.896	0.815	4.765
0.21	12.141×10.859×3.070	5.104	40.0	41.498	0.707	0.774	0.700	5.104
0.22	12.442×10.558×3.221	5.663	40.0	43.201	0.720	0.821	0.749	5.663
0.23	12.796×10.205×3.398	6.255	40.0	44.404	0.729	0.871	0.799	6.255
0.24	13.019×12.481×3.509	6.654	45.0	64.687	0.745	0.771	0.705	6.654
0.25	13.315×12.185×3.658	7.287	45.0	67.494	0.756	0.811	0.747	7.287
0.26	13.648×11.852×3.824	7.951	45.0	69.837	0.765	0.853	0.790	7.951
0.28	14.190×13.810×4.095	9.113	50.0	99.368	0.787	0.804	0.747	9.113
0.30	14.894×13.106×4.447	10.63	50.0	106.22	0.799	0.881	0.823	10.625

Table 2

Comparison of the optimum solutions for CFS lipped channels with ones manufactured by the company «Blachy Pruszyński»

C-profile	Cross-sectional sizes, cm	ρ_h	ρ_b	χ_d	A_{eff}, cm^2	$P_{\max}$, cm	$N_{bTF,Rd}$, kN
Initial profile	10.0×6.0×1.9×0.15	0.626	0.937	0.809	2.573	25.8	7.373
Profile with optimum cross-section sizes	8.8×6.2×2.3×0.15	0.691	0.919	0.839	2.698	25.8	**8.159**

Load-carrying capacity of CFS lipped channel structural members subjected to central compression has been determined by the torsional-flexural buckling resistance for all optimum solutions. The single edge fold length improves significantly the torsional-flexural buckling resistance of CFS lipped channel structural members subjected to central compression. For all optimum solutions the optimum size of the single edge fold length has been obtained larger than ones in the initial CFS lipped channels manufactured by the Ukrainian manufacturers (group of the companies «Blachy Pruszyński», companies BF Zavod and STEELCO). At the same time, for all optimum solution the local buckling of the single edge folds has not been occurred.

REFERENCES

1. *Mojtabaei, S.M., Becque, J., Hajirasouliha, I.* Structural size optimization of single and built-up cold-formed steel beam-column members // Journal of Structural Engineering. – 2021. – No. 147 (4). – No. 04021030. DOI: 10.1061/(asce)st.1943-541x.0002987.
2. *Liang, H., Roy, K., Fang, Z., Lim, J.B.P.* A Critical Review on Optimization of Cold-Formed Steel Members for Better Structural and Thermal Performances // Buildings – 2022. – 12. – 34. DOI: 10.3390/buildings12010034.
3. *Gatheeshgar, P., Poologanathan, K., Gunalan, S., Tsavdaridis, K.D., Nagaratnam, B., Iacovidou, E.* Optimised cold-formed steel beams in modular building applications // Journal of Building Engineering. – 2020. –32. – 101607. DOI: 10.1016/j.jobe.2020.101607.
4. *Ma, W., Becque, J., Hajirasouliha, I., Ye, J.* Cross-sectional optimization of cold-formed steel channels to Eurocode 3 // Engineering Structures. – 2015. – 101. – Pp. 641-651. DOI: 10.1016/j.engstruct.2015.07.051.
5. *Ye, J., Hajirasouliha, I., Becque, J., Pilakoutas, K.* Development of more efficient cold-formed steel channel sections in bending // Thin-Walled Structures. – 2016. – 101. – Pp. 1–13. DOI: 10.1016/j.tws.2015.12.021.
6. *Bilyk, S. I., Yurchenko, V. V.* Size optimization of single edge folds for cold-formed structural members // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – Kyiv: KNUBA. – 2020. – Issue 105. – Pp. 73-86. DOI: 10.32347/2410-2547.2020.105.73-86.
7. *Moharrami, M., Louhghalam, A., Tootkaboni, M.* Optimal folding of cold formed steel cross sections under compression // Thin-Walled Structures. – 2014. – 76. – Pp. 145-156.
8. *Permyakov, V. O., Yurchenko, V. V., Peleshko, I. D.* An optimum structural computer-aided design using hybrid genetic algorithm. Proceeding of the International Conference "Progress in Steel, Composite and Aluminium Structures", Taylor & Francis Group, London, 2006. –Pp. 819-826.
9. *Yurchenko, V., Peleshko, I.* Improved gradient projection method for parametric optimisation of bar structures // Magazine of Civil Engineering. – 2020. – 98(6). – 9812. DOI: 10.18720/MCE.98.12.
10. *Peleshko, I., Yurchenko, V.* An improved gradient-based method to solve parametric optimisation problems of the bar structures // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles, Kyiv: KNUBA. – 2020. – Issue 104. – Pp. 265-288. DOI: 10.32347/2410-2547.2020.104.265-288.
11. *Yurchenko, V. V., Peleshko, I. D.* Searching for optimal pre-stressing of steel bar structures based on sensitivity analysis // Archives of Civil Engineering. – 2020. – Vol. 66. – No. 3. – Pp. 525-540. DOI: 10.24425/ACE.2020.134411.
12. *Leng, J.* Optimization Techniques for Structural Design of Cold-Formed Steel Structures // Recent Trends in Cold-Formed Steel Construction. – Woodhead Publishing: Sawston, UK, 2016. – Pp. 129-151.
13. EN 1993-1-3:2006: EuroCode 3: Design of steel structures - Part 1-3: General rules – Supplementary rules for cold-formed members and sheeting.
14. EN 1993-1-5:2006: EuroCode 3: Design of steel structures - Part 1-5: General rules – Plated structural elements.
15. *Yurchenko, V.* Development of steel frames structural form made from cold-fromed profiles based on the optimization problem solution. The thesis is for taking the degree of Doctor of Technical Sciences in specialty 05.23.01 – civil engineering constructions, buildings and structures. – Kyiv National University of Construction and Architecture, Kyiv, 2019. (ukr)
16. EN 1993-1-1:2005: EuroCode 3: Design of steel structures - Part 1-1: General rules and rules for buildings.
17. *Peleshko, I. D., Yurchenko, V. V.* Parametric Optimization of Metallic Rod Constructions with using the Modified Method of Gradient Projection // International Applied Mechanics. – 2021. – Vol. 57. – No. 4. – Pp. 78-95. DOI: 10.1007/s10778-021-01096-0.
18. Assortment ranges of the cold-formed profiles for light gauge steel structures of the Ukrainian manufacturers. UCSC-014-16, 2016. 32 p. (ukr)

Стаття надійшла 06.04.2022

Перельмутер А.В., Юрченко В.В., Пелешко І.Д.
ОПТИМІЗАЦІЯ РОЗМІРІВ ПОПЕРЕЧНИХ ПЕРЕРІЗІВ СТИСНУТИХ ЕЛЕМЕНТІВ КОНСТРУКЦІЙ З С-ПОДІБНОГО ХОЛОДНОГНУТОГО ПРОФІЛЮ

У статті розглянута задача параметричної оптимізації розмірів поперечного перерізу стержневого елементу конструкції з С-подібного холодногнутого профілю, що працює під дією поздовжньої сили стиску. Задача параметричної оптимізації формулюється як: при заданих ширині та товщині заготовки (штрипси) для виготовлення холодногнутого профілю, а також типі поперечного перерізу визначити його оптимальні розміри з врахуванням закритичної роботи та конструктивних вимог.

Як критерій оптимальності приймався критерій максимізації несучої здатності профілю на втрату загальної стійкості при центральному стискові, який представлявся у формі лінійної згортки несучих здатностей, що враховують згинальне, крутильне та згинально-крутильне випучування стержневого елементу, обчислених відповідно до вимог EN 1993-1-3:2012 і EN 1993-1-5:2012. Пошук оптимальних розмірів реалізований з врахуванням можливої закритичної роботи тонкостінного холодногнутого профілю, яка характеризується втратою місцевої стійкості та втратою стійкості форми перерізу.

Сформульована задача параметричної оптимізації розв'язана з використанням програми OptCAD, у якій реалізований метод проекції градієнту функції мети на поверхню активних обмежень при одночасній ліквідації нев'язок у порушених обмеженнях.

Як результат оптимізаційного розрахунку отримані С-подібні холодногнуті профілі, які характеризуються більшою несучою здатністю на втрату стійкості при центральному стискові порівняно з холодногнутими профілями вітчизняних виробників при одній і тій самій ширині заготовки. При цьому, для всіх оптимальних рішень поперечних перерізів визначальною була несуча здатність С-подібного холодногнутого профілю на втрату стійкості за згинально-крутильною формою випучування.

Ключові слова: холодногнутий профіль, несуча здатність, місцева втрата стійкості, втрата стійкості форми перерізу, параметрична оптимізація, градієнтний метод.

UDC 624.04, 519.853
Perelmuter A. V., Yurchenko V. V., Peleshko I. D.
OPTIMIZATION OF CROSS-SECTIONAL DIMENSIONS FOR COLD-FORMED STEEL LIPPED CHANNEL COLUMNS

Parametric optimization problem of cross-sectional sizes for cold-formed C-profiles subjected to central compression has been considered by the paper. Parametric optimization problem for cross-sectional sizes of cold-formed C-profiles has been formulated as follow: to define optimum cross-sectional sizes taking into account post-buckling behavior and structural requirements when stripe width and thickness as well as type of the cold-formed profile are constant and defined by the designer.

Criterion of the profile load-bearing capacity maximization has been assumed as purpose function. The latter has been presented in the form of linear convolution of the resistance to central compression taking into account flexural, torsional and torsional-flexural buckling of thin-walled structural member determined according to the requirements EN 1993-1-3:2012 and EN 1993-1-5:2012. Searching for the optimum cross-sectional sizes has been performed taking into account a possibility of post-critical buckling behavior of the structural member based on the local buckling of the web and flanges and/or distortional buckling of the edge fold stiffeners.

Formulated parametric optimization problem has been solved using software OptCAD. Update gradient method of the purpose function projection on the active constraints hyperplanes with simultaneous liquidations of the residuals in the constraints has been implemented by the software.

As optimization results cold-formed C-profiles have been obtained. With the same stripe width optimum profiles have higher load-bearing capacity level taking into account buckling resistance under central compression comparing with the cold-formed C-profiles proposed by Ukrainian manufacturers. Besides, torsional-flexural buckling resistance of the cold-formed C-profile is determinative for all optimum cross-sectional decisions.

Keywords: cold-formed steel, load-carrying capacity, buckling resistance, local buckling, distortional buckling, parametric optimization, gradient-based methods.

УДК 624.04, 519.853
Перельмутер А. В., Юрченко В. В., Пелешко И. Д.
ОПТИМИЗАЦИЯ РАЗМЕРОВ ПОПЕРЕЧНЫХ СЕЧЕНИЙ СЖАТЫХ ЭЛЕМЕНТОВ КОНСТРУКЦИЙ ИЗ С-ПОДОБНОГО ХОЛОДНОГНУТОГО ПРОФИЛЯ

В статье рассмотрена задача параметрической оптимизации размеров поперечного сечения стержневого элемента конструкции из С-образного холодногнутого профиля, работающего под действием продольной силы сжатия. Задача параметрической оптимизации формулировалась как: при заданных ширине и толщине заготовки (штрипсы) для изготовления холодногнутого профиля, а также типе поперечного сечения определить его оптимальные размеры с учетом закритической работы и конструктивных требований.

В качестве критерия оптимальности принимался критерий максимизации несущей способности профиля на потерю общей устойчивости при центральном сжатии, который представлялся в форме линейной свертки несущих способностей, учитывающих изгибное, крутильное и изгибно-крутильное выпучивание стержневого элемента, вычисленные в соответствии с требованиями EN 1993-1-3:2012 и EN 1993-1-5:2012. Поиск оптимальных размеров реализован с учетом возможной закритической работы тонкостенного холодногнутого профиля, характеризующейся местной потерей устойчивости и потерей устойчивости формы сечения.

Сформулированная задача параметрической оптимизации решена с использованием программы OptCAD, в которой реализован метод проекции градиента функции цели на поверхность активных ограничений при одновременной ликвидации невязок в нарушенных ограничениях.

В результате оптимизационного расчета получены С-образные холодногнутые профили, которые при одной и той же ширине заготовки характеризуются большей несущей способностью на потерю устойчивости при центральном сжатии по сравнению с холодногнутыми профилями отечественных производителей. При этом, для всех оптимальных решений поперечных сечений определяющей была несущая способность С-образного холодногнутого профиля на потерю устойчивости по изгибно-крутильной форме выпучивания.

Ключевые слова: холодногнутый профиль, несущая способность, местная потеря устойчивости, потеря устойчивости формы сечения, параметрическая оптимизация, градиентный метод.

УДК 624.04, 519.853
Перельмутер А. В., Юрченко В. В., Пелешко І. Д. **Оптимізація розмірів поперечних перерізів стиснутих елементів конструкцій з С-подібного холодногнутого профілю** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2022. – Вип. 108. – С. 156-170.
У статті розглянута задача параметричної оптимізації розмірів поперечного перерізу стержневого елементу конструкції з С-подібного холодногнутого профілю, що працює під дією поздовжньої сили стиску. Задача параметричної оптимізації формулюється як: при заданих ширині та товщині заготовки (штрипси) для виготовлення холодногнутого профілю, а також типі поперечного перерізу визначити його оптимальні розміри з врахуванням закритичної роботи та конструктивних вимог. Як критерій оптимальності приймався критерій максимізації несучої здатності профілю на втрату загальної стійкості при центральному стискові. Сформульована задача параметричної оптимізації розв'язана з використанням методу проекції градієнту функції мети на поверхню активних обмежень при одночасній ліквідації нев'язок у порушених обмеженнях. Як результат оптимізаційного розрахунку отримані С-подібні холодногнуті профілі, які характеризуються більшою несучою здатністю на втрату стійкості при центральному стискові порівняно з холодногнутими профілями вітчизняних виробників при одній і тій самій ширині заготовки.
Іл. 2. Табл. 2. Бібліог. 18 назв.

УДК 624.04, 519.853
Perelmuter A. V., Yurchenko V. V., Peleshko I. D. **Optimization cross-sectional dimensions for cold-formed steel lipped channel columns** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles – Kyiv: KNUBA, 2022. – Issue 108. – P. 156-170.
A parametric optimization problem of cross-sectional sizes for cold-formed steel lipped channel structural members subjected to central compression has been considered by the paper. An optimization problem is formulated to define optimum cross-sectional sizes of cold-formed structural member taking into account post-buckling behavior and structural requirements when stripe width, profile thickness and profile type are constant and defined by the designer. Maximization of load-carrying capacity of the cold-formed structural member has been assumed as purpose function. Formulated parametric optimization problem has been solved using a modified gradient method of the purpose function projection on the active constraints hyperplanes with simultaneous liquidations

of the residuals in the violated constraints. As optimization results cold-formed steel lipped channels with optimum dimensions have been obtained. With the same stripe width optimum profiles have higher load-carrying capacities comparing with the ones proposed by Ukrainian manufacturers.
Figs. 2. Tabs. 2. Refs. 18.

УДК 624.04, 519.853
Перельмутер А.В., Юрченко В.В., Пелешко И.Д. **Оптимизация размеров поперечных сечений сжатых элементов конструкций из с-подобного холодногнутого профиля** // Сопротивление материалов и теория сооружений: науч.- тех. сборн. – К.: КНУСА, 2022. – Вып. 108. – С. 156-170.
В статье рассмотрена задача параметрической оптимизации размеров поперечного сечения стержневого элемента конструкции из С-образного холодногнутого профиля, работающего под действием продольной силы сжатия. Задача параметрической оптимизации формулировалась как: при заданных ширине и толщине заготовки (штрипсы) для изготовления холодногнутого профиля, а также типе поперечного сечения определить его оптимальные размеры с учетом закритической работы и конструктивных требований. В качестве критерия оптимальности принимался критерий максимизации несущей способности профиля на потерю общей устойчивости при центральном сжатии. Сформулированная задача параметрической оптимизации решена с использованием метода проекции градиента функции цели на поверхность активных ограничений при одновременной ликвидации невязок в нарушенных ограничениях. В результате оптимизационного расчета получены С-образные холодногнутые профили, которые при одной и той же ширине заготовки характеризуются большей несущей способностью на потерю устойчивости при центральном сжатии по сравнению с холодногнутыми профилями отечественных производителей.
Ил. 2. Табл. 2. Библиог. 18 назв.

Автор: *доктор технічних наук, старший науковий співробітник Перельмутер Анатолій Вікторович*
Адреса робоча: *03037 Україна, м. Київ, вул. Освіти 3А, оф. 2*
Робочий тел.: *+38(044)249-71-91*
Мобільний тел.: *+38(050)382-16-25*
E-mail: avp@scadsoft.com
SCOPUS ID: 6602444316
ORCID ID: https://orcid.org/0000-0001-9537-2728

Автор: *доктор технічних наук, професор кафедри металевих та дерев'яних конструкцій Юрченко Віталіна Віталіївна*
Адреса робоча: *03680 Україна, м. Київ, Повітрофлотський пр. 31, Київський національний університет будівництва і архітектури*
Робочий тел.: *+38(044)249-71-91*
Мобільний тел.: *+38(063)89-26-491*
E-mail: vitalina@scadsoft.com
SCOPUS ID: 25637856200
ORCID ID: https://orcid.org/0000-0003-4513-809X

Автор: *кандидат технічних наук, доцент кафедри будівельного виробництва Пелешко Іван Дмитрович*
Адреса робоча: *79013 Україна, м. Львів, вул. Ст. Бандери 12, Національний університет «Львівська політехніка»*
Робочий тел.: *+38 (032) 258-25-41*
Мобільний тел.: *+38(098)41-57-517*
E-mail: ipeleshko@polynet.lviv.ua
SCOPUS ID: 25637832500
ORCID ID: https://orcid.org/0000-0001-7028-9653