UDC 519.853, 624.04, 624.014.2

SIZE OPTIMIZATION OF SINGLE EDGE FOLDS FOR COLD-FORMED STRUCTURAL MEMBERS

S.I. Bilyk,
Doctor of Technical Science, Professor

V.V. Yurchenko,
Doctor of Technical Science, Professor

Kyiv National University of Construction and Architecture
Povitroflotskyj av., 31, Kyiv, 030370

DOI: 10.32347/2410-2547.2020.105.73-86

Optimization problem for single edge fold size in cold-formed structural members has been considered by the paper. Linear convolution of criteria, namely minimization criterion of design area of stiffener cross-section and maximization criterion effective area of stiffener cross-section which defines it reduced load-bearing capacity due to distortional buckling has been used as optimization criterion.

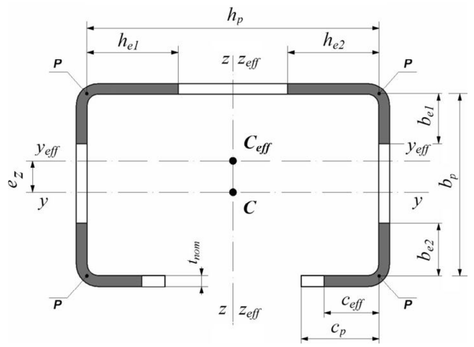
Results of performed study can be served as design recommendations for companies-manufacturers of cold-formed profiles as well as recommendations in scope of elaboration national standard – assortments of effective cold-formed profiles. It will promote wider implementation of cold-formed building structures in building practice.

Key words: load-bearing capacity, cold-formed profile, optimization problem, single edge fold, stiffener, distortional buckling, linear convolution of criteria.

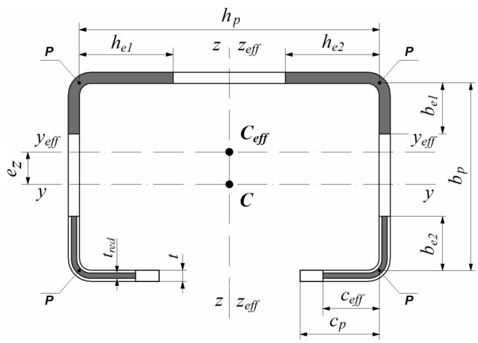
Introduction. Previously, the use of cold-formed thin-walled profiles was limited to cases where reducing the weight of the structure was a priority, such as in the aviation or automotive industries. However, due to the development of production technology, corrosion protection, product availability 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 thin-walled cold-formed profiles, 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.

Design and verification of thin-walled structural members made of cold-formed profiles is fully reflected in the European design standards implemented in Ukraine [1, 2]. The design code considers not only local and overall buckling due to flexural, flexural-torsional or lateral-torsional buckling of the cold-formed structural member, but also *distortional buckling*. The latter is a mode of buckling in which the lip stiffener is insufficient to retard the



(a)



(b)

Fig. 1. Construction of the "effective" C-profile cross-section of the cold-formed structural members according to the design code: (a) – at the first stage; (b) – at the second stage

compressed flange and attached web from becoming unstable. In other words, distortional buckling occurs in cases when flange end stiffeners (single edge folds or double edge folds) or intermediate stiffeners are not able to resist the local displacement of the cross-section plane elements conjugation nodes.

Calculation the load-bearing capacity of the cold-formed structural members includes two stages according to the design code. At the first stage calculation of the "effective" (reduced) widths of the compressed cross-section plane elements is performed taking into account local buckling effects in these elements (Fig. 1a). At the second stage calculation of the "effective" (reduced) thicknesses of the compressed cross-section plane elements is performed taking into account distortional buckling effects (see Fig. 1b). Then calculation the load-bearing capacity of the cold-formed structural members is performed using the geometrical properties calculated based on the constructed "effective" (reduced) cross-sections.

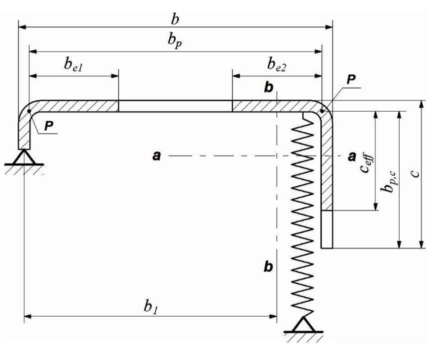


Fig. 2. Plane section element (flange) stiffened by the single edge fold (flange width b should not exceed $60t$, t is profile thickness)

Optimization problem formulation. Let consider a searching problem for optimum sizes of single edge folds which stiffens the flanges in steel structural members made from cold-formed profiles subjected to central compression (Fig. 2).

Initial data for optimization presented as follow: cross-sectional sizes of C-profile – web height h, flange width b, profile thickness t, internal radius for section plane elements conjunction $r = 1,5t$; steel basic yield strength f_{yb}, MPa; E – steel elastic modulus, MPa.

Let consider single edge fold size c as *design variable* (see Fig. 3). Plane element's design widths for C- and Z- cold-formed profiles which are considered *as state variables* of the optimization problem should be calculated depending on the profile overall dimensions h and b, internal radius $r = 1,5t$ and profile thickness t as follow:

– web plane element design width of the profile:

$$h_p = h - 2,5t \ ;$$

– flange plane element design width of the profile:

$$b_p = b - 2,5t \ ;$$

– single edge fold plane element design width of the profile:

$$c_p = c - 1,25t \ .$$

Slenderness of the profile flange with design width b_p, which is stiffened by single edge fold, is calculated according to [1, 2] as presented below:

$$\overline{\lambda}_{pb} = \frac{b_p}{28,4t\sqrt{k_{\sigma 1, jkm}}}\sqrt{\frac{f_{yb}}{235}} = \frac{b_{pb}}{56,8t}\sqrt{\frac{f_{yb}}{235}} \ .$$

Profile flange with slenderness $\overline{\lambda}_{pb}$ is subjected to local buckling effects (post-buckling behavior) in case when $\overline{\lambda}_{pb} > 0,673$ or

$$\frac{b_p}{56,8t}\sqrt{\frac{f_{yb}}{235}} > 0,673$$

or

$$b_p > 38,2264t\sqrt{\frac{235}{f_{yb}}} \ .$$

At the same time “effective” flange width b_{eff} is calculated according to [1, 2] as follow:

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

The combined action of the single edge fold and a part of the “effective” (reduced) flange is considered when calculating the flexural buckling verification of the stiffener. The part of the “effective” flange with width b_{e2} (see Fig. 2) is included to the stiffener design section and is calculated according to [1, 2] as presented below:

$$b_{e2} = 0,5b_{p,eff} = \frac{b_p}{2\bar{\lambda}_{pb}}\left(1-\frac{0,22}{\bar{\lambda}_{pb}}\right) = 28,4t\sqrt{\frac{235}{f_{yb}}}\left(1-\frac{12,496t}{b_p}\sqrt{\frac{235}{f_{yb}}}\right). \quad (1)$$

In case when the local buckling of the flange stiffened by the single edge fold does not occur, i. e. when $\bar{\lambda}_{pb} \le 0,673$ or

$$b_p \le 38,2264t\sqrt{\frac{235}{f_{yb}}}.$$

Then the combined action of the single edge fold and the half of the design flange width b_p is considered when calculating the flexural buckling verification of the stiffener:

$$b_{e2} = 0.5b_p.$$

Plane element slenderness with design width c_p of the single edge fold stiffened the flange is calculated according to [1, 2] as presented below:

– for short single edge folds (when $c_p \le 0,35b_p$):

$$\bar{\lambda}_{pc} = \frac{c_p}{28,4t\sqrt{0,5}}\sqrt{\frac{f_{yb}}{235}} = 0,0498\frac{c_p}{t}\sqrt{\frac{f_{yb}}{235}};$$

– for long single edge folds (when $0,35b_p < c_p \le 0,6b_p$):

$$\bar{\lambda}_{pc} = \frac{c_p}{28,4t\sqrt{0,5+0,83\left((c_p/b_p)-0,35\right)^{2/3}}}\sqrt{\frac{f_{yb}}{235}}.$$

For single edge fold with design width c_p local buckling occurs when $\bar{\lambda}_{pc} > 0,748$ or

– for short single edge folds (when $c_p \le 0,35b_p$):

$$\bar{\lambda}_{pc} = \frac{c_p}{28,4t\sqrt{0,5}}\sqrt{\frac{f_{yb}}{235}} = 0,0498\frac{c_p}{t}\sqrt{\frac{f_{yb}}{235}} > 0,748;$$

whence it follows:

$$c_p > 15,02121t\sqrt{\frac{235}{f_{yb}}};$$

– for long single edge folds (when $0,35b_p < c_p \le 0,6b_p$):

$$\bar{\lambda}_{pc} = \frac{c_p}{28,4t\sqrt{0,5+0,83\left((c_p/b_p)-0,35\right)^{2/3}}}\sqrt{\frac{f_{yb}}{235}} > 0,748;$$

whence it follows:

$$c_p > 21{,}2432t\sqrt{\frac{235}{f_{yb}}}\sqrt{0{,}5+0{,}83\left((c_p/b_p)-0{,}35\right)^{2/3}}\ .$$

For single edge fold with post-buckling behavior (local buckling occurs in plane element of the stiffener), "effective" width c_{eff} should be calculated according to [1, 2] as presented below:

– if $\bar{\lambda}_{pc} > 0{,}748$ and $c_p \le 0{,}35b_p$:

$$c_{eff} = \frac{t}{0{,}0498}\sqrt{\frac{235}{f_{yb}}}\left(1-3{,}7754\frac{t}{c_p}\sqrt{\frac{235}{f_{yb}}}\right); \tag{2}$$

– if $\bar{\lambda}_{pc} > 0{,}748$ and $0{,}35b_p < c_p \le 0{,}6b_p$:

$$c_{eff} = 28{,}4t\sqrt{\frac{235}{f_{yb}}}\sqrt{0{,}5+0{,}83\left(\frac{c_p}{b_p}-0{,}35\right)^{2/3}}\ \times$$
$$\times\left(1-5{,}3392\frac{t}{c_p}\sqrt{\frac{235}{f_{yb}}}\sqrt{0{,}5+0{,}83\left(\frac{c_p}{b_p}-0{,}35\right)^{2/3}}\right). \tag{3}$$

In case when the local buckling of the single edge fold plane element is not occurred, that is when $\bar{\lambda}_{pc} \le 0{,}748$, or

– for short single edge folds (when $c_p \le 0{,}35b_p$):

$$c_p \le 15{,}02121t\sqrt{\frac{235}{f_{yb}}}\ ;$$

– for long single edge folds (when $0{,}35b_p < c_p \le 0{,}6b_p$):

$$c_p \le 21{,}2432t\sqrt{\frac{235}{f_{yb}}}\sqrt{0{,}5+0{,}83\left(\frac{c_p}{b_p}-0{,}35\right)^{2/3}}\ ;$$

"effective" width of the single edge fold plane element c_{eff} should be equal to the design width:

$$c_{eff} = c_p\ .$$

Slenderness of the single edge fold corresponded to the flexural buckling of the stiffener is calculated according to [1, 2] as follow:

$$\bar{\lambda}_d = \sqrt{\frac{f_{yb}A_s}{2\sqrt{KEI_s}}} = \sqrt{\frac{f_{yb}t\left(c_{eff}+b_{e2}\right)}{\sqrt{KEtc_{eff}^3\left(\frac{1}{3}+\frac{b_{e2}}{c_{eff}+b_{e2}}\right)}}}\ , \tag{4}$$

where A_s and I_s – geometrical properties of the single edge fold design section; K – stiffness of the linear spring (using the spring partial restraint of the plane section element (flange) by the single edge fold is simulated) calculated according to [1, 2] as for cold-formed central compressed cross-sections symmetrical relating to the main axes of inertia which is perpendicular to the web plane with flange stiffened by the single edge folds as presented below:

$$K = \frac{E}{3,64} \cdot \frac{t^3}{\left(b_p - \dfrac{0,5(b_{e2})^2}{c_{eff} + b_{e2}} \right)^2 \left(1,5h_p + b_p - \dfrac{0,5(b_{e2})^2}{c_{eff} + b_{e2}} \right)}.$$

The reduction factor corresponded to the flexural buckling of the stiffener (or distortional buckling factor) should be calculated depending on slenderness $\overline{\lambda}_d$ of the stiffener as presented below:

$$\chi_d = \Xi\left(\overline{\lambda}_d\right);$$

where Ξ – is the functional dependence described in [1, 2] as follow:

$$\Xi\left(\overline{\lambda}_d\right) = \begin{cases} 1,0 & \text{if } \overline{\lambda}_d \le 0,65; \\ 1,47 - 0,723\overline{\lambda}_d & \text{if } 0,65 < \overline{\lambda}_d \le 1,38; \\ 0,66\overline{\lambda}_d^{-1} & \text{if } \overline{\lambda}_d > 1,38. \end{cases} \tag{5}$$

It should be noted, that when $\overline{\lambda}_d \le 0,65$ distortional buckling of the section does not occur.

The reduced area of the stiffener (single edge fold) design section determined the reduced load-bearing capacity of the stiffener due to flexural buckling is calculated depending on distortional buckling factor χ_d as follow:

$$A_{s,red} = \chi_d A_s. \tag{6}$$

The reduced load-bearing capacity of the stiffener due to flexural buckling is taken into account by reduction of the thickness for the stiffener design section as presented below:

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

In the paper [6] load-bearing capacity region in “axial force – bending moment” coordinates for a doubly symmetrical cross-section of the thin-walled cold-formed structural members has been constructed according to the requirements of the design code [1, 2]. Performed analysis of the constructed load-bearing capacity region has shown the non-convexity and abrupt changing of the region boundaries occurred in cases where the section goes to the post-buckling stage, which is characterized by the phenomenon of local buckling of the plane section elements and/or distortional buckling of the section. In addition, this analysis also showed an increase the load-bearing capacity with increasing axial tensile internal force due to the increase of the “effective” (reduced) design section.

Presented arguments lead to consider as a purpose function in cross-sectional sizes optimization problems formulated for cold-formed structural members the following criterion of minimum difference between initial cross-section area and "effective" (reduced) cross-section area:

$$\mathbf{FES}_A = A_s - A_{s,red} \rightarrow \min$$

or taking into account (1.6):

$$\mathbf{FES}_A = A_s - A_{s,red} = A_s - \chi_d A_s = A_s\left(1-\chi_d\right) \rightarrow \min$$

or

$$\mathbf{FES}_A\left(c\right) = t\left(c_{eff} + b_{e2}\right)\left(1-\chi_d\left(\bar{\lambda}_d\right)\right) \rightarrow \min, \tag{7}$$

where c_{eff}, b_{e2} and $\bar{\lambda}_d$ are calculated according to (2) or (3), (1) and (4) respectively depending on overall profile dimensions h, b, t and variable size of the single edge fold c, and functional dependency $\chi_d(\bar{\lambda}_d)$ is defined according to (5).

Proposed optimization criterion (7) for size optimization of the single edge fold stiffened the flanges in cold-formed structural members in fact is a linear convolution (with the same weight factors) of the following two criteria:

1) minimization of the design cross-section area of the stiffener A_s, which provides minimum material consumption;

2) maximization of the "effective" (reduced) cross-sectional area of the singe edge fold $A_{s,red}$ determined the reduced load-bearing capacity of the stiffener taking into account flexural buckling effects, or in other words, load-bearing capacity maximization of the single edge fold.

Thus, cross-section size optimization problem for cold-formed structural members has been formulated as searching problem for optimum single edge fold size c with minimization of the determined purpose function (7) taking into account state variables calculated according to (1) – (6). The parametric optimization problem stated by (1) – (7) has been solved using the method of objective function gradient projection onto the active constraints surface with simultaneous correction of the constraints violations [3, 4]. In order to realize the formulated optimization problem, software OptCAD intended to solve parametric optimization problems for steel structural systems has been used [5, 6].

Results and discussion. Optimization results of the single edge folds for the cold-formed C-profiles manufactured by «Blachy Pruszyński» [8] company are presented in Table 1, for the cold-formed C-profiles manufactured by «BF FACTORY» company – in Table 2, for the cold-formed C-profiles manufactured by «STEELCO» company – in Table 3.

Table 1

Optimization results obtained for C-profiles manufactured by «Blachy Pruszyński» company

Profile sizes, mm	Initial design				Optimum solution by the criterion				
					$A_s - A_{s,red} \to \min$				$A_{s,red} \to \max$
	c, mm	χ_d	t_{red}, mm	$A_{s,red}$, mm	$c_{\min}^{opt}$, mm	χ_d	t_{red}, mm	$A_{s,red}$, mm	$c_{\max}^{opt}$, mm
100×48×1,5	**18**	0,968	1,452	87,66	**20,5**	1,0	1,5	94,31	**28,4**
100×48×2,0	**18**	1,0	2,0	117,0	**15,7**	1,0	2,0	112,40	**28,3**
100×48×2,5	**18**	1,0	2,5	141,56	**13,3**	1,0	2,5	129,81	**28,1**
100×48×3,0	**18**	1,0	3,0	164,25	**12,0**	1,0	3,0	146,25	**28,0**
150×48×1,5	**18**	0,921	1,381	83,36	**24,5**	1,0	1,5	100,31	**28,5**
150×48×2,0	**18**	0,996	1,993	116,56	**18,3**	1,0	2,0	117,6	**28,3**
150×48×2,5	**18**	1,0	2,5	141,56	**15,2**	1,0	2,5	134,56	**28,2**
150×48×3,0	**18**	1,0	3,0	164,25	**13,5**	1,0	3,0	150,75	**28,1**
200×48×1,5	**18**	0,883	1,324	79,95	**28,3**	1,0	1,5	106,01	**28,5**
200×48×2,0	**18**	0,964	1,927	112,73	**20,7**	1,0	2,0	122,4	**28,3**
200×48×2,5	**18**	1,0	2,5	141,56	**16,9**	1,0	2,5	138,81	**28,2**
200×48×3,0	**18**	1,0	3,0	164,25	**14,8**	1,0	3,0	154,65	**28,1**
250×48×1,5	**19**	0,869	1,304	80,02	**28,5**	0,976	1,464	103,66	**28,5**
250×48×2,0	**19**	0,952	1,904	113,30	**22,9**	1,0	2,0	126,80	**28,3**
250×48×2,5	**19**	1,0	2,5	144,06	**18,4**	1,0	2,5	142,5625	**28,2**
250×48×3,0	**19**	1,0	3,0	167,25	**15,9**	1,0	3,0	157,95	**28,1**
280×48×1,5	**19**	0,853	1,279	78,51	**28,5**	0,963	1,444	102,25	**28,5**
280×48×2,0	**19**	0,938	1,876	111,62	**24,1**	1,0	2,0	129,2	**28,3**
280×48×2,5	**19**	0,996	2,491	143,52	**19,3**	1,0	2,5	144,8125	**28,2**
280×48×3,0	**19**	1,0	3,0	167,25	**16,6**	1,0	3,0	160,05	**28,1**
300×49×1,5	**18**	0,813	1,220	74,84	**29,1**	0,951	1,427	103,32	**29,1**
300×49×2,0	**18**	0,903	1,805	107,40	**25,8**	1,0	2,0	134,60	**28,9**
300×49×2,5	**18**	0,964	2,409	138,83	**20,5**	1,0	2,5	150,31	**28,8**
300×49×3,0	**18**	1,0	3,0	167,25	**17,5**	1,0	3,0	165,75	**28,7**
100×60×1,5	**19**	0,880	1,321	96,90	**30,0**	1,0	1,5	125,77	**35,7**
100×60×2,0	**19**	0,960	1,921	137,33	**21,9**	1,0	2,0	148,80	**35,5**
100×60×2,5	**19**	1,0	2,5	174,06	**18,1**	1,0	2,5	171,81	**35,4**
100×60×3,0	**19**	1,0	3,0	203,25	**15,9**	1,0	3,0	193,95	**35,3**
150×60×1,5	**19**	0,827	1,240	90,97	**35,7**	0,979	1,469	127,27	**35,7**
150×60×2,0	**19**	0,913	1,826	130,58	**25,9**	1,0	2,0	156,80	**35,5**
150×60×2,5	**19**	0,972	2,430	169,20	**21,0**	1,0	2,5	179,06	**35,4**
150×60×3.0	**19**	1,0	3,0	203,25	**18,1**	1,0	3,0	200,55	**35,3**
200×60×1,5	**22**	0,837	1,256	95,92	**35,7**	0,947	1,420	123,06	**35,7**
200×60×2,0	**22**	0,924	1,848	137,64	**29,4**	1,0	2,0	163,8	**35,5**
200×60×2,5	**22**	0,983	2,457	178,46	**23,5**	1,0	2,5	185,31	**35,4**
200×60×3,0	**22**	1,0	3,0	212,25	**20,1**	1,0	3,0	206,55	**35,3**
250×60×1,5	**22**	0,804	1,206	92,11	**35,7**	0,919	1,379	119,51	**35,7**
250×60×2,0	**22**	0,895	1,790	133,33	**32,8**	1,0	2,0	170,6	**35,5**
250×60×2,5	**22**	0,957	2,392	173,74	**25,8**	1,0	2,5	191,0625	**35,4**
250×60×3,0	**22**	1,0	3,0	212,25	**21,8**	1,0	3,0	211,65	**35,3**
280×60×1,5	**22**	0,786	1,179	90,07	**35,7**	0,905	1,357	117,61	**35,7**
280×60×2,0	**22**	0,879	1,759	131,03	**34,8**	1,0	2,0	174,60	**35,5**
280×60×2,5	**22**	0,943	2,358	171,22	**27,2**	1,0	2,5	194,56	**35,4**

Profile sizes, mm	Initial design				Optimum solution by the criterion				
					$A_s - A_{s,red} \to \min$				$A_{s,red} \to \max$
	c, mm	χ_d	t_{red}, mm	$A_{s,red}$, mm	$c_{\min}^{opt}$, mm	χ_d	t_{red}, mm	$A_{s,red}$, mm	$c_{\max}^{opt}$, mm
280×60×3,0	**22**	0,990	2,970	210,14	**22,8**	1,0	3,0	214,65	**35,3**
300×60×1.5	**21**	0,757	1,136	85,62	**35,7**	0,896	1,34	116,42	**35,7**
300×60×2.0	**21**	0,854	1,708	125,50	**35,5**	0,997	1,99	175,51	**35,5**
300×60×2.5	**21**	0,920	2,299	164,66	**28,0**	1,0	2,5	196,56	**35,4**
300×60×3.0	**21**	0,968	2,904	202,58	**23,4**	1,0	3,0	216,75	**35,3**
350×60×1,5	**23**	0,766	1,150	88,94	**35,7**	0,874	1,312	113,67	**35,7**
350×60×2,0	**23**	0,863	1,725	130,24	**35,5**	0,980	1,96	172,43	**35,5**
350×60×2,5	**23**	0,928	2,321	170,86	**30,2**	1,0	2,5	202,06	**35,4**
350×60×3,0	**23**	0,977	2,931	210,29	**25,1**	1,0	3,0	221,55	**35,3**
400×60×1,5	**22**	0,726	1,089	83,19	**35,7**	0,855	1,283	111,19	**35,7**
400×60×2,0	**22**	0,827	1,655	123,26	**35,5**	0,964	1,928	169,66	**35,5**
400×60×2,5	**22**	0,896	2,241	162,73	**32,2**	1,0	2,5	207,06	**35,4**
400×60×3,0	**22**	0,947	2,842	201,06	**26,6**	1,0	3,0	226,05	**35,3**
280×75×1,5	**24**	0,728	1,092	58,43	**44,7**	0,835	1,253	79,625	**44,7**
280×75×2,0	**24**	0,792	1,584	144,94	**44,5**	0,962	1,923	211,06	**44,5**
280×75×2,5	**24**	0,864	2,159	193,50	**38,8**	1,0	2,5	261,06	**44,4**
280×75×3,0	**24**	0,916	2,749	241,22	**32,0**	1,0	3,0	287,25	**44,3**
350×75×1,5	**20**	0,615	0,923	45,68	**44,7**	0,803	1,204	76,54	**44,7**
350×75×2,0	**20**	0,674	1,347	117,86	**44,5**	0,935	1,870	205,18	**44,5**
350×75×2,5	**20**	0,754	1,886	161,50	**43,4**	1,0	2,5	272,56	**44,4**
350×75×3,0	**20**	0,814	2,441	204,41	**35,4**	1,0	3,0	297,45	**44,3**
400×75×1.5	**20**	0,589	0,883	43,72	**44,7**	0,782	1,173	74,59	**44,7**
400×75×2.0	**20**	0,648	1,296	113,40	**44,5**	0,918	1,836	201,46	**44,5**
400×75×2.5	**20**	0,732	1,829	156,58	**44,4**	0,990	2,475	272,25	**44,4**
400×75×3.0	**20**	0,792	2,377	199,10	**37,7**	1,0	3,0	304,35	**44,3**

Table 2

Optimization results obtained for C-profiles manufactured by «BF FACTORY» company

Profile sizes, mm	Initial design				Optimum solution by the criterion				
					$A_s - A_{s,red} \to \min$				$A_{s,red} \to \max$
	c, mm	χ_d	t_{red}, mm	$A_{s,red}$, mm	$c_{\min}^{opt}$, mm	χ_d	t_{red}, mm	$A_{s,red}$, mm	$c_{\max}^{opt}$, mm
100×48×2,0	**20**	1,0	2,0	121,0	**15,7**	1,0	2,0	112,40	**28,3**
150×48×2,0	**20**	1,0	2,0	121,0	**18,3**	1,0	2,0	117,6	**28,3**
100×60×2,0	**20**	0,975	1,951	141,44	**21,9**	1,0	2,0	148,80	**35,5**
150×60×2,0	**20**	0,930	1,859	134,80	**25,9**	1,0	2,0	156,80	**35,5**
150×60×2,5	**20**	0,988	2,469	174,35	**21,0**	1,0	2,5	179,06	**35,4**
200×60×2,0	**20**	0,893	1,787	129,52	**29,4**	1,0	2,0	163,8	**35,5**
200×60×2,5	**20**	0,955	2,387	168,56	**23,5**	1,0	2,5	185,31	**35,4**
200×60×3,0	**20**	1,0	3,0	206,22	**20,1**	1,0	3,0	206,55	**35,3**
200×65×1,5	–	–	–	–	**38,7**	0,926	1,390	84,30	**38,7**

200×65×2,0	–	–	–	–	**33,5**	1,0	2,0	182,0	**38,5**
200×65×2,5	**20**	0,917	2,292	173,35	**26,5**	1,0	2,5	205,31	**38,4**
200×65×3,0	–	–	–	–	**22,5**	1,0	3,0	228,75	**38,3**
250×60×2,0	**20**	0,863	1,725	125,09	**32,8**	1,0	2,0	170,6	**35,5**
250×60×2,5	**20**	0,927	2,318	163,69	**25,8**	1,0	2,5	191,06	**35,4**
250×60×3,0	**20**	0,975	2,924	201,00	**21,8**	1,0	3,0	211,65	**35,3**
250×65×1,5	–	–	–	–	**38,7**	0,899	1,349	81,83	**38,7**
250×65×2,0	**20**	0,820	1,639	127,03	**37,5**	1,0	2,0	190,0	**38,5**
250×65×2,5	–	–	–	–	**29,3**	1,0	2,5	212,31	**38,4**
250×65×3,0	–	–	–	–	**24,6**	1,0	3,0	235,05	**38,3**
250×70×1,5	–	–	–	–	**41,7**	0,875	1,312	81,64	**41,7**
250×70×2,0	–	–	–	–	**41,5**	0,995	1,989	206,55	**41,5**
250×70×2,5	**20**	0,848	2,120	170,93	**32,9**	1,0	2,5	233,81	**41,4**
250×70×3,0	**20**	0,901	2,701	212,73	**27,5**	1,0	3,0	258,75	**41,3**
300×60×3,0	**20**	0,953	2,858	196,47	**23,4**	1,0	3,0	216,75	**35,3**
300×70×1,5	–	–	–	–	**41,7**	0,850	1,275	79,35	**41,7**
300×70×2,0	–	–	–	–	**41,5**	0,974	1,949	202,34	**41,5**
300×70×2,5	**20**	0,821	2,052	165,48	**35,9**	1,0	2,5	241,31	**41,4**
300×70×3,0	**20**	0,876	2,627	206,85	**29,7**	1,0	3,0	265,35	**41,3**

Table 3

Optimization results obtained for C-profiles manufactured by «STEELCO» company

Profile sizes, mm	Initial design				Optimum solution by the criterion				
					$A_s - A_{s,red} \to \min$				$A_{s,red} \to \max$
	c, mm	χ_d	t_{red}, mm	$A_{s,red}$, mm^2	$c_{\min}^{opt}$, mm	χ_d	t_{red}, mm	$A_{s,red}$, mm^2	$c_{\max}^{opt}$, mm
60×60×0,8	**20**	0,695	0,556	17,98	**35,8**	0,790	0,632	23,51	**35,8**
60×60×1,0	**20**	0,819	0,916	31,34	**35,8**	0,902	0,902	40,08	**35,8**
60×60×1,2	**20**	0,904	1,085	47,00	**35,7**	0,979	1,175	59,77	**35,7**
60×60×1,4	**20**	0,946	1,325	60,54	**25,3**	1,0	1,4	71,40	**35,7**
80×40×0,8	**20**	0,894	0,715	23,20	**23,8**	0,913	0,730	24,77	**23,8**
80×40×1,0	**20**	0,982	0,982	54,89	**23,4**	1,0	1,0	57,61	**23,8**
80×40×1,2	**20**	1,0	1,2	66,6	**17,5**	1,0	1,2	63,60	**23,7**
80×40×1,4	**20**	1,0	1,4	76,65	**15,0**	1,0	1,4	69,65	**23,7**
100×40×0,8	**20**	0,867	0,693	22,51	**23,8**	0,887	0,710	24,06	**23,8**
100×40×1,0	**20**	0,958	0,958	53,55	**23,8**	0,979	0,979	56,57	**23,8**
100×40×1,2	**20**	1,0	1,2	66,6	**19,3**	1,0	1,2	65,76	**23,7**
100×40×1,4	**20**	1,0	1,4	76,65	**16,4**	1,0	1,4	71,61	**23,7**
150×50×0,8	**20**	0,683	0,547	17,81	**29,7**	0,747	0,597	21,41	**29,8**
150×50×1,0	**20**	0,808	0,808	30,79	**29,8**	0,864	0,864	36,63	**29,8**
150×50×1,2	**20**	0,883	1,059	44,17	**29,7**	0,946	1,135	54,28	**29,7**
150×50×1,4	**20**	0,913	1,279	82,79	**28,4**	1,0	1,4	102,41	**29,7**
150×50×1,5	–	–	–	–	**26,2**	1,0	1,5	105,86	**29,7**
150×50×2,0	**20**	1,0	2,0	125,0	**19,5**	1,0	2,0	124,0	**29,5**
150×50×2,5	–	–	–	–	**16,1**	1,0	2,5	141,81	**29,4**
150×50×3,0	–	–	–	–	**14,2**	1,0	3,0	158,85	**29,3**
200×50×0,8	**20**	0,633	0,506	16,50	**29,8**	0,701	0,560	20,11	**29,8**
200×50×1,0	**20**	0,765	0,765	29,16	**29,8**	0,825	0,825	34,98	**29,8**

Profile sizes, mm	Initial design				Optimum solution by the criterion				
					$A_s - A_{s,red} \to \min$				$A_{s,red} \to \max$
	c, mm	χ_d	t_{red}, mm	$A_{s,red}$, mm^2	$c_{\min}^{opt}$, mm	χ_d	t_{red}, mm	$A_{s,red}$, mm^2	$c_{\max}^{opt}$, mm
200×50×1,2	**20**	0,844	1,013	42,25	**29,7**	0,912	1,094	52,33	**29,7**
200×50×1,4	**20**	0,876	1,226	79,37	**29,7**	0,974	1,364	100,74	**29,7**
200×50×1,5	–	–	–	–	**29,7**	0,995	1,493	110,49	**29,7**
200×50×2,0	**20**	0,976	1,952	121,97	**22,0**	1,0	2,0	129	**29,5**
200×50×2,5	**20**	1,0	2,5	151,56	**17,9**	1,0	2,5	146,31	**29,4**
200×50×3,0	**20**	1,0	3,0	176,25	**15,6**	1,0	3,0	163,05	**29,3**
250×50×1,4	**20**	0,844	1,181	76,49	**29,7**	0,948	1,327	98,02	**29,7**
250×50×1,5	–	–	–	–	**29,6**	0,970	1,455	107,64	**29,6**
250×50×2,0	**20**	0,949	1,898	118,64	**24,4**	1,0	2,0	133,8	**29,5**
250×50×2,5	**20**	1,0	2,5	151,56	**19,6**	1,0	2,5	150,57	**29,4**
250×50×3,0	**20**	1,0	3,0	176,25	**16,9**	1,0	3,0	166,95	**29,3**
300×87×1,5	–	–	–	–	**51,9**	0,768	1,152	76,19	**51,9**
300×87×2,0	**18**	0,595	1,190	65,42	**51,7**	0,911	1,822	147,59	**51,7**
300×87×2,5	**19**	0,653	1,633	157,75	**51,5**	1,0	2,5	322,81	**51,6**
300×87×3,0	**21**	0,769	2,306	223,12	**41,8**	1,0	3,0	352,65	**51,5**
350×67×2,0	**13**	0,507	1,013	73,47	**39,7**	0,964	1,928	191,21	**39,7**
350×67×2,5	**14**	0,642	1,604	114,86	**36,0**	1,0	2,5	234,06	**39,6**
350×67×3,0	**15**	0,742	2,227	157,52	**29,7**	1,0	3,0	256,35	**39,5**
350×67×4,0	**18**	0,911	3,644	255,09	**23,0**	1,0	4,0	300,0	**39,2**
400×90×1,5	–	–	–	–	**53,7**	0,707	1,061	70,74	**53,7**
400×90×2,0	**16**	0,462	0,925	49,57	**53,5**	0,863	1,726	141,43	**53,5**
400×90×2,5	**17**	0,494	1,236	120,67	**53,4**	0,959	2,396	318,13	**53,4**
400×90×3,0	**19**	0,639	1,918	187,46	**50,8**	1,0	3,0	388,65	**53,3**
400×90×4,0	**23**	0,833	3,334	326,68	**37,4**	1,0	4,0	449,61	**53,0**

Conclusion. Size optimization problem for single edge folds stiffened flanges in cold-formed structural members has been formulated and solved in the paper. The linear convolution of the following two criteria has been considered, namely minimization criterion for design cross-section area of the stiffener providing minimum material consumption as well as maximization criterion for the "effective" (reduced) cross-section area of the single edge fold determined the reduced load-bearing capacity of the stiffener due to flexural buckling or, in other words, maximization criterion for the load-bearing capacity of the stiffener.

The results of the performed investigation can be used as recommendations for companies-manufacturers of the cold-formed profiles, as well as a guide for creation the national assortment base of the effective cold-formed profiles promoting wider implementation of cold-formed steel structures in building practice.

REFERENCES

1. *DSTU-N B EN 1993-1-3:2012* EuroCode 3. Design of steel structures. Part 1-3: General rules – Supplementary rules for cold-formed members and sheeting (EN 1993-1-3:2006, IDT). – Kyiv, Minregionbud of Ukraine, 2012. (ukr)
2. *DSTU-N B EN 1993-1-5:2012* EuroCode 3: Design of steel structures. Part 1-5: General rules – Plated structural elements (EN 1993-1-5:2005, IDT). – Kyiv, Minregionbud of Ukraine, 2012. (ukr)
3. *Guljaev V. I., Bazhenov V. A., Koshkin V. L.* Metodyi optimizatsii v stroitelnoy mehanike (Optimisation methods in structural mechanic). – Kyiv, 1988. – 192 p. (rus)
4. *Peleshko I., Yurchenko V.* An optimum structural computer-aided design using update gradient method // Proceedings of the 8th International Conference "Modern Building Materials, Structures and Techniques" (Lithuania, Vilnius, May 19-21, 2004), Faculty of Civil Engineering, Vilnius Gediminas Technical University. – p. 860-865.
5. *Peleshko I. D., Yurchenko V. V., Beliaev N. A.* Computer-aided design and optimization of steel structural systems // Zeszyty naukowe Politechniki Rzeszowskiej "Budownictwo i inżynieria środowiska". – No. 52(264). – 2009. – p. 145-154.
6. *Perelmuter A. V., Yurchenko V. V.* Doslidzhennia oblasti nesuchoi zdatnosti tonkostinnykh sterzhnevykh elementiv iz kholodnohnutykh profiliv (Load-bearing capacity region analysis of thin-walled structural members from cold-formed profiles) // Science and construction. – № 3 (21), 2019. – p. 42 – 48. https://doi.org/10.33644/scienceandconstruction.v21i3.110 (ukr)
7. *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" / Gizejowski, Kozlowski, Sleczka & Ziolko (eds.) / Taylor & Francis Group, London, 2006. – p. 819-826.
8. *Assortment ranges of the cold-formed profiles* for light gauge steel structures of the Ukrainian manufacturers. UCSC-014-16, 2016. 32 p. (ukr)
9. *Yurchenko V.* Searching for shear forces flows in arbitrary cross-sections of thin-walled bars: numerical algorithm and software implementation // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – Kyiv: KNUBA, 2019. – Issue 103. – p. 82 – 111. https://doi.org/10.32347/2410-2547.2019.103.82-111.

Стаття надійшла 23.08.2020

Білик С. І., Юрченко В. В.

ОПТИМІЗАЦІЯ РОЗМІРІВ ВІДГИНІВ, ЩО ПІДКРІПЛЮЮТЬ ПОЛИЦІ, В СТЕРЖНЕВИХ ЕЛЕМЕНТАХ КОНСТРУКЦІЙ ІЗ ХОЛОДНОГНУТИХ ПРОФІЛІВ

У статті розглядається задача оптимізації розміру одинарного відгину, який підкріплює полиці, в стержневих елементах конструкцій із холодногнутих профілів. Як критерій оптимальності використано лінійна згортка критерію мінімізації площі розрахункового перерізу відгину та критерію максимізації «ефективної» (редукованої) площі відгину, що визначає його понижену несучу здатність за рахунок втрати стійкості при згинальному випучуванні.

Результати виконаних досліджень можуть слугувати рекомендаціями для компаній-виробників холодногнутих профілів, а також рекомендаціями для створення національного сортаменту ефективних холодногнутих профілів, що сприятиме ширшому впровадженню досліджуваного класу конструкцій у практику будівництва.

Ключові слова: несуча здатність, холодногнутий профіль, задача оптимізації, одинарний відгин, елемент жорсткості, втрата стійкості форми перерізу, лінійна згортка критеріїв.

Bilyk S. I., Yurchenko V. V.

SIZE OPTIMIZATION OF SINGLE EDGE FOLDS FOR COLD-FORMED STRUCTURAL MEMBERS

Parametric optimization problem for single edge fold size in cold-formed structural members subjected to central compression has been considered by the paper. Determination the load-bearing capacity of the cold-formed structural members has been performed using the geometrical properties calculated based on the constructed "effective" (reduced) cross-sections taking into account local buckling effects in the section as well as distortional buckling effects.

Single edge fold size in cold-formed C-profile has been considered as design variable. Linear convolution of criteria, namely minimization criterion of design area of stiffener cross-section and maximization criterion effective area of stiffener cross-section which defines it reduced load-bearing capacity due to flexural buckling has been used as optimization criterion. The parametric optimization problem has been solved using the method of objective function gradient projection onto the active constraints surface with simultaneous correction of the constraints violations. In order to realize the formulated optimization problem, software OptCAD intended to solve parametric optimization problems for steel structural systems has been used.

Optimization results of the single edge folds for the cold-formed C-profiles manufactured by «Blachy Pruszyński» company, «BF FACTORY» company as well as «STEELCO» company have been presented by the paper. The results of the performed investigation can be used as recommendations for companies-manufacturers of the cold-formed profiles, as well as a guide for creation the national assortment base of the effective cold-formed profiles promoting wider implementation of cold-formed steel structures in building practice.

Key words: load-bearing capacity, cold-formed profile, optimization problem, single edge fold, stiffener, distortional buckling, linear convolution of criteria.

УДК 519.853, 624.04, 624.014.2
Билык С. И., Юрченко В. В.

ОПТИМИЗАЦИЯ РАЗМЕРОВ ОТГИБОВ, ПОДКРЕПЛЯЮЩИХ ПОЛКИ, В СТЕРЖНЕВЫХ ЭЛЕМЕНТАХ КОНСТРУКЦИЙ ИЗ ХОЛОДНОГНУТЫХ ПРОФИЛЕЙ

В статье рассматривается задача оптимизации размера одинарного отгиба, подкрепляющего полки, в стержневых элементах конструкций из холодногнутых профилей. В качестве критерия оптимальности использована линейная свертка критерия минимизации расчетной площади отгиба и критерия максимизации редуцированной площади отгиба, определяющей его пониженную (за счет потери устойчивости при изгибном выпучивании) несущую способность.

Результаты выполненных исследований служат рекомендациями для компаний-изготовителей холодногнутых профилей, а также рекомендациями для создания национального сортамента эффективных холодногнутых профилей, что будет способствовать более широкому внедрению исследуемого класса конструкций в практику строительства.

Ключевые слова: несущая способность, холодногнутый профиль, задача оптимизации, одинарный отгиб, элемент жесткости, потеря устойчивости формы сечения, линейная свертка критериев.

УДК 519.853, 624.04, 624.014.2
Білик С. І., Юрченко В. В. **Оптимізація розміру відгину, що підкріплює полиці, у стержневих елементах конструкцій із холодногнутих профілів** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2020. – Вип. 105. – С. 73-86.

У статті розглядається задача оптимізації розміру одинарного відгину, що підкріплює полички, в стержневих елементах конструкцій із холодногнутих профілів. Як критерій оптимальності використана лінійна згортка критерію мінімізації площі розрахункового перерізу відгину та критерію максимізації «ефективної» (редукованої) площі відгину, що визначає його понижену несучу здатність за рахунок втрати стійкості при згинальному випучуванні. Результати виконаних досліджень можуть слугувати рекомендаціями для компаній-виробників холодногнутих профілів, а також рекомендаціями для створення національного сортаменту ефективних холодногнутих профілів.

Іл. 2. Табл. 3. Бібліог. 9 назв.

UDC 519.853, 624.04, 624.014.2
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 104. – P. 73-86.
The paper considers an optimization problem for single edge fold size in the cold-formed structural members. Linear convolution of criteria, namely minimization criterion of design area of stiffener cross-section and maximization criterion effective area of stiffener cross-section which defines it reduced load-bearing capacity due to distortional buckling has been used as optimization criterion. Results of the performed study can be served as design recommendations for companies-manufacturers of the cold-formed profiles as well as recommendations in scope of elaboration national standard – assortments of the effective cold-formed profiles.
Figs. 2. Tabs. 3. Refs. 9.

УДК 519.853, 624.04, 624.014.2
Билык С. И., Юрченко В. В. **Оптимизация размеров отгибов, подкрепляющих полки, в стержневых элементах конструкций из холодногнутых профилей** // Сопротивление материалов и теория сооружений: науч.- тех. сборн. – К.: КНУСА, 2020. – Вып. 105. – С. 73-86.
В статье рассматривается задача оптимизации размера одинарного отгиба, подкрепляющего полки, в стержневых элементах конструкций из холодногнутых профилей. В качестве критерия оптимальности использована линейная свертка критерия минимизации площади расчетного сечения отгиба и критерия максимизации редуцированной площади отгиба, определяющей его пониженную несущую способность за счет потери устойчивости при изгибном выпучивании. Результаты выполненных исследований могут послужить рекомендациями для компаний-изготовителей холодногнутых профилей, а также рекомендациями для создания национального сортамента эффективных холодногнутых профилей.
Ил. 2. Табл. 3. Библиог. 9 назв.

Автор: *доктор технічних наук, професор кафедри металевих та дерев'яних конструкцій Білик Сергій Іванович*
Адреса робоча: *03680 Україна, м. Київ, Повітрофлотський пр. 31, Київський національний університет будівництва і архітектури*
Робочий тел.: *+38 (044) 241-54-89*
Мобільний тел..: *+38(098)044-82-88*
E-mail: *vartist@ukr.net*
SCOPUS ID: 25636796400
ORCID ID: http://orcid.org/0000-0001-8783-5892

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: http://orcid.org/0000-0003-4513-809X