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

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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
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.

**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:

$$\lambda_{pb} = \frac{b_p}{28.4t} \frac{f_{yb}}{\sqrt{k_{\sigma1,jkm}235}} = \frac{b_{pb}}{56.8t} \frac{f_{yb}}{235}.$$  

Profile flange with slenderness $\lambda_{pb}$ is subjected to local buckling effects (post-buckling behavior) in case when $\lambda_{pb} > 0.673$ or

$$\frac{b_p}{56.8t} \frac{f_{yb}}{235} > 0.673$$

or

$$b_p > 38.2264t \frac{235}{f_{yb}}.$$  

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

$$b_{eff} = \frac{b_p}{\lambda_{pb}} \left(1 - \frac{0.22}{\lambda_{pb}}\right) = 56.8t \frac{235}{f_{yb}} \left(1 - \frac{12.496t}{b_p} \frac{235}{f_{yb}}\right).$$

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 $b_{c2}$ (see Fig. 2) is included to the stiffener design section and is calculated according to [1, 2] as presented below:
\[ b_{e2} = 0.5b_{p,\text{eff}} = \frac{b_p}{2\lambda_{pb}} \left(1 - \frac{0.22}{\lambda_{pb}}\right) = 28.4t \sqrt{\frac{235}{f_{yb}}} \left(1 - \frac{12.496t}{b_p} \sqrt{\frac{235}{f_{yb}}}\right). \] (1)

In case when the local buckling of the flange stiffened by the single edge fold does not occur, i.e. when \( \lambda_{pb} \leq 0.673 \) or

\[ b_p \leq 38.2264t \sqrt{\frac{235}{f_{yb}}}. \]

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 \( c_p \leq 0.35b_p \)):

\[ \lambda_{pc} = \frac{c_p}{28.4t \sqrt{0.5} \sqrt{\frac{235}{f_{yb}}}} = 0.0498 \frac{c_p}{t} \sqrt{\frac{f_{yb}}{235}}; \]

- for long single edge folds (when \( 0.35b_p < c_p \leq 0.6b_p \)):

\[ \lambda_{pc} = \frac{c_p}{28.4t \sqrt{0.5 + 0.83 \left((c_p/b_p) - 0.35\right)^{2/3}} \sqrt{\frac{f_{yb}}{235}}}. \]

For single edge fold with design width \( c_p \) local buckling occurs when \( \lambda_{pc} > 0.748 \) or

- for short single edge folds (when \( c_p \leq 0.35b_p \)):

\[ \lambda_{pc} = \frac{c_p}{28.4t \sqrt{0.5} \sqrt{\frac{235}{f_{yb}}}} = 0.0498 \frac{c_p}{t} \sqrt{\frac{f_{yb}}{235}} > 0.748; \]

whence it follows:

\[ c_p > 15.02121t \sqrt{\frac{235}{f_{yb}}}; \]

- for long single edge folds (when \( 0.35b_p < c_p \leq 0.6b_p \)):

\[ \lambda_{pc} = \frac{c_p}{28.4t \sqrt{0.5 + 0.83 \left((c_p/b_p) - 0.35\right)^{2/3}} \sqrt{\frac{f_{yb}}{235}} > 0.748; \]

whence it follows:
\[ c_p > 21.2432t \sqrt{\frac{235}{f_{yb}}} \sqrt{0.5 + 0.83\left(\frac{c_p}{b_p}\right) - 0.35}^{2/3}. \]

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

- if \( \lambda_{pc} > 0.748 \) and \( c_p \leq 0.35b_p \):

\[ c_{\text{eff}} = \frac{t}{0.0498} \sqrt{\frac{235}{f_{yb}}} \left(1 - 3.7754 \frac{t}{c_p} \sqrt{\frac{235}{f_{yb}}} \right); \quad (2) \]

- if \( \lambda_{pc} > 0.748 \) and \( 0.35b_p < c_p \leq 0.6b_p \):

\[ c_{\text{eff}} = 28.4t \sqrt{\frac{235}{f_{yb}}} \sqrt{0.5 + 0.83\left(\frac{c_p}{b_p} - 0.35\right)}^{2/3} \times \]

\[ \times \left(1 - 5.3392 \frac{t}{c_p} \sqrt{\frac{235}{f_{yb}}} \sqrt{0.5 + 0.83\left(\frac{c_p}{b_p} - 0.35\right)}^{2/3}\right). \quad (3) \]

In case when the local buckling of the single edge fold plane element is not occurred, that is when \( \lambda_{pc} \leq 0.748 \), or

- for short single edge folds (when \( c_p \leq 0.35b_p \)):

\[ c_p \leq 15.02121t \sqrt{\frac{235}{f_{yb}}}; \]

- for long single edge folds (when \( 0.35b_p < c_p \leq 0.6b_p \)):

\[ c_p \leq 21.2432t \sqrt{\frac{235}{f_{yb}}} \sqrt{0.5 + 0.83\left(\frac{c_p}{b_p} - 0.35\right)}^{2/3}; \]

“effective” width of the single edge fold plane element \( c_{\text{eff}} \) should be equal to the design width:

\[ c_{\text{eff}} = c_p. \]

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

\[ \lambda_{d} = \frac{f_{yb}A_s}{2\sqrt{K E I_s}} = \frac{f_{yb}t(c_{\text{eff}} + b_{c2})}{\sqrt{K E I_{c\text{eff}}} \left(\frac{1}{3} + \frac{b_{c2}}{c_{\text{eff}} + b_{c2}}\right)}; \quad (4) \]

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:

\[ K = \frac{E}{3.64} \left( \frac{b_p - 0.5(b_{e2})^2}{c_{eff} + b_{e2}} \right)^2 \left( 1.5 h_p + b_p - \frac{0.5(b_{e2})^2}{c_{eff} + b_{e2}} \right)^2. \]

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

\[ \chi_d = \Xi(\bar{\lambda}_d); \]

where \( \Xi \) – is the functional dependence described in [1, 2] as follow:

\[ \Xi(\bar{\lambda}_d) = \begin{cases} 1.0 & \text{if } \bar{\lambda}_d \leq 0.65; \\ 1.47 - 0.723 \bar{\lambda}_d & \text{if } 0.65 < \bar{\lambda}_d \leq 1.38; \\ 0.66 \bar{\lambda}_d^{-1} & \text{if } \bar{\lambda}_d > 1.38. \] (5)

It should be noted, that when \( \bar{\lambda}_d \leq 0.65 \) 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 \( \chi_d \) as follow:

\[ A_{s,\text{red}} = \chi_d A_s. \] (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:

\[ t_{\text{red}} = t \frac{A_{s,\text{red}}}{A_s}. \]

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:

\[ \text{FES}_A = A_s - A_{s,\text{red}} \rightarrow \min \]

or taking into account \((1.6)\):

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

or

\[ \text{FES}_A (c) = t \left( c_{\text{eff}} + b_{c_2} \right) \left(1 - \chi_d \left( \bar{\lambda}_d \right) \right) \rightarrow \min, \quad (7) \]

where \( c_{\text{eff}} \), \( b_{c_2} \) 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 \( A_{s,\text{red}} \) 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 |
|-------------------|----------------|-----------------------------------|
|                   | $c$, mm | $\chi_d$, mm | $t_{red}$, mm | $A_{s,red}$, mm | $c_{opt}$, mm | $\chi_d$, mm | $t_{red}$, mm | $A_{s,red}$, mm | $c_{max}$, 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 | 80.07 | 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 |
| 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 | 123.66 | 35.7 |
| 200×60×2,0        | 22     | 0.924 | 1.848 | 137.64 | 29.4 | 1.0 | 2.0 | 163.80 | 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 |
| 300×60×1,5        | 22     | 0.786 | 1.179 | 90.07 | 35.7 | 0.905 | 1.357 | 117.61 | 35.7 |
| 300×60×2,0        | 22     | 0.879 | 1.759 | 131.03 | 34.8 | 1.0 | 2.0 | 174.60 | 35.5 |
| 300×60×2,5        | 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 |
|------------------|----------------|----------------------------------|
|                  | $c$, mm        | $\chi_d$, $t_{red}$, mm          | $A_s - A_{s,red}$ $\rightarrow$ min |
|                  |                |                                  | $A_{s,red}$ $\rightarrow$ max |
|                  | $c_{opt}$, mm  | $\chi_d$, $t_{red}$, mm          | $A_{s,red}$ $\rightarrow$ max |
|                  |                |                                  | $c_{opt}$, 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 |

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

Table 2

| Profile sizes, mm | Initial design | Optimum solution by the criterion |
|------------------|----------------|----------------------------------|
|                  | $c$, mm        | $\chi_d$, $t_{red}$, mm          | $A_s - A_{s,red}$ $\rightarrow$ min |
|                  |                |                                  | $A_{s,red}$ $\rightarrow$ max |
|                  | $c_{opt}$, mm  | $\chi_d$, $t_{red}$, mm          | $A_{s,red}$ $\rightarrow$ max |
|                  |                |                                  | $c_{opt}$, 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 |
Table 3

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

| Profile sizes, mm | Initial design | Optimum solution by the criterion |
|-------------------|----------------|----------------------------------|
|                   |                | $A_{s} - A_{s, red} \rightarrow \min$ | $A_{s, red} \rightarrow \max$ |
|                   | $c$, mm        | $\chi_d$, $t_{red}$, mm | $A_{s, red}$, $mm^2$ | $c_{opt}^\min$, mm | $\chi_d$, $t_{red}$, mm | $A_{s, red}$, $mm^2$ | $c_{opt}^\max$, 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 | 1.17 | 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, 66.6 | 17.5 | 1.0, 1.2, 66.6 |
| 80×40×1.4         | 20             | 1.0, 1.4, 76.55 | 15.0 | 1.0, 1.4, 76.55 |
| 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, 66.6 |
| 100×40×1.4        | 20             | 1.0, 1.4, 76.65 | 16.4 | 1.0, 1.4, 76.65 |
| 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 | 1.13 | 54.28 | 29.7 |
| 150×50×1.4        | 20             | 0.913, 1.279 | 82.70 | 28.4 | 1.0 | 1.4 | 102.41 | 29.7 |
| 150×50×1.5        | 20             | 1.0, 2.0, 125.0 | 19.5 | 1.0, 2.0, 124.0 |
| 150×50×2.0        | 20             | 1.0, 2.0, 125.0 | 19.5 | 1.0, 2.0, 124.0 |
| 150×50×2.5        | 20             | 1.0, 2.0, 125.0 | 19.5 | 1.0, 2.0, 124.0 |
| 150×50×3.0        | 20             | 1.0, 3.0, 158.85 | 14.2 | 1.0, 3.0, 158.85 |
| 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 |
|------------------|---------------|----------------------------------|
|                  | $c_s$ mm | $\chi_d$ | $t_{red}$ mm | $A_{s,red}$ mm$^2$ | $c_{opt}^{min}$ mm | $\chi_d$ | $t_{red}$ mm | $A_{s,red}$ mm$^2$ | $c_{opt}^{max}$ mm |
| 200х50х1,2       | 20        | 0,844    | 1,013          | 42,25             | 29,7              | 0,912    | 1,094          | 52,33             | 29,7               |
| 200х50х1,4       | 20        | 0,876    | 1,226          | 79,37             | 29,7              | 0,974    | 1,364          | 100,74            | 29,7               |
| 200х50х1,5       | –         | –        | –              | –                 | 29,7              | 0,995    | 1,493          | 110,49            | 29,7               |
| 200х50х2,0       | 20        | 0,976    | 1,952          | 121,97            | 22,0              | 1,0      | 2,0            | 129               | 29,5               |
| 200х50х2,5       | 20        | 1,0      | 2,5            | 151,56            | 17,9              | 1,0      | 2,5            | 146,31            | 29,4               |
| 200х50х3,0       | 20        | 1,0      | 3,0            | 176,25            | 15,6              | 1,0      | 3,0            | 163,05            | 29,3               |
| 250х50х1,4       | 20        | 0,844    | 1,181          | 76,49             | 29,7              | 0,948    | 1,327          | 98,02             | 29,7               |
| 250х50х1,5       | –         | –        | –              | –                 | 29,6              | 0,970    | 1,455          | 107,64            | 29,6               |
| 250х50х2,0       | 20        | 0,949    | 1,898          | 118,64            | 24,4              | 1,0      | 2,0            | 133,8             | 29,5               |
| 250х50х2,5       | 20        | 1,0      | 2,5            | 151,56            | 19,6              | 1,0      | 2,5            | 150,57            | 29,4               |
| 250х50х3,0       | 20        | 1,0      | 3,0            | 176,25            | 16,9              | 1,0      | 3,0            | 166,95            | 29,3               |
| 300х87х1,5       | –         | –        | –              | –                 | 51,9              | 0,768    | 1,152          | 76,19             | 51,9               |
| 300х87х2,0       | 18        | 0,595    | 1,190          | 65,42             | 51,7              | 0,911    | 1,822          | 147,59            | 51,7               |
| 300х87х2,5       | 19        | 0,653    | 1,633          | 157,75            | 51,5              | 1,0      | 2,5            | 322,81            | 51,6               |
| 300х87х3,0       | 21        | 0,769    | 2,306          | 223,12            | 41,8              | 1,0      | 3,0            | 352,65            | 51,5               |
| 350х67х2,0       | 13        | 0,507    | 1,013          | 73,47             | 39,7              | 0,964    | 1,928          | 191,21            | 39,7               |
| 350х67х2,5       | 14        | 0,642    | 1,604          | 114,86            | 36,0              | 1,0      | 2,5            | 234,06            | 39,6               |
| 350х67х3,0       | 15        | 0,742    | 2,227          | 157,52            | 29,7              | 1,0      | 3,0            | 256,35            | 39,5               |
| 350х67х4,0       | 18        | 0,911    | 3,644          | 255,09            | 23,0              | 1,0      | 4,0            | 300,00            | 39,2               |
| 400х90х1,5       | –         | –        | –              | –                 | 53,7              | 0,707    | 1,061          | 70,74             | 53,7               |
| 400х90х2,0       | 16        | 0,462    | 0,925          | 49,57             | 53,5              | 0,863    | 1,726          | 141,43            | 53,5               |
| 400х90х2,5       | 17        | 0,494    | 1,236          | 120,67            | 53,4              | 0,959    | 2,396          | 318,13            | 53,4               |
| 400х90х3,0       | 19        | 0,639    | 1,918          | 187,46            | 50,8              | 1,0      | 3,0            | 388,65            | 53,3               |
| 400х90х4,0       | 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 creating the national assortment base of the effective cold-formed profiles promoting wider implementation of cold-formed steel structures in building practice.
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Білик С. І., Юрченко В. В.
ОПТИМАЛІЗАЦІЯ РОЗМІРІВ ВІДГІНІВ, ЩО ПІДКРИПЛЮЮТЬ ПОЛИЦІ, В СТЕРЖНЕВИХ ЕЛЕМЕНТАХ КОНСТРУКЦІЙ ІЗ ХОЛОДНОГНУТІХ ПРОФІЛІВ

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

Результати виконаних досліджень можуть слугувати рекомендаціями для компаній-виробників холодногнутих профілів, а також рекомендаціями для створення національного сортування 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 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.
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. сб. – 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.

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