On the reinforcement of thin-walled cold-drawn C-channel beams

G A Manuylov and M M Begichev

Russian University of Transport (MIIT), Moscow, Russia

E-mail: noxonius@mail.ru

Abstract. The paper considers the problem of stability of a thin-walled channel. Options for increasing the stability of the channel by changing its cross-section are proposed. Stiffness increased by adding triangular folds, as well as by adding stiffeners. The influence of initial imperfections of geometry in the channel model on the critical load of stability loss and postcritical behavior of the model is investigated. Imperfections were defined as deviations of the geometry of the pseudo-random amplitude.

1. Introduction
Currently, thin-walled steel beams (thickness $\delta = 1$–2 mm), obtained by pulling sheet blanks through rolls of a special machine have become very widespread [1-4].
The calculation of such rather thin-walled beams as compressed rods for stability has a number of features, since the possible forms of buckling - bending, bending-twisting, twisting, and also “plate-like” (in the form of wave formation of the web or flange of the beam), are usually accompanied by significant distortions of the initial contour shapes of cross sections. This circumstance significantly limits the possibility of using the theory of thin-walled rods (V.Z. Vlasov, Kappus, S.P. Timoshenko, etc.). To get the correct idea of the operation of such cold-drawn profiles, the most natural way is to build an equilibrium state curve using the FEM, taking into account geometric nonlinearity. In this paper, we consider the work of a compressed cold-drawn thin-walled bar of a channel section, which was investigated in [1]. It has been stated by the author of this work that under central compression by a load, equally distributed over the upper-end section of the rod, the smallest critical load $q_{cr, min}$ causes a loss of stability of the channel’s web as for a sufficiently thin compressed plate (i.e., the effect of “wave formation”). To get rid of this phenomenon, the author [1] describes the procedure of “removing” those areas of the web that lose stability by creating cutouts of a triangular or trapezoidal shape [1] with a simultaneous strengthening of the belts (i.e. strips) of such a “modernized beam”. The reinforcement of the belts is necessary due to the redistribution of forces in the beam with cutouts, since that part of the full load, which was perceived by the "whole" web, should now compress the reinforced flanges. The joints between the belts form a composite rod with increased flexibility and, generally speaking, a lower limit of stability of the rod compared to the initial channel.

2. Reinforcement of channel's cross section
The authors of this work took a different path of reinforcing a thin-walled compressed channel. In our perception, the option of avoiding the phenomenon of loss of stability of the compressed web by
creating holes in it (i.e., removing part of the web material), and the actual transformation of a continuous channel into a composite rod is not entirely successful. It is much easier to strengthen the web either by extruding additional stiffeners with a triangular shape of the desired depth (see Fig. 1) or by welding two longitudinal stiffeners of relatively small height [4-6]. In fig. 1, variants of the described web reinforcement are given, and the corresponding curves of deformations and displacements are shown in Fig. 2. The critical stresses in the plate web are estimated by two edges (Fig. 1b) as follows:

\[
\sigma_{cr, elast} = \frac{4\pi^2 D}{\alpha b^2} = \frac{4\pi^2 E\delta^2}{12(1-\nu^2)b^2} = \frac{4 \cdot \pi^2 \cdot 2.1 \cdot 10^6 \cdot 0.15^2}{10.92 \cdot 196} = 871.5 \text{ kg/cm}^2
\]

**Figure 1.** Types of channel stiffeners.

This figure shows the curves of the longitudinal strains of the rod compression. At the points corresponding to the critical value of the load (loss of web stability by wave formation), the equilibrium curves have a kink, since the longitudinal flexibility of the rod increases significantly as a result of wave formation. Nevertheless, since the web as a plate loses stability “in the small” (“steady bifurcation”), the post-critical equilibrium of the channel is stable, and it continues to bear an increasing load.

In the absence of any reinforcement, the web approximately works as a long articulated plate supported along the contour. For such an articulated plate, critical stress is very low

\[
\sigma_{cr} = \frac{4\pi^2 D}{\alpha b^2} = \frac{4\pi^2 E\delta^2}{12(1-\nu^2)b^2} = \frac{4 \cdot \pi^2 \cdot 2.1 \cdot 10^6 \cdot 0.15^2}{10.92 \cdot 1600} = 106.8 \text{ kg/cm}^2
\]
Figure 2. Equilibrium curves for stiffened C-channel beams.

The critical load on the compressed rod (as a bulging plate):

\[ P_{cr} = \sigma_{cr} A = 1281 \text{ kg} (A = 12 \text{ cm}^2). \]

Fixing the web with more stable flanges increased the critical load by 1.5 times (up to 1770 kg). Reinforcing the web with small longitudinal dents (4 cm wide, 1.5 mm deep) slightly increased the critical loads on the compressed channel under consideration. One such dent raised the critical load to ≈2000 kg. However, a significant strengthening of the channel was obtained for a model with longitudinal internal strips 2 cm high and 1.5 mm thick. The theoretical critical stress (as for a pinned plate) for a long strip-plate with a width of 14 cm (distance from edge to flange) has noticeably increased and is estimated at ≈871 kg / cm². A numerical calculation by the FEM showed that at a load of ≈4000 kg no signs of loss of web stability were observed (Fig. 2). However, it should be noted that the considered channel is a rather complex plate system in which loss of stability by wave formation is possible not only in the web but also in the flanges. Moreover, it may turn out that web reinforcement will result in flanges being the weakest fragments of the channel (as a folded system). These plates have (conditionally) only one long edge as articulated. The other longitudinal edge (with a small bend) is almost free. With a width of these flanges 16 cm, they can be the instigators of the loss of stability of the channel (under the conditions of the web reinforcement described above by stiffeners).

The equilibrium curve of a cold-drawn rod as a compressed double-supported beam is shown in Fig. 3. This curve is typical of a curve of a one-sided compressed long rectangular plate. The bifurcation load of wave formation in the web (loss of stability of the flat equilibrium shape of the compressed plate) was ≈17.3 kN (or 1730 kg at stresses of ≈144 kg / cm²). Significant bending deformations of the web, and indeed of the entire rectangular section, were noted (pt. 3) when reaching a supercritical load of ≈21.4 kN. The bearing capacity of the channel was preserved up to a load of ≈40 kN.
In order to strengthen the web as a plate element, two longitudinal ribs in the form of extruded grooves having a section in the form of a regular triangle with sides of 2 cm were modeled (Fig. 4). This side size corresponded to the size of one plate finite element with a uniform grid. The performed reinforcement of the web increased the critical load of buckling the web as a plate to $\approx 100.5$ kN (i.e., almost six times!). If we assume that the width of each of the three plate strips decreased by about 3 times, then the critical load (as is known, with longitudinal compression inversely proportional to the square of the plate width) should increase by 8-9 times. But that did not happen. The reason is that the channel structure is a composite prismatic fold [7, 8].
The loss of stability of the wave formation type is provoked by the "weakest" fold element [9]. While there was no web reinforcement, the role of the weakest fold element was played by this very wide web (40 cm wide with a length of 150 cm). However, as soon as the web was reinforced with two longitudinal grooves, its regiments became the "weakest" elements of the channel. They have a width of 16 cm, and the boundary conditions along one of the longitudinal sides (adjacent to the 4-centimeter "overhangs") are very close to the boundary conditions of the free edge. In fig. 4 (point 2 of the diagram), wave formation in the flanges in the initial post-critical equilibrium is clearly visible. Moreover, if there is a wave formation in the web (according to the law of continuity of deformations), then this wave formation is “forced” [10, 11] (the terminology of A. F. Smirnov). On the contrary, the “weakest” channel elements (flanges) lost stability under constrained deformations, since the wave formation of these elements was restrained until a certain point because of the contact with a stiffer (due to reinforcement) web [12].

With a further increase in load (point 3), the deformation of wave formation in the flanges significantly increased. However, deformations of the strip-plates forming the channel web remained barely noticeable. And only when the load of ≈126 kN was reached, the general deformation ("buckle" inside the profile) of the channel flanges with the simultaneous development of bending web deformations became noticeable. The described complex picture of the process of supercritical deformation of the rod became even more apparent when a load of 168 kN was reached.

3. Influence of geometric imperfections on critical load and postcritical behaviour

The influence of initial geometric imperfections in the channel web has been studied for the case when these imperfections were specified in the form of minor deviations of the nodes of the finite element grid (every fourth node) in the direction perpendicular to the plane of the channel element. The imperfection amplitudes were fractions of the web thickness (0.1; 0.25; 0.5 and 1.0). The deviation in each “perturbed node” was determined using a pseudo-random number generator.

In fig. 5b shows the displacements of the point K located on the channel web at the top of the half-wave with the loss of stability of the web. On the graph, figure a clearly shows a kink showing the beginning of wave formation in the web. In this case, the longitudinal stiffness of the channel becomes significantly less (P_c≈17 kN, point 2 on the graph corresponds to the moment of developed wave formation (Fig. 5d). Similar pseudorandom imperfections (in every fourth node) were specified in two flanges of the channel (Fig. 5a). The obtained curves of changes in the longitudinal stiffness of the channel are rather similar to the previous ones. The curves in Fig. 5a differ little among themselves. The critical fracture loads are almost the same (≈17 kN).
Figure 5. Equilibrium curves (a, b, c) and deformed model (d) for channel with pseudo-random imperfections.

If you set pseudo-random imperfections on the entire surface of the channel at the same time (Fig. 5c), then the graph of the change in the longitudinal stiffness of the channel practically repeats a similar graph for the case of imperfections on the channel web.

The influence of pseudo-random imperfections was also investigated on a channel model with a web reinforced with longitudinal triangular folds. Imperfections were made separately on the flanges (Fig. 6a) and on the web (Fig. 6b) of the channel. In the case of imperfections on the channel flanges, the difference between the lines of large and small amplitudes is insignificant (Fig. 6a). The loss of stability (kink in the diagram) occurred under compression ≈110 kN. The influence of pseudo-random imperfections in the web had some features (Fig. 6b). The graphs of the lateral displacement of point A (the middle of the upper edge of the flange) with the amplitudes of imperfections 0.1δ, 0.25δ with a loss of stability of the channel flanges received a “bend” towards each other (points 2 and 3 in the fig. 6). Such a result was obtained for the channel model without imperfections (Fig. 4). With imperfections of maximum amplitudes 0.5δ, 1δ, the flange deflection was observed outward (points 2 ’and 3’ in the fig. 6).
Figure 6. Equilibrium curves (a, b) and deformed model (c) for stiffened channel with pseudo-random imperfections.

4. Conclusion
For a thin-walled cold-drawn channel of the channel type, the setting of web-reinforcing longitudinal ribs (longitudinal extruded grooves of a triangular section or narrow long strips welded along the edge) increases the critical load of central compression by 6-8 times. With such reinforcement, the “weakest” element of the plate system (such as a channel) may no longer be a web, but a weaklier fixed channel flange. Initial imperfections in the form of pseudo-random deviations of web nodes and channel flanges weakly affect the critical buckling load.

References
[1] Astakhov I V 2006 Spatial stability of structural elements from cold-formed sections: dissertation for the degree of candidate of tech. Sciences: 05.23.01 Bely G I (St. Petersburg)
[2] Ayrumyan E L 2009 Recommendations for the calculation of steel structures from thin-walled bent beams StroyPROFIL vol 8
[3] Belyi G I and Astakhov I B 2006 Spatial stability of structural elements from cold-formed steel beams Installation and special works in construction vol 9
[4] Brudka Y and Lubinski M 1974 Lightweight steel structures ed. S S Karmilova (Moscow: Stroyizdat) p 342
[5] Pavlov A B, Ayrumyan E L, Kamynin S V and Kamenshchikov N I 2006 Prefabricated low-rise residential buildings using lightweight steel thin-walled structures Industrial and Civil Engineering 9

[6] Endzhievsky L V, Krylov I I and Kretinin A N 2010 Enclosing and supporting building structures from steel thin-walled beams (Krasnoyarsk: Siberian Federal University) p 282

[7] Ilyina A A 2004 Strength and stability of steel bending elements with regular and irregular chess web perforation: dissertation for the degree of candidate of tech. Sciences: 05.23.01 Iliina Anna Aleksandrovna (Nizhny Novgorod)

[8] Mitchin R B 2003 Local web stability and optimization of a steel perforated beam: thesis for the degree of candidate of tech. Sciences: 05.23.01 Mitchin Roman Borisovich (Lipetsk)

[9] Rybakov V A 2011 Fundamentals of structural mechanics of light steel thin-walled structures: a training manual (Publishing house of the Polytechnic University, St. Petersburg) p 207

[10] Sinelnikov A S 2015 Strength of an expanded profile in compression: a dissertation for the degree of candidate. tech. Sciences: 05.23.01 N I Vatin (St. Petersburg)

[11] Tusnin A R 2009 Numerical calculation of structures of thin-walled rods of an open profile (Moscow: ASV) p 143

[12] Crisan A, Ungureanu V and Dubina D Behavior of cold-formed steel perforated sections in compression. Part 1 — Experimental investigations Thin-Walled Structures vol 61 p 86-96