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Numerical Investigations of Notched C-Profile Compressed Members with Initial Imperfections

Численные исследования сжатых элементов из холодногнутого просечного С-профиля с учетом начальных несовершенств

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Key words: cold-formed notched profile, local buckling, thin-walled members, numerical simulation, bearing capacity, initial imperfections

Ключевые слова: просечной профиль, местная потеря устойчивости, тонкостенный стержень, численные исследования, несущая способность, начальные несовершенства

Abstract. This article contains the results of numerical investigation of compressed columns made of cold-formed notched C-profile in order to find their ultimate bearing capacity. Numerical investigations of compressed member were held in two stages: investigations of stability in elastic stage in order to define the prevalent form of buckling and the corresponding value of buckling force; investigations of member postcritical behavior in non-linear position with due consideration of physical and geometrical nonlinearity as well as initial imperfections in order to discover the factors influencing bearing capacity. In order to reach the goals of our research a required number of models were made, namely: 28 models of Solid section C-profile (SCP) and 28 models of Notched C-profile (NCP), totally 56 models with the length from 1 000 mm up to 4 000 mm, cross section height h 150 and 200 mm, thickness t 1.5 and 2.0 mm. Numerical investigations were held with the help of software package PLM Femap 10.1 Nastran. Compressed members of solid section C-profile are the most sensitive to initial imperfections, members of notched C-profile have big postcritical reserve.

Аннотация. Холодногнутый просечной С-профиль применяется в наружных стенах при строительстве быстровозводимых энергоэффективных зданий на основе стального холодногнутого тонкостенного оцинкованного профиля. Авторами были проведены численные исследования сжатых стоек из холодногнутого просечного С-профиля с целью определения их предельной несущей способности. Численные исследования были выполнены в два этапа: исследования устойчивости сжатых стоек в упругой стадии с целью определения преобладающей формы потери устойчивости и соответствующей величины критической силы; исследования закритической работы стоек в нелинейной постановке с учетом физической и геометрической нелинейности и с учетом начальных несовершенств в целях выявить факторы, влияющие на несущую способность. В рамках исследования было создано 28 моделей из сплошного С-профиля и 28 моделей из просечного С-профиля, в итоге было создано 56 моделей длиной l от 1000 мм до 4000 мм с шагом 500 мм, высотой сечения h 150 и 200 мм, толщиной t 1,5 и 2,0 мм. Численные исследования были проведены в программном комплексе PLM Femap 10.1 Nastran. По результатам были получены определенные зависимости и определена степень чувствительности стоек к начальным несовершенствам. Стойки из сплошного С-профиля более чувствительны к начальным несовершенствам. Стойки из просечного С-профиля обладают определенным закритическим резервом.

Introduction

Members made of notched C-profile are used in load-bearing and self supporting external wall panels in buildings based on steel and reinforced framing [1]. That is so because length way notches arranged in chequerwise manner in the web of cold-formed C-profile, Figure 1, increase the way heat current should overcome, decrease thermal conductivity and enable elimination of cold bridges in external walls [2].

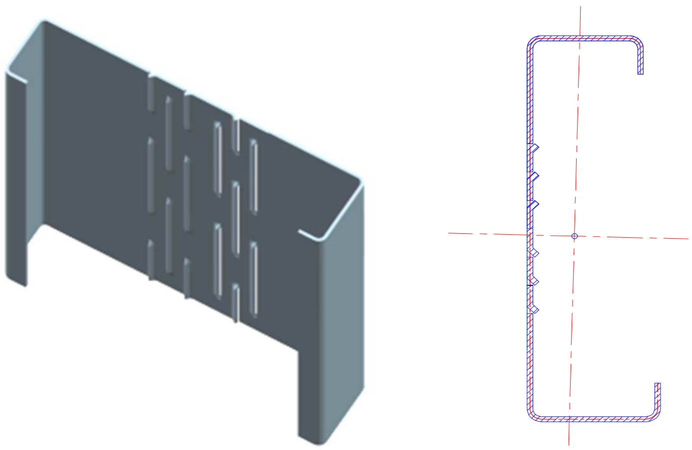

Figure 1. Steel cold-formed notched C-Profile

The thickness of cold-formed profiles doesn't exceed 3 mm, so the constructions made on their bases are called thin-walled which are calculated with the use of calculating theories of thin-walled bars.

Studies of thin-walled bars were carried out by Vlasov, Timoschenko, Winter, Karmann, Bleich and others. A major contribution to thin-walled bar studying was made by investigations of Russian scientists (our contemporaries) Tusnin, Ayrumyan, Belyi. Works by Astakhov, Katranov, Rybakov and others should be mentioned too [3-6]. Great number of experimental works is carried out at Peter the Great St. Petersburg Polytechnic University namely: Vatin, Sinelnikov, Garifullin, Trubina and others [7-13]. Among researches works of Schafer, Brune, Ungermann, Basaglia and others are the most important [14-19].

In spite of the great number of experimental works, compressed notched C-profile were not studied.

European and North-American Codes [20-21] made on the bases of broad experimental data show different kinds of thin-walled element behavior. But they do not have enough information on structures of notched C-profile. There is no systematization of thin-walled elements calculation in Russian specification documents. Official recommendations on cold-formed notched C-profile structure calculations do not exist.

So, investigation of compressed cold-formed notched C-profile member stress-strain behavior is timely for secure use of the members in construction.

Methods and Results

The authors have carried out numerical investigation of compressed columns made of cold-formed notched C-profile in order to find their ultimate bearing capacity. C-profile is an open no equilateral fully asymmetric cross-section, Figure 1, which has low torsion resistance.

There are some problems in studying of thin-walled constructions because of the thinness of wall nature as thin-walled members are influenced by plenty of factors: warping effect, sensitivity to torsion, inapplicability of Saint-Venant principle, etc. Thin-walled members are also very sensitive to initial imperfections. It is impossible to consider all the factors in one math model, so a number of calculation models and theories are used. That is why analytical dependences received with the help of theoretical methods are approximate and time-consuming. Experimental research is expensive.

Numerical investigations held with the help of modern software packages enable to extend boundaries of scientific research, decrease their time limits and get relations with high degree of reliability as well as carry out nonlinear analysis [22].

Numerical investigations of compressed member were held in two stages:

- investigations of stability in elastic stage in order to define the prevalent form of buckling and the corresponding value of buckling force;

- investigations of member postcritical behavior in nonlinear position with consideration of physical and geometrical nonlinearity as well as initial imperfections in order to discover the factors influencing bearing capacity.

In order to reach the goals of our research a required number of models were made, namely: 28 models of Solid section C-profile (SCP), and 28 models of Notched C-profile (NCP), Figure 2, totally 56 models with the length from 1 000 mm up to 4 000 mm with the pitch of 500 mm, cross section height h 150 and 200 mm, thickness t 1.5 and 2.0 mm, table 1, called «the profile type-h-t-l», e.g: NCP-150-2.0-2500. The notches configuration and dimensions are shown in Figure 3, the cross sectional geometry is shown in Figure 4.

Models of solid C-shaped profile are the basis for comparison study of work of notched C-shaped profile models. That way we can understand how notches made in profile wall influence stableness and bearing capacity of the member in whole.

а) б)

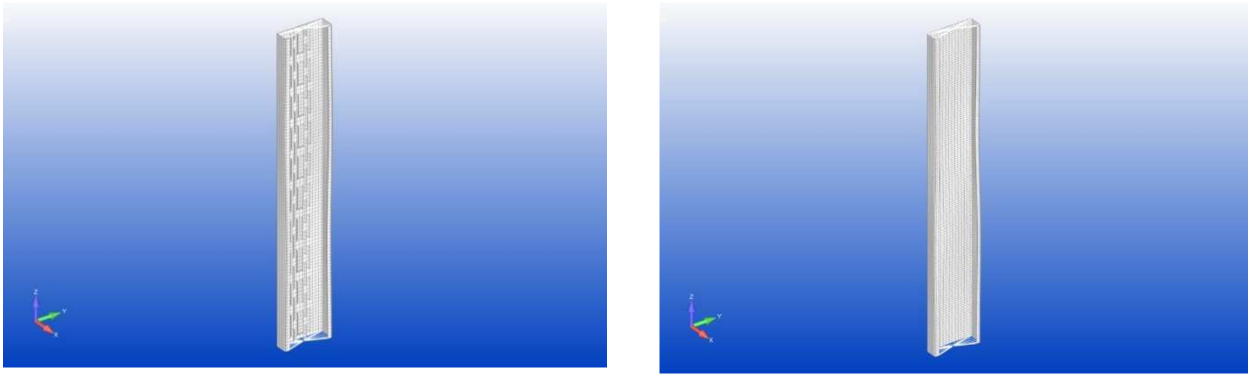

Figure 2. Numerical models: a) NCP-150-2.0-1000, b) SCP-150-2.0-1000

Table 1. Characteristics C-profile members

C-profile members		h, [mm]	t, [mm]	L, [mm]	y, [MPa]
SCP-150-2,0	NCP-150-2,0	150	2,0	1000-4000	240
SCP-150-1,5	NCP-150-1,5	150	1,5	1000-4000	240
SCP-200-2,0	NCP-200-2,0	200	2,0	1000-4000	240
SCP-200-1,5	NCP-200-1,5	200	1,5	1000-4000	240

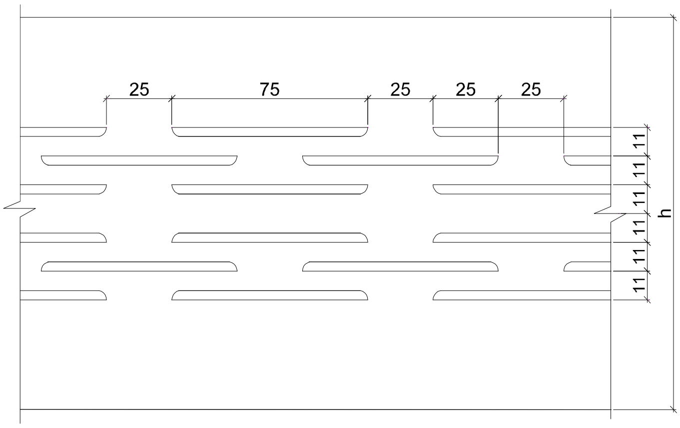

Figure 3. Notches configuration and dimensions

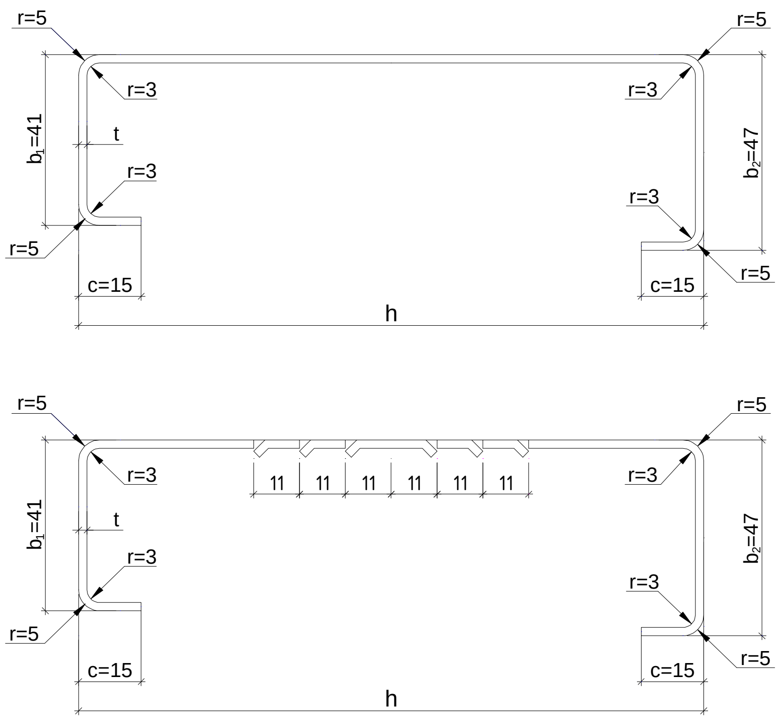

Figure 4. Cross-section of solid section C-profile (SCP) and notched section C-profile (NCP)

Numerical investigations were held with the help of software package PLM Femap 10.1 Nastran. To create calculation FE model triangle and quadrangle shell-type finite elements of Nastran software package called 'plate' which enable to carry out nonlinear analysis aimed to studying postcritical behavior of a member and finding out bearing capacity reserves.

A key requirement when creating models is to get efficient models most closely resembling real solid and notched C-profile members. For this, models made originally in graphical environment were imported to Nastran. Notches were also made in graphical environment. Blending of flange plates and profile webs were manually made in Nastran with the help of finite element mesh condensation in zones of profile bends and close to them parts.

Discrete FE model of the whole member was studied with step-type loading and Newton-Raphson iteration process. Material models – steel, modulus of elasticity E = 2,1·105 МПа, Poisson ratio v = 0,3.

At the first stage of numerical investigations linear analyses of stableness were made in Nastran 'buckling' mode. As a result, the first 5 forms of buckling were received and the first prevail form of buckling for every member was found as well as corresponding degree of buckling load. The results of the first stage are represented in graphs, Figure 5. In Figure 6 examples of numerical models got are represented in the first buckling mode.

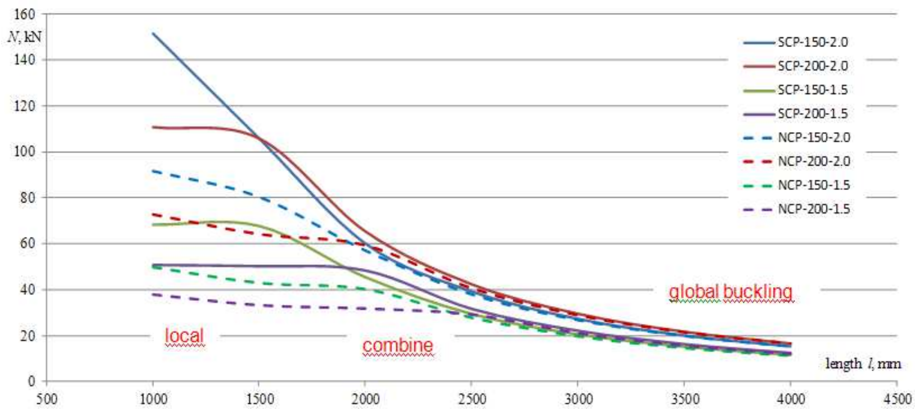

Figure 5. Elastic stage. Buckling load intensity, kN, depending on the member length

There are 3 forms of buckling (global buckling, local buckling, distortional buckling) and a number of combined buckling forms. According to this stage of investigation we can separate out 3 areas: 1 - 'short length' members up to 2 m, for which local buckling is prevalent; 2 - 'long' members with the length more than 2.5 m which are characterized by global buckling; 3 - 'medium length' members having length from 2 m to 2.5 m which have combined buckling.

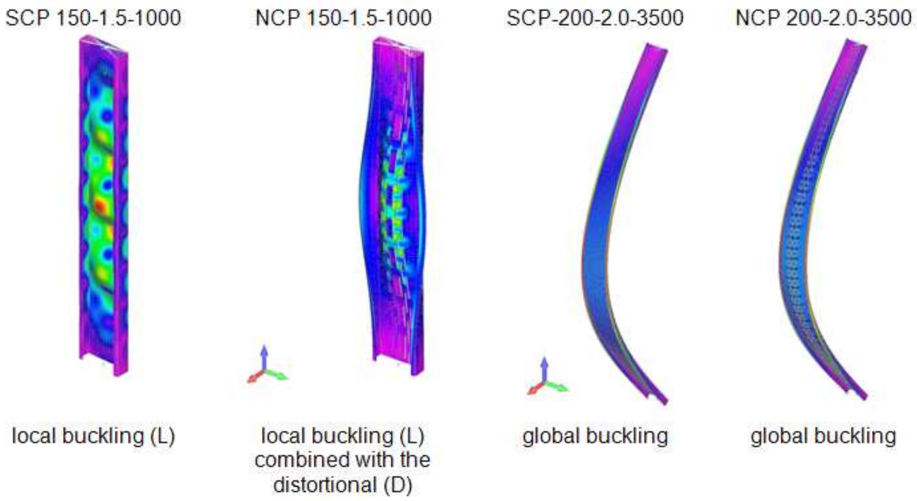

Figure 6. Numerical models are in the first buckling mode

According to Figure 5 we can also see the buckling load in elastic stage of notched C-profiles members is lower than that of usual ones, the relation is shown in the table 2 below.

Table 2. Comparison study of buckling load intensity, N, kN for C-profile members

Length [mm]	SCP-150-2,0	NCP-150-2,0	%	SCP-150-1,5	NCP-150-1,5	%	SCP-200-2,0	NCP-200-2,0	%	SCP-200-1,5	NCP-200-1,5	%
1000	151.43	91.74	39.4	68.33	49.72	27.2	110.6	72.65	34.3	50.56	38.03	24.8
1500	105.8	80.4	24.0	67.73	42.86	36.7	105.7	64.06	39.4	50.04	33.38	33.3
2000	60.1	57.0	5.16	45.4	40.17	11.5	65.32	59.21	9.35	48.18	31.91	33.8
2500	39.3	37.8	3.8	29.4	27.78	5.51	42.4	40.45	4.6	31.58	29.35	7.06
3000	27.4	26.6	2.9	20.5	19.72	3.8	29.6	28.73	2.94	22.12	21.20	4.16
3500	20.17	19.68	2.43	15.1	14.64	3.05	21.8	21.33	2.15	16.32	15.83	3.0
4000	15.46	15.13	2.13	11.58	11.27	2.67	16.7	16.42	1.67	12.52	12.23	2.3

According to the results of elastic analysis we can say notches in the profile web influence buckling resistance and buckling load intensity, especially, this has an impact on local buckling resistance of short compressed members.

In linear static analysis the structure is introduced in state of stable equilibrium [23]. Computation in Nastran 'buckling' mode means computation of buckling in Euler's sense. With some certainty it can be said the figures got in elastic analysis of buckling load intensity are approximate and serve only for differentiation of the range of members and preliminary analysis of prevailing form of buckling.

To receive more rigorous view of compressed member behavior at all stages including the stage of destruction numerical investigation of postcritical work of members in «Nonlinear Static» Nastran mode were carried out with the use of nonlinear structural mechanics on the basis of data received at the first stage. Behavior of thin-walled elements is influenced by a great number of factors which can hardly be taken into consideration with the help of elastic analysis methods [24, 25]. Terms 'buckling' and 'loss of bearing capacity' are interrelated but not identical. Buckling is often just a transition from one equilibrium condition to another. Critical load causes buckling of a compressed member but some profile elements can reach their yield points much earlier. The factor of bearing capacity exhaustion is existence of plastic yields in a compressed member cross-section, that is the profile or some its parts reach the yield point.

Thin-walled structures have some postcritical work reserve and after local buckling in the compressed cross-section area the structure continues to bear the load. But postcritical work reserve of thin-walled structures can be lost because of the profile initial imperfections received during its production. Initial imperfections are manufacturing errors, which values do not exceed maximum values according to the standards and depend on accuracy class and structure design size.

Cold-formed profile is made during stripe shaping process with the help of profile bending machines. When profiled, the cross-section shape demanded is received as a result of cold metal plastic bending and longitudinal strains which do not form during rolling appear [26]. So, some profile initial imperfections are the result of the cold-forming process. Side camber and profile tubing as well as edge waviness are often met.

Initial imperfections influence the structure buckling resistance changing not only buckling load value but the form of buckling [27]. However, influence of imperfections is different and depends on the form of buckling. It should be mentioned that imperfections can contribute to better.

Methodology of numerical investigation of compressed C-profile members in non-linear position was developed by the authors for the second stage. It takes into account physical and geometrical nonlinearity and initial imperfections. Quantity of initial imperfections is taking according to the accuracy class and basic size of the structure. Peak value of maximum initial crookedness of the structure is not more than the admissible deviation for the fabrication of structures. Otherwise, if the defects exceed the maximum figures given in the code of practice, the structure is considered a defective article and its usage in a building erection is forbidden.

The methodology is:

For nonlinear analysis strained scheme of the compressed model is taken, the strained scheme view is taken on the basis of the first stage of the numerical investigation and corresponds the first form of buckling of every member;

The deformed finite element model with geometric deflections is scaled according to the maximum amplitude of permissible variations;

Nonlinear analysis of the finite element model received is implemented, the curve stress-strain for the used material model - Prandtl diagram;

End value of critical buckling load of bearing capacity exhaustion is defined.

Overall results for critical buckling of every model depending on the load step are shown on Figure 7. Stages of the model behavior within nonlinear analysis are demonstrated on Figures 8-9.

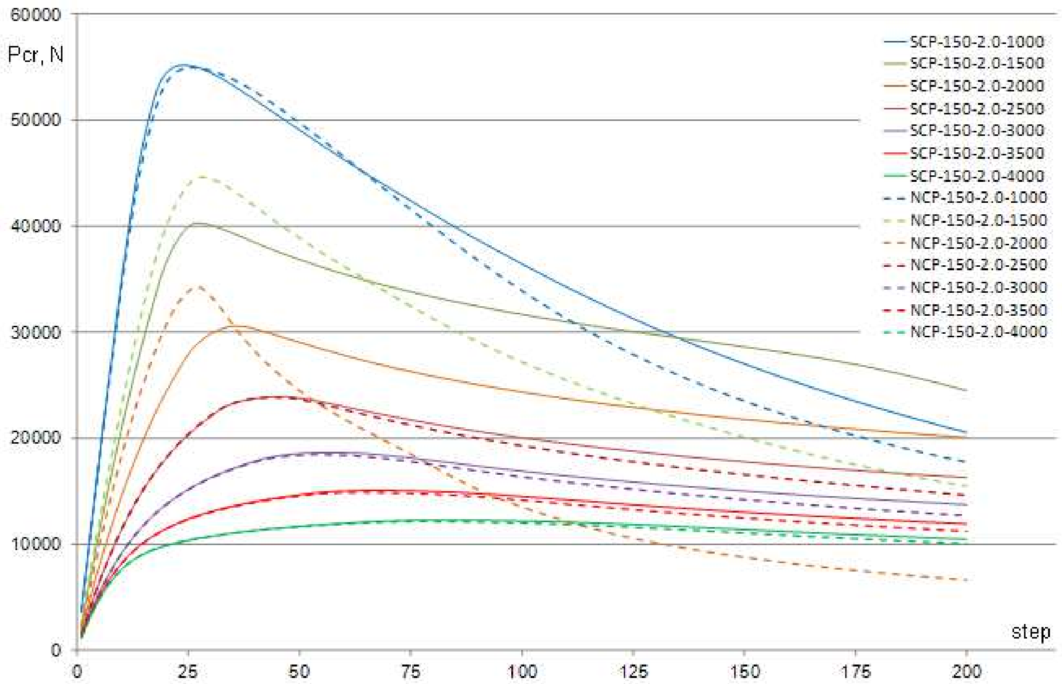

Figure 7. Non-linear stage. Buckling load dependence on load step

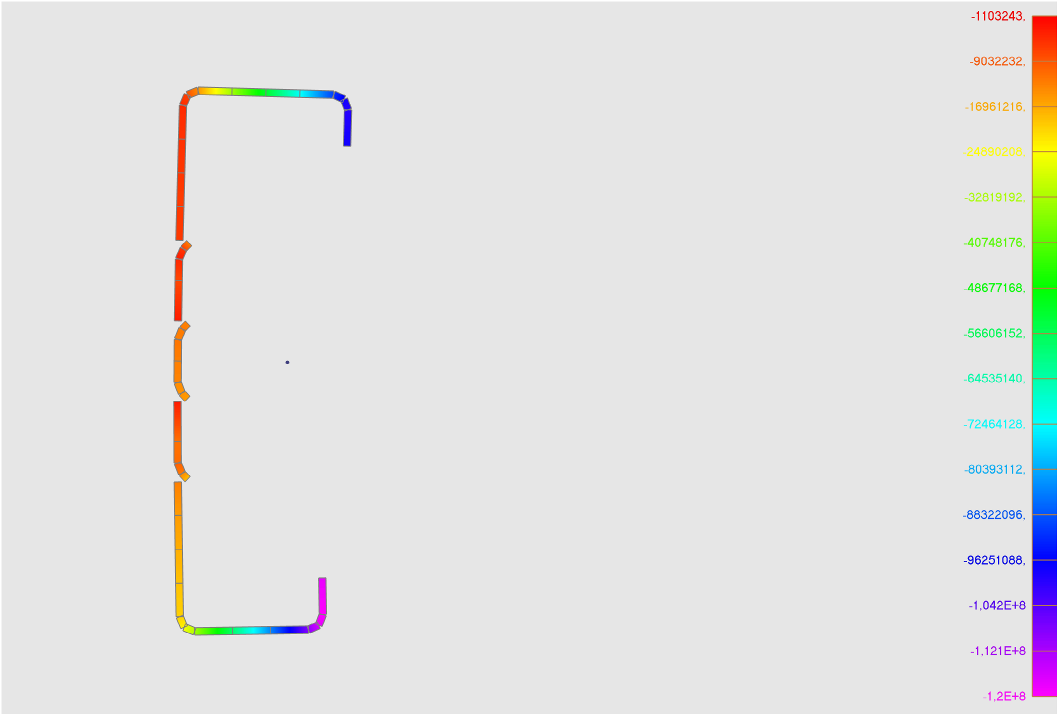

Figure 8. Elastic stage, Pcr = 16,73 kN, maximum stresses occur in the lips of flanges, 98,8-119 MPa

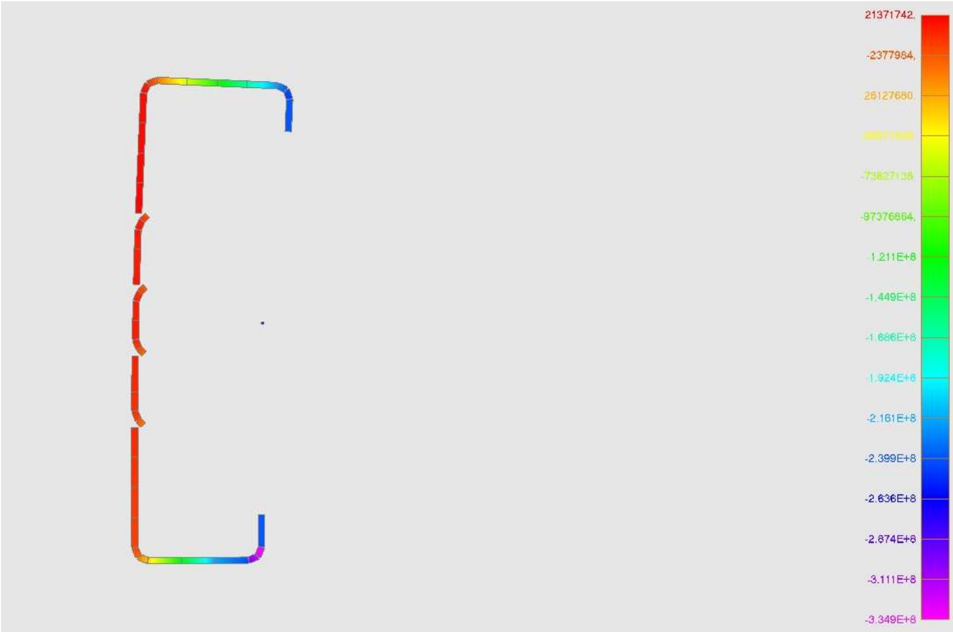

Figure 9. Nonlinear stage, parts of the profile reach the yield point

The critical force of buckling of nonlinear analysis is smaller than that got as the result of elastic analysis. The main factor influencing that is the initial imperfections. Notches do not greatly influence buckling resistance with the increase of a member length and even expand bearable critical buckling load for short members.

Numerical analysis showed the cold-formed notched C-profile members undergo complex stress-strain state which depends on many factors. To take into account all the facts is possible with the use of coefficients only. On the basis of the numerical investigations the authors of the work suggest coefficient of the conditions of work γp which is put into the formula when analytical determination of compressed cold-formed notched C-profile elements and takes into account special aspects of their work under stress.

Results of the second stage of thesis numerical investigations were compared with those of elastic analysis and results got with the use of other methods [20, 28-35].

System sensitivity to initial imperfections is estimated with the help of η coefficient depending on the form of buckling, Figure 10. Compressed members of solid section C-profile are the most sensitive to initial imperfections, members of notched C-profile have big postcritical reserve.

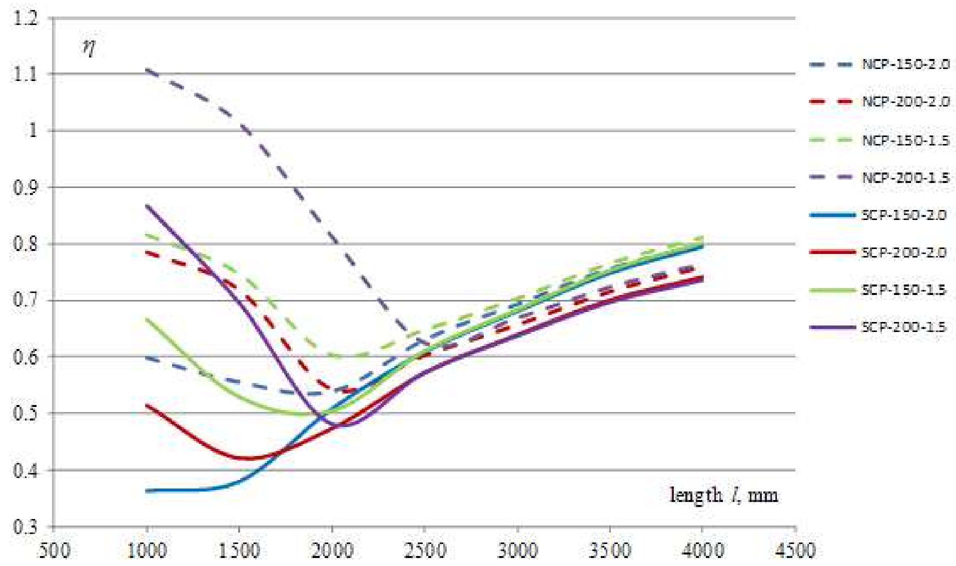

Figure 10. System sensitivity to initial imperfections η = Pcr/P0 - ratio of critical load of imperfect member to buckling load of ideal member.

Conclusions

1. Numerical models with finite element grid were developed. They make it possible to perform calculations for defining bearing capacity and stress-strain state of compressed cold-formed notched C-profile elements using finite elements method. The advantage of numerical models is the possibility of their multiple uses as distinct from experimental models.

For the development of working numerical model of a thin-walled element full identification of the numerical model with the natural element is necessary. It is created with the help of software packages like AutoCAD.

2. It is confirmed that shell finite elements should be used for a thin-walled element simulation.

3. On the basis of numerical investigations aggregate picture of stress-strain state of compressed members made of cold-formed notched C-profile has been got.

4. Numerical experiment results showed the existence of different zones of strain distribution across the profile cross-section which is the evidence of the element eccentrical compression and proves the need to use effective cross-section characteristics when analytical calculation of compressed members is done.

5. Numerical investigations have proved a postcritical reserve for cold-formed notched C-profile elements.

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