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## Computational Analysis of Cold-Formed Steel Columns with Initial Imperfections

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### Abstract

Cold-formed steel (CFS) structures experience very complicated buckling and post-buckling performance. The presence of any kind of uncertainties complicates the calculation of such structures. Thin-walled CFS members are known to be particularly vulnerable to the influence of initial geometric imperfections. These imperfections may be the outcome of the manufacturing process, shipping and storage or the construction process. The article provides the results of nonlinear buckling analyses of CFS C-shaped compressed columns and evaluates the influence of imperfections on the load-bearing capacity of the tested members.

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### 1. Introduction

Thin-walled steel sections are widely used in various fields of industrial and civil engineering, bridges, storage racks, car bodies, railway coaches, transmission towers and poles, various types of equipment [1].

In an ever-growing interest in such structures more advanced and sophisticated calculation methods are being developed. The article [2] provides a short overview of the buckling problem of cold-formed steel beams. Sinelnikov [3–5] and Nazmeeva [6,7] investigated buckling behavior of compressed cold-formed columns with thermal slots on web. Trubina [8–12] analyzed the problem of local and global buckling of thin-walled cold-formed members under bending. Rybakov [13,14] presented four types of finite elements to analyze cold-formed members

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with various boundary conditions on the ends. Belyy [15] introduced a new method for approximate estimation of steel structures service life in buildings. Tusnin [16,17] introduced thin-walled finite elements to analyze spatial cold-formed structures with open cross sections. Tusnina [18–20] presented a finite element analysis of cold-formed z-purlins supported by sandwich panels. Prokic [21,22] analyzed the behavior of thin-walled open section I-beams in torsion and bending. Björk [23–25] investigated the influence of residual stresses on the fatigue strength of cold-formed rectangular hollow sections. Ananina [26] investigated the influence of corrosion on behavior of cold-formed structures.

## 2. Problem of initial imperfections

Thin-walled cold-formed structures are known to require thorough evaluation of their structural stability. However, the critical load can rarely be achieved due to the fact that cold-formed structures are particularly sensitive to geometrical imperfections. These imperfections may be the outcome of the manufacturing process, shipping and storage, or the construction process. It is well acknowledged that the initial geometric imperfections play a significant role on nonlinear behavior of CFS members. They require accurate evaluation in order to predict buckling behavior of cold-formed structures and calculate failure loads.

One of the most common and available approaches for assessing the influence of geometric imperfections on behavior of cold-formed members is the modified Riks method [27–32]. It yields relatively accurate results without large computational costs.

Al Ali [33–36] modeled the initial imperfections of thin-walled cold-formed compressed steel members with closed cross-sections in MATLAB and conducted nonlinear buckling analysis to determine the limit loads.

Ungermann [37–39] dealt with the consistency of rules for imperfections and formulas for member resistance in Eurocode 3.

Zeinoddini [40,41] introduced spectral representation approaches for simulation of geometric imperfections in cold-formed steel members.

Currently one of the most powerful approaches for assessing the influence of geometric imperfections is the usage of general purpose software [42]. It provides an integration between deterministic solvers (i.e. finite element solvers), efficient algorithms for uncertainty management and high performance computing. General purpose software might be used not only for concerning geometric imperfections but for a wide variety of other uncertainties.

Pastor et al. [43] introduced a more sophisticated technique to model the behaviour of cold-formed members. The methodology simulates the manufacturing process of a thin-walled open section in order to obtain the residual stress and strain distribution over the cross-section, and introduces them into the finite element model as an initial state for the subsequent nonlinear analyses.

Different methods for imperfection sensitivity of thin-walled shell structures are also presented in [44–49, 54].

## 3. Simulation approach

Generally, analysis techniques for determining buckling loads of tested members include two main steps (Fig. 1) [50]:

- Linear eigenvalue buckling.
- Nonlinear buckling analysis.

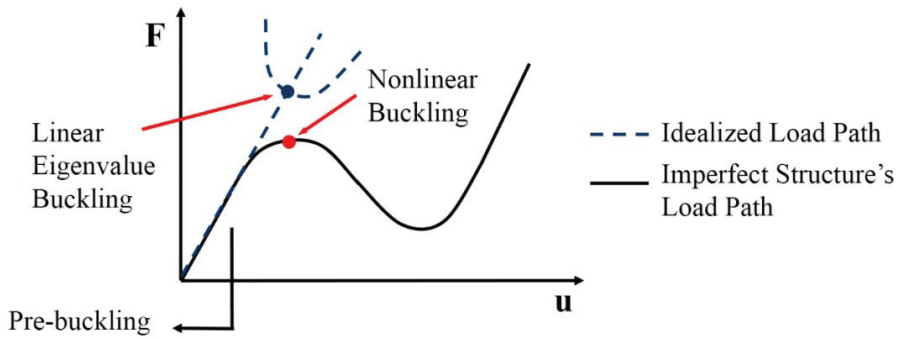


Fig. 1. Steps of the analysis in correlation with a typical load-displacement curve.

Linear eigenvalue buckling analysis predicts the theoretical buckling strength of an ideal linear elastic structure. It generally yields non-conservative results but provides relatively fast analysis. In addition, the buckled mode shapes can be used as an initial geometric imperfection for a nonlinear buckling analysis in order to provide more realistic results.

Nonlinear buckling analysis employs a nonlinear static analysis with gradually increasing loads to seek the load level at which a structure becomes unstable. At the onset of instability (buckling) a structure has a large change in displacement under essentially no change in the load (beyond a small load perturbation). In a nonlinear buckling analysis, the goal is to find the first limit point (the maximum load before the solution becomes unstable). Using a nonlinear buckling analysis makes it possible to include such features as initial imperfections, plastic behavior, contact, large-deformation response, and other nonlinear behavior. Nonlinear buckling is more accurate than eigenvalue buckling and is therefore recommended for the design or evaluation of structures.

#### 4. Description of simulation process

In this article the modified Riks analysis which is realized in ABAQUS was employed for nonlinear buckling analysis in order to determine buckling loads of compressed C-sectioned cold-formed steel (CFS) members. For validation of the results each member was calculated manually according to the Russian recommendations (hereinafter – the Rules) [51].

The C-sections from the product mix of «BaltProfile» Limited Company were used for simulation analyses. The dimensional characteristics of the cross-sections are given in the Table 1 (where  $t$  is steel thickness).

Table 1. Dimensional characteristics of the cross-sections.

Profile	H [mm]	B [mm]	c [mm]	t [mm]	Sketch
PS-150-t	150				
PS-175-t	175				
PS-200-t	200	50	15	1.2; 1.5; 2.0	
PS-250-t	250				

The mesh of the models was created using S4R finite elements from ABAQUS element library. These are shell elements with 4 nodes and reduced numerical integration and they are suitable for Riks analysis.

All the 3.0 m long models had encastre (totally fixed) boundary conditions at the ends and were loaded by compressive concentrated forces.

At the first step, a linear perturbation analysis of the model has been performed in order to obtain a buckling shape and eigenvalues of “perfect” columns. The buckling shapes of the models were associated with the geometric imperfections to create the models for the nonlinear analysis. The magnitude of imperfections was taken as a function of plate thickness (0.1 of thickness) [52,53].

Secondarily, nonlinear analysis was performed on the models from first step. Nonlinear analysis was conducted separately for members with and without initial imperfections.

Results of the research

The investigations are very extensive, therefore the results for only 2.0 mm steel sections are provided. The members with other steel thickness found the similar patterns.

Final deformation patterns together with equivalent elastic strain for PS-150-2.0 and PS-200-2.0 are shown in Fig. 2,3.

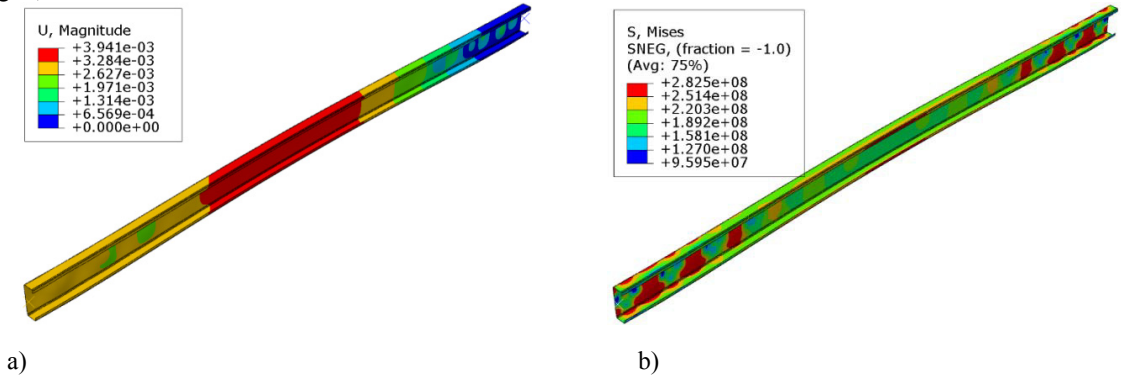


Fig. 2. Final deformation (a) and equivalent elastic strain (b), member PS-150-2.0.

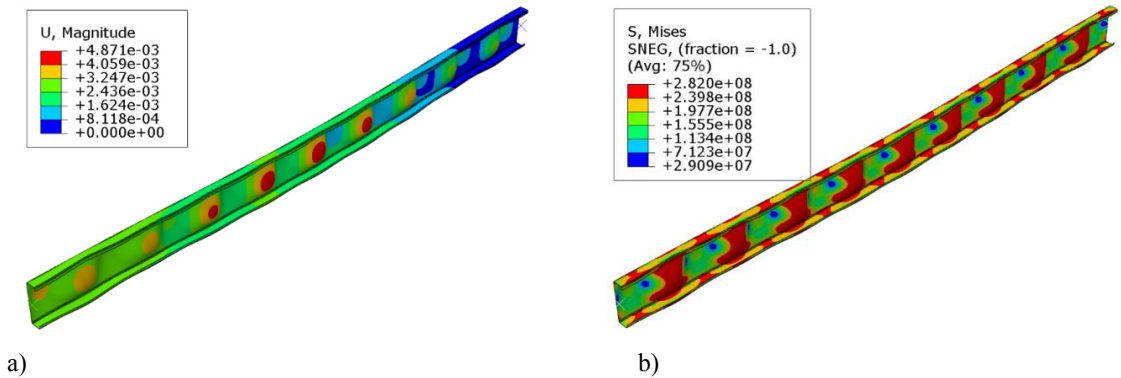


Fig. 3. Final deformation (a) and equivalent elastic strain (b), member PS-200-2.0.

One can see that the members with low web height (PS-150-t) experienced mainly global (flexural) buckling whereas the members with larger web height (PS-175-t and PS-200-t) failed with local buckling mode or combination of global-local buckling modes. The largest web height members (PS-250-t) experienced mainly distortional buckling (Fig. 4).

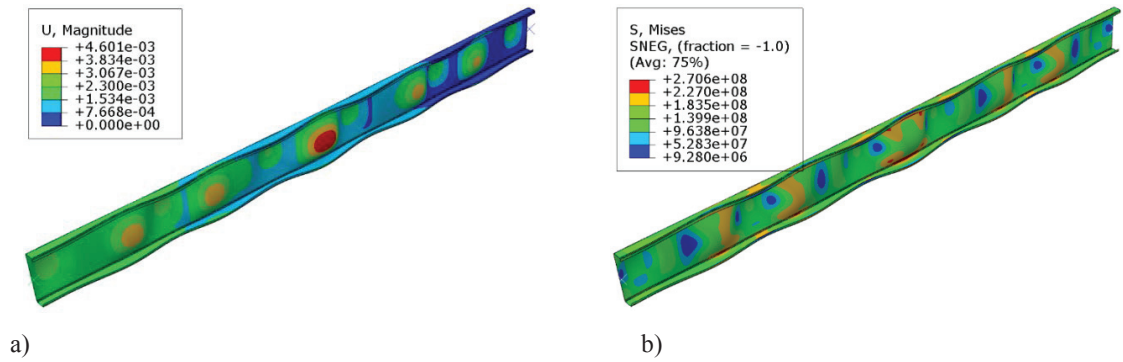


Fig. 4. Final deformation (a) and equivalent elastic strain (b), member PS-250-2.0.

Fig. 5 demonstrates the correlation between buckling forces for compressed members with and without initial imperfections and the results of manual calculations according to the Rules.

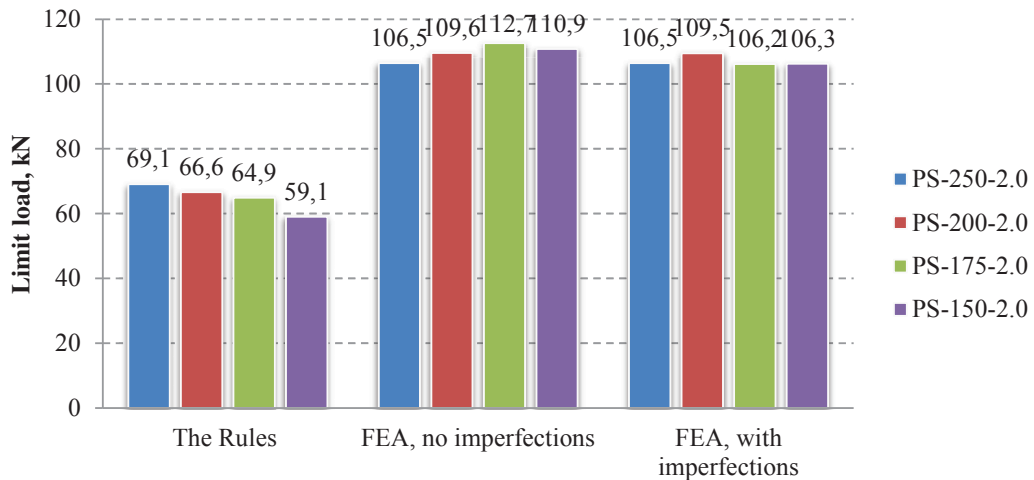


Fig. 5. Comparison of individual limit loads for members tested.

The results show that geometrical imperfections affected mainly the members with low web height (PS-150-t and PS-175-t) reducing their critical buckling load by about 5-7%. At the same time, implementing the initial imperfections to the sections with large web height (PS-200-t and PS-250-t) did not significantly change the value of their buckling loads.

### 5. Conclusions

The elastic buckling analyses on CFS C-section columns with initial imperfections were analyzed by FE models. Initial imperfections have a significant influence on the load-bearing capacity of cold-formed members. According to the results, for some members the critical force decreased by about 5-7%. For more accurate and detailed study a more extensive and thorough research is needed, necessarily confirmed by experimental data.

The results of manual calculations according to Rules are considerably lower than the results of simulation tests (by about 35-45%). This might indicate that the values of reduced cross-sectional areas given in the Rules are strongly underestimated. Nevertheless buckling loads obtained by this way provide a guaranteed reliable

performance of such members that makes the Rules fully applicable for calculation of cold-formed members with imperfect geometry.

Overall, the Riks analysis that is realized in ABAQUS provides an effective means for assessing the influence of initial imperfections on the behavior of cold-formed structures. This approach might be quite effective for analyzing a great deal of other uncertainties that affect cold-formed structures, e.g. material properties uncertainties, residual stresses, loading uncertainties and others.

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