INFLUENCE OF BOUNDARY CONDITION ON CHANNEL SECTION COLUMN BEHAVIOUR

F. KAŹMIERCZYK , T. KUBIAK

Abstract. The FEM-based, numerical study of the influence of the boundary conditions on distorsional lateral buckling phenomena during bending of cold formed steel bars with different channel sections have been performed. Beams with lip channel cross-section, channel cross-section and top-hat cross-section had been analysed. Six different boundary conditions were examined for each cross-section to check their influence on buckling load with corresponding buckling mode and describe the thin-walled beam behaviour. The proposed model of boundary conditions has been assumed the same as in other papers, where the obtained results have been compared with those obtained based on other analytical-numerical methods or within experimental tests.

Key words: torsional lateral buckling, boundary condition, pure bending, cold formed steel sections, Finite Element Method analysis.

1. INTRODUCTION AND LITERATURE RESEARCH

Cold formed steel beams are widely used in many different branches of industry. Such beams undergo bending phenomena, in which the compressed part of the beam may be subjected to torsional lateral buckling. In such situation deflection of the beam cross-section looks like in case of torsion – the lateral to load deflection appears.

Due to the fact that problem is well known from many years, the latest papers are devoted to development of numerical or analytical-numerical method sometimes validated by the results of experimental tests. Mentioned methods allow to predict the behaviour and failure of open section beam subjected to bending, where different types of buckling mode and their interaction including distortional lateral mode have been considered. Only the few of them are mentioned below.

Kolakowski and Jankowski [1] presented the influence of the distortional-lateral buckling mode on the interactive buckling of thin-walled beams with channels cross-section. The problem has been solved using semi analytical-numerical method based on Koiter asymptotic theory described e.g. in [2] or [3].

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Niu, Rasmusen and Fan [4,5] paid the special attention to the distortional-global interaction buckling, observed in results of performed experimental investigations and the numerical analysis. They performed experimental tests and numerical calculation in considered channel section beams made of steel with elastic-plastic model of material.

Ambares, Camotim and Silvestre [6] decided to employ a code based on a Generalised Beam Theory (GBT) formulation to achieve the sought decomposition of elastic buckling modes into combinations of structurally meaningful deformation modes. The Authors consider different open section beams subjected to bending. The results of the analytical-numerical calculation have been validated by results obtained in FEM. A few years earlier Adany and Shafer [7] have employed the developed finite strip method to mode decomposition of single-branched open cross-section members. Decomposition of these numerous buckling modes into the three buckling types (i.e. global, distorsional and local) allow to create the visualisation of the mode shapes and describe the load process until failure.

As far as authors of this paper can find in world wise literature, there are lack of papers showing the influence of the way of modelling the boundary conditions on buckling load and buckling mode. In very wide range of papers devoted to considered issue only one paper written by Martins et al. [8] have been found, in which authors consider different way of modelling the boundary condition for beam subjected to pure bending.

Summing up all the above, the Authors of this paper decided to present the FEM-based numerical study on the influence of the boundary conditions on the critical buckling load of cold formed steel bars of three different cross-sections. Six different boundary conditions for beams subjected to pure bending have been taken into consideration. Most of boundary conditions employed in presented paper are similar or even the same as presented in [9,10,11]. In above mentioned papers the boundary conditions modelled in FEM were validated by results (e.g. buckling load with corresponding buckling modes, postbuckling behaviour and failure load) obtained in experimental tests or analytical-numerical method based on Koiter asymptotic theory [2].

2. NUMERICAL MODEL DESCRIPTION

Numerical analysis was done using ANSYS APDL software. The beams subjected to pure bending are considered. Three cross-sections (lip channel section, C section, top-hat section) were examined with six different way of modelling boundary conditions and load introducing. The assumed models of load and beam support can be divided similarly as in [9] into two following groups:

- The boundary conditions and load introduced to ending cross-section of tested beam similar to those proposed by Martins et al. [8] and denoted the same as in mentioned paper by SCA, SCB and described in subsection 2.1.

- Examined beam subjected to pure bending the same as in case of four-point bending test, where the load and support have been introduced using grips stiffer then tested specimen (see subsections 2.2).

In all cases beam was modelled using four-node shell elements with six degrees of freedom at each node (Shell 181, where the first shear deformation theory was introduced). All parts of the beams corresponding to tested specimen were assumed to be made out of sheet metal of thickness of one millimetre with following properties: $E = 2.1 \cdot 10^5$ MPa, $\nu = 0.3$. Linear buckling analysis was performed to determine buckling modes with corresponding buckling loads and analyse how they depend on the way of modelling the boundary conditions.

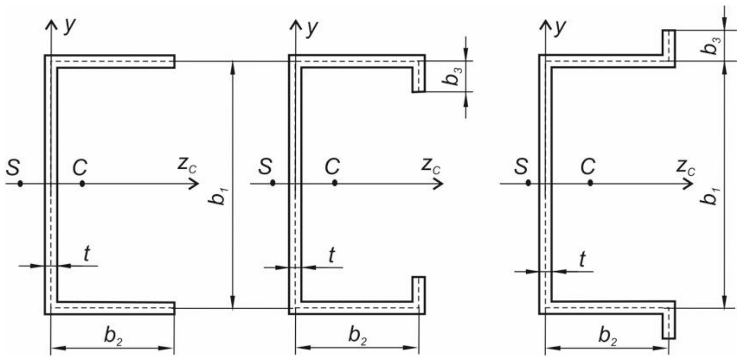


Fig. 1 – Dimensions of the cross-sections.

Table 1

Dimension and cross-section parameters.

section	Shear centre z_S [mm]	Centroid z_C [mm]	Cross-section area A [mm^2]	Second moment of inertia I_{zc} [mm^4]
C	–15.0	10.0	160	170693
lipped channel	–19.5	13.3	180	200139
top-hat	–18.0	13.3	180	211340

The shape of considered beams cross-sections are shown in Figure 1. For all examined beams the length is equal to $L = 275$ mm, and the cross-section dimension as follow:

- wall thickness t = 1mm;
- width of the web b_1 = 80 mm;
- width of the flange b_2 = 40 mm;

- width of the stiffener b_3 = 10 mm.

The rest of necessary parameters describing cross-section are presented in Table 1.

2.1. SCB and SCA boundary condition types

The idea of the way of introducing load and modelling of the boundary conditions in case of beam subjected to pure bending comes from one of Author's earlier paper [9]. The similar way of introducing the load was found in the scientific papers [8], and they are considered and called accordingly to this paper. However, it is not the same case as it is described in [8], i.e. in case of SCB, instead of applying the two oppose bending moments, in the middle of the rigid plates attached from both ends of the beam, the four forces were applied to the corners of each plate to imitate the bending moment. The boundary conditions denoted in [8] as SCA in this paper were unchanged. The assumed boundary conditions for beam with exemplary cross-section are presented in Figure 2.

a) b)

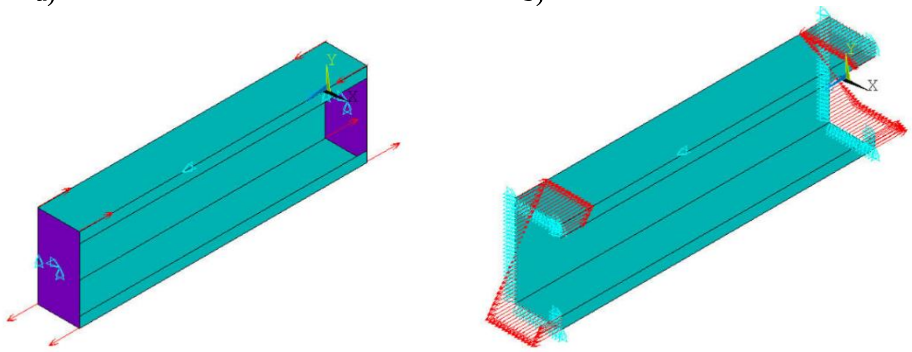


Fig. 2 – Numerical model of lip channel section for SCB (a) and SCA (b).

The length of numerical model corresponds to the length of considered beam.

In case denoted as SCB (Fig. 2a) the rigid plate (i.e. thickness eight times thicker than the thickness of the considered beam $t = 8$ mm and 10^3 times higher Young modulus $E = 2.1 \cdot 10^8$ MPa) was modelled to be sure that all the points of ending cross-sections are in plane before and after load. The load and boundary conditions have been applied to those stiff plates. The boundary conditions were applied to: the centroid of ending cross-section (zero displacement in lateral to beam of axis direction), the point of ending cross-section lying on the neutral axis (vertical displacement equal to zero) and to point lying in the mid-width of the web in the mid-length of the beam (displacement in longitudinal displacement equal to zero).

In case of boundary conditions and load denoted as SCA (see Fig. 2b) the displacement equal to zero in normal direction to the beam wall was assumed at all nodes lying on the ending cross-section. The displacement in longitudinal direction has been set the same as in SCB case (in point lying in mid-length of the beam and mid-width of the web). The load in form of forces distributed the same as cross-section stress distribution in case of pure bending in elastic range have been applied to all nodes lying in ending cross-sections.

2.2. Four point bending with grips

The well-known way to introduce the pure bending is scheme of load called four-point bending test (4PB), where the middle part of the beam is subjected to pure bending. Due to this only the middle part of the beam is examined. The scheme of four-point bending test with overall dimension is presented in Figure 3.

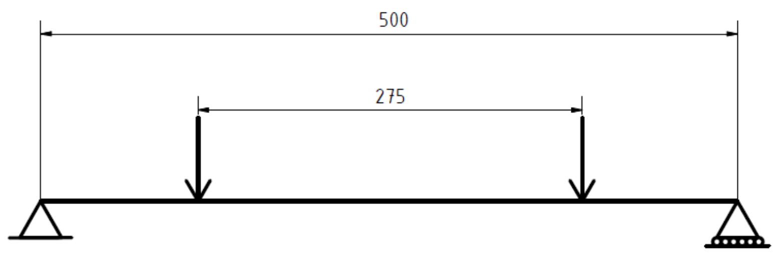


Fig. 3 – Scheme of the beam.

To ensure that in numerical models' stress concentration close to support or point where the load is applied did not appear, the stiffer (rigid) parts of the beam are employed. This rigid part further called as a grip has two following possible cross-sections:

- grip with open cross-section (further denoted as OP) – the cross-section shape of the grip is exactly the same as a beam under consideration;
- grip with close (rectangular) cross-section (further denoted as CL).

Additionally, in cross sections where the load and support are introduced, the diaphragm has been added. The thicknesses of all walls of the grips and diaphragms (purple colour in Fig. 4) are $t = 8$ mm. To ensure the rigidity of grips in numerical model the Young modulus for grip was set with 10^3 times higher Young modulus as for steel i.e. $E = 2.1 \cdot 10^8$ MPa.

It should also be mentioned that it is well-known that in case of open section grip and load applied in centroid, the part of the beam modelling the grip is subjected to torsion due to shear stress in all cross-section between support and load. Taking it into account the other solution has also been checked i.e. applying the load in shear centre.

Exemplary models of load and boundary conditions applied to considered beams subjected to pure bending using two types of grips (open section and close cross-section) and two ways of applying load are presented in Figs. 4 and 5.

Two cases of load applied were considered, one with the force applied in the "centroid" and second where the force was acting in the "shear centre". Places of force appliance were marked by quotations marks due to the fact that they were acting on the lines in which those points lay, not in particular points. In the case of centroid force appliance, additional two coupling degree of freedom were added. On the upper flange, on the lines on which the forces were applied, displacement in vertical direction was assumed constant on all nodes.

a) b)

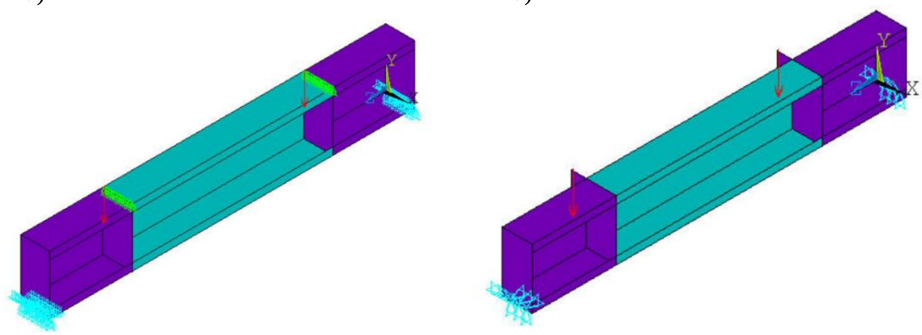


Fig. 4 – FEM models of four-point bending test with open-section grip and load applied in centroid (a) and in shear centre (b).

a) b)

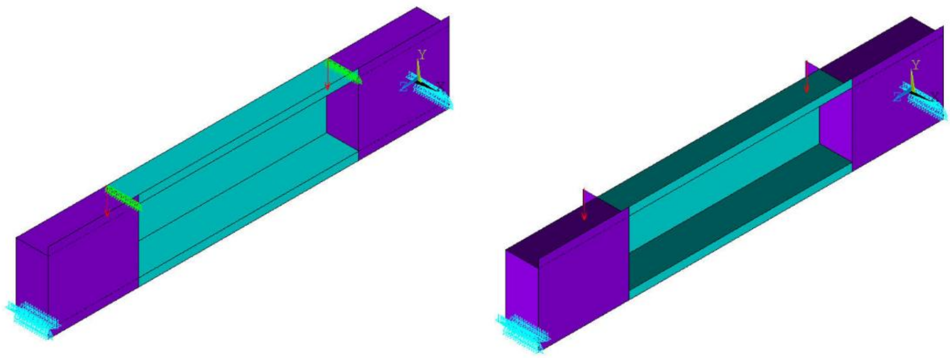


Fig. 5 – FEM models of four-point bending test with close-section grip and load applied in centroid (a) and in shear centre (b).

Summing up, the following four cases of load and boundary conditions were considered:

- 4PB-OP-C: load and boundary conditions the same as in four-point bending test with open cross-section grip and load applied in centroid – Fig. 4a;
- 4PB-CL-C: four-point bending test with close (rectangular) cross-section grip and load applied in centroid – Fig. 5a;
- 4PB-OP-S: four-point bending test with open cross-section grip and vertical load applied along line crossing shear centre – Fig. 4b;
- 4PB-CL-S: four-point bending test with rectangular cross-section grip and vertical load applied along line crossing shear centre – Fig. 5b.

3. RESULT OF CALCULATIONS

The buckling loads with corresponding buckling modes have been determined for beams with open cross-sections subjected to pure bending. All calculations have been executed using ANSYS software. The linear buckling analysis has been performed. Six different models of boundary conditions and the way of load appliance have been assumed. Due to different shape of open section beam, the corresponding to buckling load, the average compression stress on the upper flange has been determined.

Table 2

Buckling stress comparison for different beams and assumed boundary conditions.

		4PB-OP-C	4PB-OP-S	4PB-CL-C	4PB-CL-S	SCA	SCB
	mode	Buckling stress on compressed flange [MPa]					
C section	1	115	115	116	115	100	57
	2	118	117	118	118	106	59
	3	140	139	140	140	116	69
Lip-channel section	1	575	575	575	575	369	282
	2	575	575	575	575	534	282
	3	600	600	600	600	549	295
Top-hat section	1	566	566	566	566	347	261
	2	567	567	567	567	535	263
	3	593	593	592	592	539	269

The comparison of stresses from all prepared analysis is presented in Table 2. It turned out that beams with lip channel and top-hat cross sections are able to carry significantly higher loads than this with channel cross-section. Introducing the stiffeners to the beam leads to increase the buckling load approximately 5 times. As it can be observed in Figure 6 the all assumed boundary conditions have not any influence on buckling mode in case of beam with channel cross-section. However, analysing the buckling stress (Table 2), for this beam, it decreases corresponding to four-point bending case c.a. twice for boundary condition denoted as SCB and approximately 15% for SCA. Similar relations between buckling load have been observed for lip channel section and top-hat section beams, i.e. the considered grips and place when the load was applied in four-point bending test to do not change the buckling load. The value of buckling load changes (decreases) approximately twice when the SCB boundary conditions were employed and c.a. 35% in case of SCA.

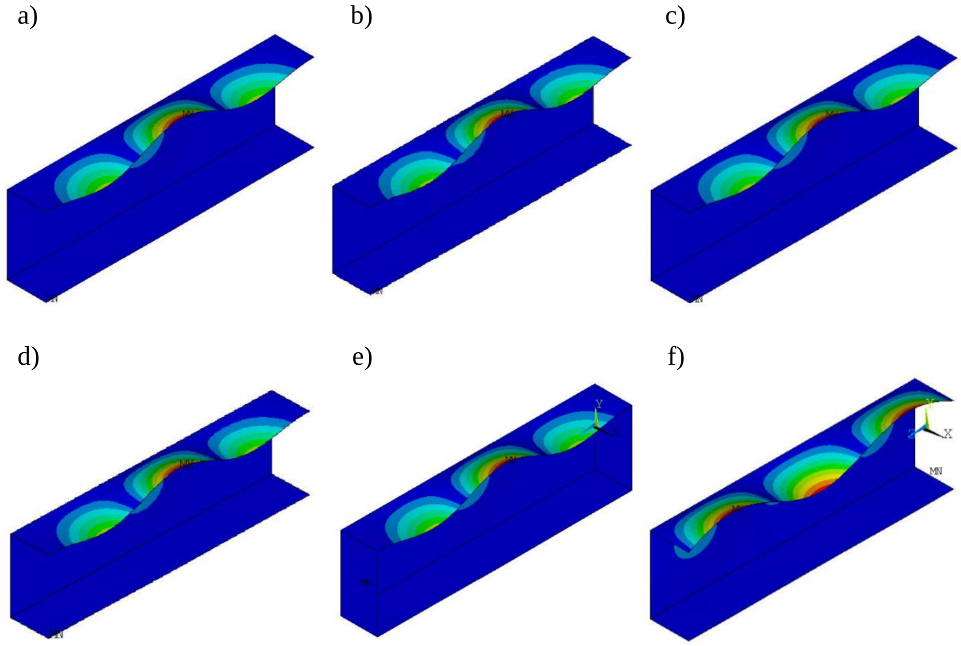


Fig. 6 – First buckling modes for 4PB-OP-C (a), 4PB-OP-S (b), 4PB-CL-C (c), 4PB-CL-S (d), SCB (e) and SCA (f) boundary condition types with channel section beam.

As it has been mentioned above the grips with open and closed cross-section do not significantly affect the buckling load and have no influence on buckling mode. The previously mention torsion in part of the beam between support and load due to shear forces applied to the beam do not have any influence of beam behaviour in prebuckling stage and also did not have impact on buckling loads (see Table 2) and corresponding buckling modes (see Figs. 7a-7d and 8a-8d).

It was found that values of buckling stresses corresponding to the first three buckling modes in those two cases (4PB for lip channel and top-hat section) are very close, difference is very small (approx. 4% of differences between the first and the third buckling stress) therefore it can be noticed that some interaction are possible.

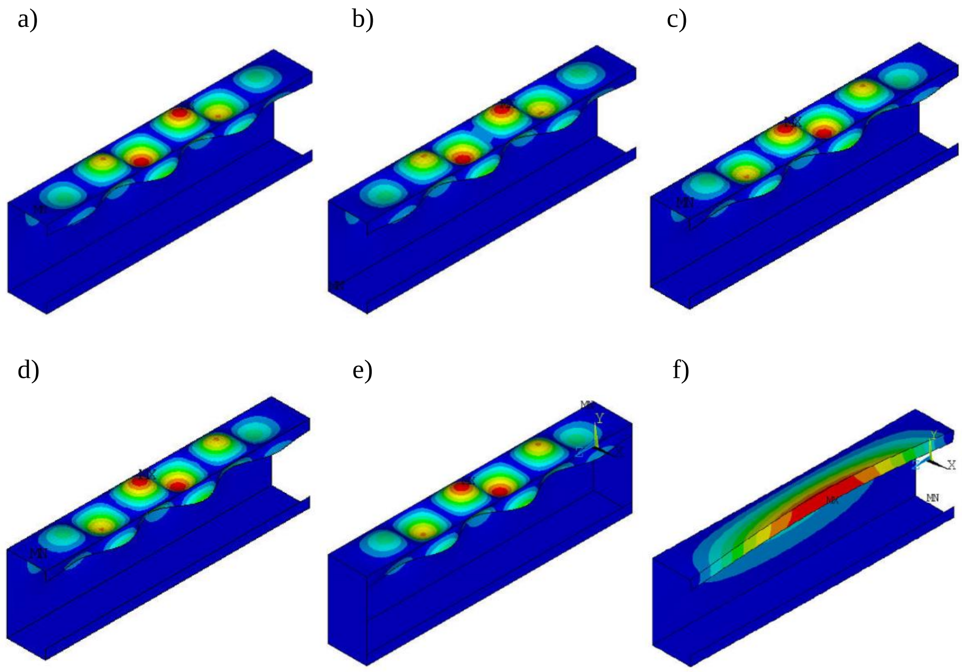
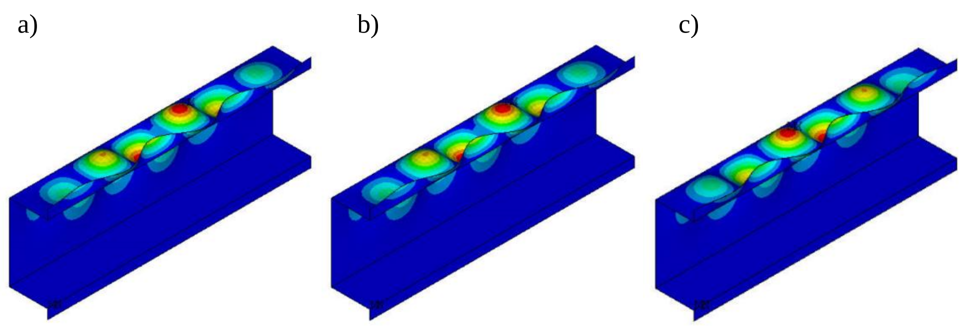


Fig. 7 – First buckling modes for 4PB-OP-C (a), 4PB-OP-S (b), 4PB-CL-C (c), 4PB-CL-S (d), SCB (e) and SCA (f) boundary condition types with lip-channel section beam.

Beams with SCB boundary condition type withstand two times lower stress than four-point bending cases. However, beams behaviour is similar, the same buckling mode i.e. number of half wave in longitudinal direction of the upper flange appears in first buckling modes except of SCA lip channel section (Fig. 7f), SCB top-hat section (Fig. 8e) and SCA top-hat section (Fig. 8f). In these cases of boundary conditions, second buckling modes correspond to local buckling mode (c.f. Fig. 9). SCA case of boundary conditions is different from others. It may seem that due to lack of rigid plates at both ends, beam supported with boundary conditions denoted as SCA leads to lower critical stress than SCB.



d) e) f)

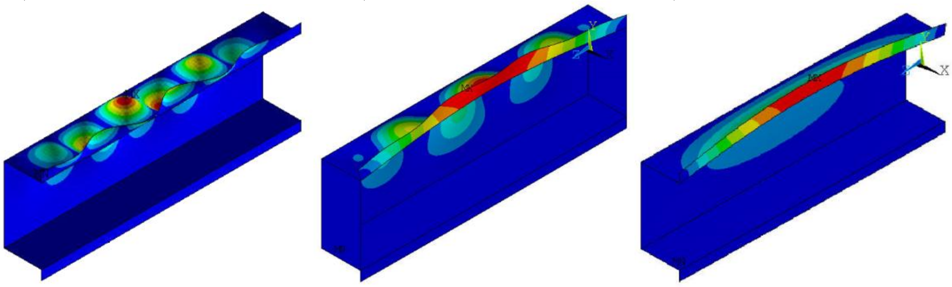


Fig. 8 – First buckling modes for 4PB-OP-C (a), 4PB-OP-S (b), 4PB-CL-C (c), 4PB-CL-S (d), SCB (e) and SCA (f) boundary condition types with top-hat channel section beam.

a) b) c)

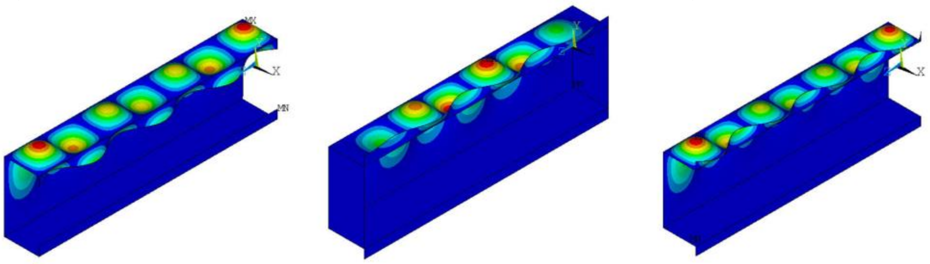


Fig. 9 – Second buckling mode in SCA lip channel section beam (a), SCB top-hat section beam (b), SCA top-hat section beam (c).

a) b)

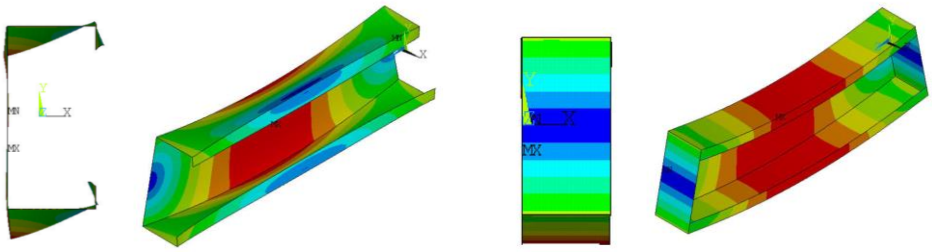


Fig. 10 – Deplanation of the beam shown on the SCA lip channel section beam (a), and SCB lip channel section beam (b).

It was found that due to significantly lower rigidity of beam's end in case denoted as SCA it is twisting and deplaning in prebuckling stage. Such behaviour causes the fact that first buckling mode corresponds to distorsional lateral buckling mode and appears under higher stress than in case of SCB, where the first mode is a local mode. The differences in behavior in prebuckling stage for both mentioned above cases of boundary conditions (i.e. SCA and SCB) are presented in Figure 10. It is very well visible that in case of boundary conditions denoted as SCA the beam cross-section rotate and deplaning. Furthermore, beams with lipped channel and top-hat cross sections have quite high stress difference between two first buckling modes.

4. CONCLUSION

Many studies that have been done are focused on the impact of the kind of boundary conditions on typical sections. Additionally, they visualize this phenomenon. However, they only tend to compare the theoretical analyses with the experimental part and the type of applied forces [12]. Purpose of this paper was to examine the influence of the boundary conditions on beam behaviour, i.e. buckling loads and modes.

First of all, it should be mentioned, that analytical or analytical-numerical methods assume the boundary conditions, which are not in good accordance to real structure. In all the cases it is only the model, which try to reflect the reality as adequately as possible. It was the main idea to check how the boundary condition model affects the results of calculations.

It turned out that for chosen dimension of considered beam, the part of the beams which was subjected to pure bending behave different for different models of boundary conditions. Assuming that the bending moment is applied using grips in four-point bending test, the distorsional lateral buckling did not appear. In contrary, when only the considered part of the beam is modelled and boundary conditions and load are applied directly to the ending cross-section the lateral distorsional buckling mode could appear. Performed analysis prove that the way of model boundary condition and load application could play a significant role on buckling load and mode and also could affect the behaviour in postbuckling range and finally can have the influence on load carrying capacity.

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