

Numerical Buckling Analysis of Thin-Walled Channel-Section Composite Profiles Weakened by Cut-Outs

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ABSTRACT

Thin-walled elements, thanks to their good properties are more often used in structural applications, particularly in aircraft or building industry. This kind structures are often perforated especially for weight reduction and to ease servicing and maintenance operations, e.g. in aircraft wing ribs. What is more, this type of elements, due to its dimension, is susceptible on buckling phenomena, and this susceptible increases with the perforation. This work present the results of numerical analysis of the composite beam subjected to a compressive load. Paper focus on the buckling behaviour of profile with specific types of cut-outs. Three parameters like: holes shape, spacing ratio S/D_o and the opening ratio D/D_o were selected to check their influence on the critical load and buckling behaviour of the channel profiles. Numerical analysis were performed by using Abaqus software. Obtained results helped to identify the best combination of the three parameters for getting the highest critical buckling load, from among to tested holes configurations. The performed analysis show that opening ratio and hole shape had the biggest influence on the value of critical load. Moreover, the combination of parameters which gives the highest value of critical force is the circular hole shape with opening ratio $D/D_o = 2$ and with spacing ratio $S/D_o = 1.67$.

Keywords: buckling, numerical analysis, critical force, holes, thin-walled structures.

INTRODUCTION

Thin-walled constructions belong to the load-bearing structures which are characterised by high strength and stiffness with a low own weight at the same time. This allow designers for a freedom in shaping construction form. Thanks to those good properties, these structures have widely application in many sectors, where low weight is decisive, for example in: aerospace [1, 2], civil engineering [3, 4] and automotive sectors. Unfortunately, thin-walled composite structures have also one important disadvantage like loss of stability when they are compressed [5, 6]. However, those kind of elements can still work after occurring buckling phenomenon provided that their postcritical paths are stable [7, 8]. This topic was described by many researches like Wysmulski [9], Banat and others [10] or Ribeiro and others [11].

In the worldwide literature it can be found easily more studies about linear and nonlinear problems of thin-walled structures stability [12, 13].

Like mentioned at the beginning, thin-walled elements are often perforated for decrease their weight as well for maintenance operations. These perforations cause a redistribution of stresses in the structure that may change the ultimate strength of the structural elements and the elastic stiffness. The buckling behaviour of structural profiles with perforations is significantly influenced by the size, location, shape and number of perforations. Therefore, it seems imperative to investigate the influence of those kind holes parameters on thin-walled structure buckling behaviour.

In literature there is a lot of investigations of plate element with different cut-out shapes. In paper [14] author tested rectangular plates with holes and it was found that buckling depends on

the cut-out rounding radius. In [15] authors investigated plates with square hole, in [16, 17] with elliptical cut-out and in [18] with circular hole. Obtained results showed that the most important parameters influenced on the buckling loads were hole size and angle of fiber orientation. Author in own research also tested plate elements weakened by cut-outs where the stability analysis of thin-walled composite plate subjected to axial compression was taken under consideration [19, 20]. Moreover author performed also analysis in postcritical range [21, 22] for plate elements in unsymmetrical configuration of composite. The obtained results showed that we can influence on buckling and postbuckling behaviour of plate elements by changing the shape and cut-out geometric parameters. In literature, it can be found number of already conducted analysis of the stability of composite plate elements weakened by holes. However, the buckling area with composite perforated columns has not yet been thoroughly analyzed. In literature it can be found some analysis performed on the aluminium alloy profiles with perforations [23]. There are a little investigation carried out on steel profiles with channel cross-section [24, 25] or Z-cross-section [26]. Moreover, in previous articles author and others tested composite profiles with different kind of cross-section like channel cross-section [27, 28], where the main focus was on influence of load eccentricity on the behavior of thin-walled compressed composite structures. Authors tested also columns with omega cross-section [29, 30] and Z-cross-section [31]. But all analysis were performed on columns without cut-outs. But the knowledge about buckling behaviour of perforated composite columns is insufficient.

Due to the wide usage of composite elements in the form of thin plates, the load carrying-capacity of composite profiles is essential. Moreover, cut-outs are very often used in composite panels as part of the project. As a result, it is important to have information about the buckling behaviour of composite profiles with cut-outs.

This study sourced on the paper conducted by Khazaal et al. [32], where the authors tested aluminium alloys profiles under compression. They chose three types of holes shapes to optimize the results: circular, rectangular and hexagon. They focused also on the parameter which has the most influence on the buckling behaviour of the aluminium thin-walled elements. The similar

analysis was made in paper [33] where authors studied the same parameters but in profiles made from GFRP composite. Therefore, this has ignited author motivation to analysis presented study, hence contributes towards the knowledge on thin-walled composite structures with cut-out.

In this paper investigated the influence of parameters like: different shapes of holes, spacing ratio and the opening ratio on the buckling behaviour of the channel cross-section profiles. The current study uses Carbon Fiber Reinforced Polymer as the material with classic symmetric configuration [0/45/-45/90]_s. The scope of research include issue of linear stability of composite profiles subjected to axial compression. Numerical calculations were performed with commercial ABAQUS program and with using the FEM (*Finite Element Method*), which finding currently a very wide applications. The focus of this study is the optimizing the parameters to have highest probable critical buckling load for composites thin-walled columns weakened by holes.

RESEARCH SUBJECT AND METHODOLOGY

The study investigated thin-walled channel-section composite profiles weakened by cut-outs and subjected to compression. The profiles had flat walls joined on the longer ends and consisted of 8 plies symmetric to the laminate mid-plane. The mean thickness of the column walls was 0.84 mm, where each ply had a thickness of 0.105 mm. The other dimensions of the column were as follows: the web = 60 mm, the profile wall $h = 30$ mm, the length $l = 250$ mm. The study was performed on a CFRP composite channel-section column, described by the symmetric configuration of [0/45/-45/90]_s (Fig. 1).

The mechanical properties of the analyzed composite material were determined experimentally in compliance with relevant ISO standards and presented in Table 1.

The characteristic feature of symmetric ply orientation is no mechanical couplings, which means that the coupling matrix $[B]$ is equal to zero. It worthy to add, that by using symmetrical configurations of composites, we can avoid warping of composite structure during the production process. The relationship between internal loads and moments can be written as [37,38]:

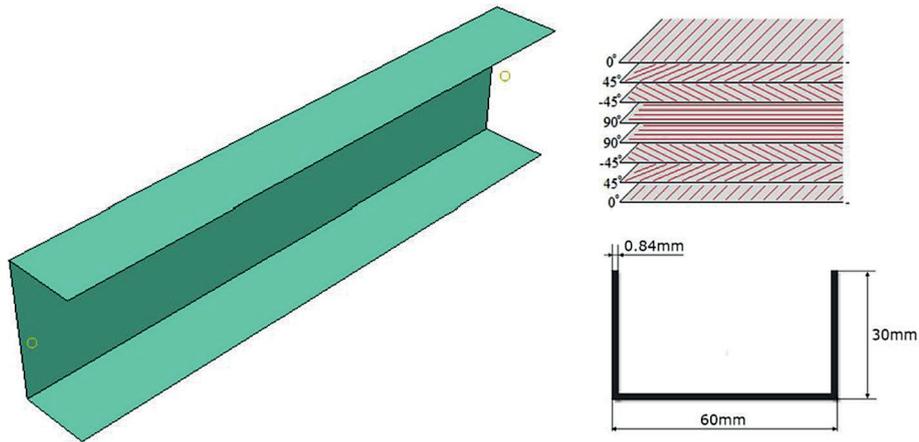


Fig. 1. Composite profile with a channel section and with cross-sectional dimensions

$$\begin{Bmatrix} \{N\} \\ \{M\} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & 0 & 0 & 0 \\ A_{21} & A_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & D_{11} & D_{12} & 0 \\ 0 & 0 & 0 & D_{21} & D_{22} & 0 \\ 0 & 0 & 0 & 0 & 0 & D_{66} \end{bmatrix} \begin{Bmatrix} \{\varepsilon^b\} \\ \{\kappa\} \end{Bmatrix} = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix} \begin{Bmatrix} \{\varepsilon^b\} \\ \{\kappa\} \end{Bmatrix} = [K] \begin{Bmatrix} \{\varepsilon^b\} \\ \{\kappa\} \end{Bmatrix} \quad (1)$$

where: $\{N\}$ – the normal forces matrix,
 $\{M\}$ – the bending moments matrix;
 $[A]$ – the membrane stiffness matrix,
 $[D]$ – the bending stiffness matrix,
 $[B]$ – the coupling stiffness matrix;
 $\{\varepsilon^b\}$ – denotes mid-plane strains of the membrane state,
 $\{\kappa\}$ – a mid-plane curvature.

In this work, according to paper [32], three shapes of holes made on the profile web were designed (Fig. 2). In mentioned work, authors tested aluminium profiles where the geometry of web holes must be within the given ranges of Eurocode (Eqs. 2 and 3) in order to prevent any unwanted failures like cracks between holes, and to achieve a maximum possible reduction in weight.

$$1.25 < D/D_o < 1.75 \quad (2)$$

$$1.08 < S/D_o < 1.5 \quad (3)$$

where: D – width of profile web,
 D_o – diameter/width of hole,
 S – distance between holes,
 D/D_o – opening ratio;
 S/D_o – spacing ratio.

For composite profiles this kind of Eurocode doesn't exist but it was good reason to take those equations under consideration and perform numerical analysis for composite columns with a channel section.

The shapes of the holes were circular, square, and hexagonal (Fig. 2). The opening ratio (D/D_o) and spacing ratio (S/D_o) were selected according to the equations (2) and (3). What is more, author took under consideration also parameters which were outside the bounds of above equations. The parameters and levels presented in Table 2.

Table 1. Mechanical properties of the analyzed composite material, determined in compliance with relevant ISO standards [34–36]

Young's modulus [MPa]		Shear modulus [MPa]	Poisson's ratio	Tensile strength [MPa]		Shear strength [MPa]	Compression strength [MPa]	
E_1 (0°)	E_2 (90°)	$G_{1,2}$	ν_{12}	F_{TU1} (0°)	F_{TU2} (90°)	F_{SU} (45°)	F_{CU1} (0°)	F_{CU2} (90°)
143530	5826	3845	0.36	2221	49	83.5	641	114

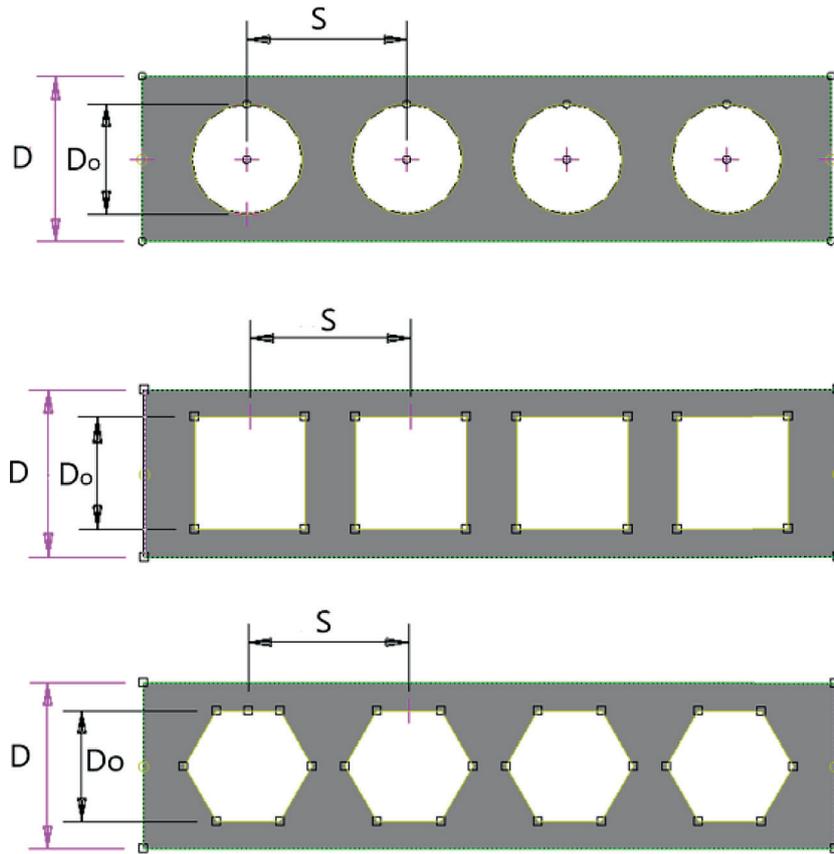


Fig. 2. Dimensions and shapes of holes

NUMERICAL ANALYSIS

Numerical calculations enabled a detailed analysis of the perforated profiles behaviour under compression, with using the finite element method. The scope of numerical simulations involved describing the critical state of the structure (linear analysis of an eigenproblem) and influence of shape and parameters of cut-out on critical force. The critical state of the structure, i.e., buckling, was described by a linear model using the minimum total potential energy principle. Equation (4) present mathematic notation of the loss of stability phenomenon. This approach made it possible to determine the lowest buckling mode of the compressed composite column and its corresponding critical load.

$$|[K] + \lambda_i [H]| = 0 \tag{4}$$

where: $[K]$ – structural stiffness matrix,
 λ_i – the i-th eigenvalue,
 $[H]$ – stress stiffness matrix.

Equation 4 represents the eigenvalue problem which allows for finding n values of the buckling load multiplier λ and the corresponding buckling mode shape.

The numerical analysis performed in Abaqus programme. The structure was discretized using 8-node shell elements (S8R) of second order with, reduced integration. Mesh density which was used for the composite profiles equal 4 mm. The structure of the composite material was defined depending the thickness of the finite element. The discrete model of the structure and boundary conditions are presented in Figure 4.

To check the influence of meshing size, author performed convergence test. The mesh density was increased in each part of the model by changing the size of element from 1 mm to 5 mm. Obtained results showed that differences are minimum and increment of mesh density is unnecessary (Fig. 3). What is more denser mesh lengthens

Table 2. Parameters and levels

Parameter	Levels		
	1	2	3
Shapes of holes	Circular	Square	Hexagonal
D/D_0	2	1.67	1.5
S/D_0	1.25	1.45	1.6

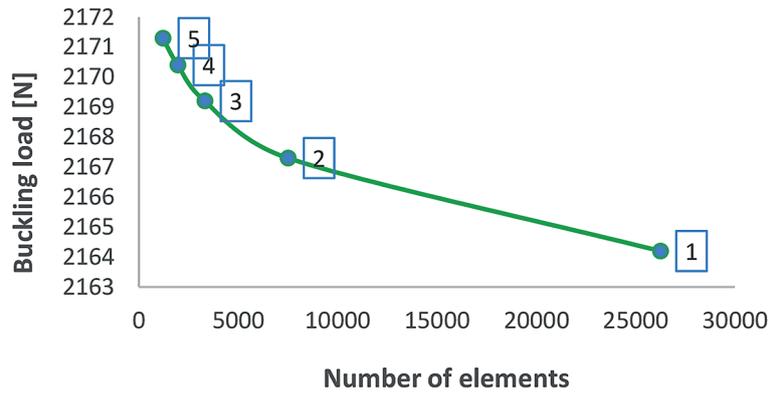


Fig. 3. The results from convergence test

the processing time. Therefore, in further analysis element size of 4 mm was used. The similar analysis was performed in works [39,40].

The boundary conditions used in this analysis were the same like in paper [41]. The ends of the profile were simply supported on the rigid plates. The column model was fixed at the created reference points RP connected to the plate. In the bottom all translational degrees of freedom were constrained, i.e., $U_x=U_y=U_z=0$. What is more, the rotation relative to the all axis of the column, was also constrained i.e., $U_{R_x}=U_{R_y}=U_{R_z}=0$.

The reference point on the top, was described by similar boundary conditions, except ability to move in the Z-axial direction, i.e., $U_x=U_y=0$ and $U_{R_x}=U_{R_y}=U_{R_z}=0$, where the compressive load was applied. The plates and reference points were

described by rigid relations connected all degrees of freedom.

RESULTS AND DISCUSSION

In this part the achieved results from the numerical analysis are presented. In Table 3 depicted the values of critical forces for all tested cases. In the green colour marked those ratios which exceed ranges of Eq. 2 and 3. Whereas in Figure 5 shows the obtained first buckling form and the related critical load for one exemplary case. The same figures were obtained for the rest analyzed cases.

The obtained results from FE analysis show that for all tested cases with hole, the value of critical force has been decreased. The presence of

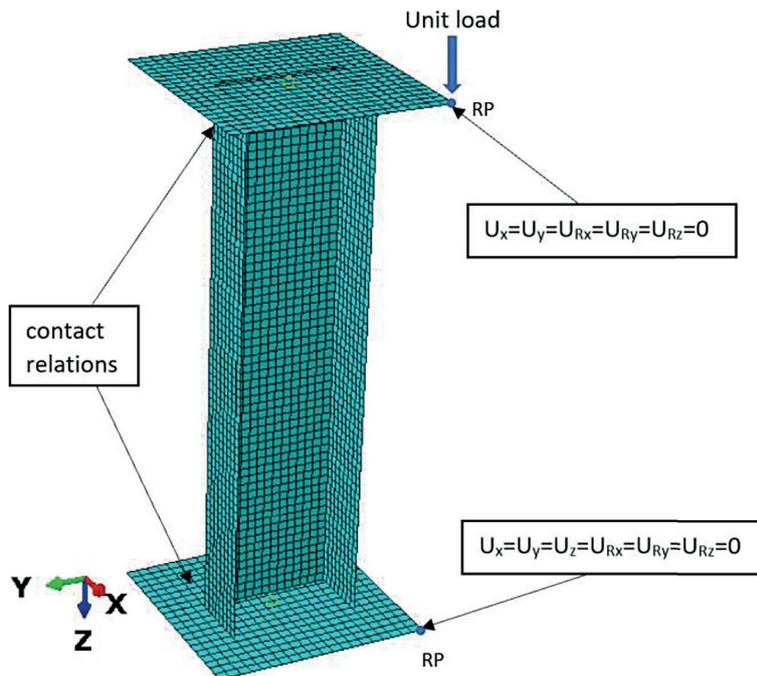


Fig. 4. Discrete model and boundary conditions of column with channel cross-section

Table 3. Buckling load value for all tested cases

No.	Holes shape	Opening ratio D/D_0	Spacing ratio S/D_0	P_{cr} [N]
1	Without holes	---	---	2172.4
2	Circular	2	1.67	1802.3
3	Square			1709.6
4	Hexagonal			1764.8
5	Circular	1.67	1.39	1667.3
6	Square			1541
7	Hexagonal			1612.9
8	Circular	1.5	1.25	1561.3
9	Square			1415.2
10	Hexagonal			1492.1
11	Circular	1.5	1.45	1551.3
12	Square			1410.8
13	Hexagonal			1487.3
14	Circular	1.5	1.6	1553.8
15	Square			1422.9
16	Hexagonal			1493.2

perforations caused decrease of the critical loads of the profiles with the percentage decrease of appropriately: 17÷28.48% for the circular hole shape, 21.30÷35.06% for the square hole shape and 18.76÷31.54% for the hexagonal hole shape.

In Figure 6 presented the influence of spacing and opening ratio on the value of critical buckling load for different holes shapes.

On the basis of the obtained results, we can conclude that, the load decrease seemed significant when the holes were introduced. Figure 6a indicates a upward trend when the opening ratio increased. A higher opening ratio resulted in a greater buckling load for all profiles. For all tested profiles, the graph shows that circular shape led to getting the highest critical load compared to hexagonal and square holes shapes. The effect of the spacing ratio (Fig. 6b) did not show any significant influence on the value of critical load. Similar conclusions got in paper [33].

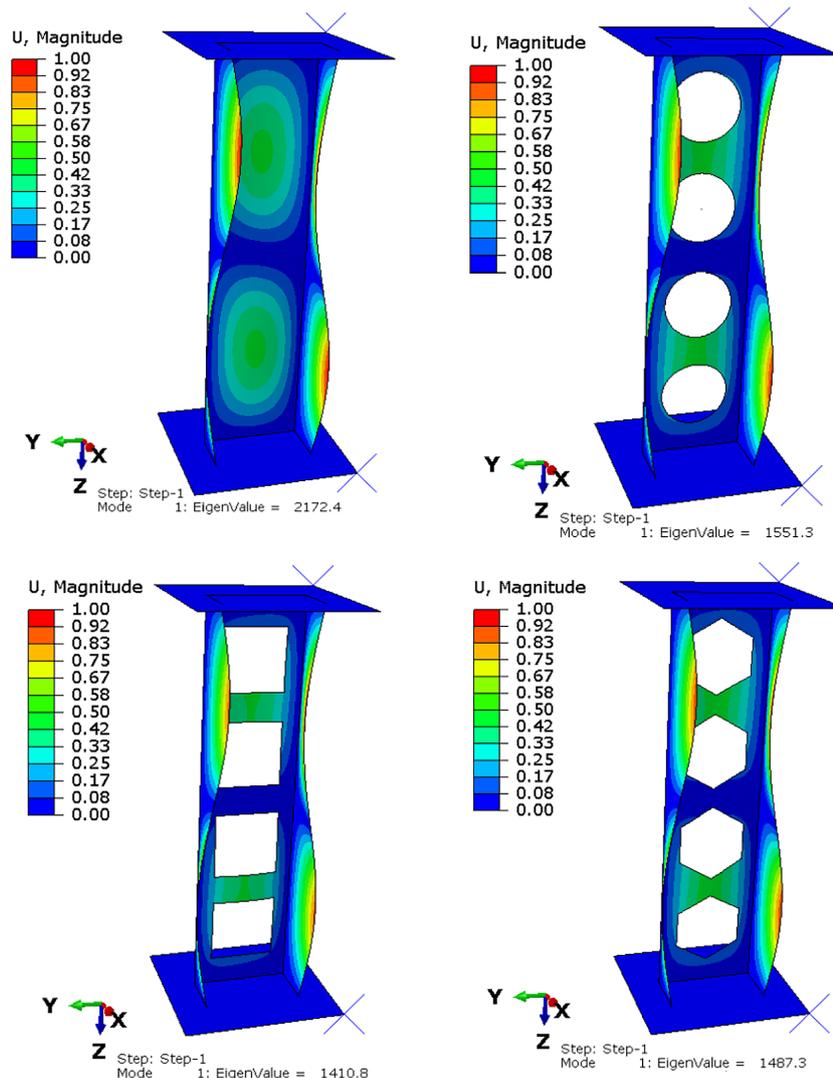


Fig. 5. Buckling simulation results for all types of holes for $D/D_0=1.5$ and for $S/D_0=1.45$

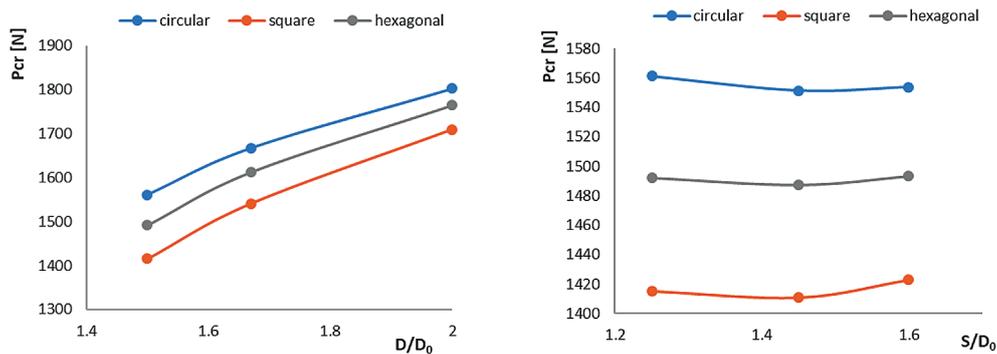


Fig. 6. Influence of opening ratio (a) and spacing ratio (b) on value of critical buckling load for different holes shapes.

Figure 6a shows that when opening ratio increase then buckling load also increase. Those results confirm the results got in work [33] for GFRP composite profiles. Whereas according to equations (2) and (3), it can be observe that the spacing ratio decrease as the size of holes increase. What confirm information from previous paragraph, where described that the buckling load decrease with introducing increasing the perforation on the web of the thin-wall CFRP composite profile. The plots in Figure 6b, shows an insignificant decrease of critical load value as the spacing ratio decreased. We can observe that from all tested samples with different kind of holes, the highest critical load obtained profile with circular hole shape, opening ratio equal 2 and with spacing ratio equal 1.67. In paper [33] the best ultimate strength got also for circular shape, while in paper [32] the best results were for hexagonal shape.

CONCLUSIONS

This research investigated the buckling behaviour of perforated composite profiles with channel cross-section under compression. At work focused on the effect of three shapes of holes, opening ratio D/D_0 and the spacing ratio of S/D_0 on buckling behaviour. The results present the best set of factors which gives the highest buckling load among different tested type of cut-out shapes. From the results obtained, the following conclusions can be obtained. The presence of perforations caused decrease of the critical loads of the profiles with the percentage decrease of appropriately: 17÷28.48% for the circular hole shape, 21.30÷35.06% for the square hole shape and 18.76÷31.54% for the hexagonal hole shape. The performed analysis show that opening ratio

and hole shape had the biggest influence on the buckling load. The effect of the spacing ratio did not show any significant influence on the critical load. The combination of parameters which gives the highest value of critical force is the circular shape of hole, $D/D_0 = 2$ and $S/D_0 = 1.67$.

The obtained results can have a practical significance in the aspect of calculating this type construction for applications as a load-bearing elements.

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