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THEORETICAL ANALYSIS OF PERFORATED RACK COLUMNS

Arlene M. S. Freitas*, Marcílio S. R. Freitas* and Flávio T. Souza**

* Departamento de Engenharia Civil, Escola de Minas, Universidade Federal de Ouro Preto
e-mails: arlene@em.ufop.br, marcilio@em.ufop.br

** Instituto Federal de Minas Gerais, Campus Congonhas
e-mail: flavio.souza@ifmg.edu.br

Abstract. *Industrial Storage Systems are usually built with cold-formed profiles. Their sections, called "rack sections", are specially designed with perforations to accommodate connections and bolts for easy assemblage. This, however, induces unexpected failure modes in other sections. The aim of this research was to analyze the effects of perforations on column behavior and resistance using the commercial software ANSYS and the finite element method. The numerical values for this procedure were previously obtained using the finite strip method and the generalized beam theory. These results were then calibrated by comparing them to the finite element models of columns without perforation. The element type, mesh refinement and boundary conditions were carefully chosen to ensure that the finite element model reproduces actual column behavior. The finite element model was used to evaluate the effects of perforation size, quantity and distribution on column behavior.*

Keywords: Industrial Storage Systems, Thin-walled perforated members, Finite element analysis, Columns.

1 INTRODUCTION

Industrial Storage Systems are widely used in factories, warehouses and other places where high-density storage is needed. They are usually built with cold formed profiles, and their "rack" sections are specially designed for easy assemblage. In addition, their columns have perforations throughout their length to accommodate connections and bolts. The specially perforated rack sections modify column behavior and resistance because they induce unexpected failure modes in other sections, as the channel, for example. These failure modes involve buckling, which can be local, overall, or distortional and can occur separately or coupled.

There are several works that analyze rack-system behavior. These are focused on the system's overall stability and its component behavior (Freitas [1,2], Godley [3,4]).There are also recent works that consider perforated sets (Moen and Schaffer [5], Eccher, Rasmussen and Zandonini [6]).

The existence of perforations modifies the column's behavior. Previously this analysis was especially difficult because the numerical tools available, such as the finite strip analysis (CUFSM [7]) and the generalized beam theory (GBTul [8]), were only able to evaluate imperforated sections. Nowadays, the analysis of a perforated rack column can be carried out by using finite element analysis (ANSYS [9]).

Herein, a finite element analysis of rack sections with perforations is presented. This analysis was developed as follows:

- An imperforated column section was analyzed in CUFSM and GBTul, with pinned ends;
- An imperforated column section was analyzed in GBTul with fixed ends. These boundary conditions were chosen in order to permit comparison with future experiments;

- A finite element model for an imperforated column was created in ANSYS and its results were compared with the GBTul results. These analyses were carried out in order to validate the finite element model's properties, such as mesh refinement, support and loading conditions.
- From procedures developed in the previous step, more finite element models were constructed for perforated columns, in order to evaluate the influence of the size and number of holes on column resistance and behavior. The elastic buckling loads were determined in all analyses, and the buckling modes were compared. Non-linear elastic were carried out in order to verify column equilibrium paths.

2 THE ANALYSIS AND BEHAVIOR OF IMPERFORATED RACK SECTIONS

2.1. Columns with pinned ends

In this section, the analysis of imperforated rack sections is carried using the finite strip method (CUFSM), generalized beam theory (GBTul) and finite element method (ANSYS). The first two methods of analyses were carried out in order to develop a finite element procedure to evaluate imperforated column behavior and prove its efficiency by comparing it with the other numerical technique results. A Brazilian-made commercial rack section was chosen (Águia [10]). Section components and dimensions are shown in figure 1.

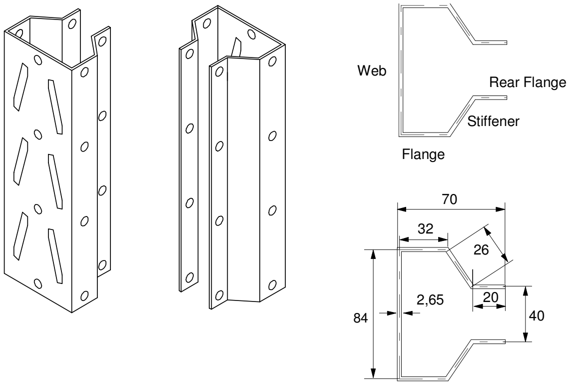

Figure 1. Column elements and dimensions in mm.

In the first stage, an overall beam analyses was carried out using the GBTul method and these results were then compared with results from the finite strip method. This research aimed to compare the GBT and finite strip results for columns with pinned (free warping) ends. In a second stage, the data obtained from these analyses were compared to the finite element results for columns with pinned ends; carried out for a few column lengths. Figure 3 shows the finite element model. The ends support the chosen conditions for the pinned column simulation when the restriction had translational degrees of freedom in a perpendicular-to-the-column-axis direction in the end nodes. In order to avoid rigid body displacement, the degree of freedom in the axial direction of the model's mid-height node was also constrained. Loading was applied by compressive forces in all end nodes. An eigenbuckling analysis was carried out in order to capture the buckling load and the failure mode of the column.

The purpose of this comparison was to choose the finite element type (from ANSYS internal library) and mesh refinement to be used for the finite element lengths. Simulations for the column were performed for the *first buckling* mode where the local mode was 70 mm, the distortional mode was 400 mm, the torsion flexural mode was 4000 mm and the flexural mode was 5000 mm. The results obtained from these analyses are shown in figure 3. It can be seen that the finite element model, in general, is suitable for capturing the failure mode and buckling load.

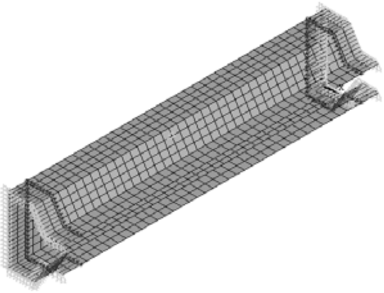

Figure 2. Finite element model with pinned ends.

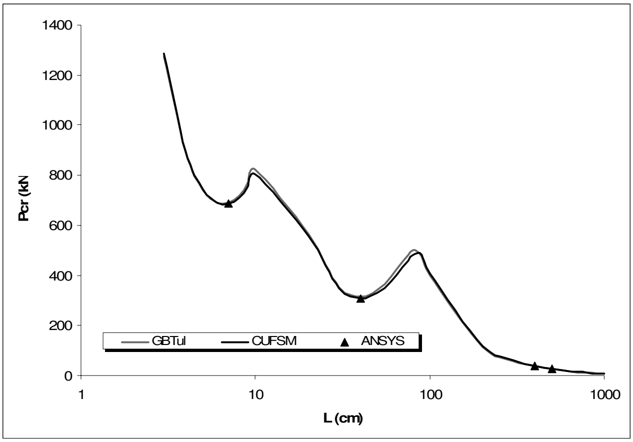

Figure 3. Comparison of the GBTul, CUFSM and ANSYS results.

Three shell element types were tested to simulate the column: SHELL63, SHELL181 and SHELL281. They are similar and have the same input data, but SHELL63 is suitable for elastic analysis, SHELL181 is strongly indicated for plastic analysis and SHELL281 has midway nodes, i.e. this element has eight nodes, while SHELL63 and SHELL181 have four nodes. Finite element models with lengths of 70 mm (local mode) and 400 mm (distortional mode) were used in this analysis. Results from these analyses and their comparison with the finite strip method and generalized beam theory results are presented in tables 1 and 2.

It can be observed that, in both comparisons, SHELL63 showed good efficiency in local mode prediction, but the same doesn't occur for the distortional mode. SHELL181 showed bad agreement for the local and distortional modes. SHELL281 showed good agreement in both buckling modes, and was chosen to be used in this study.

Once the finite element type was chosen, a mesh refinement suitable for column analysis had to be determined and this was achieved by comparing the finite strip and generalized beam theory results. For this, the manual element size set-up available in ANSYS was used. A range of element side sizes were tested, and the best result agreement was observed when the element size was equal to a 10% web width (8.4 mm). Table 3 shows finite element results compared to finite strip and generalized beam theory results.

Table 1. Comparison between ANSYS and CUFSM results.

	Buckling Load (kN)				*Deviation (%)*		
L(mm)	CUFSM	Shell281	Shell63	Shell181	Shell281	Shell63	Shell181
70	686.0	673.2	695.8	713.9	-1.86	1.43	4.08
400	308.8	295.3	288.3	287.4	-4.36	-6.61	-6.90

Table 2. Comparison between ANSYS and GBTul results.

	Buckling Load (kN)				*Deviation (%)*		
L(mm)	GBTUL	Shell281	Shell63	Shell181	Shell281	Shell63	Shell181
70	689.7	673.2	695.8	713.9	-2.39	0.88	3.51
400	315.3	295.3	288.3	287.4	-6.34	-8.55	-8.82

Table 3. Influence of mesh refinement.

Element side size			*7mm*	*10mm*	*8,4 mm*
L=70 mm	CUFSM	GBTUL	Shell281	Shell281	Shell281
B. Load (kN)	674.1	678.3		673.2	678.0
Deviation CUFSM	-	0.6		-0.1	0.6
Deviation GBTul	-0.6	-		-0.8	-0.1
L=400 mm	CUFSM	GBTUL	Shell281	Shell281	Shell281
B. Load (kN)	303.0	306.1	290.0	295.3	304.7
Deviation CUFSM	-	1.0	-4.3	-2.5	0.6
Deviation GBTul	-1.0	-	-5.3	-3.5	-0.4

From Table 3, it can be observed that for the local buckling mode (L = 70 mm), element size does not have significant influence on the column's buckling load. For the distortional mode, however, it can be seen that an element size equal to 10% web width leads to results with excellent agreement with the finite strip method and the generalized beam theory. These latter results indicate that this mesh refinement should be used in finite element models.

2.2. Columns with fixed ends

After choosing the element type and mesh refinement, a column with fixed ends was analyzed. Consideration of this support condition is very important because it is the real situation observed in experimental tests, where load plates restrict warping effects. For analyzing this, the generalized beam theory carried out with GBTul is used as reference.

The finite element model developed to carry out this analysis is similar to the model presented in figure 1. The element SHELL281 and the refinement level presented in section 2.1 were used in the model. The main difference between models with pinned and fixed ends is that in this latter, the degrees of freedom (translational and rotational) of the end nodes are all coupled and this assures that all of them will move equally, completely restricting the warping effects. Two nodes in each column extremity have translational degrees of freedom restricted in directions perpendicular to the column axis, and a mid-high node in the column had its axial degree of freedom constrained. Loading was applied on all end nodes. Figure 4 shows boundary conditions for the fixed members.

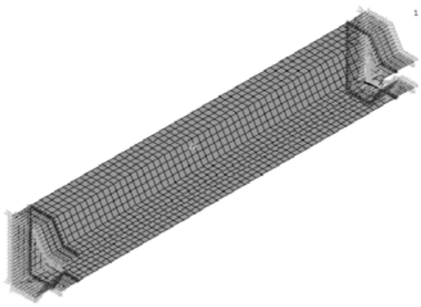

Figure 4. Fixed ends finite element model.

Various column lengths were simulated in ANSYS by eigenbuckling analysis, in order to obtain a buckling curve. A comparison between the finite element (ANSYS) and the GBT (GBTul) results is shown in figure 5. It can be observed that there is an excellent fit between results, which indicates that the finite element protocol developed is suitable for evaluating columns with perforations.

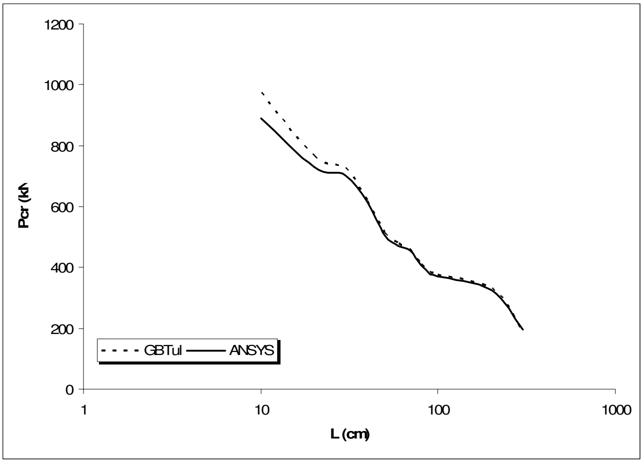

Figure 5. Comparison between GBtul and ANSYS with fixed ends.

3 THE ANALYSIS AND BEHAVIOR OF RACK SECTIONS WITH HOLES

In this section, finite element analysis is used to evaluate perforation influence on column resistance and stability. Moen and Schaffer [5] have done similar analyses to channel sections in ABAQUS. These studies were conducted in two steps. First, a GBTul analysis of an imperforated section indicated a column length with potential for mode coupling. This was done by expanding the three first modes. This analysis showed that for the column length equal to 500 mm, the local and distortional elastic buckling loads are very near to each other, indicating potential mode coupling.

The analysis is carried out in ANSYS. The model assumptions for fixed ends are presented in section 2. Three models were built. The first is the full imperforated section column. The second has one rectangular hole, midway in the column length. The other has two rectangular holes, in the column's end proximities.

The perforation size is also modified. Perforation length assumes two values: the web width (84 mm) and half of the web width (42 mm). The width of the hole is always 20% of the web's width (16,8mm).

Figure 6 presents the column used in these analyses. It can be seen that meshes are strictly equal, and only the elements in the perforated region are discounted.

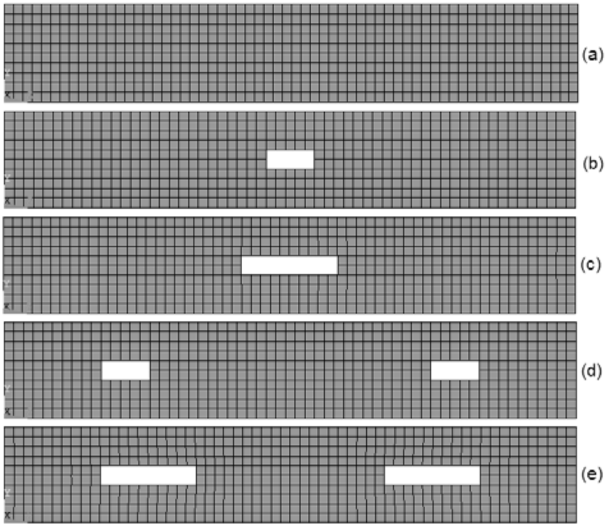

Figure 6. Web layouts: (a) imperforated; (b) 1 hole = 42 mm; (c) 1 hole = 84 mm; (d) 2 holes = 42 mm; (e) 2 holes = 84 mm.

The eigenbuckling analysis was carried out for all columns, to determine buckling loads and their correspondent buckling mode. Some buckling loads were determined from each case, in order to evaluate buckling evolution. Figure 7 presents buckling modes for columns with 1 and 2 holes (42 mm) and Table 4 presents results from the eigenbuckling analysis.

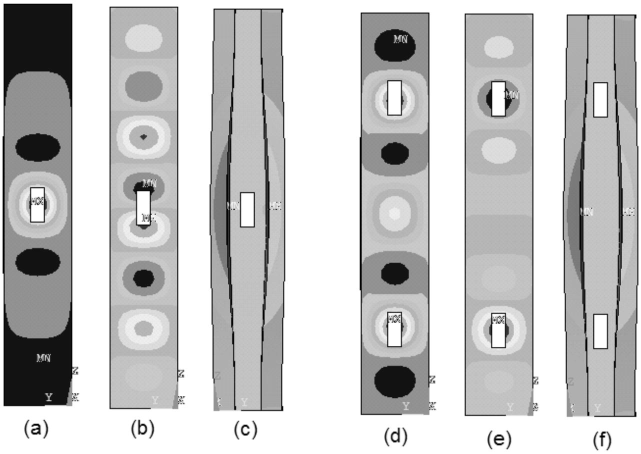

Figure 7. Columns with 1- and 2-hole (42 mm) buckling modes (Table 4).

From these results, it can be seen that holes with a length = 84 mm significantly reduced column resistance, due mainly to local effects in the hole region. Holes with a length = 42 mm have less influence on the column buckling load. It can also be seen that the existence of holes changes the buckling mode. In all specimens with holes, the hole's region is susceptible to local effects that reduce resistance. It can be noted that the hole's position is more important than the number of holes because columns with one midway hole are less resistant than columns with two holes; each hole being near an extremity.

Table 4. Eigenbuckling results.

Case	*Mode*	*Critical Load (kN)*	*Buckling modes*
No. holes	1	299.8	Local with 7 half-waves
	2	300.3	Local with 8 half-waves
	3	312.6	Distortional
1 hole (42 mm)	1	280.8	Local at perforation (a)
	2	311.4	Local with 8 half-waves (b)
	3	314.0	Distortional (c)
2 hole (42 mm)	1	293.8	Local with 7 half-waves (d)
	2	299.1	Local at perforation (e)
	3	310.3	Distortional (f)
1 hole (84 mm)	1	263.0	Local at perforation
	2	288.0	Local at perforation
	3	289.1	Local at perforation
	4	321.0	Distortional
2 hole (84 mm)	1	280.8	Distortional
	2	293.7	Local at perforation
	3	299.0	Local at perforation

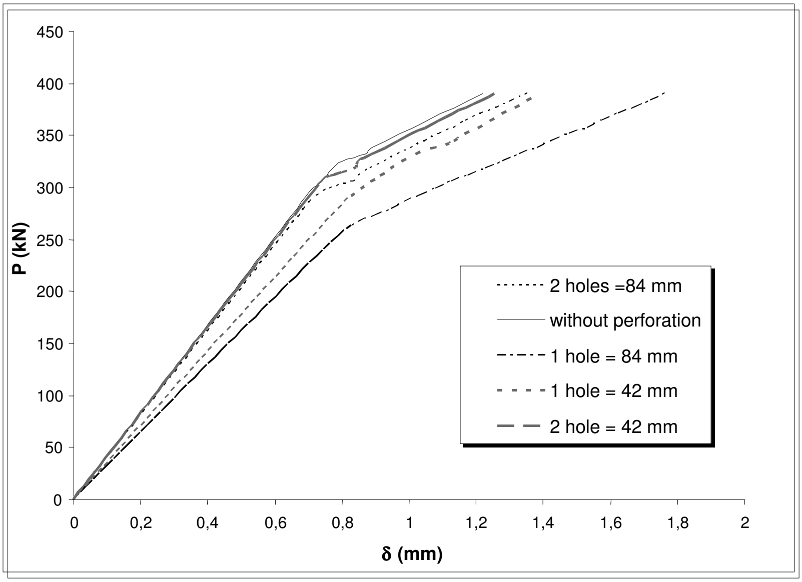

Figure 8. Column axial displacement.

Non-linear elastic analysis was also conducted for the specimens presented above. The target of this analysis was to evaluate the mode influence on column resistance. Figure 8 shows the column's axial displacement. It can be seen that the load x displacement curve follows the tendency appointed by the eigenbuckling analysis (Table 4). It is clearly seen that the columns with one midway hole have less resistance and stiffness than their equivalent with two holes; each being near the column's end.

It can also be observed that with the first buckling load, shown with horizontal lines in the figure, the line inclination changes. This indicates that every buckling, whether it is local, distortional or even in the hole's region, has a strong influence on column behavior. This influence is still greater when holes are positioned midway in the column's length.

4. CONCLUSIONS

The numerical analysis conducted in this research demonstrated the influence of perforations in cold-formed rack sections on their behavior. From eigenbuckling analysis, it was seen that the position and dimensions of the perforation influence column resistance; inducing buckling modes and reducing resistance. The existence of holes that are midway in the column's length is worse than the existence of a hole at each end of the column. This is understandable because midway in the column length there are no boundary conditions, so it is more susceptible to the instability phenomena.

The non-linear elastic analysis verified the eigenbuckling observations, and indicates that, in all analyzed cases, the first buckling occurrence induced resistance and stiffness losses. For the columns with a hole midway in its length, a local buckling in hole region leads to more accentuated resistance and stiffness losses than in the other cases. It shows that section weakening in the hole region can be very determinant in perforated steel rack columns.

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