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Research Article

Industrial storage system continuous perforated uprights: a combined design proposal

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Abstract: Brazilian standards for design of cold-formed steel (ABNT NBR 14762:2010, 2010) and design of pallet racks (ABNT NBR 15524-2:2007, 2007) have different procedures to determine the strength of columns under axial compression, using different buckling curves. This paper aims to evaluate the efficiency of using cold-formed Brazilian standard buckling design curve instead of the formulations of the pallet-rack design standard to study the use viability of the equations in the calculation procedure for computing the uprights compressive strength. This strength was calculated in four ways: one using the original equations of pallet-rack Brazilian standard, and the other three using adaptations of the buckling curve from the cold-formed steel design standard. A theoretical and numerical procedure based on finite element analysis concerning local, global, and distortional buckling and imperfections was performed. Furthermore, experimental results were also consulted to determine the effective area of studied cross-sections considering the effects of local buckling and the presence of continuous perforations. The results show that the proposed modifications are consistently correlated to the results obtained using the original equations of ABNT NBR 15524, indicating the viability of using the buckling curve of ABNT NBR 14762.

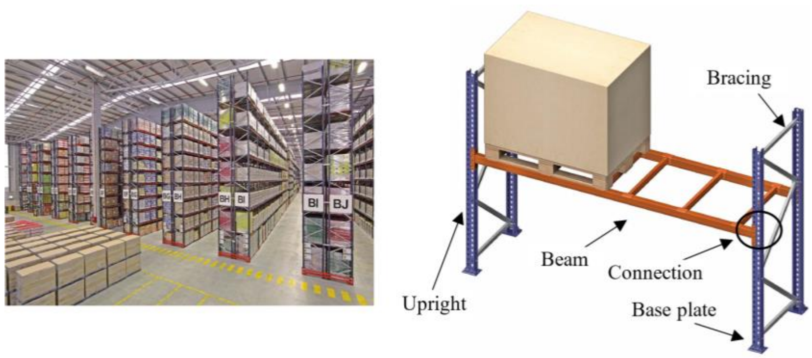
Keywords: Industrial storage systems; rack; continuous perforations; cold-formed steel; compression members; buckling design curve.

1. Introduction

Industrial storage systems are commonly used in industries and supermarkets for storing different types of manufactured goods. The products are usually stored on pallets and in box-containers. These systems' primary categories are selective pallet racks, drive in, drive through and flow rack. The difference between each one is the way loads are stored and the access to them.

The selective pallet rack is one of the most used systems. This main characteristic is verticalization of the useful space allowing direct access of the forklift to all the stored items (Figure 1a).

The industrial storage systems are also known as racking systems. They are constructed of steel, and their main structural components are upright frames, beams, and base plates. They are formed by three-dimensional steel braced structures with special connections between beams to uprights. Their components are shown in detail in Figure 1b. The uprights are connected by bracing, forming the braced panel. They are responsible for transferring the resulting load from the goods stored on beams to the floor. The racking system's structural elements have continuous perforated uprights. These perforations facilitate the connection between beams and uprights, presenting great practicality. It offers several configurations of storage arrangements considering the characteristics of the goods. These perforations influence the behavior and strength of these elements. For that reason, the design procedure for perforated compression members must take proper account of holes presence.



(a) (b)

Figure 1. (a) Selective pallet rack type; (b) Selective pallet rack components. ("Mecalux," 2020).

The structural members are shaped from carbon or low-alloy steel sheet, strip, plate, or bar not more than 1in thickness (25.4 mm). Due to the manufacturing process are called cold-formed. The cold-formed profiles are obtained from the folding or roll forming of steel sheets at ambient temperature. Roll forming is a process applicable to high strength steels. This process utilizes a series of rolls that form the required shape of steel gradually. It is a continuous process on straight line and the cross section needs to be constant throughout the length. A detail of roll forming is shown in Figure 2.

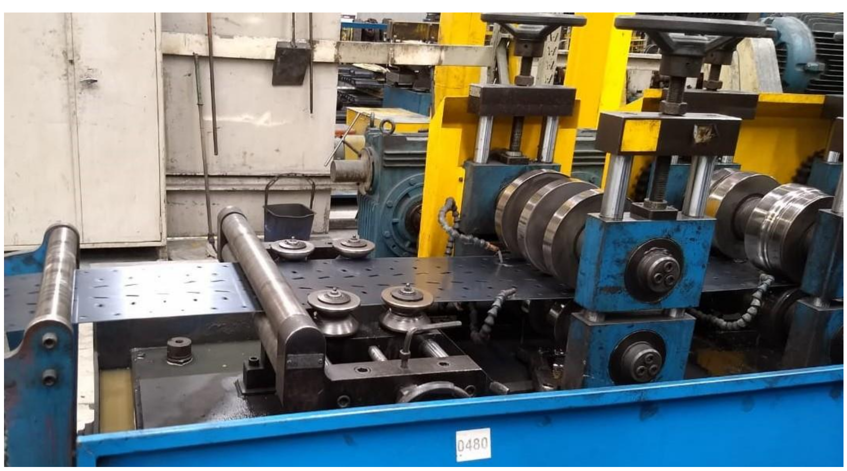


Figure 2. Roll forming process.

Bonada, Pastor, Roure, & Casafont (Bonada et al., 2015) made a study of the influence of the cold-work effects on uprights under pure compression load. The mechanical properties change due to cold work depends on the parameters like corner radius, steel grades and thickness. Pastor, Bonada, Roure, & Casafont (Pastor et al., 2013) simulates the roll forming operation in non-linear finite element analysis and study the effect of the process. The numerical results were compared with experimental tests for short and intermediate length columns, where the failure mode is due to local and distortional instabilities.

The cold-formed profiles present high width/thickness wall ratios. These characteristics make them susceptible to instability phenomena, such as local, distortional, and global buckling. The local buckling occurs when the component plates of the cross section lose stability by deflecting laterally out of its original plane, where the line junctions between elements remain straight, and the angles between elements do not change. The distortional buckling involves the loss of stability with the translation of some of the cross-section vertices. That changes the angles between elements. Global buckling is characterized by instability due to lateral displacements along the element length due to flexural, torsional, or flexural-torsional buckling. More information on the instability modes can be found at (Bonada et al., 2015; C D Moen & Schafer, 2011; Cristopher D. Moen & Schafer, 2009; Neiva, Sarmanho, Faria, Souza, & Starlino, 2018; Pastor et al., 2013; Ribeiro, 2006; Silva, L. S.; Simões, R.; Gervásio, H.; Vellasco, P.; Lima, 2016).

Studies conducted by Moen & Schafer (C D Moen & Schafer, 2011; Cristopher D. Moen & Schafer, 2009; Cristopher D Moen & Schafer, 2009) showed that the first impact of continuous perforations is to reduce the rotational stiffness in elements subjected to distortional buckling. An extensive study was carried out, considering several approaches, using gross area, minimum cross-sectional area, and effective area. An expression was provided to reduce the cross-section thickness and determine the strength reduction due to distortional buckling. The American Standard AISI S100:2016 (Specification & Members, 2016) included this methodology to consider the influence of perforations. There are numerous studies regarding industrial storage systems constructed of cold-formed steel. The main elements are studied separately, including continuous perforated uprights, beams, and connections (Baldassino, Bernuzzi, & Simoncelli, 2019; Bernuzzi & Simoncelli, 2017; Elias, Neiva, Sarmanho, Alves, & Castro, 2018; Huang, Wang, Zhao, & Sivakumaran, 2021; Liu, Pekoz, Gao, Ziemian, & Crews, 2021; Neiva et al., 2018; Pierin & Pignatta, 2015; Prabha, Marimuthu, Saravanan, & Arul Jayachandran, 2010; Sena Cardoso & Rasmussen, 2016).

Neiva et al. (Neiva et al., 2018) carried out a numerical and experimental study about uprights with perforated section rack-type in a cold-formed profile. Axial compression tests were performed, and a numerical model with material and geometric nonlinearities was calibrated. The results were compared to the direct strength method (DSM) predictions, using both a minimum cross-sectional area and the effective area. Modifications were proposed to the DSM original coefficients to consider the continuous perforation along with the element.

Thasan & Rajendran (Thasan & Rajendran, 2020) studied the interaction of expansion bolts with base plate connect cold-formed steel storage racks, under axial, shear and bending interaction. A finite element model using Abaqus has been created, to permit comparisons with experimental results. The authors developed an interaction equation to estimate the stiffness and ultimate moment of resistance of the base plate connection.

In Brazil, the structural design of industrial storage systems with perforated uprights is made using the Brazilian standard ABNT NBR 15524 – Storage systems – Part 2: Selective pallet racks (ABNT NBR 15524-2:2007, 2007). This standard is an adaptation of the British standard, BS EN 15512 – Steel static storage system – Adjustable pallet racking systems – Principles for structural design (EN 15512, 2009). Thus, most of the equations, as the buckling design curve, refer to the Eurocode (EN1993-1-3:2006, 2006). However, the cold-formed Brazilian standard ABNT NBR 14762 (ABNT NBR 14762:2010, 2010) uses theoretical equations based on the American standard (Specification & Members, 2016).

Therefore, the objective of this paper is to evaluate the efficiency of the use of cold-formed Brazilian standard (ABNT NBR 14762:2010, 2010) buckling design curve instead of the formulations of the pallet-rack design standard (ABNT NBR 15524-2:2007, 2007), to study the use viability of the equations present in the ABNT NBR 14762 to calculate the design strength of industrial storage systems perforated uprights under compression with the calculation procedure provided for the ABNT NBR 15524.

2. Brazilian standard of pallet racking design

The NBR 15524 (ABNT NBR 15524-2:2007, 2007) is the Brazilian standard responsible for laying out the principles for the structural design of adjustable pallet racking systems of static steel storage systems. The standard establishes the design of the component structural elements of storage systems based on theoretical and numerical formulations associated with test procedures.

The continuous perforations along the lengths of uprights in storage systems influence these elements' behavior and strength. For this, the design procedure for perforated compression members must take proper account of holes presence. Three alternative procedures are available: (a) design by experimental tests; (b) a theoretical procedure which takes rational account of the perforations, using finite elements to consider local, global and distortional buckling and imperfections; and (c) a mixed calculation procedure with the theoretical formulation and experimentally determined effective area. In this paper, the alternatives (b) and (c) were used.

2.1. *Perforated compression members strength*

The design strength concerning flexural buckling, N_b, shall be determined as follows:

$$N_b = \frac{\chi A_{ef} f_y}{\gamma_m} \tag{1}$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \overline{\lambda}^2}} \qquad \phi = 0.5\left[1 + \alpha\left(\overline{\lambda} - 0.2\right) + \overline{\lambda}^2\right] \tag{2}$$

$$\overline{\lambda} = \sqrt{\frac{A_{ef} f_y}{N_{cr}}} = \frac{\lambda}{\lambda_1}\sqrt{\beta_1} \qquad \beta_1 = \frac{A_{ef}}{A_g} \qquad \lambda_1 = \pi\sqrt{\frac{E}{f_y}} \tag{3}$$

A_g is the gross area of cross-section; A_{ef} is the effective area; f_y is the yielding strength; N_{cr} is the elastic critical axial force for flexural buckling of the cross-section; λ is the slenderness ratio for relevant buckling mode = l/r; l is the buckling length; r is the radius of gyration of the gross section; α is the imperfection factor; and χ is the global buckling reduction factor.

The design buckling resistance, N_b, corresponding to flexural-torsional buckling, N_{crft}, (for monosymmetric cross-sections that are symmetrical about the y-y axis) is determined by using the expressions given in Equations (1) to (3) by substituting the value of N_{crft} for N_{cr}, with:

$$N_{crt} = \frac{1}{{r_0}^2}\left(GJ + \frac{\pi^2 E C_w}{{L_{et}}^2}\right) \tag{4}$$

$$N_{crft} = \frac{N_{cry}}{2\beta}\left[1 + \frac{N_{crt}}{N_{cry}} - \sqrt{\left(1 - \frac{N_{crt}}{N_{cry}}\right)^2 + 4\left(\frac{y_0}{r_0}\right)^2 \frac{N_{crt}}{N_{cry}}}\,\right] \tag{5}$$

Where N_{crt} is the critical force for torsional buckling; N_{crft} is the critical force for flexural-torsional buckling; N_{cry} is the elastic critical load of the upright for flexural buckling about the y-y axis according to Figure 3.

2.2. *Experimentally determined effective area*

To determine the influence of perforations, local buckling, and distortional buckling on the upright compressive resistance, two tests procedures are performed on NBR 15524 (ABNT NBR 15524-2:2007, 2007): (a) a stub column test to observe the influence of perforations and local buckling on the compressive strength of an upright; and (b) a compression test on uprights to determine the influence of the distortional buckling mode, using a column length equal to the length of the storage system single bracing panel.

The failure load is corrected due to variations in the yield stress of the material and the thickness of the test specimen.

$$R_{co} = R_{ob}\left(\frac{f_y}{f_t}\right)^{\alpha}\left(\frac{e}{e_t}\right)^{\beta} \quad (6)$$

R_{co} is the corrected failure load for each test; R_{ob} is the observed failure load for each test; f_t is the observed yield stress for the specimen; f_y is the nominal yield stress; et is the observed thickness for the specimen; e is the design thickness; α and β are parameters relating to the yield stress and thickness of the specimen, respectively.

The mean of corrected values, R_m, on tests are corrected to a characteristic value, R_k, as follows:

$$R_k = R_m - K_s s \quad (7)$$

K_s is the coefficient of test samples; s is the standard deviation of the adjusted test results.

The influence of local buckling and the perforations are presented by the form factor, Q, as follows:

$$Q = \frac{R_k}{f_y A_{min,liq}} \quad (8)$$

$A_{(min,liq)}$ is the minimum cross-sectional area obtained by passing a plane through the upright, normal to its axis.

The effective area of the cross-section, A_{ef}, is calculated from:

$$A_{ef} = Q A_{min,liq} \quad (9)$$

Distortional buckling effects are considered with an experimental test as the stub column test. The upright length should be equal to the length of the storage system single bracing panel. The design strength value for this test is N_{db}. The design strength, N_b, at this column length, in the absence of distortional buckling, is calculated using the effective area and the nominal values of yield stress and thickness and considering the flexural and flexural-torsional buckling following Equations (1) to (5). The flexural buckling lengths are equal to the distance between the centers of support of the member, and the torsional buckling length is half the length of the cold-formed section in the sample. If the ratio $\varepsilon = N_{db}/N_b \geq 1$, no adjustment to the effective area is made. If $\varepsilon<1$, the value of Aef is reduced to a new value at which the calculated value of Nb is equal to the value obtained from the distortional buckling test, N_{db}, and $\varepsilon = 1$. This new value of A_{ef} is used in all subsequent calculations.

2.3. *Buckling curve of ABNT NBR 14762*

The Brazilian standard for the design of cold-formed steel structures NBR 14762 (ABNT NBR 14762:2010, 2010) has theoretical formulations similar to the American standard AISI S100 (Specification & Members, 2016). However, NBR 15524 (ABNT NBR 15524-2:2007, 2007) formulations primarily share similarities with the design presented in Eurocode (EN1993-

1-3:2006, 2006) since it is based on BS EN 15512 (EN 15512, 2009). The NBR 14762 (ABNT NBR 14762:2010, 2010) global buckling reduction factor is not calculated as Equation (2), but as follows:

$$\chi = \begin{cases} 0.658^{\lambda_0^2} & , \lambda_0 \leq 1.5 \\ \dfrac{0.877}{\lambda_0^2} & , \lambda_0 > 1.5 \end{cases} \qquad \lambda_0 = \sqrt{\frac{A_g f_y}{N_{cr}}} \tag{10}$$

3. Methodology

The dimensions (in millimeters) of the upright cross-sections (named H50) studied are presented in Figure 3. It is a rack section, with continuous perforations along the length. The hole height is 50 mm, and the cross-section thickness is 2.25 mm.

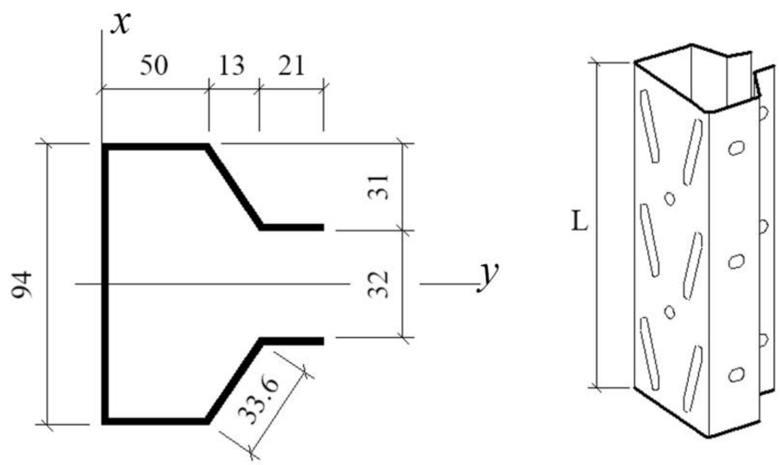


Figure 3. Dimensions of uprights cross-section and perforations.

Stub column tests for measuring the influence of local buckling and the perforations for H50 sections were performed by Ribeiro (Ribeiro, 2006). The load application in the test was done through the universal machine model DL 30000, manufactured by EMIC, with a load capacity equal to 300kN. The assemble and test scheme are indicated in Figure 4. The material properties of the steel, f_y (yield stress), and f_{yu} (ultimate stress), were obtained performing a tensile coupon test. The tensile test specimens were removed from the column stiffeners, as shown in Figure 5.

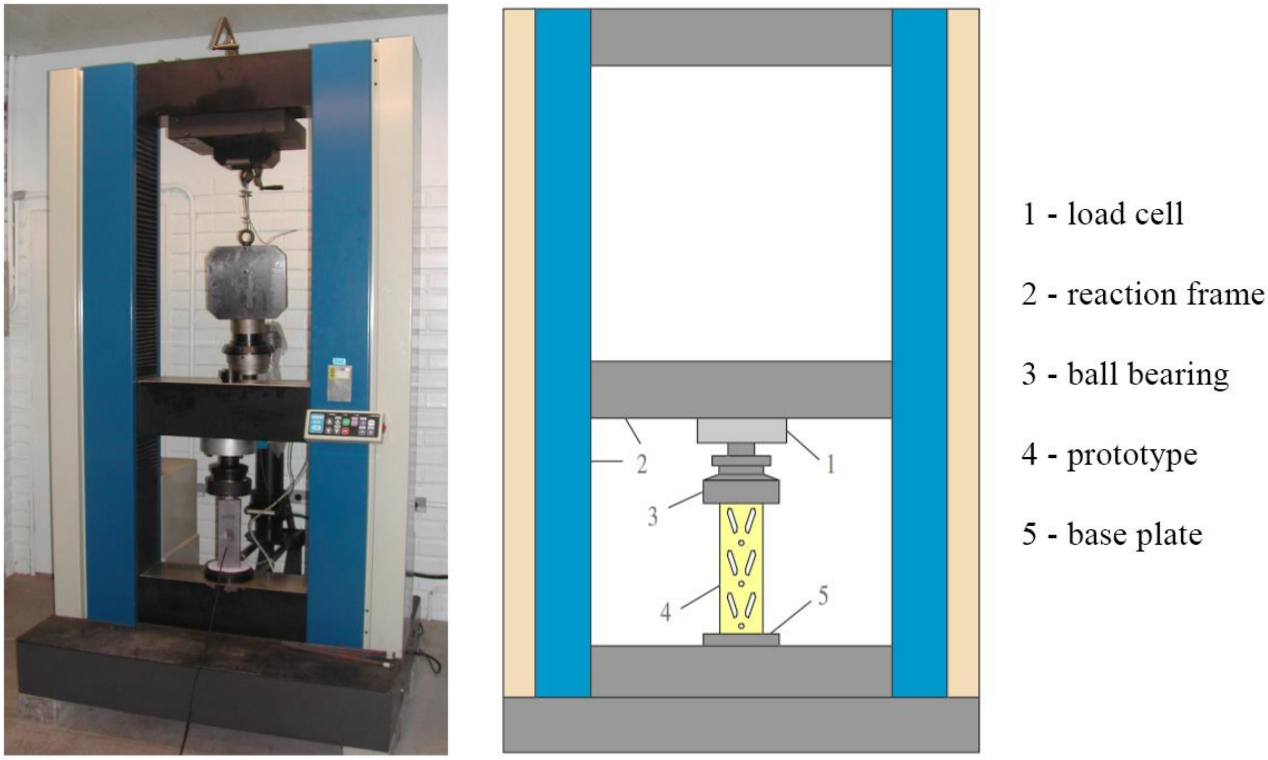


Figure 4. Stub column test scheme.

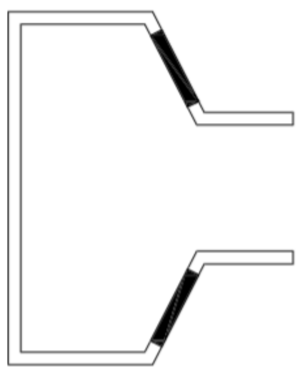


Figure 5. Removal position of the tensile test specimens.

NBR 15524 (ABNT NBR 15524-2:2007, 2007) provides two possibilities to consider the effects of distortional buckling: using experimental tests or numerical analysis. To evaluate the distortional buckling, a finite element analysis using the calibrated numerical model of Neiva et al. (Neiva et al., 2018) via software ANSYS (ANSYS Inc, 2012) was performed. NBR 15524 (ABNT NBR 15524-2:2007, 2007) evaluates the distortional buckling influence by considering a column length closest to one meter (1 m), therefore, in order to accommodate the perforations and guarantees the normative prescriptions, the column length of 960 mm was chosen. The numerical model with all holes and perforations is represented in Figure 6.

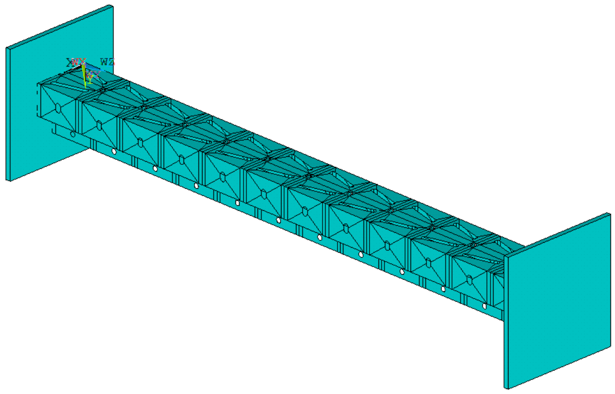


Figure 6. Finite element numerical model.

For modeling the upright, the element type SHELL181 was chosen. This element has six degrees of freedom (three translations and three rotations) per node. To avoid warping deformation of the section, an endplate (with 8 mm thickness) was simulated with element type SOLID45. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The coincident nodes of endplates and upright ends were coupled. The boundary conditions simulate a column with pinned ends, and for this, a node on the centroid of both endplates have the transversal displacements (*x* and *y*) prescribed to zero. The node of one plate is prescribed to zero in the longitudinal direction (*z*). In the same node of the other endplate, the axial force is increased by ANSYS until the upright ultimate load is reached. Figure 7 shows the boundary conditions, the mesh and the axial force of the model.

The steel behavior has been reproduced using an elastic-plastic multilinear model (Neiva et al., 2018). The geometrical nonlinearity is incorporate based on a linear buckling analysis of the model subject to axial compression. After that, the model geometry was updated from the first buckling mode shape with an imperfection amplitude factor equals to half of the thickness (*t/2*).

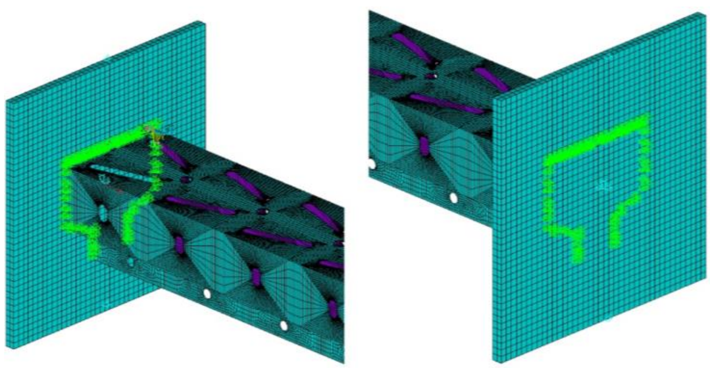


Figure 7. Boundary conditions.

4. Experimental results and analysis

4.1. Stub column results

The upright length of the experimental test, L, the observed yield and ultimate stress for the specimen, f_t and f_u, the nominal yield stress, f_y, minimum cross-sectional area, $A_{(min,liq)}$, the characteristic value of stub column test result, R_k, the form factor, Q, and effective area, A_{ef}, calculated according to ABNT NBR 15524 equations are listed in Table 1.

Table 1. Results obtained for stub column tests of uprights H50.

Perforation type	L (mm)	f_t (MPa)	f_u (MPa)	f_y (MPa)	$A_{min,liq}$ (cm²)	R_k (kN)	Q	A_{ef} (cm²)
H50	300	414	516	310	5.46	117.44	0.69	3.79

4.2. Numerical results

The numerical ultimate load, N_{db}, obtained for the upright was 151.71 kN. Performing the procedures of NBR 15524 (ABNT NBR 15524-2:2007, 2007) for the distortional buckling effects, the design strength, N_b, obtained is equal to 112.52 kN, resulting in a ratio $\varepsilon = N_{db}/N_b$ equals to 1.35. Since ε was greater than 1, it was unnecessary to adjust the effective area obtained from the stub column test.

With the effective area corresponding to the types of perforation studied (H50), the compressive strengths, N_b, of pinned ends were calculated for uprights with lengths ranging from 10 cm to 1200 cm. The nominal yield stress, f_y, used was 300 MPa.

4.3. Discussion

Figure 8 shows a schematic of the four ways used to obtain the compressive strength: (a) with NBR 15524 (ABNT NBR 15524-2:2007, 2007) equations; (b) using the NBR 14762 (ABNT NBR 14762:2010, 2010) global buckling reduction factor (Equation 10); (c) using the global buckling reduction factor of NBR 14762 substituting A_g for $A_{min,liq}$; d) using A_{ef} instead of Ag from Equation 10.

Using the four methods presented in Figure 8, the design strength of H50 uprights were calculated (Figure 9). From the figure, it can be observed that the third proposal (using the buckling curve of NBR 14762 (ABNT NBR 14762:2010, 2010) considering the effective area in place of the gross area) shows a good correlation with the results obtained using the equations of NBR 15524 (ABNT NBR 15524-2:2007, 2007), where the major differences between the two curves occur at the range of 200 and 400 cm. This fact can be justified because for this range, the columns are classified as intermediate columns. Design standards use experimental results to predict the strength in these regions. Thus, NBR 14762 and NBR 15524 use different formulations for predicting the strength of intermediate columns.

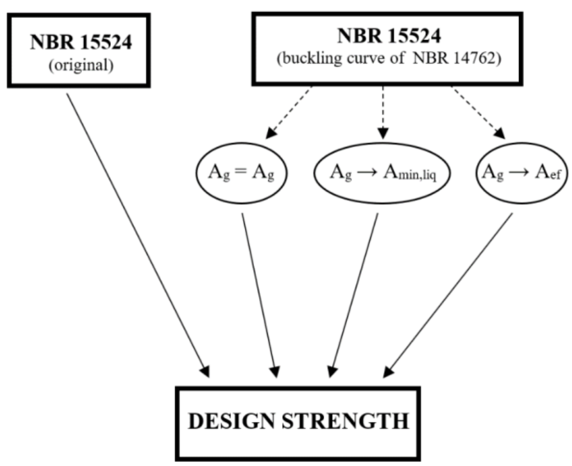


Figure 8. Determination of compressive design strength.

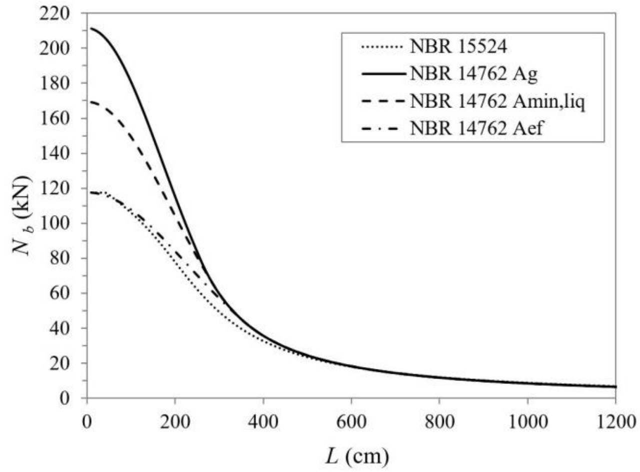


Figure 9. Compressive design strength, N_b, versus upright length, L for H50 models.

5. Conclusions

This paper presented a combined study of experimental, theoretical, and numerical results to the design of continuous perforated members under compression according to the Brazilian standard NBR 15524 (ABNT NBR 15524-2:2007, 2007). The continuous perforations along the lengths of uprights in storage systems influence the behavior and strength of these elements. For that, the design procedure for perforated compression members must take proper account of the presence of holes. The objective of this paper was to evaluate the efficiency of the use of cold-formed Brazilian standard (ABNT NBR 14762:2010, 2010) buckling design curve instead of the formulations of the pallet-rack design standard (ABNT NBR 15524-2:2007, 2007) in order to study the use viability of the equations present in the NBR 14762 to calculate the design strength of industrial storage systems perforated uprights under compression with the calculation procedure provided for the NBR 15524.

Four ways were used to obtain the compressive strength of the continuous perforated upright: (a) with NBR 15524 (ABNT NBR 15524-2:2007, 2007) equations; (b) using the buckling curve of NBR 14762 (ABNT NBR 14762:2010, 2010); (c) using the buckling curve of NBR 14762 (ABNT NBR 14762:2010, 2010) substituting A_g for $A_{(min,liq)}$; and (d) using A_{ef} instead of Ag from buckling curve of NBR 14762.

The results showed that proposal (c) shows a good correlation with the results obtained using the equations of NBR 15524 (ABNT NBR 15524-2:2007, 2007). Therefore, the authors suggest adapting the buckling curve of NBR 15524 to the equations present in NBR 14762 (ABNT NBR 14762:2010, 2010), since the latter is already found in other Brazilian standards.

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Conflicts of interest: not applicable.

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