Structural reliability for the design of rack columns using the Direct Strength Method

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Abstract. Cold-formed steel profiles have been increasingly used in civil engineering applications. A very common section of cold formed profiles is the rack section, mainly used in industrial storage systems. In a few situations, rack profiles present repeated perforations along the length of the member to provide greater freedom of assembly. The structural design standards need to ensure that profiles used in these conditions guarantee the required safety. This work aimed to evaluate the reliability indexes (β) of perforated rack profiles under axial compressive load, using the FOSM and FORM reliability methods and the Monte Carlo Simulation (MCS). In order to obtain the professional factor (P), a database of experimental tests from several authors was elaborated, to be compared to three proposals for adapting the Direct Strength Method (DSM) to perforated columns. The reliability indexes were calculated for the load combinations of AISI S100 (2016) and NBR 14762 (2010) specifications. The β values obtained using two of the methodologies were shown far from the 2.5 and 3.0 calibration targets. The β values obtained by the third methodology were close to the 2.5 target. The last method proved to be the safest, although it requires the Form Factor (Q), that needs to be obtained experimentally.

Keywords: rack columns, perforations, Finite Strip Method, Direct Strength Method, structural reliability.

1 Introduction

Cold-formed steel profiles are obtained by bending flat steel sheets, and due to their versatility, they have achieved a prominent place among steel structures in small constructions and steel frame. The most common method to calculate the resistance of these profiles is the Direct Strength Method (DSM), present in the ABNT NBR 14762 [1] and AISI S100 [2] standards. For the most common profiles, the AISI S100 [2] standard presents one of the DSM adaptations proposed by Moen [3] to calculate the resistance if they have perforations, very common in these profiles for the execution of connections and compatibility. A very common cross-section of cold formed steel profiles is the rack section. Rack profiles are mainly used in industrial storage systems. In current standards, there is no prescribed analytical model for calculating the strength of rack profiles. The strength of rack components is usually obtained by experimental tests or finite element analysis.

There is imprecision in strength calculation models, as in the case of DSM, and this is just one of several involved in structural analysis and design. Therefore, according to Galambos et al. [4], the contemporary trend in the development of technical standards is the use of probabilistic concepts in the choice of design criteria. The design method present in the Brazilian standard ABNT NBR 14762 [1] is the Limit State Method, which stablishes weighting factors to the loads and the resistance of a structural component. These factors are obtained through calibration using advanced reliability methods. A reliability method aims to evaluate a Reliability Index (β) or a probability of failure of a structural component [5].

This paper aimed to evaluate the reliability indexes of perforated rack profile columns, using the reliability methods FOSM, FORM and Monte Carlo Simulation (MCS). In order to obtain the Professional Factor (P), a database of compression tests from several authors was elaborated, to be compared to three proposals for DSM adaptation to perforated columns. One of the proposals analyzed comes from the work of Moen [3], and the other two, based on the paper from Casafont et al. [6]. The critical loads necessary for the DSM were obtained using CUFSM v5.01 ® [7] and CUTWP ® [8]. Reliability methods were applied to calculate β obeying the weighting coefficients present in the AISI S100 [2] and ABNT NBR 14762 [1] standards, for the relations Live Load/Dead Load equal to 3 and 5. For values of β target of these two standards, the values of the resistance factor (ϕ or γ) were also calculated, necessary to ensure the required safety. The values work as proposals for using on future standard versions.

2 Perforated rack columns

The most common method used to calculate the strength of cold formed profiles is the DSM, which uses local elastic buckling stresses for the profile as a whole and geometric properties of the cross-section to predict local and distortional buckling modes. For columns, the method stablishes that the load capacity is given by the smallest value between the global (P_{ne}), local-global (P_{ne}) and distortional (P_{nd}) buckling nominal loads. To obtain P_{nl} and P_{nd}, local (P_{crl}) and distortional (P_{crd}) critical buckling loads are required, which can be obtained by simple computer programs, such as CUFSM ® [7], which uses the Finite Strip Method (FSM) to discretize the columns. P_{cre}, the global critical buckling load can be obtained in CUTWP ® program [8]. However, neither DSM or FSM in their original models cover situations where the structural components have perforations. As a result, several studies have been carried out in recent decades to adapt this methodology to perforated structures, in particular, publications by Moen [3] and Casafont et al. [6].

To adapt the FSM, Moen [3] recommends the input of the net-section with constrained vertices for local buckling analysis, perforated plate thickness reduction for distortional buckling and thickness reduction in the hole region for global buckling. For the DSM to consider the holes, Moen [3] presented 6 options for adapting its equations, all of them considering the holes to obtain the critical loads. In Option 1, holes are included only when critical loads are determined. Option 2 uses the net section to calculate the yelding load. Option 3 defines limits to P_{nl} and P_{nd} to P_{ynet}. Option 4 also limits P_{nl} to P_{ynet}, and defines a transition in the P_{nd} calculation. Option 5 maintain Option’s 4 transition, but includes a transition to P_{nl} as well. And Option 6 is similar to Option 5. However, it has another model for P_{nl}’s transition.

Casafont et al. [6], presented a proposal focused on rack profiles, a reduced thickness method (RTM), where the FSM and the global buckling analysis are applied in models of the cross-section with reduced thickness in the perforated region, to obtain P_{crl}, P_{crd} and P_{cre}. Furthermore, the authors suggest DSM to be applied considering P_y relative to the smallest net-section area found in the profile length. Casafont et al. [9] proposed small changes in the thickness reduction equations of Casafont et al. [6], and reinforced the method's imprecision in the analysis of local buckling. Professor Teoman Peköz also suggested changes to the equations of Casafont et al. [6], the main one being the use of the ANSI MH16.1 [10] Form Factor (Q) in the calculation of local-global and global nominal buckling loads, due to the imprecision pointed by Casafont et al. [9].

3 Reliability methods

Structural reliability studies the safety presented by a structure when evaluating the accomplishment of its function foreseen in the project useful life. The most common method in current standards, which uses a probabilistic base in the design of structures is the Limit State Method (LSM), where the structural reliability is represented by some parameters. It is used in the Brazilian ABNT NBR 14762 [1] and in the AISI S100 [2] (as LRFD or LSD).With both the actions (Q) and the strength (R) of a structure being consider random variables, the structure failure can be represented by the probability of R being shorter than Q. However, obtaining this probability by integration is very difficult, so the concept of reliability index (β) is used to quantify the structural reliability [11].

In the FOSM method, the means R_m and Q_m and the standard deviations σ_R and σ_Q are used, and it is assumed that Q and R follow the lognormal probability distribution. The method also takes the variance of the failure function as equal to the sum of the coefficients of variation of Q and R (V_Q^2 and V_R^2 respectively). The FORM method demands an explicit process to transform random variables of known probability distribution (U) into statistically independent standard normal variables (V). The failure function is represented in the space of reduced variables and the failure surface $g(V) = 0$ is approximated by a linear surface at the point closest to the origin, called as design point (V^*). β is then given by the distance from V^* to the origin. To define V^*, the algorithm proposed by Hasofer and Lind [12] and improved by Rackwitz and Flessler [13] (HLRF) was used. Monte Carlo Simulation (MCS) is a repetition process that generates deterministic solutions to a given problem; each solution corresponds to a set of deterministic values of an underlying set of random variables [14]. From a set $g(x)$ of results from a deterministic solution of the MCS, I is a function that assigns 1 if $g(X) \leq 0$ (failure region) and 0 if $g(X) \geq 0$ (safe region). The probability of system failure is given by an iterative process, in which is counted how many times $g(X) \leq 0$ in a N number of random variable sets (in this paper: $N = 1000$).

According to Nowak and Collins [11], the possible sources of uncertainties in the resistance R of a structural component come from the material (M), the fabrication (F), and the adopted calculation model (P). P is called the professional factor. Considering the average of the values of the uncertainty factors, also random variables, and R_n the nominal resistance (obtained by the model), the average value of R is calculated according to eq. (1):

$$R_m = R_n(P_m M_m F_m) \tag{1}$$

with P being given by the ratio of experimental ultimate strength by the one calculated by the chosen model.

4 Main results

This paper evaluated 98 rack columns whose properties and experimental compression loads were obtained from these publications: Souza [15], Faria, Freitas and Souza [16], Faria et al. [17], Silva [18], Faria [19], Gilbert e Rasmussen [20], El Kadi e Kyimaz [21], Koen [22] and Trouncer and Rasmussen [23]. A statistical summary of the P values is shown in Fig. 1. The P mean values were in general, far from 1.0, and with high values of coefficients of variation. These means were obtained considering the best fit of probabilities from Anderson-Darling test, with the best distribution being chosen among Normal, Lognormal, Gumbel, Uniform, Exponential, Gamma, Weibull, Triangular and PERT for each group. Only RTM 2, proposed by Professor Peköz, presented P values close to 1.0. Figures 2, 3 and 4 shows the values of the reliability indexes calculated respectively via FOSM, FORM and MCS method, considering LRFD and LSD combinations of the AISI S100 standard [2] and the combination from Brazilian standard ABNT NBR 14762 [1].

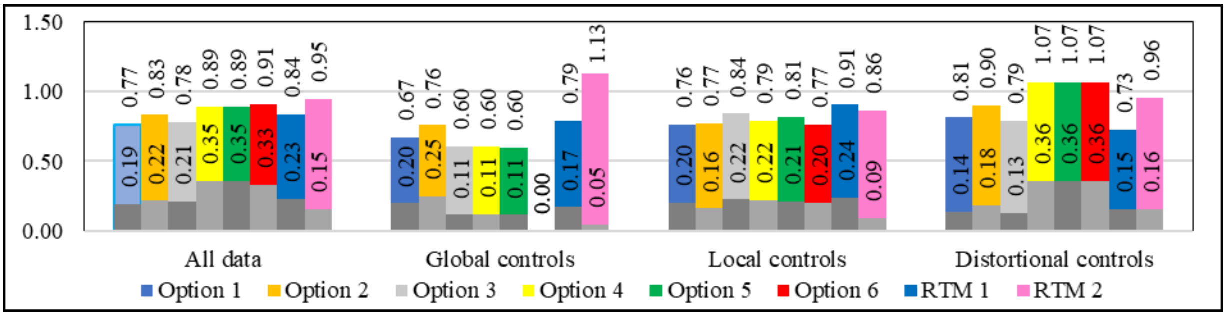

Figure 1. P mean values and coefficients of variation for Moen's options and two reduced thickness models

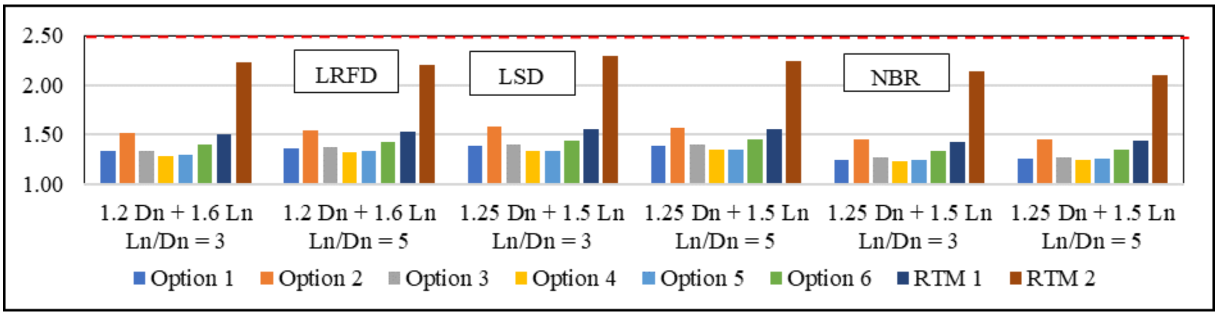

Figure 2. Reliability indexes calculated by FOSM method

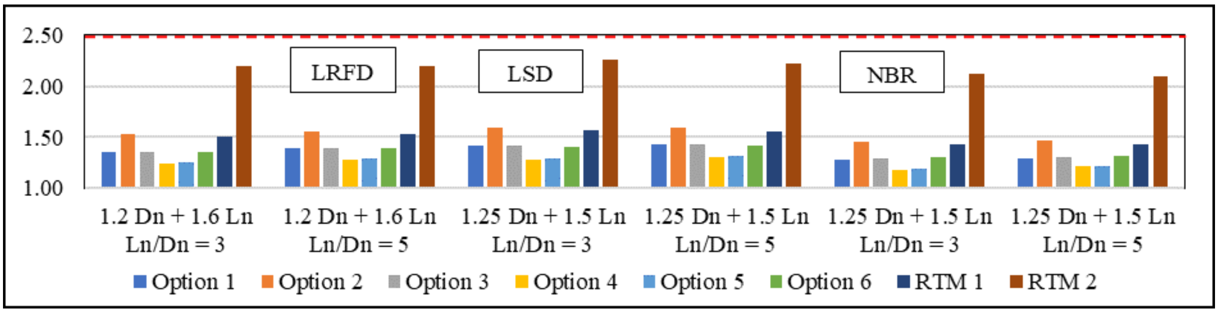

Figure 3. Reliability indexes calculated by FORM method

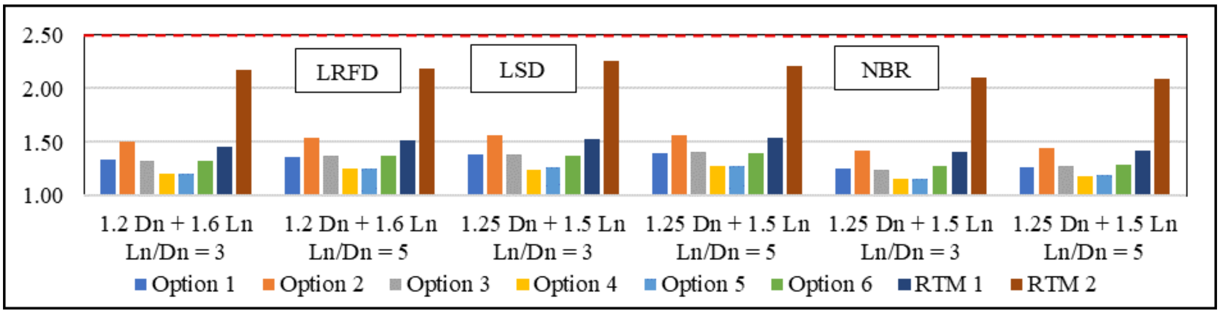

Figure 4. Reliability indexes calculated by MCS

The values calculated by the three methods were close. However, none achieved the target reliability indexes of 2.5 (LRFD and NBR) and 3.0 (LSD). The RTM 2 values are the closest to 2.5. That is why the values of the resistance factors for the RTM 2 are shown in Tab. 1. The ϕ values need small adjustments to reach the target reliability indexes of the LRFD and NBR limit states. However, to reach the LSD β_0, the resistance factor needs higher values, for all data or for individual failure modes.

Table 1. Resistance factors calculated for RTM 2

Failure	Method	Limit state					
		LRFD β_0 = 2.5		LSD β_0 = 3.0		NBR β_0 = 2.5	
		1.2 D_n + 1.6 L_n		1.25 D_n + 1.5 L_n		1.25 D_n + 1.5 L_n	
		L_n/D_n = 3	L_n/D_n = 5	L_n/D_n = 3	L_n/D_n = 5	L_n/D_n = 3	L_n/D_n = 5
All data	γ_{FORM}	1.29	1.30	1.56	1.60	1.34	1.36
	ϕ_{FORM}	0.78	0.77	0.64	0.62	0.75	0.73
Global	γ_{FORM}	0.97	0.99	1.16	1.20	1.01	1.04
	ϕ_{FORM}	1.03	1.02	0.86	0.83	0.99	0.97
Local	γ_{FORM}	1.31	1.33	1.58	1.62	1.37	1.40
	ϕ_{FORM}	0.76	0.75	0.63	0.62	0.73	0.72
Distortional	γ_{FORM}	1.29	1.30	1.60	1.63	1.35	1.37
	ϕ_{FORM}	0.80	0.79	0.67	0.65	0.77	0.75

5 Conclusions

This work aimed to evaluate the reliability of three proposals for adopting DSM to calculate the resistance of perforated rack profile columns. It was possible to obtain the following conclusions: Moen's adaptation options [3] were not suitable for rack columns; Option 2 presented the most reasonable results, but still far from the P value of 1.0; the second method of thickness reduction proved to be the most suitable for calculating columns strengths via DSM, but it needs some adjustments as it did not reach the target reliability indexes and all methods were imprecise in cases of failure due to local buckling, as pointed out by Casafont et al. [9].

Acknowledgements. This study was financed in part by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 and Federal University of Ouro Preto (UFOP).

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