Optimum Positioning of Outriggers in High-Rise Buildings Subjected to Wind Loads

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Abstract. Regarding the design of tall buildings, there are two main criteria that are extremely relevant as the structure height increases: maximum lateral drift (MLD) and core base moment (CBM). The position and number of outriggers (ORs) throughout the height directly affect both aforementioned criteria. Therefore, knowing the locations where the structural system under study is most efficient is a way to minimize even more the MLD and CBM. This work aims to perform a structural optimization of the OR location along the structure height using a heuristic algorithm in order to find its optimal positions/quantities for each criterion separately. In addition, a multi-objective optimization is performed with the intention of obtaining the Pareto frontier. Therefore, in order to achieve this objective, a three-dimensional parameterized numerical model of a tall building will be employed under the action of the lateral wind loads.

Keywords: outrigger, tall buildings, integer programming, wind loads.

1 Introduction

Tall buildings construction has been a global phenomenon in recent decades, as explained by their growing number, mainly, in the Asian continent [1]. Scarcity of land in large urban centers combined with the growing pace of urbanization in this period are factors that contributed to this fact. Hence, vertical solutions are considered the main and recognized options for accommodating the high population density, with a low impact on the environment [2].

However, the design of tall buildings is an engineering challenge, especially in relation to the structural design, because they are highly sensitive to natural actions such as wind and earthquakes. From a structural design point of view, these loads begin to dominate when buildings increase in height. In this way, stability and stiffness criteria become more relevant than strength criterion and, therefore, begin to control the final design. That is, choosing the correct structural system is a determining factor for reducing the amount of materials, as well as for meeting safety, service and aesthetic criteria [3].

Among the several structural systems used to mitigate lateral load actions in tall buildings, the system known as outrigger is one of the most used and efficient. The outrigger is a rigid horizontal element that has the function of perform the connection between the inner core and the perimeter columns, adding stiffness and so lateral strength to the structure. The behavior of the system can be explained in a simple way: when the structure is subjected to lateral actions, the core tries to lean and, because there are rigid arms (OR) connected to the perimeter columns, the rotation is transmitted to them, inducing compression and tension forces. The result is an increase in the effective width of the building. The core moment reduction can be highlighted, with the consequent increase in axial loads in the columns [4].

Outriggers, in principle, can be introduced on any floor along the height of the building. However, there are specific floors that its influence is greater to reduce certain objectives. The maximum lateral displacement, as well as the moment at the base of the core, are important objectives to be reduced in order to obtain an optimized design. Therefore, knowing the optimal floors is extremely important.

In this work, we intend to investigate which are the optimal floors to reduce both the maximum lateral drift of the structure and the bending moment at the base of the core, separately and together. The finite element analysis of the tall building was performed using commercial software, ANSYS. The single-objective optimization is performed using the modified Nelder-Mead method and, later, the multi-objective optimization for both design objectives, using the utility function method (weighted sum of the objective functions) is investigated.

2 Bibliographical review

Along the literature on ORs analysis and design, some involve the optimization task, where objective functions are always related to relevant design code criteria or economic factors. Maximum lateral displacement, inter-story drift, core base bending moment, differential axial shortening between the core and the outer columns and volume of the OR system can be cited as some pursued to be minimized, like in [5-8].

Park et al. [5] investigated the optimal design of OR's structural system elements, i.e., core, external columns and the OR itself, in a 400 m high reinforced concrete building. They also included the optimal position and number of ORs. The solutions were obtained using a genetic algorithm, where the objective function is to minimize the volume of the structural system containing displacement constraints at the top of the building and bending stress at the base of the core.

Chen and Zhang [6] carried out a study involving a multi-objective genetic algorithm based in a simplified mathematical formulation for ORs. Pareto optimal solutions were obtained for 1 to 10 ORs, i.e., the several optimal positions according to the number of ORs. The objectives used in the analysis were: top displacement and core base bending moment.

Kim, Lim and Lee [8] performed a study involving 3 tall buildings with 80 floors (280 m) and each of them with vertical elements with different shapes, aiming to obtain the optimal position of the truss OR over the height that minimizes the maximum lateral drift. The gradient-descent method with the addition of linear and quadratic interpolations was used in the optimization process. In addition, it was verified the influence of the wind loading shape and the best position of the OR with respect to the minimum bending moment at the base of the core.

3 Theoretical basis

3.1 Problem formulation

The objective functions to be optimized in this work are: (a) the maximum lateral drift and (b) the core base bending moment. The position of the OR directly interferes with each of the objectives, thus there is an ideal floor to introduce this element. The amount of design variables depends on the number of ORs that will be placed throughout the height of the tall building. The formulation of the first problem is given by:

$$\begin{gathered} \text{Minimize: } f_1(\mathbf{x}) = \Delta_{top}, \\ \text{Subject to: } \quad \mathbf{x} \in \mathbb{Z}^n \\ x_{i,\min} \le x_i \le x_{i,\max} \quad i = 1, \ldots, n \ , \end{gathered} \tag{1}$$

where x are the design variables (floors with ORs), Δ_{top} is the MLD, $\mathbb{Z}^n$ is the set of integer variables, n is the number of design variables, $x_{i,min}$ and $x_{i,max}$ represent the lower and upper limits, respectively.

The second problem is given by:

$$\begin{gathered} \text{Minimize: } \quad f_2(\mathbf{x}) = M_{base}, \\ \text{Subject to: } \quad \mathbf{x} \in \mathbb{Z}^n \\ x_{i,\min} \le x_i \le x_{i,\max} \quad i = 1, \ldots, n \ , \end{gathered} \tag{2}$$

where M_{base} is the CBM.

The minimization of each of these problems is performed by the Nelder-Mead algorithm. A specially modified version of this algorithm for dealing with integer variables is presented later in Section 3.2. It is noteworthy that the upper and lower limits for design variables are defined according to the number of floors and also with the number of floors that a single OR comprises. In this case, as will be explained in Section 3.3, the range limits are from the 4^{th} to the 80^{th} floor.

Python programming language was used to connect the optimization code and the structural analysis performed by ANSYS APDL. To start the Nelder-Mead algorithm iterations it is necessary to define how many ORs are to be used, the number of story they comprise and the lateral constraints for the design variables (building height). Once stop criterion is met, the optimal position of the ORs that minimize the objective function of interest is obtained.

Multi-objective optimization

As previously defined, both objective functions, f_1 and f_2, participate in the multiobjective optimization. The Utility Function method was chosen in this study. This method assigns weights to each objective function, where the sum of the weights equals 1. Therefore, it is possible to prioritize one of the functions increasing its weight in the optimization. Although, according to Arora [9], this approach is the most common among the multi-objective optimization methods, as seen later, it converges to a defined quantity of optimal values as the weight step decreases.

So, the problem containing both functions can be now defined as:

$$\begin{gathered}\text{Minimize: } f(\mathbf{x}) = \omega f_1(\mathbf{x}) + (1-\omega) f_2(\mathbf{x}), \\ \text{Subject to: } \quad \mathbf{x} \in \mathbb{Z}^n \\ x_{i,\min} \le x_i \le x_{i,\max} \quad i = 1, \ldots, n,\end{gathered} \tag{3}$$

where ω is the weight factor which varies from 0 to 1.

According to Eq. (3) it is possible to see that when the weight is equal to 0 or 1, only one function appears in optimization, i.e., the problem behaves as a single objective optimization. It is noteworthy that these points will represent the extremes of the Pareto Frontier.

3.2 Nelder-Mead algorithm for integer design variables

Introduced by Nelder and Mead [10], Nelder-Mead is a numerical method that aims to minimize or maximize mathematical functions. According to Arora [9], it is a direct search method that does not use gradients in its solution procedure, and can solve non-linear functions. Its approach is based on the comparison of the values of the objective function of $n + 1$ vertices of a geometric configuration known as Simplex, where n is the number of design variables. In the case of a function with only two variables, the problem is considered two-dimensional, with the simplex being a triangle formed by three vertices.

At each iteration of Nelder-Mead algorithm, one seeks to improve the worst vertex of the Simplex through some operations - reflection, expansion or contraction. The worst result function perturbation is always in the mean direction of the remaining points. If none operation results an acceptable point, all vertices are approached in the direction of the best particle [11]. However, it was verified through benchmark functions that this procedure is very susceptible to be stuck in local minima and, therefore, the global minimum is not obtained. For this reason, algorithm modifications will be proposed to avoid undesirable situations in the optimization process.

The modified Nelder-Mead algorithm shown below follows the same step-by-step as described by the original version, as referred in [11]. However, in this case, it will be introduced: (a) randomizations in each of the operations mentioned above; (b) a new operation when all particles are identical. Only particles with integer variables aimed to dealing with integer programming problems. Always at the beginning of each iteration all particles are arranged in ascending order so that

$$f(x_1) \le f(x_2) \le \cdots \le f(x_{n+1}) \tag{4}$$

and therefore the centroid can be calculated according to:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i . \tag{5}$$

The first operation to be carried out is always the reflection and, depending its result, other operations are performed. The mathematical expression that defines all operations mentioned is modified and takes the following form:

$$x = round\left[\bar{x}(1 + c_n R_{normal}) + coef(\bar{x} - x_{n+1})\right], \tag{6}$$

where $round$ represents the rounding operation to the nearest integer number, $c_n = 0.1$ is the reducing coefficient, R_{normal} is a vector containing samples of a standard normal distribution (with mean of 0 and standard deviation of 1) and $coef$ varies according to the type of operation: in reflection $coef = 1$; in expansion $coef = 2$; in the external contraction $coef = 0.5$; in the internal contraction $coef = -0.5$.

If none of the operations improves the result of the objective function, retraction is applied, in which all particles approach the one with the best result. This can be calculated according to

$$x_i = round\left[x_1 + \left(\frac{1}{2} + c_n R_{normal}\right)(x_1 - x_i)\right] \quad (i = 2, 3, \ldots, n+1). \tag{7}$$

Furthermore, before applying the contraction, it is always checked if all vertices are identical, i.e., $(x_1 = x_2 = \cdots = x_{n+1})$. In case this condition is true, x_1 is stored and then a random dilation is applied to x_1, given by the expression:

$$x_i = round(x_1 + c_d R_{normal}) \quad (i = 2, 3, ..., n+1). \tag{8}$$

where $c_d = 0.5$ is the dilatation coefficient.

As previously stated, all the coefficients used in the operations are the same as those proposed by Nelder and Mead [10] in the original method. The ones included in the new programming, c_n and c_d, were chosen according to the best results obtained through tests on eight benchmark functions for integer variables.

A commercial software is used to perform the structural analysis along optimization. Every time the objective function is evaluated, a computational cost of few seconds is spent. Thus, in order to speedup this process, a database was created. This procedure allows that a value already in the database does not need to be evaluated twice in the optimization process, since the analysis for those design variables has already been performed previously.

3.3 High-Rise building modelling

The tall building model used in the analysis has 80 floors (280m). Its plan shape is regular and has dimensions of 43×43m, as shown in Fig. 1 (b). The elements that make up the structure are: concrete core with elastic modulus $E = 3.88 \times 10^4\ MPa$, Poisson's ratio $\nu = 0.25$ and thickness of $t = 0.8\ m$; Steel truss ORs with elastic modulus $E = 210 \times 10^3\ MPa$, Poisson's ratio $\nu = 0.3$ and, horizontal and diagonal OR cross-section area, respectively, of $A_h = 0.12\ m^2$ and $A_d = 0.12\sqrt{2}\ m^2$; perimeter columns with elastic modulus $E = 4.62x10^4\ MPa$, Poisson's ratio $\nu = 0.25$ and cross section of 1.5x1.2 m (see Fig. 1 (b) for orientations); and steel shear connected beams with elastic modulus $E = 210x10^3\ MPa$, Poisson's ratio $\nu = 0.3$ and cross-section area of $A_v = 0.08\ m^2$. An important aspect that can be observed in Fig. 1 (a) is that the OR crosses 3 floors.

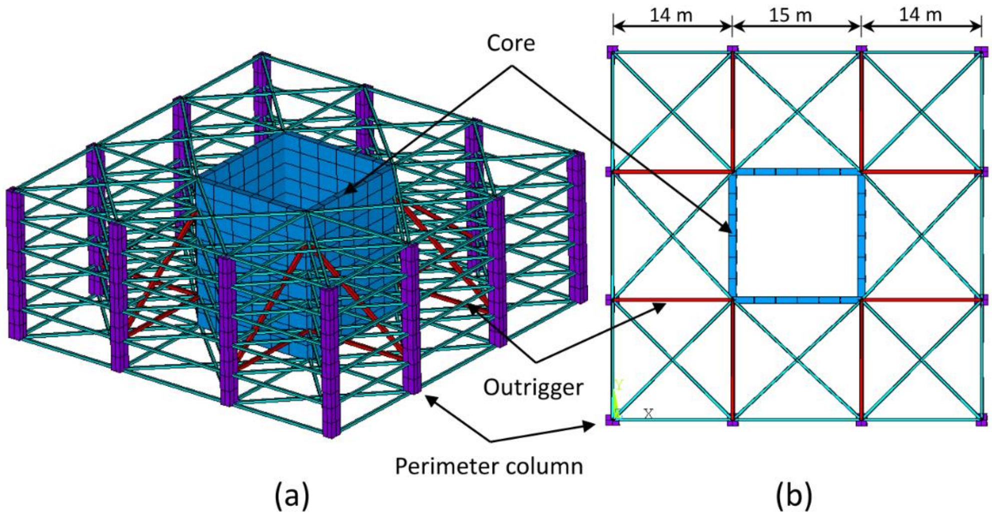

Figure 1. (a) Perspective view. (b) Floor plan view.

Shell finite elements (Shell 181) are used to model the core, truss element (Link 180) are used to model the ORs and shear connected beams, and beam elements (Beam 188) used for the columns. Based on a mesh study carried out to ensure the convergence of results, it was decided to use 2 beam elements per floor with quadratic interpolation functions for the columns and the shell elements were divided into 12 elements per floor using reduced integration. The building base is fully fixed connected with the soil. It is noteworthy that the shear-connected beams introduced into all stories are meant to simulate the rigid diaphragm promoted by the slabs.

The lateral wind loads were statically applied according to NBR6123 [12], considering that the building is located in the urban center of Porto Alegre (category V and class C). In this case, the used basic speed of the wind was $V_0 = 46\ m/s$.

4 Numerical Analysis

4.1 Single-objective optimization

Maximum lateral drift:

Table 1 shows the obtained optimal positions to minimize the maximum lateral drift of the tall building model, together with their respective results normalized by the values obtained without ORs. It is noteworthy that by introducing at least 1 OR along the height, the lateral drift reduction is extremely relevant, about 48%. As the quantity ORs increases, the reduction also continues to decrease, however, at small rate. When 6 ORs are used, a 66% percent reduction is obtained.

Table 1. Single objective optimization results for MLD

Number of ORs	Optimum floor OR position	Normalized lateral drift
1	52	0.5192
2	36, 60	0.4280
3	28, 44, 64	0.3888
4	23, 36, 50, 67	0.3667
5	20, 30, 41, 53, 68	0.3524
6	17, 26, 35, 45, 56, 70	0.3423

Core base bending moment:

Table 2 shows the optimal positions to minimize the core base bending moment of the tall building model, together with their respective results normalized by the values obtained without ORs. Likewise, the lateral drift, core base bending moment reduction follows the same pattern. By introducing 1 OR, a 35% reduction is achieved, and when using 6 ORs, a reduction of 64% is obtained.

Table 2. Single objective optimization results for CBM

Number of ORs	Optimum floor OR position	Normalized bending moment
1	27	0.6541
2	12, 30	0.5357
3	4, 13, 31	0.4657
4	4, 8, 15, 32	0.4104
5	4, 8, 12, 17, 34	0.375
6	4, 8, 12, 16, 20, 37	0.3546

Initially, the reduction of the MLD objective is more pronounced than the CBM. As the number of ORs increases, a smoothing in the curves occurs, as both objective functions converge to very close results, as described in Fig. 2. In all observed cases, the decrease in the lateral drift is higher, with the trend that the CBM objective exceeds the MLD if more than 6 ORs are implemented. In relation to the optimal positions observed in both objectives, lower floor positions were always obtained to reduce the CBM, regardless the ORs numbers.

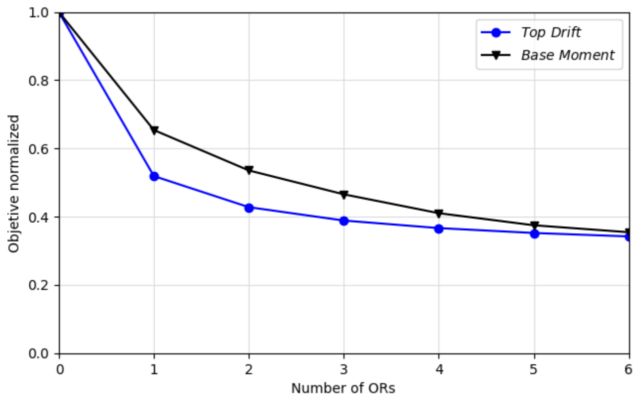

Figure 2. Result of each objective by the ORs numbers.

4.2 Multi-objective optimization

Each weight applied in Eq. (3) provides only one optimum point in the Pareto frontier. Thereat, it is necessary to discretize the weights to obtain a convergence of results, i.e., all Pareto solutions. As can be seen in the Tab. 2, the minimum weight discretization, dw, to reach all Frontier points for 1 and 2 ORs are, respectively, 0.025 and 0.004. It is noteworthy that the extreme points of the Pareto frontier are the results of mono-objective optimization. In case of optimization with 1 OR, the extreme positions are floors 27 and 52, which results in exactly 26 points found. A similar behavior happens using 2 ORs.

Table 2. Number of optimal points from weight discretization.

Number of ORs	dw						
	0.1	0.05	0.025	0.0125	0.00625	0.004	0.002
1	11	18	26	26	-	-	-
2	11	21	33	42	45	47	47

Figure 3 shows the all points of the Pareto frontier for 1 and 2 ORs. It can be noted that the amplitude of the MLD results is more noticeable than the CBM. In other words, CBM has a smaller change compared to MLD.

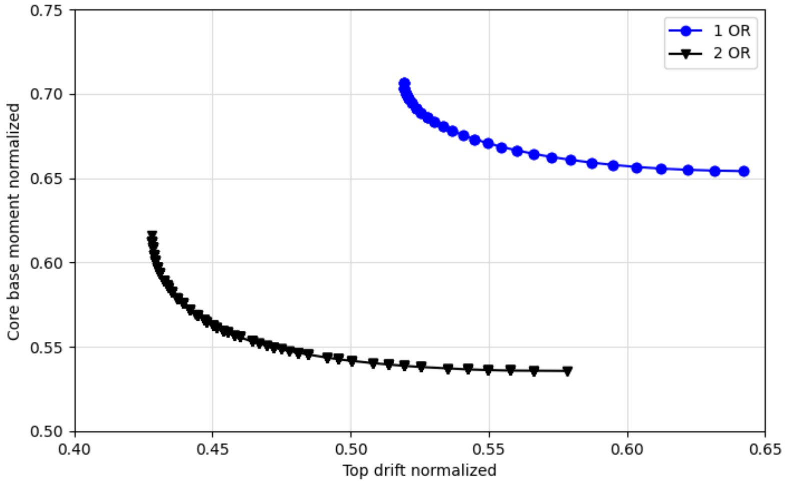

Figure 3. Pareto frontier for 1 and 2 ORs.

4.3 Code validation

In order to prove that the algorithm is really obtaining a global minimum, an exhaustive search was carried out considering 2 ORs being the objective the minimum top drift, as shown in Fig. 4. The graph is symmetric because there is no difference in the value of the objective function when OR's positioning is changed within the design variable. The presence of a continuous diagonal is merely illustrative, as both ORs cannot be present at the same place.

From Tab. 1, the ideal floor for 2 ORs is 36 and 60 with a normalized result of 0.428, being exactly the same values observed using the exhaustive search.

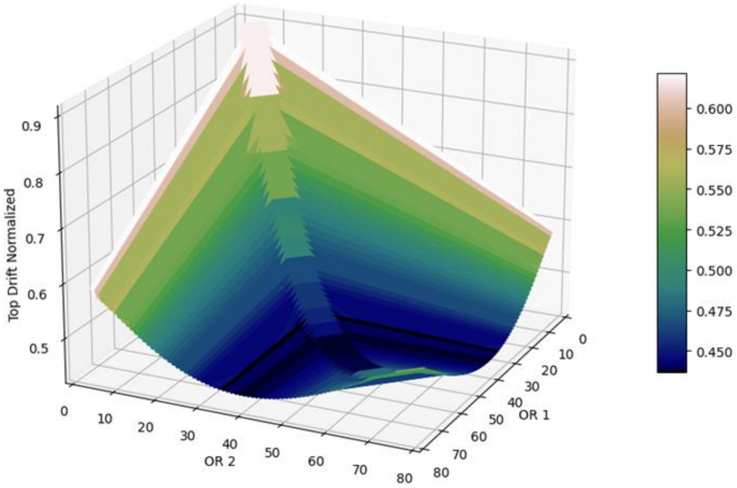

Figure 4. Exhaustive search with two ORs.

5 Conclusions

It was proven by the reduction criteria used in the optimization process that introducing the OR system to mitigate lateral wind actions in tall and narrow buildings is effective. Additionally, there is always a floor throughout tall building height, depending on the chosen objective, which more influences in reducing these criteria. It is observed that the optimum floors are different for each objective employed, i.e., MLD and CBM are conflicting. The optimal positions to reduce the CBM are always lower than the MLD. As new ORs are introduced both criteria decrease up to a certain limit. Finally, using both objectives together gives a range of different solutions, which provides to designers more options to choose.

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