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Structural optimization of plane frame and analyze of the static effect of the wind

Emanuely U. Cardoso[1], Rene Q. Rodriguéz[2], Lucas Q. Machado[3], Felipe F. Kunz[3], Patrick S. Santos[3], Jorge L. A. Ferreira[4]

[1]*Dept. of Engineering Materials Integrity, University of Brasília, Brazil*
emanuely.ugulino@gmail.com
[2]*Dept. of Mechanical Engineering, Federal University of Santa Maria, Brazil*
rene.rodriguez@ufsm.br
[3]*Dept. of Civil Engineering, Mato Grosso State University, Brazil*
lucasqmachado@gmail.com, felipefaustinokunz@hotmail.com, patrick.santos_@hotmail.com
[4]*Dept. of Mechanical Engineering, University of Brasília, Brazil*
jorge@unb.br

Abstract. Structural optimization is used in engineering in order to find elements with optimal characteristics, such as the size of the cross-sections. From this determination it is possible to obtain the weight of the structure, and to find the optimal results it is necessary that some constraints are met, such maximum stresses and displacements. The teaching-learning based optimization method (TLBO) can be used to solve structural problems, making a correlation with a class of students. In this case, students' performance is measured through grades, where in the structural system the grades correspond to weight. The consideration of wind forces in a structural design is essential, as these loads can generate high efforts and require larger dimensions for the elements. The Brazilian standard NBR 6123:1988 regulates the application of wind forces in buildings, both for static and dynamic analysis. Thus, this work aims to analyze a building with application of forces due to static wind loads, as well as the structural optimization of a plane frame. The teaching-learning based optimization method will be used in order to determine the areas of the cross sections, being developed through the Matlab software based on the Finite Element Method.

Keywords: structural behavior, dimension of cross-section, weight.

1 Introduction

Technology for the construction of buildings has grown in recent years, due to the use of computer programs, the development of more resistant materials, such as concretes and high-strength steels, more accurate tests and new construction techniques. With these technologies, buildings now have higher heights and need a more efficient technological control, so that structural performance is still analyzed in the design phase in order to avoid problems during the execution phase or even in use.

According to Soriano [1], structures can be defined as physical systems subject to external actions, capable of transmitting efforts, and these actions are called dynamics when they generate forces of inertia. External actions can cause vibrations in the structures and affect the users' comfort, in which the slender buildings are more susceptible to these effects.

Tall and slender structures have, in general, low frequencies and small rates of damping and under the action of dynamic environmental forces, such as those generated by the wind, can present great amplitude of oscillation, causing problems related to the comfort of users, use in service and even safety and service life of the structure [2].

Regarding structural optimization, Rodríguez et al. [3] carried out an analysis of 3D trusses, in which the effect of the dynamic forces of the wind was considered and from this verification it was possible to determine the cross sections of the structure.

According to Castro [4], a structural design needs to find optimal dimensions for the elements when subjected to different loads. Thus, structural optimization seeks to assist in the engineering area the determination of structures that offer the best performance, through numerous analyses.

The present work was carried out with the objective of analyzing a building receiving static loads from the wind and also the optimization of a plane frame using the based on teaching-learning based optimization method (TLBO), in order to minimize the total weight of the structure.

2 Theoretical Background

2.1 Teaching-Learning Based Optimization

The TLBO method considers the participation of the teacher and students in a class, being subdivided into two different consecutive processes: a teacher phase, that simulates his influence on students; and a student phase that models collaborative learning among students [5]. The teacher is considered the most educated person, who shares his knowledge with students and his ability to influence the class average, because the greater the teacher's capacity, the greater the average achieved by the class. In the same way that the interaction between the students themselves also improves the individual performance of each student [6]. A normal distribution is assumed to represent the performance of students in a class, that is, the grades obtained.

As explained by Rao [6], performance curve A presents the class average as M_A and the best student is considered to be the teacher, who is considered to be the most educated, represented as T_A. The teacher tries to pass his knowledge to the class in order to improve the students' grade. With this, the T_A teacher will try to move the M_A class average to his own level. Consequently, there will be an increase in the level of students to a new M_B average. Through the interaction between the teacher with the class and between the students themselves, the average will increase and, thus, the class will need a new teacher with better quality, that is, the new teacher becomes T_B.

Relating the TLBO method to an optimal structure design, the following relationships can be established: a class of students represents the size of the population to be analyzed; the design variables are considered as the subjects offered to students; the grade is the result of the weight of the structures and the teacher is considered as the best solution obtained. This process is carried out until the objective function is minimized according to the imposed constraints [7].

The steps for applying the TLBO method will be detailed in the following topics, being subdivided into three main steps. In the first step, the parameters and the analysis population are defined, in the second step, the phase related to the teacher and, finally, the phase related to the student.

Definition of the problem and optimization parameters

Firstly, the number of students (population size), the stopping criteria (maximum number of iterations), the number of subjects (design variables) and the limits of the design variables (stresses and displacements) are defined. The optimization problem is also defined as the minimization of $f(X)$, in this case the weight of the structure.

The matrix that represents the class is filled with randomly generated students, according to the population size (*np*) and the number of project variables (*nd*) [7]. Each line represents a candidate project (a student) in the population and $f(X^{1,2,\ldots,np,np-1})$ is the corresponding value of the objective function without restrictions.

Teaching phase

The influence of the teacher is considered, with the objective of verifying the improvement of the knowledge of the students of the class based on the information transmitted by the teacher. In the optimization process, the design vector relates a student's current knowledge in different disciplines. Thus, the student's learning during this interaction with the teacher is expressed as:

$$X_{new}^{k}(j) = X_{old}^{k}(j) \pm \Delta(j) \quad (1)$$

$$\Delta(j) = T_F * r|M(j) - T(j)| \tag{2}$$

where $X^k(j)$ indicates the j-th design variable for the k-th design vector, T_F is the teaching factor, r is a random number uniformly distributed within the range of [0,1], $M(j)$ is the class average, $T(j)$ is the teacher's status and $\Delta(j)$ indicates the difference between the teacher and class average for each project variable, and its sign must be selected so that the student always move towards the teacher. The T_F teaching factor is used to increase the size of the local research space around each student, and can take the value of 1 or 2.

As presented by Camp [5], in a modification to the TLBO method, the class average is calculated by a weighted average based on the student's grade (structure weight), to give more emphasis to the most qualified students, defined by Equation (4):

$$M(j) = \frac{\sum_{k=1}^{np} \frac{X^k(j)}{F^k}}{\sum_{k=1}^{np} \frac{1}{F^k}} \tag{3}$$

If the calculation shows that $X_{new}^k(j)$ is better than the previous $X_{old}^k(j)$, the new solution will be replaced by the current solution, otherwise the old solution will be maintained.

Learning phase

It analyzes the interaction between students in the class, this being another mechanism that helps students to improve their knowledge and also improve the performance of the class. A given solution interacts at random with other solutions, which have more knowledge, in order to obtain new information [7]. The procedure for this phase starts with a random choice of two students in the class, p and q, so that p is different from q. Then it analyzes the aptitude of each student, p being considered as the most qualified student, who seeks to improve his individual performance [5].

Considering that F^p and F^q are the students' grades and represent, in structural optimization, the weight of the structure, the following criteria are analyzed to determine the new solution:

- If $F^p < F^q$

$$X_{new}^p(j) = X_{old}^p(j) + r\left[X_{old}^p(j) - X^q(j)\right] \tag{4}$$

When student p is better than student q he tends to improve his performance even more and, therefore, he goes in the opposite direction to what q is.

- If $F^p > F^q$

$$X_{new}^p(j) = X_{old}^p(j) + r\left[X^q(j) - X_{old}^p(j)\right] \tag{5}$$

However, when the student q shows better performance, the student p tends to approach in order to become better. Where r is a random number uniformly distributed within the range [0,1]. The value of $X_{new}^p(j)$ is accepted if it provides a better value for the objective function.

The steps for choosing the teacher and the student are continued until the best solution is found, ending when the algorithm converges to an optimal solution or reaches the maximum number of iterations.

2.2 Methods of Analysis of the Influence of Wind

The wind acting occurs randomly on the buildings, that is, it affects all horizontal directions, thus taking as reference for study the most critical situation for the structure, knowing that the incidence occurs perpendicular to the plane vertical [8].

According to Chávez [9], the study of wind action in buildings should consider static solicitation, which depends on their mean velocity and fluctuations in their velocity. These fluctuations are the gusts or turbulences that give rise to vibrations due to the various ways in which their force acts on the structure, producing a short term random loading that makes direct stress analysis difficult.

The brazilian standards NBR 6123 [10], regulates the study of the effects of winds on structures and specifies the conditions required to consider the forces due to static and dynamic wind action, for the purpose of building calculation.

Static wind analysis according to ABNT NBR 6123:1988

The brazilian standard NBR 6123 presents for the model of static forces due to the wind the consideration of the parameters of the basic wind speed (*Vo*), suitable for the place where the structure will be built; the factors *S1*, *S2* and *S3*, to be obtained the characteristic speed of the wind (*Vk*), and with the characteristic speed, it is possible to determine the dynamic pressure (q). Then, to obtain the forces, the pressure and shape coefficients are verified [10].

The basic wind velocity (*Vo*), is defined as the velocity of a 3 s gust, exceeded on average once in 50 years, 10 m above ground, in the field open and flat field. It is admitted that the basic wind can blow from any horizontal direction [10].

The topographic factor (*S1*) considers the topographic characteristics of the land on which the construction will take place. This coefficient is 1.0 for flat or slightly rugged locations, 0.9 for deep wind-protected valleys, and has a variation for slope-side buildings [11].

The factor *S2* considers the variation of the wind speed according to the roughness of the terrain, height and dimensions of the construction. Thus, to perform the calculation of this factor one must determine the category to which the building belongs, as well as its class. The category is related to the roughness of the terrain, being established five categories, according to the norm [10].

For the determination of the class that the building belongs to, one must consider the duration of the gust so that the wind encompasses the entire building, as well as the largest dimension. The standard establishes three classes, according to the norm [10].

It is necessary to consider the category and class to determine the parameters contained in the calculation of factor *S2*. This factor can be calculated according to Equation (7):

$$S2 = bF_r \left(\frac{z}{10}\right)^p \tag{6}$$

The gust factor (*Fr*) always corresponds to category II, in which b and p are related to meteorological parameters and z the height corresponds to the analysis floor. The above expression is applicable up to height z_g, which defines the upper contour of the atmospheric layer. These parameters can be obtained according to the norm [10], which presents the respective values considering the roughness category and the building class previously defined.

NBR 6123:1988 also establishes tabulated values of *S2* for the various categories of terrain roughness and building classes, as well as the values of parameters b, F_r, and p, for various time intervals in the five categories. The tabulated values for these parameters can be obtained through the standard.

The statistical factor (*S3*) considers five groups for the required degree of security and the useful life of the building, according to the norm [10].

From the values of *Vo*, *S1*, *S2* and *S3* it is possible to calculate the characteristic wind speed, in m/s, using Equation (8):

$$V_k = V_o S1S2S3 \tag{7}$$

And then obtain the dynamic wind pressure, in N/m2, with Equation (9):

$$q = 0.613{V_k}^2 \tag{8}$$

From the result of q, the wind force is calculated by multiplying the dynamic pressure by the area of influence and a pressure coefficient. This coefficient considers the building in external and internal parts, relating to the permeability, the shape of the building and the wind direction in the structure. The coefficients are described by means of tables and abacuses in NBR 6123:1988 and if the difference between the external and internal pressure coefficients is positive, the total effective pressure will have the direction of the external overpressure, otherwise it will have the direction of a external suction [11]. For the force calculation the drag coefficient can also be considered.

$$F = qAcp \tag{9}$$

Thus, the static analysis of the wind follows the parameters previously defined, in which the force value provides the application of the loads on a structure so the study of structural behavior.

3 Results and Discussions

For this work, we first analyzed two existing cases in the literature, the first in relation to the calculation of static wind forces and the other on structural optimization.

3.1 Static Wind

The bidimensional frame used for the analysis of the wind has a total height of 21.60 m, with the width of the facade in the X direction being 32 m and in the Y direction being 9 m. The scheme of the building used is shown in Figure 1.

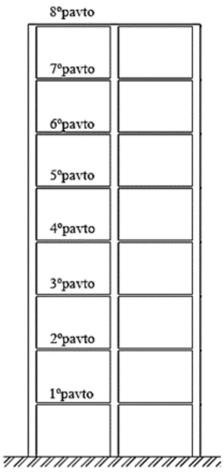

Figure 1. Facade of the building [12]

Table 1. Data for the calculation of wind forces [12]

Floors	Height (m)	Factor *S2*
1º	2.70	0.720
2º	5.40	0.720
3º	8.10	0.720
4º	10.80	0.724
5º	13.50	0.751
6º	16.20	0.773
7º	18.90	0.792
8º	21.60	0.809

To perform the wind forces calculation, the same values presented in Costa's [12] work were used, with the basic wind speed being 33 m/s, the coefficients *S1* and *S3* equal to 1.00, the drag coefficient for the X direction is 1.235 and the Y direction is 0.765. The value of the coefficient *S2* and the height of the floors are shown in Table 1.

The methodology presented by Costa [12] adopts each level of slab as a point of application of wind forces, as these elements present greater rigidity. For this, it was considered that the area of influence for each node would be composed of half of the upper floor and half of the lower floor, except for the load applied on the first floor, which was considered the entire lower floor. This methodology was also adopted for this work and the results obtained are shown in Table 2.

Table 2. Comparison of results

	Wind forces (kN)			
	Direction X		Direction Y	
Floors	Costa [12]	Present	Costa [12]	Present
1º	55.40	55.39	9.65	9.65
2º	36.93	36.93	6.43	6.43
3º	37.15	36.93	6.47	6.43
4º	38.75	37.34	6.75	6.50
5º	41.34	40.17	7.20	6.70
6º	43.62	42.56	7.60	7.42
7º	45.67	44.68	7.96	7.78
8º	23.32	23.31	4.07	4.06

The results obtained in both studies showed close values, and in this study the pavements that presented small variations in wind forces had a reduction when compared to the results of Costa [12]. This small reduction is linked to the fact of the precision of the values used, in which the results obtained in this work through MATLAB are more efficient in precision, due to the calculations being performed through a computer program.

3.2 Optimization Analysis

To carry out the analysis of the optimization code, the weight of the framework structure, implemented for the development of this work, the example shown in Figure 2 was used. For this work, the optimization method based on teaching-learning was used, with the objective of finding the cross sections of the elements that result in the minimum weight of the structure. The analyzed frame shows forces concentrated in both directions and bending moments.

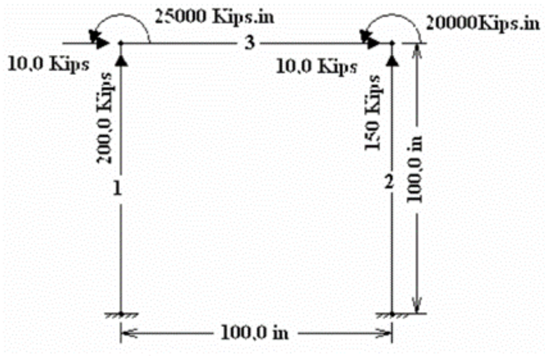

Figure 2. Plane frame optimization [4]

The analysis was carried out in three different cases, varying the displacement and tension constraints, according to the one presented in the work of Castro [4] and shown in Table 3:

Table 3. Data from the analyzed cases [4]

Case	Characteristics
I	Nodes restricted to displacement of ± 0.10 in. All bars restricted to tension of ± 24.0 Ksi.
II	Nodes restricted to displacement of ± 0.07 in. All bars restricted to tension of ± 24.0 Ksi.
III	Nodes restricted to displacement of ± 0.20 in.

The information regarding the material properties and the geometric characteristics of the analyzed frame are described in Table 4.

Table 4. Structure data [4]

Properties	Values
Sizing range	0.1 in2 – 150.0 in2
Modulus of elasticity (E)	3x104 Ksi
Density (ρ)	0.283 lb/in3
Moment of inertia (I)	75*Ai in4
Neutral line (Y)	I / (9*Ai) in

Khan [13] and Castro [4] used continuous area variables in their analysis, and in the work carried out by Castro, the optimization method of genetic algorithms was used and in Khan's, an optimization algorithm based on restrictions was developed. For this work, discrete variables were used with discretization between the established area limits of 0.01 in². Regarding the optimization method used was the TLBO, with the results presented in Table 5.

Table 5. Comparison of results

	Cross section area (in^2)								
	Case I			Case II			Case III		
Element	Khan [13]	Castro [4]	Present	Khan [13]	Castro [4]	Present	Khan [13]	Castro [4]	Present
1	19.81	14.15	13.42	17.78	18.84	18.70	6.43	6.28	6.38
2	105.39	95.55	94.29	130.07	135.36	134.94	46.42	47.24	47.07
3	30.18	42.26	44.05	69.31	62.57	63.12	23.04	22.37	22.42
Weight (lb)	4397.25	4300.46	4294.81	6145.63	6134.59	6134.31	2147.69	2147.68	2147.12

The results regarding the weight of the structure in the three cases analyzed were lower when using the TLBO as an optimization method, with the greatest variation occurring in case I, in which the present one studied obtained a reduction of 2.33% in relation to the weight found by Khan [13]. Thus, the efficiency of the TLBO method is apparent for the optimization of frames, in which the results found in this study were lower when compared to those presented in the literature.

4 Conclusions

Through the study it was possible to observe the application of wind forces in a building, in which these loads are essential to perform a structural analysis, as they can generate efforts that cause significant changes in the behavior of the structure, such as vibrations and displacements.

The structural optimization of plane frames is necessary to verify the variation and the relationship of the cross sections with the applied loads, in order to verify the behavior of the structure when subjected to different loads. In addition, the optimization helps to find the ideal dimensions for the structure, in a way that meets the imposed restrictions and allows the reduction of areas when possible.

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