Civil Engineering
Engenharia Civil

Clarifying the theoretical basis of the global geometric imperfection analysis (out-of-plumb columns)

http://dx.doi.org/10.1590/0370-44672020740092

Petrus Gorgônio Bulhões da Nóbrega[1,2]
https://orcid.org/0000-0002-8597-0158
Rodrigo Bezerra Andrade[1,3]
https://orcid.org/0000-0003-3448-5205
Selma Hissae Shimura da Nóbrega[1,4]
https://orcid.org/0000-0002-0279-273X

[1]Universidade Federal do Rio Grande do Norte - UFRN,
Centro de Tecnologia,
Natal – Rio Grande do Norte - Brasil.

E-mails: [2]petrus@ufrn.edu.br,
[3]rodrigo31ba@hotmail.com, [4]shsnobrega@gmail.com

Abstract

The concrete structures present several geometric deviations, some of them considered indirectly in the safety factors of the design. However, the imperfections of the element axes, especially columns, should be explicitly considered in the structural analysis because they have great influence over the building stability. The NBR 6118:2014, Brazilian standard code for the design of concrete structures, defines a global geometric inclination to the columns, also called "out-of-plumb columns", that causes additional forces not presented in the "perfect" structure, which must be considered as a permanent action. The code also sets the design equations, as well as the load combination criteria. Although the expressions for the out-of-plumb angle calculation are used in the designs, they are not well understood by the technical community or even really explained in Brazilian publications. This paper discusses the theoretical basis that supports such expressions and compares what is presented in NBR 6118:2014 to other international codes. Structural analysis results are discussed, considering buildings with different heights and loadings, to evaluate how the global out-of-plumb effect seems to be relevant. The main objective is to contribute to a better understanding of the concrete building design principles and, specifically, fill a gap in national technical literature about this global imperfection.

Keywords: global imperfection, geometric imperfection, out-of-plumb columns, out-of-plumbness.

1. Introduction

The limit state concept (serviceability and ultimate limit states) associated to partial safety factors (which reduce the design strength of materials and increase the design value of loads), based on a semi-probabilistic approach, was introduced in the 1970's to produce more rational structural design procedures. Despite this, the structural calculation still follows essentially a deterministic process.

However, there are several uncertainties in the strength of materials, in the loads and in engineering calculation models, among other aspects. The resistance and dimensions of a member, for example, are not deterministic quantities, but stochastic due to the scatter in the materials used and in the construction process itself. So, a great point of interest is the deviations of actual properties from nominal values, and the definition of limiting values for these deviations, named "tolerances", in accordance with the safety concept.

Zilch and Schießl (2010) express that tolerances are criteria that indicate whether an imperfectly executed structure complies with the requirements of safety, durability and serviceability, and their definitions are part of the design concept as well as the definition of safety factors. According to the authors, the geometric deviations (and the corresponding tolerances) may be subdivided into: (a) deviations in cross section dimensions; (b) deviations in the position of reinforcement; (c) deviations in span; (d) deviations from perfect shape (curvature) and direction of members; and (e) deviations in the location of members (Figure 1 illustrates this).

All buildings, including precast concrete structures built with the greatest practical accuracy, will contain imperfections due to the construction methods, errors or natural effects. Some of these are unavoidable, for example over-turning moments due to balconies, hanging facade panels, etc. resulting in horizontal deflection and curvature in columns and walls (Elliott, 2017).

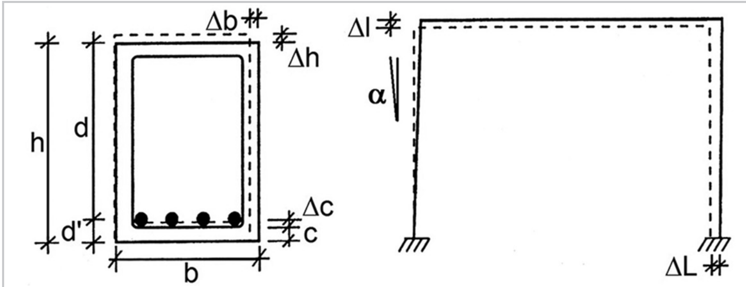

Figure 1 – Different types of deviations (adapted from Zilch and Schießl, 2010).

Ibracon (2015) divides the deviations into similar categories to the ones set by Zilch and Schießl (2010), stating that many of these imperfections may be considered only by partial safety factors, but not those regarding the members' axial direction. These should be investigated directly due to important effects on a building stability. Elliot (2017), in a similar manner, points that "deviations in cross section dimensions are taken into account in material safety factors".

Indeed, geometric imperfections on the axes of elements should be contemplated in structural analysis, as they will be subjected to additional loadings, proportionally to the story's displacements. Figure 2 shows a "perfect" structure (a), and the same building with axial deviations (b). The different force equilibrium configuration is noticeable, especially due to the extra moment reaction in the columns and foundation, generated by the new loading eccentricities.

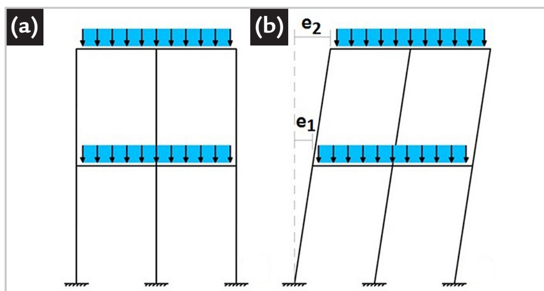

Figure 2 – Structure without (a) or with (b) global geometric imperfections.

The NBR 6118:2014 is the current Brazilian standard code for the design of concrete structures (ABNT, 2014), which classifies the geometric imperfections into two groups: local and global, establishing that they should be considered in the ultimate limit states, but not in the serviceability ones. This procedure is consistent with a vast majority of concrete codes. One of the global geometric imperfections is the out-of-plumb columns, situation where, due to construction errors, the centroids of the tops of the columns are not directly over the centroids of the bottoms.

The calculation procedure and its expressions were accepted by the technical community without a detailed discussion, and despite the elapsed time, a doubt about them and about a clear understanding of the subject still remains. Because there is no paper in the Brazilian literature that contains further explanations about the topic (but only transcriptions of the code expressions and simple explanations), the objective of this study is to clarify the theoretical basis that supports this analysis (the local geometric imperfections are not the focus), answering some questions and filling a gap in the technical publications:

1) Why is it necessary to consider a global geometric imperfection analysis (out-of-plumbness)?

2) What is the origin of the NBR 6118 global out-of-plumb (lack-of-plumb) columns expressions?

3) What does the parameter "n" (number of columns) mean and how does its influence take place?

4) In what kind of building (height and load level) does the out-of-plumb effect seem to be relevant?

2. Code's requirements

The ACI 318-19 Building Code Requirements for Structural Concrete (ACI, 2019) and the CSA A23.3-14 Code for Design of Concrete Structures (CSA, 2014) are silent regarding the global effect due to out-of-plumb columns. Another American code, ASCE/SEI 7-16 (ASCE, 2016) defines that each structure shall be analyzed for static lateral forces applied independently in each of two orthogonal directions. In each direction, the forces at all levels shall be applied simultaneously, determined by the expression $F_x = 0.01\ W_x$, where W_x is the portion of the total dead load of the structure located or assigned to level "x". So, the ASCE/SEI 7-16 does not explicitly consider this geometric global imperfection, although the force F_x may consider it indirectly.

The inclusion of this topic in NBR 6118 is inspired by European codes, more specifically the Fib Model Code 2010 (FIB, 2010) and Eurocode 2 (CEN, 2004), which will be presented next. For the discussion of sections 2.1 to 2.3, Figure 3 should be observed.

It is important to remark that in structural analysis this global geometric imperfection effect is usually considered by fictitious notional horizontal loads, which is different from modeling the whole leaning structure. This is a simplified procedure, but the notional loads simulate in an adequate manner the equivalent moment caused by the eccentricity of vertical load.

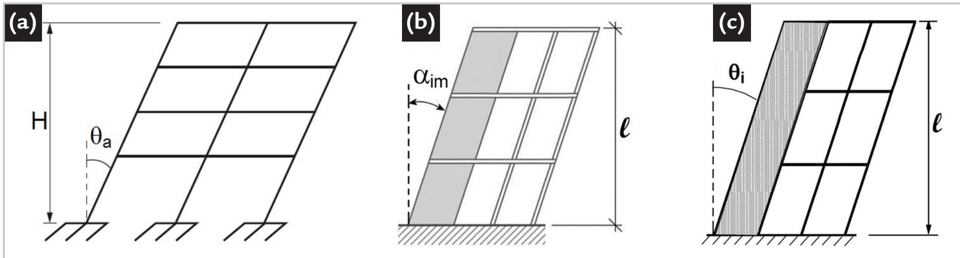

Figure 3 – Out-of-plumb columns in NBR 6118:2014 (a), Model Code 2010 (b) and Eurocode 2 (c) (adapted from ABNT, 2014; FIB, 2010; and CEN, 2004).

2.1 ABNT NBR 6118:2014 (NBR 6118)

The requirements about this topic did not exist in the old editions of NBR 6118, they appeared for the first time in 2003 edition and were slightly modified in the NBR 6118:2014. This latter code defines a global inclination angle θ_a (Figure 3a), expressed by Equation (1).

$$\theta_a = \theta_1 \sqrt{\frac{1+1/n}{2}} \quad \text{where} \quad \theta_1 = 1/(100\sqrt{H}) \tag{1}$$

"H" is the total height of the building (in meters), and "n" is the number of columns considering a plane (2D) frame model. In fact, about this parameter, the original text in Portuguese is "*número de prumadas de pilares no pórtico plano*", which is a different definition when compared to the MC 2010 and EC2 codes, causing doubt. This specific subject will be detailed in the section 4.1 of this paper. NBR 6118 code also sets the extreme values for the angle θ_1: $\theta_{1\,min}$ = 1/300 (0.33%) for framed structures (braced or unbraced), and $\theta_{1\,max}$ = 1/200 (0.5%). For buildings with flat slabs, with or without drop panels or column heads, $\theta_a = \theta_1$ (this is equivalent to consider n = 1), and for any other structure $\theta_a = \theta_1$, depending on the value of "n".

Lastly, it should be noticed that the out-of-plumb effect may be ignored (or neglected, maybe a better expression) depending on the intensity of the wind load. The criteria for this and its numerical application will be discussed in section 4.2.

2.2 *Fib* Model Code 2010 (MC 2010)

MC 2010 indicates that the average unintended inclination α_{im} (Figure 3b) of a group of vertical compression members can be estimated from Equation (2), where "m" denotes the number of compression members which have to be included in determining this effect and ℓ denotes the height (in meters) of the compression member or compression members standing on top of one another. For the stabilizing structure, MC 2010 explicitly indicates that "m" is the number of vertical structural members that contribute to the horizontal force on the stabilizing structure, and ℓ is the height of the building. α_i is the unintended inclination of vertical compression members, whose extremes values are $\alpha_{i\,min}$ = 1/300 and $\alpha_{i\,max}$ = 1/200.

$$\alpha_{im} = \alpha_i \sqrt{0.5\,(1+1/m)} \quad \text{where} \quad \alpha_i = 0.01/\sqrt{\ell} \tag{2}$$

It is noticeable that α_i and α_{im} are analogous to θ_1 and θ_a from NBR 6118, and that the limit values of the deviation angle are the same. That is, both design codes are equivalent, with exception to the definition of number of columns to be considered. NBR 6118 mentions a 2D frame model, while MC 2010 defines this parameter as the number of vertical members that contribute to causing the horizontal force, independently from considerations to the structural model used.

2.3 Eurocode 2 (EC2)

The EC2, Part 1-1, indicates that the global imperfection may be represented by an inclination θ_i, given by Equation (3) and shown in Figure 3c. θ_0 is the basic value, which varies depending on the country, but the recommended value is 1/200. α_h is the reduction factor for length or height, with the limits $2/3 \le \alpha_h \le 1$; α_m is the reduction factor for number of members; ℓ is the length or height (in meters); and "m" is the number of vertical members contributing to the total effect. For the effect on stabilizing structure, EC2 explicitly indicates that ℓ is the height of the building, and "m" is the number of vertical members contributing to the horizontal force on the bracing system.

$$\theta_i = \theta_0 \alpha_h \alpha_m \quad \text{where} \quad \alpha_h = 2/\sqrt{\ell} \quad \text{and} \quad \alpha_m = \sqrt{0.5\,(1+1/m)} \tag{3}$$

The product of the first two terms of θ_i ($\theta_0 \cdot \alpha_h$) results as analogous to the term θ_1 from NBR 6118, if θ_0 is considered as the recommended value 1/200. This last value, in turn, multiplied to the limits of α_h ($2/3 \le \alpha_h \le 1$), results in the extreme values $\theta_{1\,min}$ = 1/300 and $\theta_{1\,max}$ = 1/200 from NBR 6118. At last, the product of the three terms of θ_i is analogous to θ_a from NBR 6118. In conclusion, the expression from EC2 is similar to that of NBR 6118, excluding the definition of the term "m", the number of columns to be considered. Eurocode 2, as well as MC 2010, does not mention a 2D frame model, but only the number of members that cause the effect.

3. Origin of the out-of-plumb columns analysis expressions

Equations (1) to (3) indicate, generally, that the global geometric imperfection effect in a building is a function of total height and number of columns. In fact, the angle is inversely proportional to the square root of the height and to the term associated with the number of columns. It is possible to conclude: (a) taller buildings are related to smaller out-of-plumb angles; and (b) a great number of columns justifies an angle reduction because it is less probable that all members present an equal inclination in the same direction.

Two important papers for the historical review are MacGregor (1979) and Beaulieu and Adams (1977). The first author affirms that the CEB Model Code, 1978 edition, for the design of "frames with displaceable nodes" employed an "unintentional lean" of Δ_d/ℓ = 1/150 (≈ 0.7%) for single-story frames or frames loaded mainly at the top, and a value of 1/200 (0.5%) for other types of frames, considering Δ_d as displacement of the story and ℓ is the height of the frame. In addition, the equivalent lateral loads must be amplified in some cases to account for creep deflections.

The Swedish concrete code from that time, apud MacGregor (1979), set the value 0.7% (≈ 1/143) for one bay structures (a relatively severe lean) and the value 0.35% (≈ 1/286) for multi-bay structures (half of the first value), recognizing a random nature of the column out-of-plumbs. MacGregor (1979) also reported that the 1971 West German code presented an expression to calculate the lean equals to $\Delta_d/\ell = 1/(100\sqrt{h_t})$, where h_t is the total height of the building (in meters). The use of the square root, specifically, is an attempt to recognize the random nature of the column leans by reducing its magnitude.

Notice that the expression considered in the West German code remains directly within NBR 6118 and MC 2010 requirements. In addition, the cited limits for the inclination are similar with the current ones. However, no relationships indicated above consider a term related to the number of columns. Beaulieu and Adams (1977) exposed two important conclusions: (1) a statistical analysis is required to correctly represent the actual problem; and (2) only consistently planned field measurements should serve as the basis for the derivation of design equations.

MacGregor (1979) investigated several studies reporting measurements of out-of-plumb columns taken in precast and cast-in-place structures. Based on the mean and standard deviation of the measurements, the author proposed Equation (4), where the parameter "N" is the number of columns involved, and the relation Δ_d/ℓ is the mean lean. Equation (5) derives from (4) taking into account the creep deflections and rewritten in terms of a square-root. Obviously, for this fact, its results are higher than that obtained by Equation (4). The increment depends on the parameter "N" and it is lower (in percentage terms) as the number of columns increases. In other words, the difference between the results, by Equations (4) and (5), decreases when the value of "N" increases.

$$\Delta_d/\ell = 0.0001+0.0077/\sqrt[2.2]{N} \qquad (4)$$

$$\Delta_d/\ell = 0.00015+0.015/\sqrt{N} \qquad (5)$$

In the same year, and also based on pre-cast structures measurements, Stoffregen and König (1979) proposed the Equation (6) for calculation of the inclination angle (φ_2) taking into account the number of columns involved (k) and the number of stories (ℓ).

$$\varphi_2 = 1/1000+7/(1000\sqrt{k\,\ell}) \qquad (6)$$

Zilch and Schießl (2010) report important information about the term associated to the number of columns. They comment that for single columns, the imperfection must be assumed to have the most unfavorable shape and direction, but for frames and columns acting in parallel systems, this is conservative from a probabilistic point of view. The destabilizing force F_i of a column inclined with an angle α_i, illustrated in Figure 4, is $F_i = N_i \tan \alpha_i \approx N_i\alpha_i$.

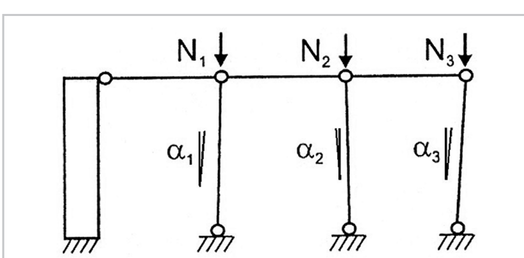

Figure 4 – Inclinations in a frame system (adapted from Zilch and Schießl, 2010).

If the inclination is a random variable with zero mean and N_i is deterministic, the standard deviation of F_i may be expressed by $\sigma_F = N_i\,\sigma_\alpha$, where σ_α is the standard deviation of the angle α_i. There are two possibilities for the standard deviation of total horizontal force $\sigma_{F,tot}$. In both situations, it is assumed that there is an equality of all vertical forces N_i.

a) If the columns inclinations have a full correlation (called systematic): $\sigma_{F,tot} = n\,N_i\,\sigma_\alpha$. "n" is the number of columns and it should be highlighted that the assumption is very conservative, since it considers all columns related to the design value of the inclination;

b) If the imperfections are mutually independent (called random): $\sigma_{F,tot} = \sqrt{\sum (N_i\,\sigma_\alpha)^2} = \sqrt{n}\,N_i\,\sigma_\alpha$.

The authors also indicate that because this last expression assumes a complete lack of correlation, as well as the equality of all vertical forces, it is on the unsafe side when there is a systematic error (*i.e.* some degree of correlation) in the unintentional inclination. In this case, the total variation may be split into a systematic part α_s and a random part α_r. The combination of the two parts gives a total standard deviation of the acting horizontal force.

$$\sigma_{F,tot} = \sqrt{(\sigma_{F,tot\,s})^2 + (\sigma_{F,tot\,r})^2} = \sqrt{(n\,N_i\,\sigma_{\alpha,s})^2 + (\sqrt{n}\,N_i\,\sigma_{\alpha,r})^2} = N_i\,n\sqrt{\sigma_{\alpha,s}{}^2 + \frac{1}{n}\,\sigma_{\alpha,r}{}^2} \quad (7)$$

According to the authors, due to the lack of data, the choice of the ratio α_s / α_r is rather arbitrary, and the formula given in MC 2010 is based on the assumption that $\sigma_{\alpha,s} = \sigma_{\alpha,r}$. Equation (7) becomes:

$$\sigma_{F,tot} = N_i\,n\,\sigma_\alpha\,\sqrt{(1+1/n)} \quad (8)$$

Finally, it would be advisable to consider in Equation (8) a parameter associated to the horizontal force transference between columns and the horizontal elements. So, for that, and also taking into account an averaging effect, a reduction factor equal to 0.5 is applied in Equation (8) (Zilch and Schießl, 2010), resulting in Equation (9). Evident is the similarity between the radicand of this equation and those given by NBR 6118, MC 2010 and EC2, Equations (1), (2) and (3).

$$\sigma_{F,tot} = N_i\,n\,\sigma_\alpha\,\sqrt{0.5\,(1+1/n)} \quad (9)$$

It is important to highlight two hypotheses to obtain Equation (9): first, the systematic standard deviation $\sigma_{\alpha,s}$ was considered equal to the random standard deviation $\sigma_{\alpha,r}$; and second, all the vertical forces N_i were admitted as equal. For this last hypothesis, the term N_i could be put outside of the radicand and of the reduction factor.

In conclusion, the average unintended inclination (θ_a) of NBR 6118 Code is the union of the expression $1/(100\sqrt{H})$ with the square root existent in Equation (9). The first term is the unintended inclination of the columns (θ_1), or the basic value multiplied by the reduction factor for length or height, and the second term is the reduction factor for the number of elements.

4. Assessment of the out-of-plumb columns expressions

4.1 Evaluation of the parameter "n" (number of columns)

In out-of-plumb analysis, the engineer faces a difficulty in interpreting the NBR 6118 with respect to the parameter "n". While this code assigns the particularity of the "plane frame model" in the definition, MC 2010 and EC2 define it as the number of vertical members associated to the global imperfection or that contributing to the horizontal force on the structure, independently whether the frame model is plane (2D) or tridimensional (3D). It seems that this last definition is more correct and the decision if a column is part or not of the bracing system should be delegated to the engineer. Elliot (2017), for example, presents examples of precast concrete structures based on EC2 code, where the number "n" is defined considering all the columns, just as done by Covas and Bandiera (2015) for cast-in-place structures. So, it is important to use a precise definition of the number "n", because it will influence the radicand of Equation (1) ($\sqrt{(0.5\,(1+1/n)}$) and, directly, the final result of the angle θ_a.

A simple but didactic example is shown in Figure 5: a five-story building (four floors and roof) composed of 3 frames (5 columns each), in horizontal x-direction, and 5 frames (3 columns each), in vertical y-direction. For Figure 5, consider "L" for slab, "P" for column and "V" for beam. The length in x-direction is twice the y-direction and as the story height is 3m, the total height results in 15m. The intended occupancy of the live load specification is by offices. The CAD/TQS version 21 software package, which is a program widely known in Brazil, was used to perform the structural analyses. The objective is to evaluate how the parameter "n" influences the results, comparing the total moment reaction value in foundation caused by the out-of-plumb effect (named as M_{ggi}, moment due to global geometric imperfection).

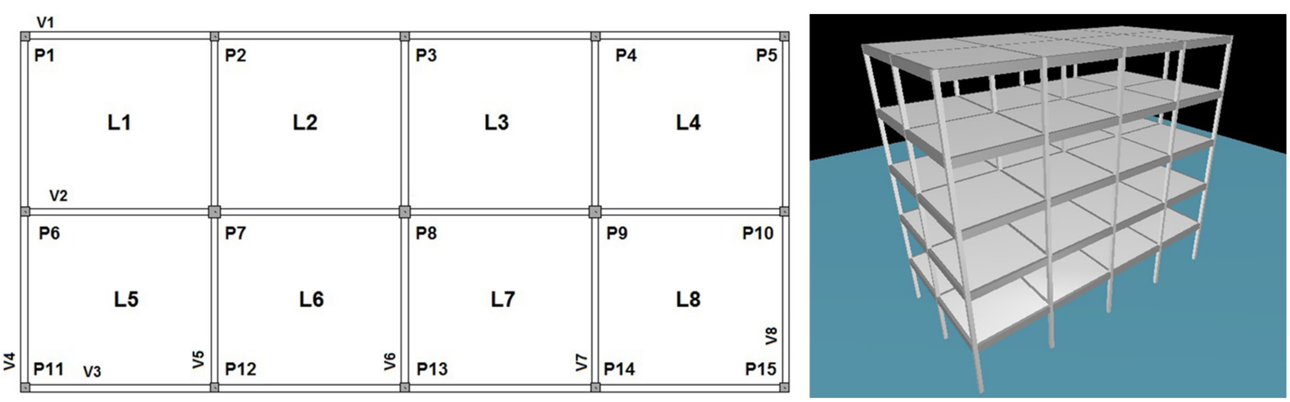

Figure 5 – Five-story building floor with 15 columns (building 1).

The unintended inclination is $\theta_1 = 1/(100\sqrt{H}) = 1/387$, not considering $\theta_{1\,min} = 1/300$. The reason for this hypothesis (the non-consideration of the $\theta_{1\,min}$) will be justified in the next section. The most conservative option, although inconsistent, would be to model the effect of all the column leans as only one ($n = 1$), as if the building inclination had the same behavior of only one column. In this case, the reduction factor would be calculated as $\sqrt{0.5\,(1+1/1)} = 1.00$ and $\theta_a = \theta_1$. If the 2D frame model is considered, the effect from global imperfection should be separately calculated in both horizontal and vertical directions. For the horizontal direction, $n = 5$ and $\sqrt{0.5\,(1+1/5)} = 0.774$; for the vertical direction, $n = 3$ and $\sqrt{0.5\,(1+1/3)} = 0.816$. Finally, for the 3D frame structure and for all columns that contribute to the effect, $\sqrt{0.5\,(1+1/15)} = 0.730$, which is lower than before.

Hence, the result for the 3D frame will be reduced in 6% for the inclination angle when compared with the horizontal 2D frame model, and 11% when compared with the vertical direction 2D frame model. Table 1 summarizes the total moment reaction (M_{ggi}), not considering $\theta_{1\,min}$. It should be emphasized that M_{ggi} is the sum of the moment reaction in each column foundation and its value is unique for both directions (x or y) because, obviously, the number of columns, the inclination angle and the vertical loading is the same considering x-direction or y-direction.

Table 1 - Total moment reaction in foundation for building 1, not considering $\theta_{1\,min}$.

Model	"n"	θ_a	M_{ggi} (kN.m)	Note
"Unique column"	1	1/387	161.0	Inconsistent
Plane x-dir. frame	5	1/500	124.0	
Plane y-dir. frame	3	1/475	131.0	
3D frame	15	1/530	117.0	Reduction of 6% (x-dir.) and 11% (y-dir.)

However, although there is no doubt that a more correct procedure would consider $\theta_{1\,min} = 1/300$, it is important to notice that there is a relatively low limit of the height H related to $\theta_{1\,min}$. Above H = 9 m, the analysis will always get $\theta_{1\,min}$.

4.2 Evaluation of the influence of building height and load level

In the structural design, there should be considered all the loads applied to the building, including the dead, live and wind loads. In NBR 6118 code, the global geometric imperfection (out-of-plumbness) is a permanent action and the wind load is a variable action. However, the NBR 6118 allows one of these actions to be disregarded depending on its magnitude relationship. The code stipulates that this decision should be made comparing both total reaction moments on the building foundation, in each direction of the wind load.

Consider, to understand the code requirements, that F_{wind} and M_{wind} are the load and the total reaction moment in foundation related to the wind, respectively; F_{ggi} and M_{ggi} are the load and the total reaction moment in the foundation related to the global geometric imperfection, respectively. It should be highlighted that the out-of-plumb analysis is performed with the deviation θ_a not considering $\theta_{1\,min}$ in M_{ggi} assessment. That is the explanation because $\theta_{1\,min}$ was not considered in the previous section.

The code expresses three possibilities: (1) when $0.3\,M_{wind} > M_{ggi}$, consider only F_{wind}; (2) when $0.3\,M_{ggi} > M_{wind}$ consider only F_{ggi} (now respecting the parameter $\theta_{1\,min}$ in the real analysis); (3) in the other situations, the two loads (F_{wind} and F_{ggi}) should be combined, allowing to ignore $\theta_{1\,min}$ again.

The analyzed building is similar with that of Figure 5, but with modification in height and live load. The results from M_{wind} and M_{ggi} were compared for a 3-story, 4-story, 6-story and 8-story building, considering three scenarios: as residential, as office and as store use. The wind speed is 30 m/s with usual associated parameters. The number of columns used was that of the 3D model, that is, n = 15. Tables 2 and 3 summarize the results for x-direction and y-direction, respectively. Figures 6a and 6b illustrate the tendency curve for x-direction and y-direction, respectively.

Table 2 - Total moment reaction in x-direction considering n = 15.

Building	Use	M_{wind} (kN.m)	M_{ggi} (kN.m)	M_{ggi} / M_{wind}	Mandatory
3-story	residential	117	52	0.444	$F_{wind} + F_{ggi}$
	office	117	55	0.470	$F_{wind} + F_{ggi}$
	store	117	64	0.547	$F_{wind} + F_{ggi}$
4-story	residential	222	80	0.360	$F_{wind} + F_{ggi}$
	office	222	85	0.383	$F_{wind} + F_{ggi}$
	store	222	95	0.428	$F_{wind} + F_{ggi}$
6-story	residential	567	146	0.257	F_{wind}
	office	567	155	0.273	F_{wind}
	store	567	180	0.317	$F_{wind} + F_{ggi}$
8-story	residential	1113	223	0.200	F_{wind}
	office	1113	238	0.214	F_{wind}
	store	1113	276	0.248	F_{wind}

The x-axis is the number of the stories of the building, and the y-axis is the relationship M_{ggi}/M_{wind}. The straight line cyan color is a reference where the point above the line implies that the consideration of M_{wind} plus M_{ggi} is mandatory, and the point below the line allows the non-consideration of M_{ggi}.

It is important to highlight some points: (a) M_{wind} is independent on the occupancy (on the respective vertical live load) but depends only on the horizontal force (wind) and on the facade area of the building (length and height); (b) M_{wind} in y-direction will always be greater than the x-direction one because the facade area along the x-direction is twice the other; (c) M_{ggi} is dependent on the occupancy (on the magnitude of the vertical live load).

Table 3 - Total moment reaction in y-direction considering n = 15.

Building	Use	M_{wind} (kN.m)	M_{ggi} (kN.m)	M_{ggi} / M_{wind}	Mandatory
3-story	residential	309	52	0.168	F_{wind}
	office	309	55	0.178	F_{wind}
	store	309	64	0.207	F_{wind}
4-story	residential	595	80	0.134	F_{wind}
	office	595	85	0.143	F_{wind}
	store	595	95	0.160	F_{wind}
6-story	residential	1525	146	0.096	F_{wind}
	office	1525	155	0.102	F_{wind}
	store	1525	180	0.118	F_{wind}
8-story	residential	2977	223	0.075	F_{wind}
	office	2977	238	0.080	F_{wind}
	store	2977	276	0.093	F_{wind}

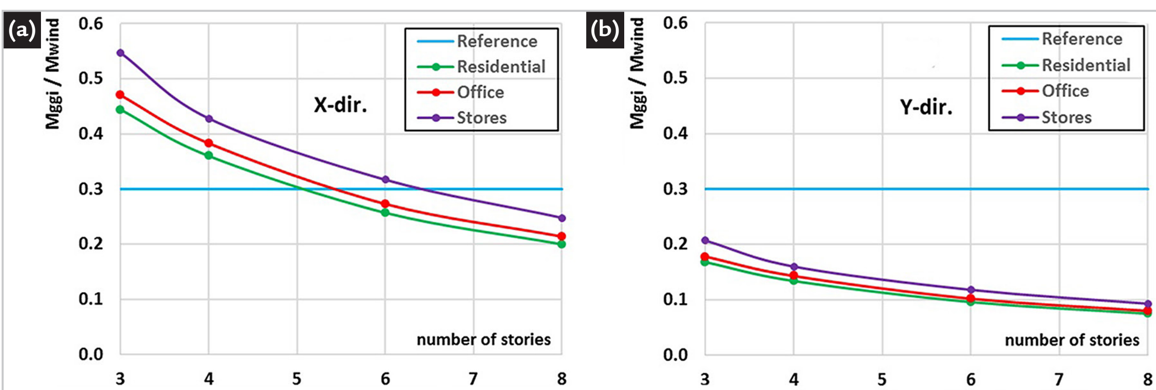

Figure 6 – Relation M_{ggi} / M_{wind} for x-direction (a) and y-direction (b) considering different occupancies and stories.

It should be noticed that the out-of-plumb columns effect is more important than wind action in short buildings or those with greater gravity loads values. As the building becomes taller, or the vertical load magnitude becomes smaller, the effects of the wind load become dominant, which allows to ignore the out-of-plumb effect according to the NBR 6118 requirements. Also, a remark is done at this point: the process of ignoring any of the effects does not exist in the European codes, and the global geometric imperfection is always considered. On the other hand, as the building becomes taller, indeed the importance of geometric imperfection becomes smaller when compared with wind.

Beaulieu and Adams (1980) studied two buildings and compared the effects from out-of-plumbness with the corresponding results from wind and earthquake loads. They observed that some effects were very significant, but others were negligible, and that localized effects involving few columns tended to be very large as compared to the corresponding wind effects. On the other hand, effects involving the structure as a whole, such as forces in the core, were in general comparatively small and negligible. At last, the authors concluded that the stability of a structure is ensured only when all the major destabilizing forces in the structure are properly resisted.

5. Conclusions

This paper reviews the subject of global geometric imperfections (out-of-plumbness) in concrete buildings. Considering the NBR 6118 code, an explanation was given about the origin of the expressions and its parameters, and a comparison was made among the Brazilian prescriptions and those from other standards codes. A discussion like this cannot be found in technical Brazilian publications, and it is one of the motivations of this study.

The expression presented by NBR 6118 is similar with those existing in European codes Model Code 2010 and Eurocode 2, but completely different from the American code. Basically, the calculation expression consists of two terms, based on probabilistic and statistical techniques relied on the results of out-of-plumb measurements: the first is a reduction factor for length or height, and the second is a reduction factor for the number of elements. The definition of the "n" parameter (number of columns) was debated, which frequently raises questions because the Brazilian code uses a different definition from those of other codes. In fact, this is an opportune time to correct this NBR 6118 specification, as it is under a revision process.

The influence of the building height and the vertical load magnitude for the importance of the out-of-plumb and wind forces were also analyzed, because NBR 6118 allows one of these effects to be disregarded, if it is considerably smaller than the other. It can be observed that the out-of-plumb effects are mandatory only for short buildings or those with a high magnitude of vertical loads. When the vertical loading magnitude decreases or the height increases, the wind effects present a far greater influence allowing the non-consideration of the out-of-plumbness. This second fact happens because NBR 6118 code expresses $\theta_{1\,min}$ as 1/300 and, for this, any structure whose height is equal or more than 9 meters, the unintended inclination θ_1 will result the same, while the wind action increases gradually according to the height. However, the maximum and minimum θ_1 values set by NBR 6118 are similar to the European codes. It is very difficult to set proper limits for θ_1 because the out-of-plumb measurements are statistical independent variables and the standard deviations obtained in many studies are specific to the buildings measured (Beaulieu *et al*., 1976; Beaulieu; Adams, 1978; Beaulieu *et al*., 1979).

References

ACI COMMITTEE 318. ***Building code requirements for structural concrete: (ACI 318-19) and Commentary (ACI 318R-19)***. Farmington Hills: American Concrete Institute, 2019.

AMERICAN SOCIETY OF CIVIL ENGINEERS. ***ASCE/SEI 7-16***: Minimum design loads and associated criteria for buildings and other structures. Reston: ASCE, 2016.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. ***ABNT NBR 6118***: Projeto de estruturas de concreto - procedimento. Rio de Janeiro: ABNT, 2014.

BEAULIEU, D.; PERLYNN, M.; DUNBAR, A.; ADAMS, P. F.; KELKER, D. The effects of column out-of-plumbs on the stability of core-braced buildings. ***Canadian Journal of Civil Engineering***, v.3, n.3, p.417-427, 1976. DOI: https://doi.org/10.1139/l76-042

BEAULIEU, D.; ADAMS, P. F. ***The destabilizing forces caused by gravity loads acting on initially out-of-plumb members in structures***. Edmonton: University of Alberta, 1977. (Structural engineering report SER 59). DOI: https://doi.org/10.7939/R3VQ8W

BEAULIEU, D.; ADAMS, P. F. The results of a survey on structural out-of-plumbs. ***Canadian Journal of Civil Engineering***, v.5, n.4, p.462-470, 1978. DOI: https://doi.org/10.1139/l78-052

BEAULIEU, D.; KELKER, D.; ADAMS, P. F. Probability considerations in assessing the effects of structural out-of--plumb. ***Canadian Journal of Civil Engineering,*** v.6, n.4, p.610-616, 1979. DOI: https://doi.org/10.1139/l79-073

BEAULIEU, D.; ADAMS, P. F. Significance of structural out-of-plumb forces and recommendations for design. ***Canadian Journal of Civil Engineering***, v.7, n.1, p.105-113, 1980. DOI: https://doi.org/10.1139/l80-009

BUENO, S.; KIMURA, A. (coord.). ***ABNT NBR 6118:2014***: comentários e exemplos de aplicação. São Paulo: IBRACON, 2015. p. 84-96.

CANADIAN STANDARDS ASSOCIATION. ***CSA A23.3-2014***: Design of concrete structures. Mississauga: CSA Group, 2014.

COMITÉ EUROPÉEN DE NORMALISATION. ***EN 1992-1-1:2004***: Eurocode 2: design of concrete structures - Part 1-1: general rules and rules for buildings. Brussels: CEN, 2004.

COVAS, N.; BANDIERA, C. Exemplo de aplicação dos conceitos da seção 11: imperfeição geométrica global. *In*: BUENO, S.; KIMURA, A. (coord.). ***ABNT NBR 6118:2014***: comentários e exemplos de aplicação. São Paulo: IBRACON, 2015. p. 171-185.

ELLIOTT, K. S. ***Precast concrete structures***. 2.ed. Boca Raton: CRC Press, 2017.

FÉDÉRATION INTERNATIONALE DU BÉTON. ***FIB model code for concrete structures 2010***. Berlin: Wilhelm Ernst & Sohn, 2013.

MACGREGOR, J. G. Out-of-plumb columns in concrete structures. ***Concrete International***, v.1, n.6, p. 26-31, 1979.

STOFFREGEN, U.; KÖNIG, G. Schiefstellung von stützen in vorgefertigten skelettbauten. ***Beton und Stahlbetonbau***, n.74, p.1-5, 1979. DOI: https://doi.org/10.1002/best.197900010

ZILCH, K.; SCHIEßL, A. Practical aspects. *In*: STRUCTURAL Concrete: textbook on behaviour, design and performance. 2 ed. Lausanne: Fib, 2010. v. 4., cap. 8. (*fib* Bulletin 54).

Received: 20 August 2020 - Accepted: 23 November 2020.