Twisted Tall Building Structural Response Under Lateral Wind-Induced Loads

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Abstract. The purpose of the present work is to show structural challenges and solutions in constructing twisted tall buildings. The research presents state-of-art results of recent papers, and then compares the behavior of two reinforced concrete building models with square floor plan under wind loads, one prismatic and the other with a total 90º twisting rotation along its 102.96m height. The buildings were analyzed with the software TQS v25 within the brazilian concrete design codes, CFD results for drag coeeficients were applied to estimate wind loads. Results show that twisting significantly increases vertical displacements and overturning moments and did not greatly increase the total horizontal displacement and the base shear. The study concludes that twisted forms need additional bracing and must balance aesthetics and functionality to ensure stability and efficiency.

Keywords: Twisted Tall Building, Wind Loads, Reinforced Concrete Structures.

1 Introduction

The design and construction of tall structures have consistently presented unique difficulties as architectural pushes limits continuously. Such building challenges demands from engineers' innovative structural solutions. Among these problems, a particularly notable one is the definition of twisted tall buildings structural system, which demand breakthrough designs to guarantee stability, safety, and functionality. The first twisted building, Turning Torso in Sweden, is a 190m tower designed by Santiago Calatrava with a total rotation of 90 degrees and its construction was completed in 2005.

Twisted tall buildings, in contrast to prismatic ones, have non-uniform floor layouts and facades that spiral upwards, resulting in a visually appealing architecture. Nevertheless, this aesthetic innovation brings benefits and drawbacks to all building subsystems. Leone [1] have studied that the facade spiral decreases the natural illumination, other postulated that this shape reduces the magnitude of wind loads but decreases the lateral stiffness of the building.

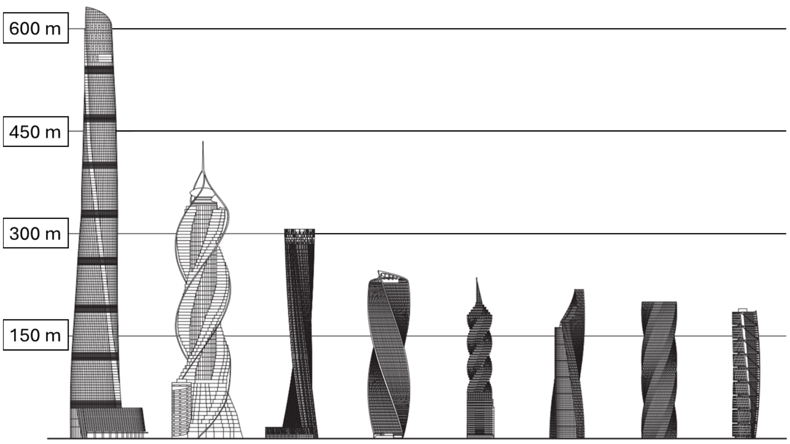

Figure 1. Twisted Buildings until 2016. Source: CBTUH [4]

In terms of architectural design processes, Moon [2] argues that pluralism affects architecture, and it affects design approaches for tall buildings. The complex-shaped tall buildings, such as the twisted forms, began to be designed inspired by the desire to create variations in form. Sev [3] had a similar point of view, stating that the society needs to create 'iconic' and monumental buildings.

The Council on Tall Buildings and Urban Habit (CBTUH) [4] published a survey correlating the total angle of rotation and building heights of all twisted tall buildings in the world constructed from 2005 to 2016. In Fig [2], the rotation angle is the cartesian angles and the building height is the dashed circles. The numbers in the pink circles represents the ranking in total height of each building. The figure presents that from the 28 twisted buildings at that year, 57% have total twisting angles of less than 90º and 64% have a maximum height of less than 200 m.

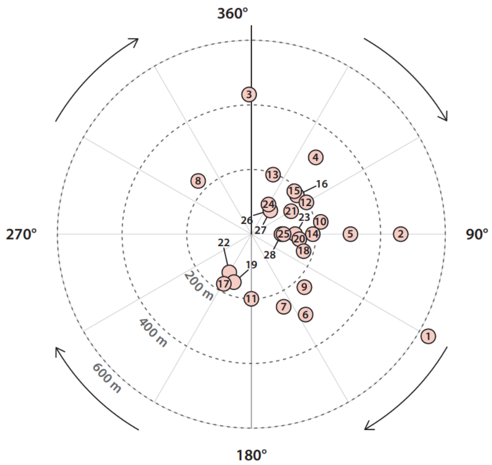

Figure 2. Twisted Building Perspective and Floor Plan . Source: CBTUH [4]

Complex-shaped tall buildings are still a recent architectural phenomenon, and only few buildings in the world have a twisted form. The first one in Latin-America, the HB Square Building (Fig [3]), was presented in 2024 and will be built in Fortaleza, in northeastern Brazil, and is estimated to be finished by September 2027.

Figure 3. HB Square architecture render. Source: BTB Engenharia

There are few studies about twisted structural shape and its architectural form and structural performance, and none of them developed in Brazil. Among the most recent studies Yadav [5] presented seismic behavior of buildings with regular plan according to IS 1893:2016 and concluded that diagrid in twisted building facades increases the lateral stiffness. Shaikh [6] used response spectrum analysis to evaluate wind and seismic loads according to the Indian Code, concluding that the structural system is directly influenced by the building height, more than in prismatic buildings. Taskin [7] studied various alternative structural systems of twisted towers on Middle East and Asia, evaluating the structural responses of them.

Orbay [8] investigated wind effects on twisted buildings and made a comparison between the wind loads on a twisted model and those on its prismatic counterpart, both with numerical and experimental wind-tunnel tests, standing that lateral wind loads are reduced with the twisting form. Shahab [9] used Computational Fluid Dynamics (CFD) to obtain the wind force and moment coefficients for different rotation angles of twisted towers, studying total angles of 0º, 90º, 180º, 270º and 360º. It was shown that a 180º total rotation conduces to a minimum wind drag coefficient, once the wind hits the less perpendicular area.

The construction of such a tower is a challenge from the development of the architectural to the structural engineering and construction site. Scott [10] described the construction of non-prismatic members as a challenging process and mentioned issues in the construction sequence due to creep and shrinkage estimation issues. If those effects cannot be properly evaluated, additional torsional forces shall occur in the building structure.

Within the fact that each floor is unique, designing the plan layouts and circulations is a challenging task for tall buildings. Once the twisted form is less rigid than the prismatic ones, a relatively large area is devoted to the columns, compromising the net floor area. The lifts and staircases must be fully vertical, and that fact leads to a non-twisted structural core.

Among the critical parameters to deal with, twisting forms it's global stability may be challenging. Taskin [7] states that the lateral stiffness of the structural frame is reduced as the rotation angle increases, but on the other hand, Shahab [9] shows that wind loads are reduced. The design team must then find the optimal form-function relation to reduce the costs from the construction and achieve the desired financial purpose of the project.

Many different materials may be applied to the construction. There are examples of reinforced concrete twisted buildings, prestressed ones, steel and concrete, and even timber structures, even if they're unusual. None of the most recent authors studied the impacts of the architectural form in the pre-dimension and design of concrete members and in the net floor area of the building. The aim of the research is to apply the existing wind studies and the brazilian concrete code to bring the technology of twisted tall buildings to the brazilian reality.

2 Objectives

The primary objective is to present a comparative study on the structural behavior of reinforced concrete twisted buildings under wind loads. This involves analyzing two models with identical floor plans, heights, and materials, but differing rotation angles. Wind drag coefficients obtained from CFD analysis will be used to calculate the total horizontal displacement of the buildings, story drift, and the overturning moment. The results will further base a pre-dimension and design process of twisted buildings adapted to the brazilian concrete codes.

3 Methods

The steps followed for Numerical Analysis involved the definition of a valid floor plan whereas the design of all structural columns are possible according to the Brazilian Code NBR 6118:2023 [11]. Numerous research paper were analyzed from different authors in order to identify the state-of-art and understand their limitation which provide a base and scope for further research.

The definition of a square structural floor plan with a rigid and vertical core and circular columns rotating with the facades was then made. In this step, all buildings characteristics were modelled, analyzed and designed within the commercial software TQS v25. The structural model is a 30 m x 30 m square plan with 102.96 m height (Figure 4), divided into 26 floors with 3.96m height each. The slabs and floor plan beams were designed to a dead load of 2 kN/m² and a live load of 3 kN/m². The concrete material C50 is defined with the following data:

Table 1. Concrete data

Concrete Property	Nomenclature	Value
Compressive strength	f_{ck}	$50MPa$
Concrete density	γ_c	$25kN/m^3$
Young Modulus	E	$39.5GPa$
Clear cover	C_{ob}	$0.03m$

The outer circular columns have a diameter of 1.4 m and the rotation angle between floors is 3.46º, totalizing 90º at the 26th roof. The base wind load is considered to be 45 m/s according to NBR 6123:2023 [12]. A prismatic building with the same floor plan but no rotation was used as a control model. The concrete structural elements were code-checked, and the cross-sections were defined.

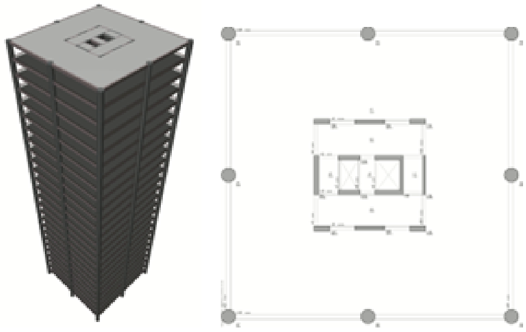

Figure 4. Prismatic Building Perspective and Floor Plan

The wind drag coefficient were defined for the prismatic model using the "low turbulence wind" abacus of NBR 6123:2023 [12] (Figure 5), resulting in the value of $c_a = 1.33$. The NBR 6123 [12] S1, S2 and S3 wind factors for topography, terrain roughness and statistical safety, were all defined as 1.

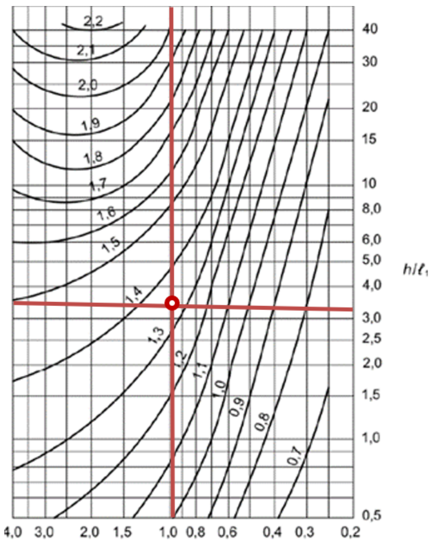

Figure 5. Wind drag coefficient abacus for prismatic buildings submitted to low turbulence wind. Source: NBR 6123:2023 [12]

To the prismatic building floor plan was then applied a rotation of 3.46º per floor, resulting in the model shown in figure 6, and the wind drag coefficient was adjusted to $c_a = 1.148$, 13.7% lower, according to the CFD analysis results of Shahab [9]. All the elements cross sections and material properties remained the same.

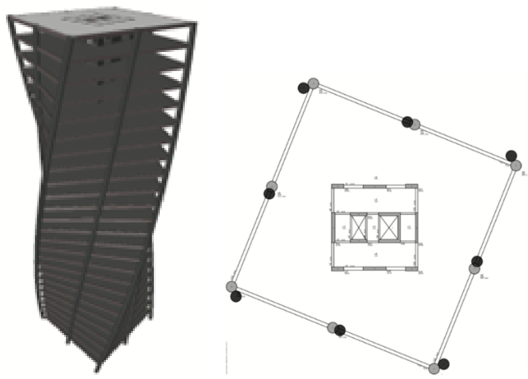

Figure 6. Twisted Building Perspective and Floor Plan

Both models have its columns fixed at the bottom and no masonry loads were applied. The geometric nonlinearity was considered with the P-Delta method and the same load combination was used to evaluate the results of both models, and is described as:

$$ULS = 1 \cdot SW + 1 \cdot DL + 0.8 \cdot LL + 1 \cdot WIND \quad (1)$$

Where ULS defines an Ultimate Limit State combination, SW is the unfactored Self Weight of elements, DL the unfactored Dead Load, LL the unfactored Live Loads and $WIND$ the unfactored wind loads.

4 Results

The analysis results extracted from models will be further used in the pre-dimension and design of reinforced concrete members. The author expects to run more analysis in future papers aiming to establish expressions to architects and structural engineers pre-dimension their future projects according to the brazilian code NBR 6118:2023 [11] more precisely and spare time in the design process.

The initial variables authors like Abdullah *et. al.* [13] have been exploring are the total Vertical Displacement, the sum of Base Shear Forces, and the Overturning Moments. Deeper papers, such as Taskin [7] investigates the influence of outriggers in the global stability of the building.

4.1 Vertical Displacement

The vertical displacements of the building are shown in Fig [7], with 2.59 cm for the prismatic model and 24.36 cm for the twisted model, expliciting the need for structural stiffness increase.

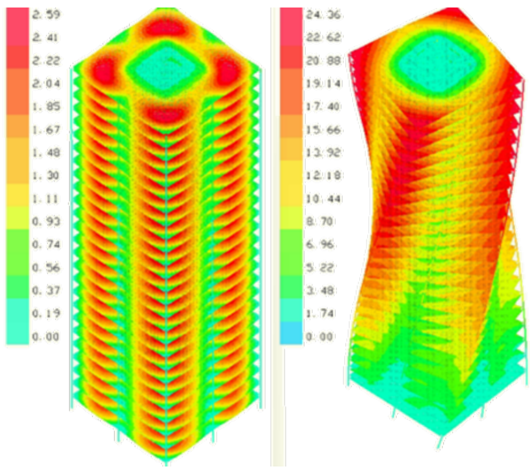

Figure 7. Vertical Displacement of models (units: $10^{-2}m$)

4.2 Base Shear Forces

The base shear forces are defined as the sum of all column shears at the base, it value comes majorly from wind loads. The base shear for individual columns varies, but the sum of all shear remais unaltered.

Table 2. Base Shear Forces

Load Type	Prismatic Building	90º Twisted Building
Wind Loads	$F_x = 6980kN$	$F_x = 7860kN$
	$F_y = 6980kN$	$F_y = 7860kN$

4.3 Overturning Moments

The overturning moments are defined as the sum of all column bending moments at the base, it value comes majorly from wind loads and from the building twisting. The torsion effect ampifies the overturning moments.

Table 3. Overturning Moments

Load Type	Prismatic Building	90º Twisted Building
Wind Loads	$M_x = 42141kN.m$	$M_x = 85260kN.m$
	$M_y = 42141kN.m$	$M_y = 47131kN.m$
Geometrical Nonlinearity	$M_x = 1.3kN.m$	$M_x = 390kN.m$
	$M_y = 16.4kN.m$	$M_y = 9454kN.m$

4.4 Wind Load Cases

The Brazilian code-based wind loading was used in the wind analysis, applying the loads as point loads at the column nodes each floor. The wind loads were applied in both X and Y directions, separately. The maximum horizontal displacement of the building stories is shown in Fig [8], and the story drifts in Fig [9]. The Brazilian code NBR 6118:2023 [11] imposes that the horizontal displacement at the building top should not exceed $H/1700$ (serviceability criteria), where H is the total height, and the story drift should not exceed $H_i/850$, where H_i is the height between consecutive floors.

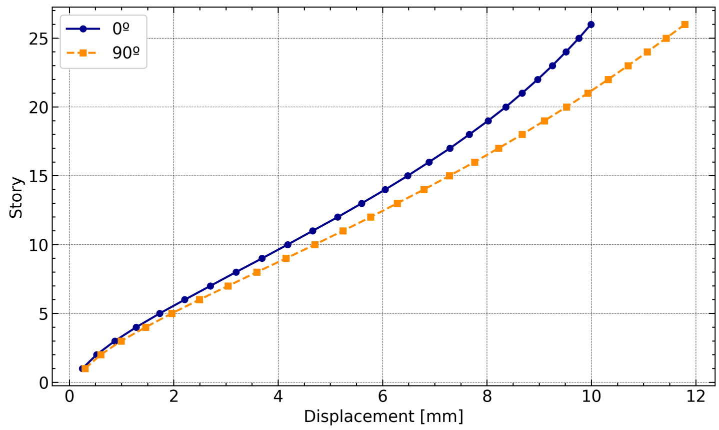

Figure 8. Horizontal Displacement of models

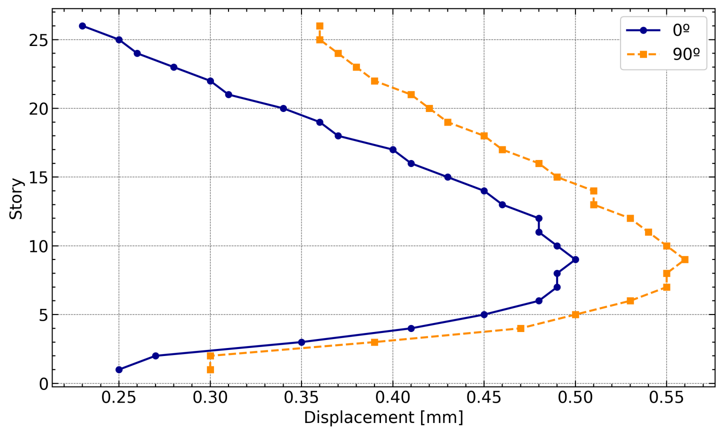

Figure 9. Story drift of models

5 Conclusions

In a model with a 30 m x 30 m square plan with 102.96 m height, the building become more flexible as the façade rotates 3.46º per floor.

The vertical displacement of the building increased by 841%, it indicates that the structural frame shall be braced, or the peripheral columns shall have its diameter increased.

The horizontal displacement of the building increased by 18%, suggesting that the lateral stiffness decreases more than the wind loads. The displacement did not exceed the code limits of $102.96m/1700 = 60.56mm$. The story drift increased by 57%, because of the torsional effects. The drifts did not exceed the code limits of $3.96m/850 = 4.66mm$.

The base shear increased by 13%, as part of the vertical loads of the columns became shear at the bottom.

The overturning moments increased by 102% in the X direction and 12% in the Y direction, indicating that a better arrangement of core columns may stiff the whole frame.

The nonlinear overturning moment due to the P-Delta analysis increased by 300 to 575 times, owing to the fact that a 0º twisted building (the prismatic counterpart) have almost none geometrical nonlinearity in comparison with the 90º twisted.

The presented results will be further expanded with a series of computational models varying the total height and number of floors, as well as the twisting angle between floors, considering the Drag Coefficients presented by Shahab [9] for the wind loads and exploring the structural design with the brazilian codes.

This preliminary results, especially the vertical displacement one, remains clear that the twisting of the floor plans will impact the design of concrete columns, and will reduce the net floor area of the building stories. Further research will measure the actual impact of each twisting angle, and search if an equilibrium point does exist.

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