Technical University of Munich
School of Engineering and Design
Statics
Structural Wind Engineering

Report:
Bank of America Plaza

Students:
Javad Mohebi
Rodrigo Castedo-Hernández
Raúl San Miguel Peñas

M.Sc. students in Computational Mechanics

Supervisors: Anoop Kodakkal

February 2023

Contents

1 Introduction

1.1 Motivation

Structural engineering and wind go hand in hand, regardless of whether the structure is a cookie-cutter warehouse, in which case construction codes might be sufficient to make sure the building can handle all statistically relevant winds; or a supertall skyscraper with a peculiar geometry, in which case physical experiments and numerical simulations will, in all likelihood, be integral parts of the design process. This project, as part of the class Structural Wind Engineering, aims to offer students the opportunity to understand the multidisciplinary concepts that are part of wind engineering and then apply them to a real-world high-rise building. In this manner, students can, as is rare in engineering courses, truly take part in learning by matching as closely as possible what ”real” engineers do on a day to day basis. For this project, the building to be studied is Bank of America Plaza, located in Atlanta, Georgia, in the United States.

1.2 Objectives

The objectives for this project are rather straightforward, but each entails covering a large amount of details and making decisions and assumptions which will be explained in each section:

1. Gather information on building structure (dimensions, materials, location)
2. Gather information on wind data at relevant location
3. Perform analysis of structure using Eurocode
4. Perform analysis of structure using numerical methods

1.3 Structure of this Report

This report, beyond this very introduction, can be broadly divided into two large sections. The first one focuses on the background knowledge needed to undertake a project like this one and on non-numerical methods used to analyze structures. It contains a summary of the main topics involved in structural wind engineering, including the Davenport chain, the concept of the atmospheric boundary layer, the dynamics of highrises, and the wind effect on these structures; an in-depth discussion on the necessary information (structural, wind, and terrain data) regarding the Bank of America Plaza skyscraper; the results from applying the guidelines offered by the Eurocode to this structure; and a simplified dynamic analysis of the building. The second section focuses on numerical methods used in computational wind engineering and, more generally, computational fluid dynamics, to solve complex problems. It contains a description of the tools used, including GiD, the Kratos Multiphysics library, the in-house library ParOptBeam and several other Python scripts; the description of three different simulations varying geometry and wind conditions as well as their results; and comparisons between them. Finally, the overall project is summarized and discussed in a Conclusions and Future Work section.

2 Context: Structural Wind Engineering

Before moving on to the analysis of the structure itself, it is worth taking a look at what structural wind engineering entails and what effects wind can have on a structure. Doing so will make the results of the calculations performed using standard codes and numerical methods much clearer in the long run.

2.1 The Process of Structural Wind Engineering

Design as as a function of the effect of wind on a structure follows a series of data gathering and analysis steps, some of which have already been discussed in this report, such as wind climate and terrain condition. These two terms are part of the so-called ”wind load chain” proposed by A.G. Davenport, a professor at Western Ontario University and founder of its Boundary Layer Wind Tunnel Laboratory, as seen in Figure 1. This wind load chain takes into account the combined effect of local wind climate as expressed in statistical terms, the local wind exposure as determined by terrain and topography, the aerodynamic characteristics of the shape of the structure, and finally the structural response, and especially potential wind-induced vibrations. These effects combined make it possible to study the lateral deflection, fatigue, strength, frequency and amplitude of sway, resonance, and other factors related to the structure, sometimes for safety, sometimes for comfort.

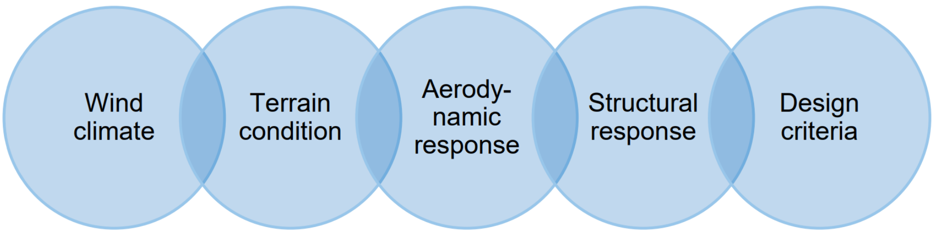

Figure 1: Wind load chain proposed by A.G. Davenport.

2.2 Wind and the Atmospheric Boundary Layer

The base values of wind in a region are then closely linked with the concept of an atmospheric boundary layer (ABL), which is precisely the same as a boundary layer found typically in fluid mechanic courses but at a much larger scale. The ABL is the lowest layer in the atmosphere where ground friction is influential; given the size of the atmosphere, any and all man-made skyscrapers are affected the ABL. Given a no-slip condition at the very surface of the Earth, the ABL can be mathematically represented by a logarithmic or power-law expression. Furthermore, turbulence in wind as well as differences in measurement are dependent on statistical methods. A diagram of the mean wind and the instantaneous wind component of the ABL as well as the effect that terrain can have on it is depicted in Figure 2. For instance, the period used to measure a certain wind or average out fluctuations in data determines the threshold of the size of the fluctuations recorded, acting as filter.

Statistically, wind at a certain location is usually taken as a ”50 year wind”, that is to say, a wind with these properties is expected to appear once very 50 years. It is measured at 10 m altitude and it is 10-minute time-averaged. In order to obtain this information from a larger set of data, statistical methods like the Gumbel method are used.

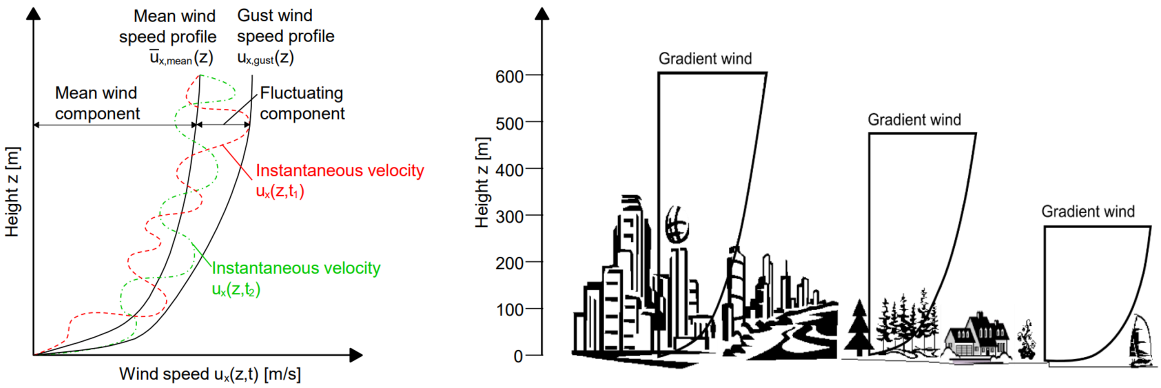

Figure 2: Components of the atmospheric boundary layer and effect of terrain.

2.3 Bluff Body Aerodynamics and the Equation of Motion

The wind profile translates to a pressure profile on the structure to be analyzed. The structure deforms and moves in response to this pressure, and, in turn, this may or may not affect the wind profile. This loop between the two key components is known as coupling, and it can be interpreted in different ways depending on conditions and needs of the analysis of a structure.

In terms of the structural and material properties that determine a structure's response to wind loads, the mass m, the stiffness k and the damping c of the structure are the key components. A continuous system, additionally, can be interpreted as a single-degree- or multi-degree-of-freedom system, leading to manageable expressions like the equation of motion of a single-degree-of-freedom system (SDoF) in solid mechanics: $m\ddot{x}+c\dot{x}+kx = f(t)$. Note that m, k, and c here are scalar values and not matrices. Through this simplification, key values such as the natural frequency of a body can be easily calculated: $f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad [Hz]$. Other key expressions include the critical damping of a system ($c_{crit} = 2m\sqrt{\frac{k}{m}} = 2m\omega_n \quad [rad/s]$) and its damping ratio ($D = \frac{c}{c_{\text{crit}}}$). When the system has more than one degree of freedom or the boundary and initial conditions are not optimal, there might be a need for a numerical solution to this expression using both space-discretization (forward, central difference) and time-discretization (explicit, implicit), each with its own set of advantages and disadvantages. Flow-induced vibrations depend precisely on these parameters (mass, stiffness, damping, wind velocity, turbulence, etc) of the coupled system, and will be explored further in the following section.

2.4 Wind Effects on Highrises

Given all the concepts laid out in the previous section, one must consider how to apply them depending on the type of structure. These include, but are not limited to, low-rise buildings like warehouses or single-family homes; towers, chimneys, and masts, bridges and decks; membranes and lightweight structures; and high-rise buildings like skyscrapers, the focus of this project. The definition of a high-rise or tall building can vary, but, in summary, it has to be considerably higher than the surrounding buildings and has to be slender. According to Fazlur Khan, the designer of Chicago's famous Sears Tower, tall buildings have a limit in slenderness of an 8:1 height-to-width ratio. Khan also points out that the decisive factor in tall building design is not the ultimate limit state, that is to say, the stresses undergone by the structural members, but rather the serviceability limit state, i.e. the maximum movements and accelerations allowed that occupants can tolerate without discomfort.

There are many types of structural systems for tall buildings. These include simple semi-rigid or rigid frames that take care of both vertical and lateral (shear) loads, interacting or outrigger systems with cores and columns, in which the service core acts as the main structural element in the form of a cantilever, partial tubular systems, and tubular systems. Each has its own advantages and disadvantages, but, over the past few decades, most, if not all, supertall skyscrapers have used either outrigger or core-tubular systems. In the case of the Bank of America Plaza, information on its structural system was hard to find, but a shot from its construction in 1991, seen in Figure 3, suggests that the building is composes of a core and column outrigger system, with the core being a framed tube responsible for shear loads and bending moments, surrounded by hinged slabs and columns that can only carry a vertical loads.

Figure 3: Photograph of the construction of Bank of America Plaza, 1991 [1]. No higher quality found.

Pressure loads on buildings generally follow a set pattern, as dictated by fluid mechanics. With respect to the direction of the wind, the front part of the building is pressure loaded, with the lowest load at the bottom as expected when looking at the shape of the ABL; the roof and sides are mainly under suction, with friction drag very limited or functionally non-existent (unlike airfoils), and finally the back is also under suction. In the case of supertall skyscrapers, it can be considered that the self-weight is secondary to pressure loads and especially to aeroelastic phenomena known as flow-induced vibrations (FIV). These phenomena include externally-induced excitation forces (EIE), i.e. buffeting, in which vortex separation in the ABL excite the structure; instability-induced excitation forces (IIE), i.e. vortex shedding, in which unstable flow and vortex shedding from the structure itself causes excitation; and finally motion-induced excitation forces (MIE), i.e. galloping or flutter, in which there is an interaction between the aerodynamic forces and the structural motion.

In movement induced excitation, the structure might move at a natural frequency, but the fluid flow that causes this motion will have a higher frequency than the natural frequency of the structure. The elasticity of the structure will be the culprit of the negative damping, however, as the displacement of the structure leads to the increasing amplitude. A very rigid structure will always move at its natural frequency, but it is unlikely it will suffer from flutter/galloping. The natural frequency/velocity for vortex shedding and the velocity for flutter for a bridge (a pretty non-rigid structure) are fairly close. They are usually much farther apart in high-rises and other buildings, making instability-induced excitation less relevant. The relationship between the freestream velocity a structure's response amplitude can be seen in Figure 4.

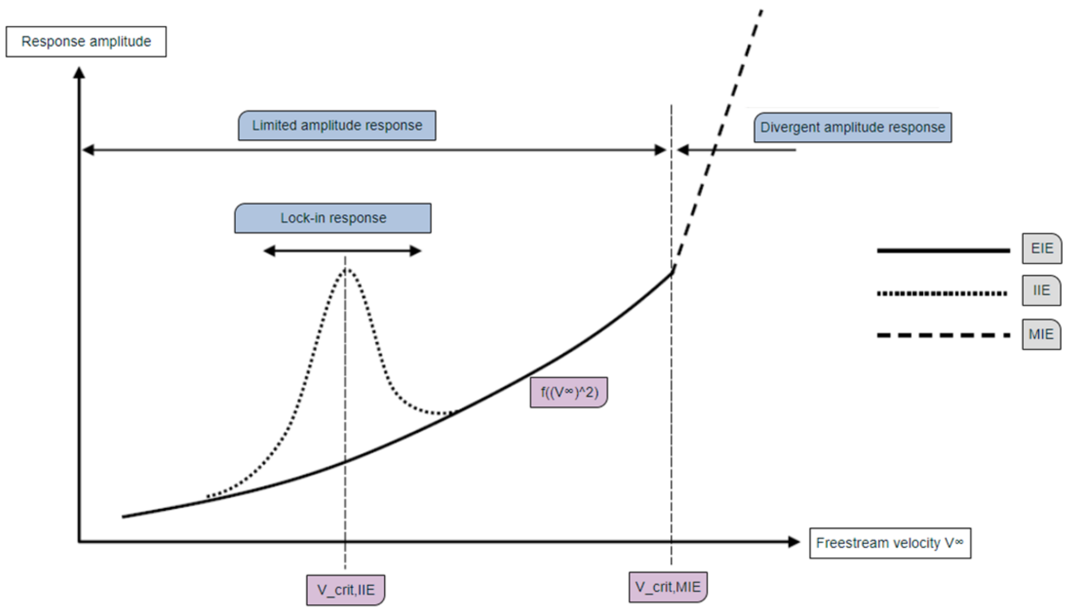

Figure 4: Structural reponse amplitude and freestream velocity.

Given the types of loads described in the previous paragraphs, the response of the structure has two components: the along-wind response (quasi-static response, buffeting) and the across-wind response (vortex shedding, galloping). The along-wind response takes into account the mean load component of the wind and translates it to pressure and load coefficients while the fluctuating loads are determined separately and compared if needed with the structure's natural frequency. The across-wind response focuses on the dynamic motion perpendicular to wind direction, determined by flow separation, vortex shedding as described by the Strouhal number, galloping, and how these relate to the structure's natural frequency. Most design codes, including the Eurocode that is used in this project, follow this two-component approach, as will be discussed in Section 3.3.

Strategies to reduce excitation in high-rise buildings include softening or tapering corners to limit and change flow separation, tapering and changes in cross-section to alter vortex shedding frequencies, spoilers, and openings.

3 Bank of America Plaza

3.1 Structural Information

The Bank of America Plaza building in Atlanta, in the state of Georgia, should not to be confused with the namesake structure found in Dallas, Texas. This supertall skyscraper, often referred to as the "pencil building" can be seen in the context of Midtown Atlanta in Figure 5. Finding accurate information about the building apart from very basic tidbits, such as the ones included in the previous paragraphs, has proven to be difficult. This is understandable, as it is a security risk to have structural information on such large and highly transited buildings available online, but it has nevertheless forced the group to make some assumptions which line up with the information that is available.

Bank of America Plaza was built in 1992 from a design by architectural firm Kevin Roche John Dinkeloo and Associates, and apparently it took only 14 months to complete despite having a total height of 311.8 meters. This height makes it the 21^{st} tallest building in the US and the 125^{th} tallest in the world. A considerable chunk of this height (around 61.8 total meters according to available information) is taken up by a hollow pyramid of girders and a golden spire between 22.6 and 27 meters long, making the habitable space and structurally relevant part of the building 250 meters tall. As far as the cross section of the building is considered, it is approximated as a square or despite some differences in its corners, but nowhere on the internet have the precise dimension of its sides been found. Based on diagrams, satellite imagery and other sources, the most appropriate value is 50 meters [1] [2] [3].

The height difference previously mentioned has been discussed thoroughly in the group and with the supervisors in order to determine whether it is worth taking the pyramid and the spire into account. Since this last portion of the building is considered ornamental, is mostly hollow and is assumed to be simply supported on top of the rest of the structure, it is considered that modelling it or taking it into account in standard code calculations is not necessary. Additionally, the complexity of the pyramid of girders is deemed too high for the level of complexity expected in this project. Using a simple, solid pyramid to model wind behavior is, in all likelihood, not accurate to real-world behavior, so it is better to ignore it completely.

The building is assumed to be be constructed using a steel-concrete composite, as indicated by the Chicago-based Council on Tall Buildings and Urban Habitat (CTBUH). The council's website describes this type of structure as "a combination of materials", e.g. steel, concrete, or timber, that are used together in the main structural elements. Examples include buildings which utilize steel columns with a floor system of reinforced concrete beams, a steel frame system with a concrete core, concrete-encased steel columns, or concrete-filled steel tubes, among others. Where known, the CTBUH database breaks out the materials used within a composite building's primary structural elements" [4]. Due to the lack of definite values regarding the building's density (ρ), damping ratio D, and bending (E and shear G stiffness moduli, the group decided to take similar values to the standard values provided for the Check Your Knowledge on Topic 4: Wind Effect on Structures - Highrises. The values used for this project are therefore: $\rho = 150kg/m^3$, $D = 1.5\%$, $E = 2.86e8Pa$, $G = 1.19e8Pa$. Based on the aforementioned simplification of a square cross-section, $I = \frac{b*h^3}{12} = \frac{b^34}{12} = 1.01e5m^4$.

Bank of America Plaza is oriented with the normal vectors of each face at 45° with respect to the cardinal directions. That is to say, each vertex of the cross-section corresponds to a cardinal direction. This is a slightly surprising decision, as streets in most American midtown districts, like the case of Midtown Atlanta, are aligned north to south and east to west. It is also worth highlighting the architectural firm's post about the building on their own website, which contains some drawings and diagrams of interest, even if they reveal very little information about the structure [5].

Figure 5: Bank of America Plaza as seen from Downtown Atlanta [6].

3.2 Wind and Terrain Data

Finding accurate wind information also proved to be a challenge, as data was not always up to date and it was not always clear precisely what type of wind (specially in statistical terms) it was referencing. The most comprehensive database available, with monthly mean 10 meter wind speed data going back to 1979, was one offered by the United States's National Centers for Environmental Information (NCEI) [7]. It lacked, however, directional information for the wind, which is essential for proper modelling of the resulting forces.

Therefore, to determine the main wind directions and the value of the wind corresponding to each, two different sources were used: a database belonging to the National Institute of Standards and Technology, and a wind rose from Meteoblue, a meteorological service from the University of Basel, a seen in Figure 6 [8] [9]. The first source included the fastest 3-second gust speed for each year between 1935 and 1976 as well as its direction. This, combined with dominant wind directions indicated in the wind rose (West Northwest (WNW) and East Northeast (ENE)) and the considerable wind from the West (W) allowed the group to obtain two key data points: the gust speed v_p for WNW and ENE is 29.5 m/s, and the one for W is 25.1 m/s.

The process to calculate these two values follows the same steps as the Omaha, Nebraska example found in slides 33 to 36 of the presentation ”SWE_WS2223_Slides_1_WindClimateABL”, in which the calculations are based on the Gumbel method, the Gringorten method, and the method of moments. The code to perform said calculations is found in the Jupyter notebook ”swe_ws2223_1_1_wind_speed_computation.ipynb”.

Furthermore, it is necessary to determine what type of terrain the building is found in. In this case, as is the case for most skyscrapers, Bank of America Plaza is in the middle of a dense urban area, with other skyscrapers of considerable height in the vicinity and all other adjacent buildings being high-rises or similar. This information, together with the gust wind speed data, will come into play in further sections of this report.

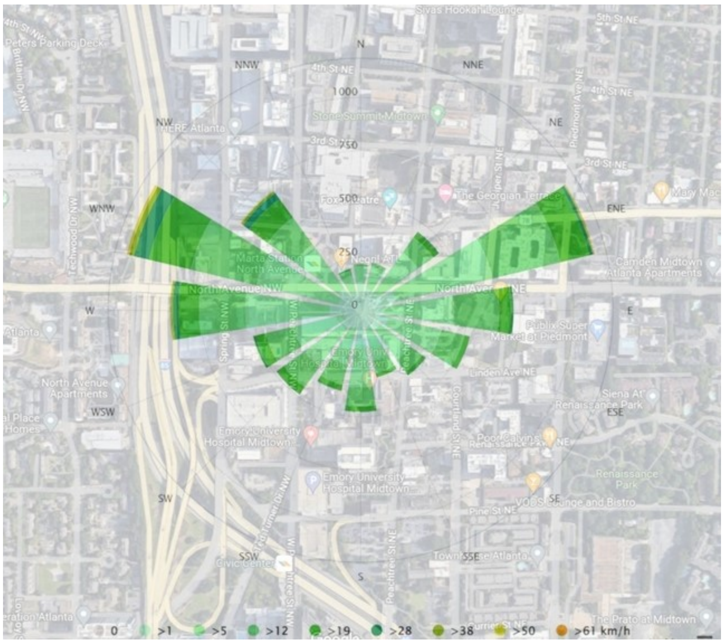

Figure 6: Wind rose overlaying satellite imagery of Bank of America Plaza.

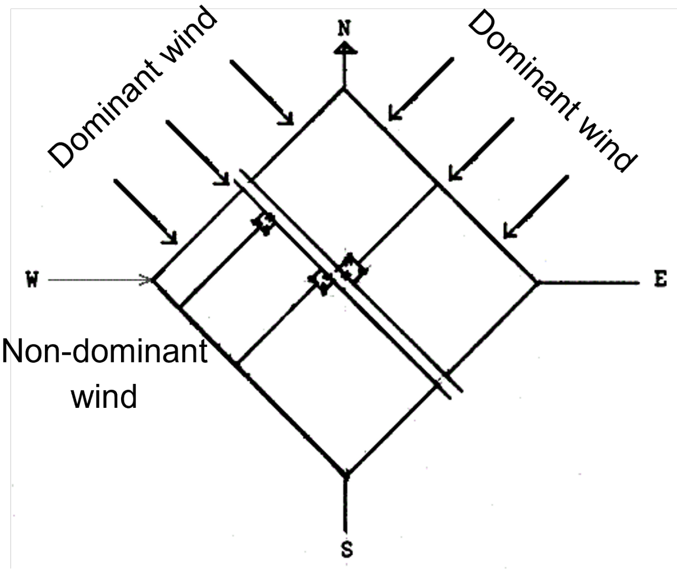

Figure 7: Principal wind directions with respect to structure cross-section

3.3 Eurocode

3.3.1 What is the Eurocode?

The Eurocodes are ten European standards or harmonized technical rules that lay out a set of rules and guidelines for structural design within the European Union. They aim to provide sufficient strength and stability in the case of fire, a basis for construction and engineering in contract specifications, and a basis for technical specifications of building products. In these objectives it can be seen that their aim is to provide a foundation; a common ground for all buildings and related products within the EU. They do not however, cover every single use-case, every risk, or every type of building, meaning that, like the in the case of Bank of America Plaza, they can provide a good basis for further calculations, but are not the only source or tool that should be used. Nevertheless, it is important to follow the steps in the Eurocode as summarized in this section.

3.3.2 Methodology

The values and calculations in the following section are based specifically on *Eurocode 1: Actions on structures - Part 1-4: General Actions - Wind actions*. Most values were obtained using the Jupyter Notebook "swe_ws2223_4_2_structural_effects.ipynb", which performs the calculations laid in the code given a reduced set of inputs. An equivalent notebook but modified for the values required for Bank of America Plaza, "BankofAmericaPlaza.ipynb", is available in the repository and was used to perform all calculations and obtain all values unless noted otherwise in this report. The steps followed are also laid in slides 71-104 of the presentation "SWE_WS2223_Slides_4_WindEffOnStruct_Highrise". Additionally, the tables and formulas used for the assessment of the terrain and the design wind speed are taken from the German annex to the Eurocode, DIN EN 1991-1-4 NA to be exact.

3.3.3 Acquisition of values

The following process is repeated for each of the two principal directions, NW/NE and W.

First, the focus is on the along-wind response. Given the gust wind speed v_p specified in Section 3.2, which is recorded at a height of 10 meters, and, assuming, as in the Omaha example, that the data was recorded at an airport, that is to say, terrain category II as seen in Table NA.B.1 of the German annex, the gust speed v_b can be obtained from expression $1,45 \times v_{\mathrm{b}}(z/10)^{0,120}$, found in Table NA.B.1 of the German annex, which is simplified to $u_{\text{mean}} = u_{\text{gust}}/1.45$. Bank of America Plaza is situated on terrain of category IV, as explained in section 3.2, so the following expressions, where $u_{mean} = v_b$, are used to mathematically represent the ABL wind profile velocity in the x direction:

$$u_{\text{mean}}(z) = 0.56 \cdot v_b \cdot (z/10)^{0.3} \tag{1}$$

and the turbulence intensity, which is defined as the standard deviation of the velocity over its mean, can be calculated in this case as follows:

$$I_v(z) = 0.43 \cdot (z/10)^{-0.3}. \tag{2}$$

From expression 1, the reference velocity u_{ref} at 60% of the building's height (the reference height $z_s = 250m$) can be obtained.

Finally, the length scale, which represents the average gust size of natural wind is expressed,given the characteristics of the building, via the following formula:

$$L(z) = 300 \cdot (z/300)^{0.46} \tag{3}$$

From here the key factor to determine is the structural factor $c_s c_d$, which takes into account the effect of wind actions from the non-simultaneous occurrence of wind pressures on the surface via c_s and the effect of vibrations of the structure due to turbulence via c_d. $c_s c_d$ is a factor that plays a major role in the determination of the wind loads on a building, as will be seen in the next section, and for skyscrapers like Bank of America Plaza its obtained using:

$$c_s c_d = \frac{1 + 2k_p \cdot I_v(z_s) \cdot \sqrt{B^2 + R^2}}{1 + 6I_v(z_s)}, \tag{4}$$

where K_p is the peak factor (ratio of maximum fluctuation of response to its standard deviation, B^2 is the background factor (accounts for lack of full correlation of the pressure on the structure surface), and R^2 is the resonance response factor (turbulence resonance with the vibration mode).

The next aspect to analyze is the building's across-wind response, which include vortex shedding (IIE) and flutter or galloping (MIE).

Vortex shedding, as mentioned already in Section 2.4, is usually not a problem for skyscrapers due to the mismatched natural frequencies, but it is nevertheless worth it to confirm, according to the Eurocode, this superposition. The code states that vortex shedding is not relevant when

$$V_{crit} > 1.25 \cdot V_m, \tag{5}$$

where

$$V_{crit} = \frac{b \cdot n_{i,y}}{St} \tag{6}$$

and, in this case, $V_m = u_{ref}$. The first eigen-frequency of buildings taller than 50 meter can be estimated, according to the code, using: $n_1 = \frac{46}{h}[\,\text{Hz}]$, and b being the width of the building's cross section. The key factor here is the Strouhal number St, which is defined as

$$St = \frac{fL}{U} \tag{7}$$

and defines the relation between local acceleration and and the convective acceleration, i.e. it defines the dimensionless frequency of vortex shedding. Taking $L = b$ and $U = u_{ref}$, the vortex shedding frequency f can be obtained. Note that the Strouhal number is one of the few parameters which have to be manually obtained from the code and put into the Jupyter Notebook, specifically from Figure E.1 (0.12 for dominant wind diection) and Table E.1 (0.16 for non-dominant wind direction). In all cases, condition 5 was satisfied and therefore vortex shedding did not have to be taken into account.

Galloping or flutter is finally analyzed. Here, galloping is not relevant if

$$v_{CG} > 1,25 \cdot v_m \tag{8}$$

is satisfied and if

$$0,7 < \frac{v_{\text{CG}}}{v_{\text{crit}}} < 1,5 \tag{9}$$

is *not* satisfied. This last condition is necessary to make sure there is no interaction between the vortex shedding and the galloping. The onset wind velocity of galloping is defined as:

$$v_{CG} = \frac{2 \cdot Sc}{a_G} \cdot n_{1,y} \cdot b, \tag{10}$$

where Sc is the Scruton number, which is the ratio of the structural damping and the structural mass to the fluid mass.

There are other relevant measures that can be obtained using Sc and St along with other coefficients like the the lateral force coefficient C_{lat} that don't directly apply to safety. C_{lat}, which can be interpreted as a dimensionless force amplitude, can be obtained from Table E.2 in the Eurocode. With these values, the largest displacement can be calculated with:

$$\frac{y_{F,\max}}{b} = \frac{1}{St^2} \cdot \frac{1}{Sc} \cdot K \cdot K_{\mathrm{w}} \cdot c_{\mathrm{lat}} \tag{11}$$

where K is the mode shape factor and K_w is the effective correlation length factor. Assuming that these factors are valid for a SDoF system, the maximum y-acceleration in cross-wind direction can also be calculated using:

$$acc_{f,max} = n1^2 \pi^2 y_{F,\max} \tag{12}$$

These expressions, taken from the Eurocode and the German annex, lead to the results compiled in Tables 1 and 2.

Table 1: Eurocode values for dominant direction: WNW / ENE

u_{gust}	29.50	m/s	v_{crit}	76.67	m/s
u_{mean}	20.34	m/s	c_{lat}	0.22 (1.1)	[-]
u_{ref}	25.67	m/s	v_{cg}	361.28	m/s
c_f	2	[-]	f	0.062	1/s
St	0.12	[-]	1^{st} eigen f	0.184	1/s
Sc	23.56	[-]	$y_{F,\max}$	2.354	m
$L(z_s)$	218.10	m	$acc_{f,max}$	0.197	m/s^2
$c_s c_d$	0.919	[-]			

Table 2: Eurocode values for non-dominant direction: W

u_{gust}	25.10	m/s	v_{crit}	76.67	m/s
u_{mean}	17.31	m/s	c_{lat}	0.28 (1.4)	[-]
u_{m-ref}	21.84	m/s	v_{cg}	361.28	m/s
c_f	1.5	[-]	f	0.07	1/s
St	0.16	[-]	1^{st} eigen f	0.184	1/s
Sc	23.56	[-]	$y_{F,\max}$	1.686	m
$L(z_s)$	218.1	m	$acc_{f,max}$	0.141	m/s^2
$c_s c_d$	0.896	[-]			

3.3.4 Forces and moments at base of structure

As mentioned in the previous section, the structural factor $c_s c_d$ is paramount in determining the load on a structure with the respect the along-wind response. It is present in the expression for the external forces on the building, i.e. the shear load due to wind pressure:

$$F_{w,e} = c_s c_d \cdot \sum_{\text{surfaces}} w_e \cdot \mathrm{A}_{\mathrm{ref}} \tag{13}$$

where

$$w_e = q_p(z_e) \cdot c_{pe} \tag{14}$$

For the case of a skyscraper like Bank of America Plaza, the pressure coefficient c_p can be taken as 1 while the velocity pressure can be expressed as $q_b(z) = \frac{1}{2}\rho v_b^2(z)$. Using the German annex, $v_b(z)$ can be replaced with Equation 1, a power law representation of the ABL. Using, instead, the Eurocode, a logarithmic law is provided in Section 4 of the Eurocode, equivalent to $u_{mean}(z)$:

$$v_m(z) = c_r(z) \cdot c_0(z) \cdot v_b \tag{15}$$

with

$$\begin{aligned} c_r(z) &= k_r \cdot \ln\left(\frac{z}{z_0}\right) \quad &\text{for} \quad z_{\min} \leq z \leq z_{\max} \\ c_r(z) &= c_r(z_{\min}) \quad &\text{for} \quad z \leq z_{\min} \end{aligned} \tag{16}$$

and

$$k_{\mathrm{r}} = 0.19 \cdot \left(\frac{z_0}{z_{0,II}}\right)^{0.07}. \tag{17}$$

Here, $z_{0,II} = 0.05\ m$, $z_0 = 10\ m$, $c_0(z) = 1$, and $vb = u_{mean}$.

Using Equation 13 and a simple discretization of the building, the shear force and the bending moment can be obtained at the base of the building, as seen in Table 3. The spreadsheet used for these calculations is found in the repository under the name ”loads.xlsx”.

Table 3: Shear force and bending moment at base of building due to dominant wind according to codes

	SHEAR FORCE (N)	MOMENT (Nm)
GERMAN ANNEX	5.21E+08	9.75E+10
EUROCODE	5.87E+08	1.09E+11

3.3.5 SDoF System: Mass, Stiffness, and Damping Calculations

In a similar vein to Equation 11, if the building is assumed to be a SDoF with all the mass lumped at the top (meaning that only mode deformation shape can be expressed as $\psi(z) = \left(\frac{z}{L}\right)^2$), the following expressions can be used to discretely obtain the generalized mass and generalized stiffness of the structure. With this information, the corresponding natural frequency ω_n can be obtained as well. These results as well as the main material properties assumed for the building are found in Table 4. The spreadsheet used for these calculations is found in the repository under the name ”sdof.xlsx”.

$$\bar{m} \approx \sum_{i=1}^{n} m_i \left[\psi_i\right]^2 \Delta z \tag{18}$$

$$\bar{k} \approx \sum_{i=1}^{n} EI_i \left[\psi_i''\right]^2 \Delta z \tag{19}$$

Table 4: Generalized values for SDOf representation

ρ	150	kg/m^3	Gen. mass	3.86E+06	kg
D	1.50	%	Gen. stiffness	2.75E+07	Nm^2
E	2.86E+08	Pa	Gen. damping	3.01E+05	Ns/m
G	1.19E+08	Pa	ω_n	0.435	1/s
I	5.21E+05	m^4			

4 Computational Wind Engineering

INCLUDE TYPES OF COUPLING?? – IN CFD SECTION

4.1 What is CWE?

4.2 Tools

4.2.1 GiD

4.2.2 Kratos Multiphysics

4.2.3 ParOptBeam

4.3 Simulation 1

4.4 Simulation 2

4.5 Simulation 3

4.6 Comparison

5 Conclusions and Future Work

5.1 Conclusions

5.2 Future Work

References

[1] ezaruvinky3, *Bank of america plaza*, 2018. [Online]. Available: https://web.archive.org/web/20220929084808/https://ceelondonblogs.ce.gatech.edu/blog_1/bank-of-america-plaza/.

[2] *Bank of america plaza*. [Online]. Available: https://web.archive.org/web/20150512020655/http://www.emporis.com/buildings/121137/bank-of-america-plaza-atlanta-ga-usa.

[3] *Bank of america plaza*. [Online]. Available: https://skyscraperpage.com/cities/?buildingID=57.

[4] *Bank of america plaza*. [Online]. Available: https://www.skyscrapercenter.com/building/bank-of-america-plaza/429.

[5] *Bank of america plaza (formerly nationsbank)*. [Online]. Available: http://www.krjda.com/Sites/BankAmericaGraphics1.html.

[6] photographersouthflorida, *Bank of america plaza, 600 peachtree street ne, atlanta, georgia, u.s.a.* 2015. [Online]. Available: https://www.flickr.com/photos/miamiboy/23844379570.

[7] *Extreme wind speed data sets*, 2018. [Online]. Available: https://itl.nist.gov/div898/winds/data/nondirectional/datasets/atlanta_ga.prn.

[8] *Us wind climatology*, 2022. [Online]. Available: https://www.ncei.noaa.gov/access/monitoring/wind/.

[9] *Simulated historical climate and weather data for atlanta*, 2022. [Online]. Available: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/atlanta_united-states_4180439.