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Comparative structural analysis of overhead transmission lines: Colombian vs. Italian regulations applied to the Val Formazza project

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"Al borde del vacío comprendió lo más importante: que solo vuela el que se atreve a hacerlo" -Sepúlveda

Abstract

Overhead transmission lines are verified against climatic actions whose statistical definition depends on the country, so the same line can be designed under very different criteria depending on the standard applied. This thesis compares the Colombian framework (RETIE and the ISA design guide, LRFD format) with the Italian one (CEI EN 50341-2-13 and NTC 2018, limit-state theory), applying both to suspension tower BP.25 of the 220 kV Val Formazza line, at 2000 m a.s.l., with a 223.94 m span and a 1657-AL1/209-ST1A conductor.

The theoretical comparison reveals that the two codes are not different theories, but two parameterizations of the same one: the wind action follows an identical sequence in both, and the material model of the conductor is proven formally equivalent. The differences lie in the safety approach, the structure of the wind model, and the treatment of vertical loads.

Both components satisfy the verification under both standards, but the Italian framework is more demanding: conductor utilization of 0.34 against 0.38, and insulator utilization of 0.17 against 0.29. Since the conductor design resistances coincide numerically (426.24 kN), the entire gap originates in the action, governed by the prescribed temperature (5.31 °C against -20 °C) rather than by wind.

A graphical interface was developed to reproduce both calculation chains and vary span, altitude and wind speed one at a time. Altitude is the decisive divergence: the Colombian transverse load decreases with elevation while the Italian one increases, the curves intersecting between 1000 and 1500 m, so the Colombian criterion is conservative below that band and progressively under-conservative above it.

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Chapter 1

Introduction

This project continues the research presented in a bachelor's thesis on the structural analysis of transmission lines [1]. In general, the structural design of these lines aims to ensure the safety and continuity of electrical energy under various extreme conditions.

This structural analysis is linked to meteorological factors (wind pressure, temperature variations, ice or snow formation) and the topography of the terrain.

Due to global geographical variability, each country has established its own regulatory frameworks that respond to its climatic reality and reliability philosophies.

1.1 Motivation

Coming from a tropical country like Colombia, which is situated in the equatorial zone and consequently lacks of thermal seasons, the structural design of infrastructure is not heavily conditioned by extreme temperature fluctuations or severe winter loads (such as ice and snow). In contrast, European engineering standards have been developed to withstand seasonal variations and extreme climatic events. These geographic and climatic differences have inspired me to conduct a comparative structural analysis of overhead transmission lines.

That is, the sensitivity analysis will determine under which specific topographic and climatic conditions the criteria of the Colombian regulations prove viable, excessively conservative, or unsafe when applied in the Italian territory.

Finally, the thesis will not only document the regulatory differences, but will also provide a tool to evaluate at how the two standards behave.

1.2 Objectives

- To compare Colombia's and Italy's standards for overhead transmission lines applied to a real project in Italy (Val Formazza).
- To develop a computational interface to perform a parametric sensitivity analysis by varying topographic and climatic conditions. This tool will determine the technical feasibility of extrapolating tropical Andean design methodologies to Italian environments. Also this interface will calculate the utilization factor of the conductor and insulator.

1.3 Scope of the thesis

This document will focus on the application of real case studies of transmission lines, and from these models, an interface will be developed to perform a parametric sensitivity analysis by varying critical conditions such as altitude, span length, and wind velocity.

The investigated case will work under normal conditions (extreme wind and coincident temperature in Colombian standards, and EDS conditions at 15 °C for Italian standards) working only with suspension towers at any elevation difference, therefore longitudinal loads will not be taken into account. Furthermore, it will be assumed that there are no loads due to the deflection angle.

1.4 List of variables

Table of Variables

Table 1.1: Variables used in the Colombian and Italian regulations

Variable	Description	Chapter
	Chapter 2: Colombian Regulations	
V_R, V_Q	Coefficients of variation for structural resistance and loads	2
$\sigma_R, \overline{R}$	Standard deviation and mean structural resistance	2
$\sigma_Q, \overline{Q}$	Standard deviation and mean applied load	2
R_c	Characteristic value of resistance	2
Q_c	Characteristic value of loads	2

Table 1.1

Variable	Description	Chapter
Φ	Resistance reduction factor	2
γ	Load factor	2
f_s	Overload factor	2
$\overline{t_{min}}$	Coincident temperature	2
H	Altitude above sea level	2
L	Cable length (catenary approximation)	2
C	Catenary parameter (T_0/ρ)	2
T_0	Horizontal cable tension	2
ρ	Unit weight of the conductor	2
S	Horizontal span (distance between supports)	2
h	Elevation difference between attachment points	2
T_{max}	Maximum tension	2
$V_{maximum}$	3-second wind gust (maximum velocity)	2
$V_{corrected}$	Corrected wind speed	2
$k_{r,c}$	Terrain roughness coefficient	2
v_X	Wind speed corrected for height Z	2
α	Roughness exponent	2
Z_g	Gradient height	2
E_{cond}	Equivalent Young's modulus for composite cable	2
E_A, E_S	Moduli of elasticity (aluminum, steel)	2
m	Area ratio between aluminum and steel	2
α_{cond}	Thermal expansion coefficient of the composite conductor	2
q_b	Reference dynamic pressure	2
K_p	Correction factor for elevation above sea level	2
$q_p(Z)$	Corrected dynamic pressure at height Z	2
K_x	Exposure coefficient for height	2
F_c	Wind force on the conductor	2
$C_{c,c}$	Drag coefficient of the conductor	2
d	Conductor diameter	2
F	Considered wind span	2
F_{RV}	Wind span reduction factor	2
Ψ	Incidence angle of wind direction	2
$G_{C,c}$	Gust response factor for the conductor	2
F_i	Wind force on insulators	2
S_i	Area of the insulator string (with shape factor 0.6)	2
F_t	Wind load on lattice structures	2

Table 1.1

Variable	Description	Chapter
C_f	Force coefficient for the structure	2
ϕ	Solidity ratio of the tower	2
C_v	Vertical load	2
V_p	Weight span	2
NSC, NCA	Number of subconductors and insulator strings	2
PCA	Weight of an insulator string	2
I_1, I_2	Normal load current and emergency current	2
t_1, t_2	Initial and final stringing temperature	2
ϵ	Creep deformation	2
Δt_{Eq}	Equivalent temperature of creep	2
XI	Distance from catenary vertex to the preceding support	2
ρ_1, ρ_2	Self-weight (initial) and composite weight (final) of the conductor	2
	Chapter 3: Italian Regulations	
E_d	Design value of the effect of actions (loads)	3
R_d	Design structural resistance	3
γ_F, γ_M	Partial safety factors for actions and material	3
a, b	Half of horizontal span and half of vertical elevation difference	3
c_a	Altitude coefficient	3
$V_{b,0}$	Basic wind velocity (by zone in Italy)	3
V_b	Calculated basic wind velocity	3
a_s	Effective altitude above sea level of the site	3
a_0, k_s	Reference height and altitude factor (by region)	3
$c_e(z)$	Exposure coefficient at height z	3
$k_{r,i}$	Terrain coefficient (roughness)	3
c_t	Orography coefficient	3
z_0	Roughness length	3
z_{min}	Minimum height for wind profile	3
α_a, α_s	Area ratio of aluminum and steel to total area	3
β_a, β_s	Coefficients of linear expansion for aluminum and steel	3
Q_w	Wind action (force)	3
G_x	Dynamic factor	3
C_x	Dynamic resistance factor (drag)	3
$I_v(z)$	Turbulence intensity	3

Table 1.1

Variable	Description	Chapter
B^2	Background factor	3
L_m	Mean value of the two adjacent spans	3
$L(z)$	Integral scale of turbulence	3
R^2	Resonance factor	3
f	Conductor sag	3
$C_{i,i}, G_{i,i}$	Drag and structural factor for insulators	3
$C_{t,i}, G_{t,i}$	Drag and structural factor for the tower	3
χ	Solidity ratio of structure members	3
$\gamma_G, \gamma_{G1}, \gamma_{G2}$	Partial safety factor for permanent loads	3
γ_W	Extreme wind load factor	3
γ_I	Extreme ice load factor	3
x_M	Horizontal distance of the lower support	3
x_r	Horizontal distance to the minimum point of the catenary	3

1.5 Meteorology and climatic conditions in Colombia and Italy

According to Aragón Rodríguez in [2], Colombia is located in the Intertropical Convergence Zone (ITCZ), an atmospheric belt situated at the equator, where winds from the northern hemisphere and the southern hemisphere converge, causing intense cloudiness, high precipitation, and storms; furthermore, being located at a latitude close to the equator, this implies a low annual thermal variation, which is why the four thermal seasons do not exist. Permanent snow is limited exclusively to the highest altitude thermal zones, such as in the Sierra Nevada de Santa Marta (5755 meters above sea level), however, snow/ice loads are not taken into account for any structural calculation of overhead lines.

Italy, unlike Colombia, is located in the temperate zone of the northern hemisphere, within the European Mediterranean region. In winter, cold winds from northeastern Europe can generate significant temperature drops and snowfalls, especially in the north of the country; additionally, it presents a marked annual thermal variation (from 42°C as maximum temperature to −15°C according to the Norme tecniche per le costruzioni in [3]) and relevant snow/ice loads in mountainous areas, conditions that influence and are taken into account in structural design of overhead lines.

Chapter 2

Colombian Regulations

The RETIE (Reglamento técnico de instalaciones eléctricas in [4]) is Colombia's mandatory technical regulation that ensures the safety of all electrical installations. This standard may have technical gaps that allows the use of recognized international standards such as IEC, IEEE, ASCE, and ANSI in case the standard omits a process or formula.

According to the RETIE [4] "the loads of suspension towers under normal conditions are defined as all conductors and shield wires intact, maximum design wind, and coincident temperature".

For this structural analysis of overhead lines, we will use the guide of Interconexiones Eléctricas ISA in [5], the company in charge of operating all transmission lines in Colombia that has a standardization guide for metallic structures which was written in 1989 with the help of Électricité de France, together with the Colombian Institute of Scientific Research and Projects.

The ISA reference in [5] will be used as a guide for the structural evaluation of the Colombian regulations in this work, and in case of not having a definition or formula, reference will be made to the book by Carlos Alberto Ortiz, "Diseño de líneas de transmisión" in [6]

2.1 LRFD overload factor method

The overload factor method on the ISA guide in [5], aims to guarantee a predetermined level of safety, using the reliability index β as a measure. The reliability index β in [5] is defined as a direct numerical measure of structural safety.
Defining a random function $F = R - Q$ or $F = \ln(R/Q)$, the index graphically represents the number of standard deviations that separate the mean value of the safety margin from the failure condition; this means that, the larger the value of β, the farther the structure will be from failing.

The ISA guide indicates by means of calibration studies conducted on transmission lines already built in different countries, that a value of β equal to three provides highly reliable service.

Table 2.1 shows the classification of transmission lines that are organized into three main categories (classes 1, 2, and 3) that determine their level of structural safety through four parameters: the annual failure probability (p_f), the reliability index (β), the overload factor (f_s), and the return period (T).

For example, the most demanding and safest design, corresponding to class 1, a minimum acceptable risk is established with $p_f = 0.0005$ and the highest safety level $\beta = 3.5$, which requires amplifying the design forces by a factor $f_s = 1.65$ to withstand extreme climatic events with return period $T = 1000$ years.

At an intermediate level, class 2 relaxes these requirements to $p_f = 0.0020$, an index $\beta = 3.0$, and a multiplier factor $f_s = 1.30$, contemplating $T = 250$ years.

Class 3 represents the basic and least strict design, tolerating a higher probability of risk of $p_f = 0.0100$ with $\beta = 2.5$, without requiring an extra amplification of the design load ($f_s = 1.00$) against an event with $T = 50$ years; it should be noted that all these values assume constant coefficients of variation for both resistance ($V_R = 0.20$) and load ($V_Q = 0.25$).

Table 2.1: Overload factor according to the annual probability of failure P_f. [5]

Class	P_f **annual**	**Index** β ($V_R = 0.20, V_Q = 0.25$)	f_s	**Return period (years)**
1	0.0005	3.5	1.65	1000
2	0.0020	3.0	1.30	250
3	0.0100	2.5	1.00	50

The variables V_R and V_Q represent the coefficients of variation for the statistical distributions of structural resistance and applied loads, respectively. They measure the degree of dispersion or uncertainty of the data relative to their average values:

$$V_R = \frac{\sigma_R}{\bar{R}} \quad \text{and} \quad V_Q = \frac{\sigma_Q}{\bar{Q}} \tag{2.1}$$

Where:

- σ_R and $\bar{R}$: are the standard deviation and the mean structural resistance. Their ratio (V_R) depends on the variability of the material characteristics, the type of structure, and the level of quality control maintained during manufacturing.
- σ_Q and $\bar{Q}$: are the standard deviation and the mean applied load. Their ratio

(V_Q) reflects how significantly the potential maximum loads (such as extreme wind gusts) deviate from the average expected loads.

According to ISA guide [5], the structural design of transmission line components are based on the condition that the resistance capacity of the materials (R) must be greater than the applied loads (Q). In practice, this condition is expressed through the fundamental equation of probabilistic design.

$$\Phi R_c \geq \gamma Q_c \tag{2.2}$$

Where:

- R_c: It is the characteristic value of the resistance. It represents the physical capacity that the structure has to withstand the loads.
- Q_c: It is the characteristic value of the loads or of the effects that these loads produce on the structure.
- Φ: It is the resistance reduction factor. Its function is to decrease the theoretical resistance value to take into account that materials have defects and imperfections.
- γ: It is the load factor. It is a multiplier that increases the value of the expected loads to take into account their level of uncertainty or random nature (for example, unforeseen wind gusts).

2.2 Coincident temperature

The coincident temperature, as mentioned on the introduction, is needed to compute the LRFD method. This temperature is defined in the book of Carlos Alberto Ortiz Eastman [6] as the "average value of the series of absolute minimum temperature records, which is given by the correlation between temperature and altitude above sea level" This temperature coincides with the maximum winds of the location:

$$\overline{t_{min}} = \frac{2770 - H}{145} [^{\circ}\mathrm{C}] \tag{2.3}$$

Where H is the altitude above sea level in meters, and t_{min} is the minimum coincident temperature in ^{o}C.

2.3 Conductor length

For the calculation of the conductor length in unlevel spans, the catenary approximation is used, based on the methodology of Ortiz Eastman in [6]. The length of the cable is given by:

$$L = \sqrt{\left(2C \sinh \frac{S}{2C}\right)^2 + h^2} \quad [m] \tag{2.4}$$

Where the catenary parameter, C, is defined as:

$$C = \frac{T_0}{\rho} \quad [m] \tag{2.5}$$

In these expressions:

- C: Catenary parameter, defined as the quotient between the horizontal tension of the cable, T_0 [kgf], and the unit weight of the conductor, ρ [kgf/m].
- S: Horizontal span or distance between supports [m].
- h: Vertical height difference (elevation difference) between the two attachment points of the cable [m].

2.4 Maximum tension for cables

According to the book of Ortiz [6], "the conductor forms a catenary curve under its own weight and environmental loads, the tension along the cable is not constant. The tension reaches its minimum value at the lowest point of the curve (the catenary vertex) and increases as the elevation of the cable rises". Therefore, for an inclined span with an elevation difference (h) between the two supports, the maximum tension occurs at the highest attachment point.

In order to calculate this maximum tension (T_{max}), the following information is needed:

The geometric shape of the catenary is governed by the catenary parameter (C), which represents the ratio between the horizontal tension (T_2) obtained from the change of state equation and the composite unit load (ρ_2, from Equation 2.35) acting on the cable:

$$C = \frac{T_2}{\rho_2} \tag{2.6}$$

To evaluate the tension at the supports, it is necessary to determine their horizontal distances relative to the catenary vertex. Let x_1 and x_2 be the horizontal

distances from the vertex to the lower and upper supports, respectively, such that the total horizontal span S is:

$$X_2 - X_1 = S \tag{2.7}$$

In a perfectly level span ($h = 0$), the vertex is located exactly at mid-span, meaning $x_1 = -L/2$ and $x_2 = L/2$. However, in inclined spans, the vertex shifts towards the lower support. In cases of strongly inclined spans, the vertex may even be located virtually outside the actual span (for example in exercise 25 of [7], they showed a distance of -50 meters) resulting in both x_1 and x_2 being positive values and significantly larger than $L/2$.

The tension variation along the conductor $T(x)$ can be expressed in terms of the horizontal distance x from the vertex using the hyperbolic cosine function of [6]:

$$T(x) = T_2 \cosh\left(\frac{x_2}{C}\right) \tag{2.8}$$

2.5 Velocity correction calculation

To calculate the reference dynamic pressure, it is necessary to make a correction according to the terrain exposure category. This classification is defined in Table 2.2, as stipulated by the ANSI A58.1 standard in [8] and the ISA guide in [5].

Table 2.2: Exposure categories according to the ANSI A58.1 standard.[8][5]

Category	Characteristics
A	Centers of large cities, with at least 50% of the buildings taller than 20 meters.
B	Suburban areas and forests.
C	Open, flat terrain, with scattered obstructions. It is the exposure category that must be used when the terrain characteristics do not fit the descriptions of the other categories.
D	Flat areas without obstacles and coastal zones.

If the terrain category is different from category C, a correction , $k_{r,c}$ must be applied using the following formula:

$$V_{corrected} = k_{r,c} \cdot V_{o,maximum} \tag{2.9}$$

Where $k_{r,c}$ is the roughness coefficient and $V_{maximum}$ is the 3-second wind gust. Table 2.3 presents the corresponding values depending on the terrain category:

Table 2.3: Roughness coefficient $k_{r,c}$ [5].

Exposure Category	**A**	**B**	**C**	**D**
$k_{r,c}$	0.67	0.85	1.00	1.08

If the wind speed is not referred at a height of 10 meters, a correction must be made using the following formula:

$$v_X = v_0 \left(\frac{Z}{X_0}\right)^{\frac{1}{\alpha}} \tag{2.10}$$

Where:

- v_X: is the wind speed corrected for a height Z [m/s].
- v_0: is the maximum speed corrected by the roughness coefficient [m/s].
- X_0: is the reference height for which v_0 is defined (usually 10 m) [m].
- Z: is the height at which the speed is being corrected [m].
- α: is the roughness exponent that depends on the terrain category. It is found in Table 2.4.

Table 2.4: Parameters of the Exponential Model for Wind Variation with Height [5]

Exposure Category	α	Z_g [m]
A	3.0	457
B	4.5	366
C	7.0	274
D	10.0	213

2.6 Calculation of the modulus of elasticity and coefficient of expansion

To calculate the modulus of elasticity of a cable that contains two materials, it is necessary to find the equivalent Young's modulus through the following formula, given by the book of Alberto Ortiz in [6]:

$$E_{\text{cond}} = \frac{mE_A + E_S}{m+1} \tag{2.11}$$

$$m = \frac{\text{area of aluminum}}{\text{area of steel}} \tag{2.12}$$

Where:

- E_A, E_S: Moduli of elasticity of each material (aluminum and steel)[kg/mm^2]
- m: Area ratio between aluminum and steel.

For the calculation of the thermal expansion coefficient of two composite conductors, the following formula is obtained also by reference [6]

$$\alpha_{\text{cond}} = \frac{mE_A\alpha_A + E_S\alpha_S}{mE_A + E_S} \tag{2.13}$$

Where:

- α_A, α_S: Thermal expansion coefficients of each material [$1/°C$].
- E_A, E_S: Respective moduli of elasticity [kg/mm^2].
- m: Area ratio defined previously.

2.7 Calculation of transverse loads

The process to find the wind force over the conductor is shown in Figure 2.1. The circular nodes are coefficients that must be find in standards and rectangle nodes denote for application of formulas also from standards.

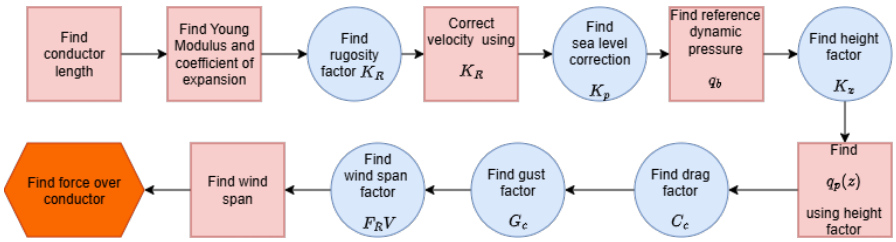


Figure 2.1: Overall process to find wind force over the conductor

The reference dynamic pressure is calculated with the ISA guide in [5]:

$$q_b = K_p V_b^2 [N/m^2] \tag{2.14}$$

$$K_p = 0.603 - 0.0514A \tag{2.15}$$

Where

- V_b is the wind speed in m/s (wind gust of 3 seconds), at a height of 10 m, for category C terrain.
- K_p is a correction factor that takes into account the elevation above sea level, where A is the altitude above sea level expressed in kilometers.

Then, the pressure is corrected to a specific height above ground level. If the height is lower or equal than 10 meters, we won't correct.

$$q_p(Z) = K_x * q_b[N/m^2] \tag{2.16}$$

$$K_x = \left(\frac{300}{10}\right)^{\frac{2}{7}} \left(\frac{Z}{Z_g}\right)^{\frac{2}{\alpha}} = 2.6 \left(\frac{Z}{Z_g}\right)^{\frac{2}{\alpha}} \tag{2.17}$$

Where

- The first fraction $\left(\frac{300}{10}\right)$: It is a fixed conversion factor. It takes the standard measurement at a height of 10 meters and raises it to the gradient height of a standard reference terrain (Category C), which in this case the ISA guide approximates to 300 meters.
- The second fraction $\left(\frac{Z}{Z_g}\right)$: It takes that maximum pressure at the top of the boundary layer and lowers it to the actual height of the structure Z, adjusting it by the gradient height Z_g of Table 2.4 and the exponent α specific to the roughness of the actual terrain where you are going to build the line. These values are found in Table 2.4.
- $q_p(z)$: Corrected dynamic pressure (N/m^2), which is the actual pressure value at the height of the cable.
- K_x: Exposure coefficient. It adjusts the pressure based on the height Z.
- Z: Actual height of the point of application above the ground (in meters). It only applies if $Z \geq 10$ m.
- α: Exponent that depends on the roughness of the terrain (obtained from Table 2.4).
- Z_g: Gradient height, which varies according to the terrain category (obtained from Table 2.4).

Then, the force due to the wind effect on the conductor, applied to the structure and perpendicular to the span, is:

$$F_c = q_p(z) * C_{c,c} * G_{C,c} * d * F * F_{RV} * \sin^2 \Psi \quad [\text{N}] \tag{2.18}$$

Where:

- $C_{c,c}$: Drag coefficient of the conductor.
- d: Diameter of the conductor [m].
- F: Considered wind span [m]. The ASCE 74 standard in [9] is used to calculate as the average of the preceding and succeeding spans $(S_p + S_s)/2$
- F_{RV}: Wind span reduction factor.
- Ψ: Incidence angle of the wind direction. The ISA methodology [5] assumes that the wind strikes the cable perpendicularly, so $\Psi = \pi/2$.
- $G_{C,c}$: Gust response factor for the conductor. It is found using Figure 2.4.

The gust response factor for conductors is defined by the type of terrain (A, B, C, and D) shown in Figure 2.4.

Also it can be obtained with Davenport's equation [5]:

$$G_{c,c} = 0.5 + 5.4\sqrt{k}\left(\frac{10}{Z_o}\right)^{\alpha} \sqrt{\frac{1}{1 + 0.8\frac{S}{L_s}} + \frac{0.16 \cdot D \cdot O^{1/3} \cdot V_{3s}^{2/3} \cdot Z_o^{2(1-\alpha)/3\alpha}}{S \cdot Z_g^{2/3\alpha}}} \tag{2.19}$$

Where:

- Z_o: Height of the conductor above ground [m]
- S: span length [m].
- V_{3s}: 3-second wind gust velocity [km/h].
- D: Total diameter of the conductor [mm].
- O: Conductor sag corresponding to the wind span [m].
- α, Z_g, k, L_s: Empirical parameters depending on the terrain exposure category (Categories A, B, C, or D) given by Table 2.5

Table 2.5: Variables for the definition of G_c

CATEGORY	α	Zg [m]	k	Ls (m)
A	3.0	457	0.025	30.5
B	4.5	366	0.010	52.0
C	7.0	274	0.005	67.0
D	10.0	213	0.003	76.0

The wind span reduction factor is given by Figure 2.2 or equation 2.20

$$F_{RV} = 1.3 - 0.0012 * F \tag{2.20}$$

Where F is the wind span in meters. For long spans (greater than 500 m), the reduction factor is constant and equal to 0.7. Below is the graph of this factor F_{RV}:

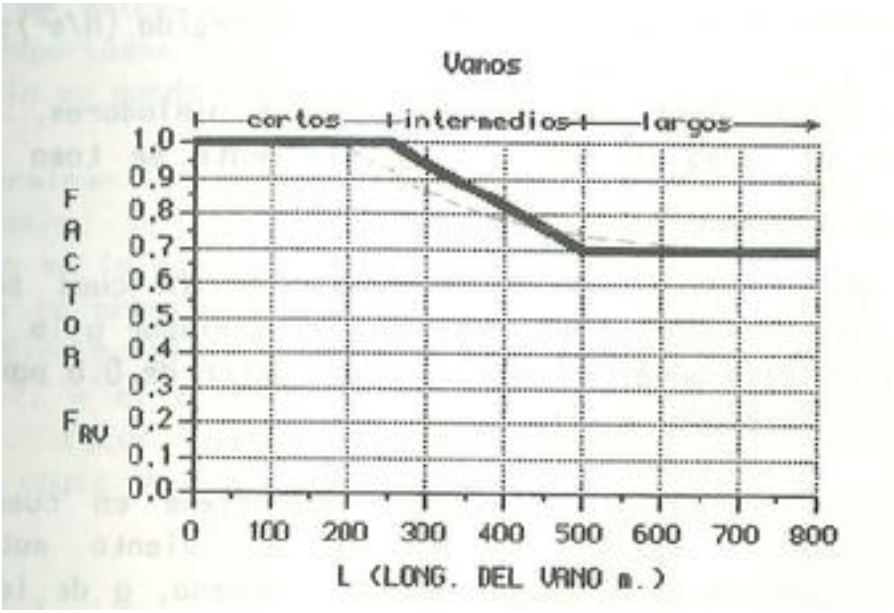


Figure 2.2: Span reduction factor [5]

After finding the wind force over the conductors an overload factor is added to the wind force on the conductor, $F_c = f_s F_c$. For this work, we will work with a safety factor f_s of 1.65 meaning that is class 1 of Table 2.1

To continue the process to calculate transverse loads, the wind load on the insulators is given by Figure 2.3

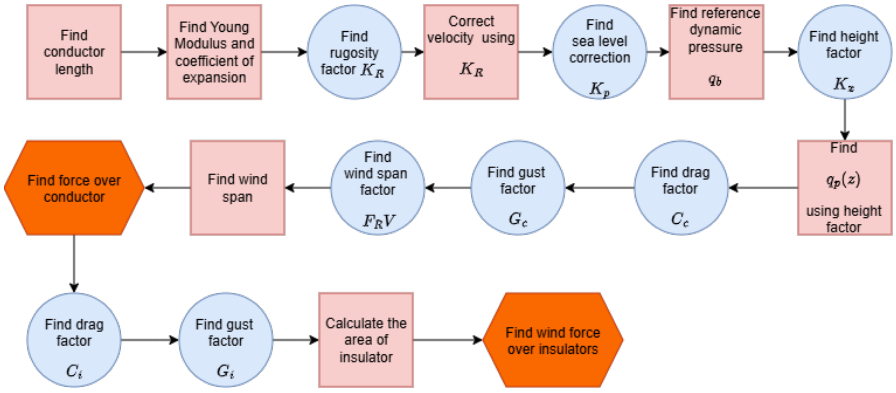


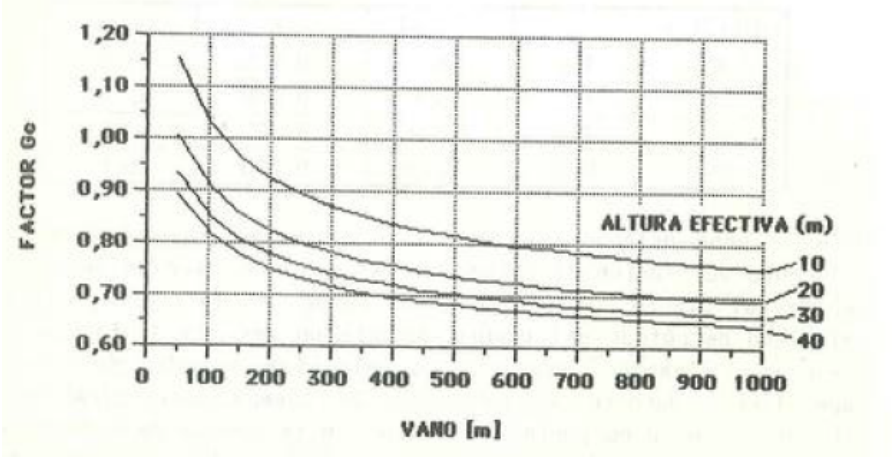
Figure 2.3: Process to find wind force over insulator+conductor

To calculate the wind force over the insulator we use equation 2.21

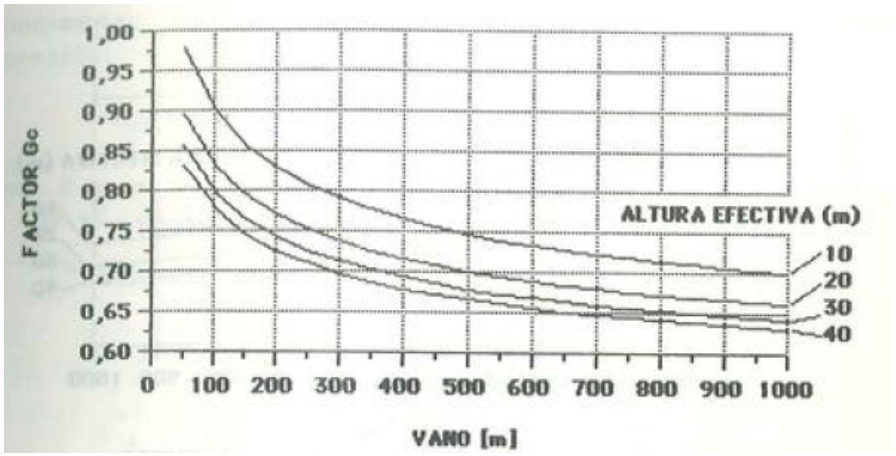
$$F_i = q_p(z) * C_{i,c} * G_{i,c} * S_i \quad [\text{N}] \tag{2.21}$$

Where:

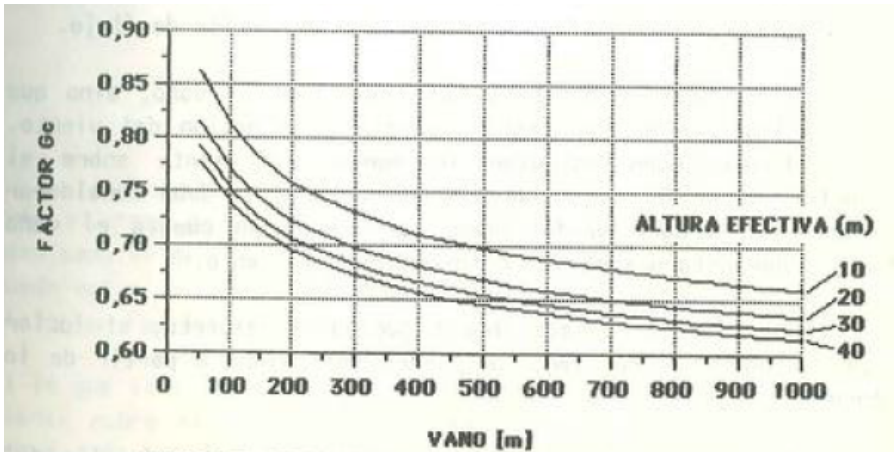
- $q_p(z)$ is the corrected dynamic pressure $[N/m^2]$
- $C_{i,c}$: Drag coefficient of the insulators, generally taken as 1.2.
- S_i: Area of the insulator string [m^2], calculated as the product of the diameter and the length of the string, affected by a shape factor of 0.6, formula given by Alberto Ortiz [6]
- $G_{i,c}$: Gust response factor for insulators. It can be observed in Figure 2.6.



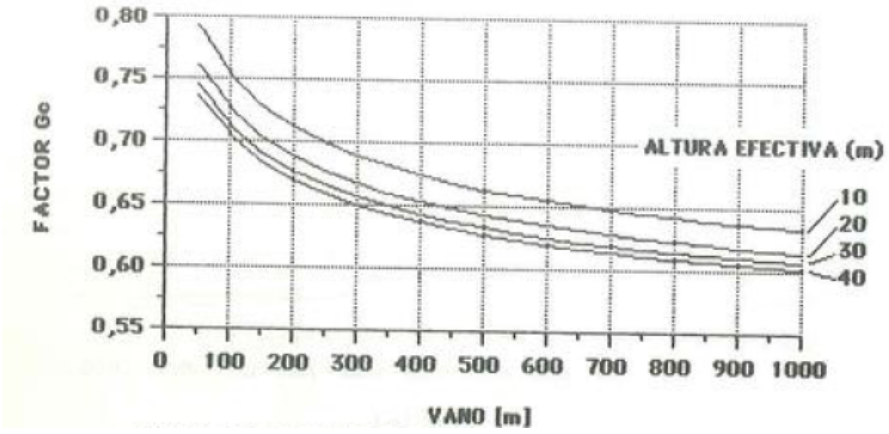
a) Category A



b) Category B



c) Category C



d) Category D

Figure 2.4: Gc factor for terrain categories A, B, C, and D [5]

The last step for wind transversal loads is shown in Figure 2.5

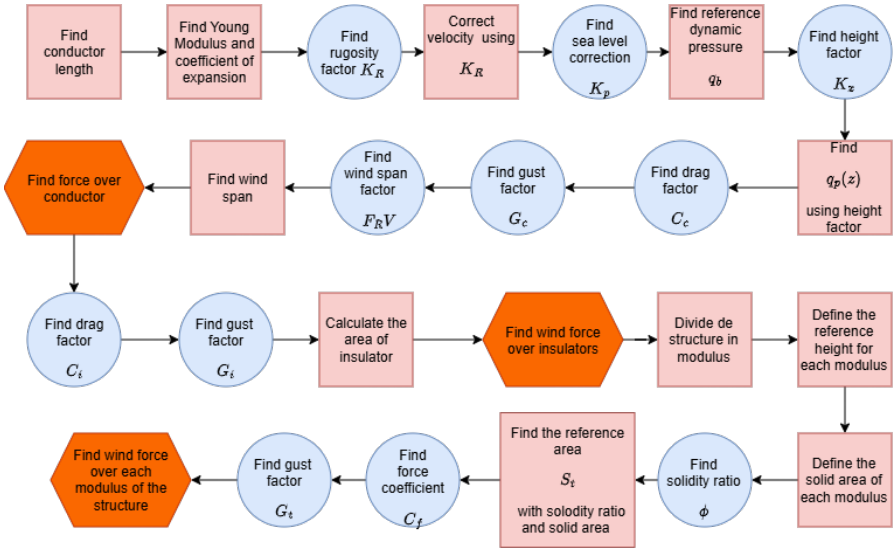


Figure 2.5: Process to find wind force over the +insulator+conductor

The load due to wind on lattice structures is calculated for each module or body of the tower with the pressure corrected to the height of the corresponding center of mass, and the gust response factor shown in Figure 2.6.

$$F_t = q_p(z) C_f G_{t,c} S_t \quad [\text{N}] \tag{2.22}$$

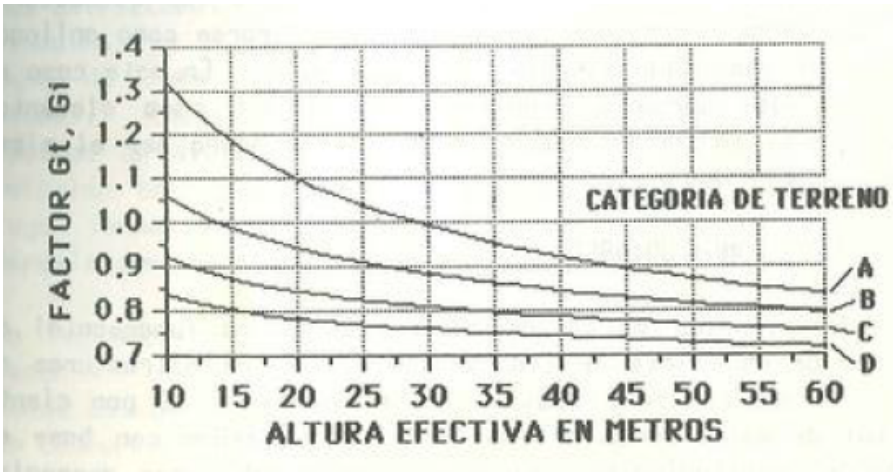


Figure 2.6: Gt, Gi factor for insulators and structures [5]

Then, to calculate the factor C_f, Table 2.6 is used, where the solidity ratio ϕ is:

$$\phi = \text{solidity ratio} = \frac{\text{Area of all elements}}{\text{Solid area of the panel}} \tag{2.23}$$

Table 2.6: Force Coefficients (C_f) for Lattice Structures according to Solidity Ratio[5]

Solidity Ratio (ϕ)	**Coefficient** C_f
< 0.025	4.0
0.025 to 0.44	$4.1 - 5.2\phi$
0.450 to 0.69	1.8
0.700 to 1.00	$1.3 + 0.7\phi$

Due to the lack of data for the calculation of the solidity ratio of the lattice modules, typical solidity ratio values for transmission towers will be used, based on Figure 5-1 of the ASCE 74 standard [9]. The values to consider are presented in Table 2.7.

Table 2.7: Solidity ratio according to the tower zone. [9]

Zone	Solidity ratio ϕ
Upper zone	0.26
Middle tower body	0.24
Lower tower body	0.16

To complete the tower analysis, all modules must be summed to obtain the wind load on the structure.

Then, an overload factor of 1.65 is applied to the structure $F_t = F_t * 1.65$

2.8 Calculation of vertical loads

The process to find vertical loads is shown in Figure 2.7. The yellow node represents the value that differs from italian methodology.

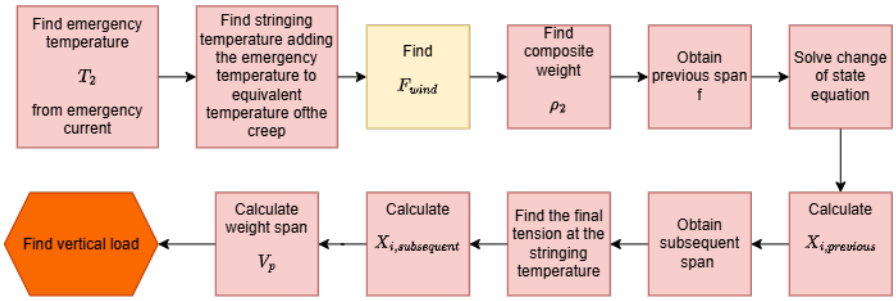


Figure 2.7: Process to find the vertical load

The vertical load is calculated as:

$$C_v = 1.1 * \rho \cdot V_p \cdot NSC + 1.0 * NCA \cdot PCA[N] \tag{2.24}$$

Where:

- C_v: Vertical load [N].
- ρ: Unit weight of the conductor [N/m].
- V_p: Weight span [m], which can be negative if the tower is subjected to uplift loads.
- NSC: Number of subconductors.
- NCA: Number of insulator strings.

- PCA: Weight of an insulator string [N].

According to the ISA methodology in [5], the permanent load due to the weight of the conductor is multiplied by a safety factor of 1.10. The insulator string is multiplied by a value of 1.00.

To calculate V_p we need the stringing temperature. The stringing temperature t_2 is defined in [6], and it takes into account the maximum ambient temperature, solar radiation, and the maximum current that the line must carry.

The currents and temperatures are defined as:

- I_1: Normal load current of the conductor [A].
- I_2: Emergency current [A].
- t_1: Initial or equilibrium temperature of the conductor when carrying the normal load current I_1 [ºC].
- t_2: Final limit temperature of the conductor when subjected to the emergency current I_2 [ºC].
- t_∞: Average temperature of the environment surrounding the conductor [ºC].
- t: Instantaneous temperature of the conductor at a time τ during the change of state [ºC].

The physical and electrical characteristics of the conductor are defined as:

- A: AC resistance per unit length of the conductor at 0°C [Ω/m].
- B: Resistance coefficient that describes how quickly the resistance changes with temperature. It is defined as A/M, where M is Material-dependent constant representing the inferred temperature of zero electrical resistance (for example, 234.5 for copper and 228.1 for aluminum) [$\Omega/m°$C]
- A': Simplified factor that groups the resistance and ambient temperature variables, defined as $A + Bt_\infty$ [Ω/m].
- d: External diameter of the conductor [m].
- m': Mass per unit length of the conductor [kg/m].
- C_p: Specific heat at constant pressure of the conductor material [$\mathrm{J\,kg^{-1}\,K^{-1}}$].
- t_c: Thermal time constant of the conductor.
- E: Linearization factor. Approximates the non-linear radiation term in the energy balance equation, allowing for a direct calculation of the emergency temperature. It is defined as: $1.38 \times 10^8 + 1.39 \times 10^6 \cdot t_{inf}$

Thus, the solution to the equation for the load current I_1 is:

$$t_1 - t_\infty = \frac{I_1^2 A' + \varepsilon_s dQ_{Sun}}{\pi hd + \varepsilon_l \pi d\sigma E - I_1^2 B} \tag{2.25}$$

For the emergency current I_2, it is:

$$t_2 - t_\infty = \frac{I_2^2 A' + \varepsilon_s dQ_{Sun}}{\pi hd + \varepsilon_l \pi d\sigma E - I_2^2 B} \tag{2.26}$$

To this temperature t_2, the effect of creep must be added, which is the plastic deformation that a material undergoes when subjected to the action of a load over a period of time. This load is calculated using equations 2.27 and 2.28.

For Aluminum-Steel conductors:

$$\varepsilon = K \left(\frac{100T}{T_{Rup}} \right)^{\alpha} t^{\phi} \tau^{\mu} \text{ [mm/km]} \tag{2.27}$$

For Aluminum and Aluminum alloy conductors

$$\varepsilon = K \sigma^{\alpha} t^{\phi} \tau^{\mu} \text{ [mm/km]} \tag{2.28}$$

Where:

- K, α, ϕ, μ: Coefficients that depend on the characteristics, manufacturing process, and type of conductor.
- T: The tension to which the conductor is subjected [kgf].
- T_{Rup}: Ultimate tensile strength of the conductor in [kgf].
- σ: Tensile working rate of the cable, T/area[kg/mm^2].
- t: Basic conductor temperature at 20°C.
- τ: Time of tension application to the conductor [hours].

The total creep must be found as the difference between the creep developed over its useful life (using basic tension) and the creep developed during installation, for which the following formula is used:

$$\varepsilon = \varepsilon \text{ Useful life} - \varepsilon \text{ Installation [mm/km]} \tag{2.29}$$

Then, this creep is taken to a base scale in m/m:

$$\varepsilon' = \frac{\varepsilon \text{ [mm/km]}}{1{,}000{,}000 \left[\frac{\text{mm}}{\text{m}} \times \frac{\text{m}}{\text{km}} \right]} \tag{2.30}$$

If this value is divided by the thermal expansion coefficient, the equivalent temperature value is obtained, as follows:

$$\Delta t_{Eq} = \frac{\varepsilon\ (\text{m/m})}{\alpha\ (1/°\text{C})}\ [°\text{C}] \tag{2.31}$$

The final stringing temperature will be

$$t_2 = t_2 + \Delta t_{Eq} \tag{2.32}$$

To find the weight span, the equation from Alberto Ortiz [6] is used, first we need to find the distance of the vertex to the preceding support, which is:

$$XI = \frac{\text{S}}{2} - \frac{T}{\rho}\sinh^{-1}\left(\frac{h}{2\frac{T}{\rho}\sinh\left(\frac{\text{S}}{2\frac{T}{\rho}}\right)}\right) \quad [\text{m}] \tag{2.33}$$

- XI: Distance from the catenary vertex with respect to the preceding support [m]
- S: Horizontal distance between the supports [m]
- T: Conductor tension at the stringing temperature, [kgf]
- ρ: Unit weight of the conductor [kgf/m]
- h: Elevation difference of the span [m]

Then the weight span is calculated as follows:

$$V_P = \text{Preceding} - XI(\text{preceding}) + XI(\text{succeeding}) \quad [\text{m}] \tag{2.34}$$

To find the conductor tension at the stringing temperature, the conductor change of state equation is used, following the methodology of Alberto Ortiz in [6].

$$T_2^3 + T_2^2 * (\alpha * EA * \Delta t - T_1 + (S^2 * \rho_1^2 * EA)/(24 * T_1^2)) = (\rho_2^2 * S^2 * EA)/24 \tag{2.35}$$

Where;

- T_1: Conductor tension under initial or basic conditions [kg].
- T_2: Conductor tension under final conditions (the new state to be analyzed) [kg].
- E: Modulus of elasticity of the conductor [kg/mm^2].

- A: Cross-section of the conductor [mm^2].
- S: Span length (the horizontal distance between supports) [m]
- ρ_1: Self-weight of the conductor in the initial state [kg/m].
- ρ_2: Composite weight of the conductor in the final state. It is expressed in kg/m. This weight is the vector resultant between the vertical self-weight of the conductor and the horizontal force exerted by the wind on it ($\rho_2 = \sqrt{\rho_1^2 + F_{\text{wind}}}$) Where F_{wind}^2 is calculated as $0.0045 \cdot (V \cdot 3.6)^2 \cdot d$, where V is the wind velocity and d is the external diameter.
- α: Coefficient of linear thermal expansion of the conductor material [1/°C].
- Δt: Temperature difference between the final state to be analyzed and the initial state temperature ($t_2 - t_1$) [°C].

Chapter 3

Italian Regulations

In Europe, the design, construction, and structural verification of overhead lines are governed by the european standard EN 50341-1 [10] and the Norme tecniche per le costruzioni [3]. However, due to topographic and geographic diversity and climatic variations, the European standard includes National Normative Aspects (NNA) [11], which allow each country to adapt and supplement the general guidelines according to its specific territorial conditions. In the case of Italy, the reference regulatory framework is the CEI EN 50341-2-13 standard, which adopts the European directives and specifies them for the Italian territory.

The Italian regulation defines the standard load cases in 4 categories [10]:

- Case 1 (Wind loads): The load condition for extreme wind and wind load at the site's minimum temperature are taken into account.
- Case 2 (Ice and snow loads): The presence of uniform ice/snow, transverse bending due to ice, longitudinal bending due to unbalanced ice loads, and torsional bending due to ice unbalance are assumed.
- Case 3 (Combined loads): The simultaneous presence of wind and ice/snow is considered.
- Case 4 (Safety / Breakage loads): Simulates line failures by evaluating the torsional loads and longitudinal loads generated by the breakage of conductors.

The minimum temperature is obtained from the NNA [11] on Table 3.1. The minimum temperature to be considered depends on the following zones A and B of the Italian territory:

- Zone A Territory with an altitude not exceeding 800 m a.s.l. in the central, southern and insular areas of Italy (zones 3, 4, 5, 6, 9); the minimum temperature is $-7°C$

- Zone B Territory with an altitude exceeding 800 m a.s.l. in the central, southern and insular part of Italy (zones 3, 4, 5, 6, 9) plus all the territory of northern Italy (zones 1, 2, 7, 8); the minimum temperature is −20°C.

Table 3.1: Temperature, wind and ice/snow combination [11]

Condition of tests		Temperatures (°C)	Extreme wind	Ice/snow
a)	Every Day Stress	15	0	0
b)	Minimum temperature	Zone A −7 Zone B −20	$\sqrt{C_e}\ V_b$ 0,76 $\sqrt{C_e}\ V_b$	0
c)	Wind action	−7	$\sqrt{C_e}\ V_b$	0
d) e)	Co-existence of wind and ice or snow (*) actions	−2	0,6 V_b	S_k
f1)	Verification of design clearances – Method of maximum reference temperature	Zone A 75 Zone B 75	0	0
f2)	Verification of design clearances – Method at limit states	Zone A 55 Zone B 48	0	0
f3)	Verification of clearances at extreme temperature conditions – Method at limit states	96	0	0
g)	Check of electrical clearances in conditions of swung catenary	Zone A 55 Zone B 48	0	0
(*) This verification is not applicable to zones where $S_k = 0$ (zone where the type 3 load per $a_s \leq 600$ m is expected). In zone where the type 1 and type 2 loads can be expected, both verifications are required.				
The temperature values for verifications of f1), f2), f3), g) on high temperature conductors shall be indicated in project specifications.				

3.1 Limit state theory

In the EN 50341-1:2012 [10] standard, the objective of the limit states is to verify that the structure does not reach a load limit when the design values are applied. To apply this approach, a basic design formula is used that must be fulfilled to avoid the rupture or excessive deformation of a component or element, we have:

$$E_d \leq R_d \tag{3.1}$$

Where E_d is the total design value of the effect of actions (such as an internal force or moment) and R_d is the design structural resistance. It can also be written in the following way, breaking down E_d and R_d

$$\gamma_F \cdot F_k \leq \frac{R_k}{\gamma_M} \tag{3.2}$$

Where F_k is the base statistical value of the load and Fd is the design value of the action. The factors for γ_F and γ_M are found in Table 3.2.

The standard mentions two categories of limit states:

1. Ultimate Limit States (ULS): These are the states associated with collapse or other similar forms of structural failure due to excessive deformation, loss of stability, overturning, rupture, or buckling.

A state of severe damage just before structural collapse can also be treated, for simplicity, as an ultimate limit state.The design must ensure that the effects of the loads do not exceed the design resistance of the overhead line components (supports, foundations, conductors, insulators, etc.) in this state.

2. Serviceability Limit States (SLS): These refer to a state beyond which the specified service or functional criteria for a structure or element are no longer met.

Unlike the ultimate state which deals with collapse, the serviceability state is usually related to the geometry of the structure, verifying that there are no excessive deflections and that the required safety clearances or electrical insulations are maintained.

Table 3.2: Partial factors γ and combination factors Ψ for actions in the ultimate limit state [10]

Action	Symbol	Reliability level		
		1	2	3
Variable actions (Climatic loads):				
Extreme wind load	γ_W	1,0	1,2	1,4
Nominal wind load	Ψ_W	0,4	0,4	0,4
Extreme ice load	γ_I	1,0	1,25	1,5
Nominal ice load	Ψ_I	0,35	0,35	0,35
Permanent actions:				
Self-weight	γ_G	1,0		
Security loads (Accidental actions):				
Torsional loads due to conductor tension	γ_{A1}	1,0		
Longitudinal loads due to conductor tension	γ_{A2}	1,0		

Safety loads Construction and maintenance loads [a]	γ_P	1,5
The partial factors on actions mentioned above should be considered in conjunction with the partial factors on material properties, which are defined in other clauses.		
[a] The combination value of wind and ice actions may be taken as the actual forces likely to occur during construction and maintenance. Frequently, the effects of wind and ice actions may be neglected.		

Table 3.3: Partial safety factors for loads (γ_F)[3]

		Coefficient γ_F	**EQU**	**A1**	**A2**
Permanent loads G_1	Favorable	γ_{G1}	0.9	1.0	1.0
	Unfavorable		1.1	1.3	1.0
Non-structural permanent loads G_2	Favorable	γ_{G2}	0.8	0.8	0.8
	Unfavorable		1.5	1.5	1.3
Variable actions Q	Favorable	γ_{Qi}	0.0	0.0	0.0
	Unfavorable		1.5	1.5	1.3

The partial factors γ are defined in Norme tecniche per le costruzioni in reference [3], and they are used to increase the characteristic value of a climatic or mechanical load. They serve to take into account the possibility of unfavorable deviations occurring in the loads. The combination factor ψ is applied specifically when extreme events occur simultaneously. In the case study of this thesis, since there is a hypothesis of extreme wind and minimum temperature, combination factors are not used.

3.2 Conductor length

For the length of the conductors, the document of "Modellazione dei conduttori di un elettrodotto aereo: la catenaria" in [12] is used where the cable length is calculated, which is the same as the methodology used in Section 2.

$$L(C) = \sqrt{4C^2 \cdot \sinh^2\left(\frac{a}{C}\right) + 4b^2} \tag{3.3}$$

Where the variables are defined as follows:

- L It is the total length of the catenary suspended between the two support points [m].
- C It is the tensioning parameter of the catenary. It defines the geometric shape of the curve and is constant throughout the span ($C = T_0/\rho$) [m]. Where T_0 It is the horizontal component of the tension applied to the cable [N], and ρ is the self-weight of the cable per unit length (or resulting force of the loads) [N/m].
- a It is half of the horizontal distance between the two supports ($S = 2a$) [m].
- b**:** It is half of the vertical elevation difference between the suspension points ($h = 2b$) [m].

3.3 Velocity correction calculation

First, the geographical zone is defined on the map, of Figure 3.1 of the NNA in [11].

Once the region is identified, the values of $v_{b,0}$, a_0, and k_s are obtained from Table 3.4.

The effective altitude above sea level of the site (a_s) needs to be evaluated according to the NTC in [3]. For altitudes greater than 1500m, the standard directly assumes $a_s = 1500$.

$$c_a = \begin{cases} 1 & \text{for } a_s \leq a_0 \\ 1 + k_s \left(\frac{a_s}{a_0} - 1 \right) & \text{for } a_0 < a_s \leq 1500 \text{ m} \end{cases} \tag{3.4}$$

The velocity V_b is found as it follows:

$$V_b = c_a * V_{b,0}[m/s] \tag{3.5}$$

Then the dynamic wind pressure is calculated as:

$$q_b = \frac{1}{2} \rho V_b^2 [N/m^2] \tag{3.6}$$

Where

- q_b: is the basic dynamic wind pressure [N/m].
- ρ: is the air density (typically $1.25\, kg/m^3$).
- V_b: is the basic wind velocity calculated previously [m/s].



Figure 3.1: Map of the regions of Italy [11]

To obtain the real force applied to the cables, insulators, or supports, we need the exposure coefficient $c_e(z)$ of normative [11]:

$$c_e(z) = k_{r,i}^2 c_t \ln(z/z_0)[7 + c_t \ln(z/z_0)] \quad \text{for } z \geq z_{min} \tag{3.7}$$

$$c_e(z) = c_e(z_{min}) \quad \text{for } z < z_{min} \tag{3.8}$$

The following parameters are involved in these expressions:

- z is the effective height above the ground [m].
- $k_{r,i}$: terrain coefficient of Table 3.5
- c_t: orography coefficient (usually 1.0 if there are no steep hills).
- z_0: roughness length of Table 3.5 [m].
- z_{min}: minimum height for the wind profile calculation of Table 3.5 [m].

Table 3.4: Parameters for wind determination [11]

Zone	**Description**	$\mathbf{v_{b,0}}$ [m/s]	$\mathbf{a_0}$ [m]	$\mathbf{k_s}$
1	Aosta Valley, Piedmont, Lombardy, Trentino-Alto Adige, Veneto, Friuli-Venezia Giulia (with the exception of the province of Trieste)	25	1000	0.40
2	Emilia-Romagna	25	750	0.45
3	Tuscany, Marche, Umbria, Lazio, Abruzzo, Molise, Apulia, Campania, Basilicata, Calabria (excluding the province of Reggio Calabria)	27	500	0.37
4	Sicily and province of Reggio Calabria	28	500	0.36
5	Sardinia (zone east of the line connecting Cape Teulada with Maddalena Island)	28	750	0.40
6	Sardinia (zone west of the line connecting Cape Teulada with Maddalena Island)	28	500	0.36
7	Liguria	28	1000	0.54
8	Province of Trieste	30	1500	0.50
9	Islands (with the exception of Sicily and Sardinia) and open sea	31	500	0.32

The coefficients $k_{r,i}$, z_0 and z_{min} are obtained from Table 3.5. The exposure category type of the site is determined with Table 3.6 and Figure 3.2

Table 3.5: Parameters for the definition of the exposure coefficient

Site exposure category	$k_{r,i}$	z_0 [m]	z_{min} [m]
I	0.17	0.01	2
II	0.19	0.05	4
III	0.20	0.10	5
IV	0.22	0.30	8
V	0.23	0.70	12

Table 3.6: Parameters to define the site exposure coefficients

Terrain roughness class	Description
A	Urban areas in which at least 15% of the surface is covered by buildings whose average height exceeds 15 m
B	Urban (not class A), suburban, industrial and wooded areas
C	Areas with widespread obstacles (trees, houses, walls, fences,...); areas with roughness not attributable to classes A, B, D
D	a) Sea and relative coastal strip (within 2 km from the coast); b) Lake (with a maximum width of at least 1 km) and relative coastal strip (within 1 km from the coast); c) Areas free of obstacles or with at most rare isolated obstacles (open countryside, airports, agricultural areas, pastures, marshy or sandy areas, snow-covered or icy surfaces, ...)

3.4 Calculation of the modulus of elasticity and thermal expansion coefficient

The BS EN 50182:2001 standard in reference [13] provides tables in Annex F with predefined values for Young's modulus for various countries. In case the information is not found in these annexes, as is the case for Italy, the standard recommends using the IEC 61597 [14]. The IEC 61597 remits to the methodology of the CIGRE [15] :

$$E_{cond} = E_a \alpha_a + E_s \alpha_s \tag{3.9}$$

- E_{cond}: Modulus of elasticity of the complete conductor (MPa).
- E_a: Modulus of elasticity of the aluminum wires (MPa).
- E_s: Modulus of elasticity of the steel wires (MPa).
- α_a: Ratio (fraction) between the aluminum area and the total area of the conductor (A_a/A).
- α_s: Ratio (fraction) between the steel area and the total area of the conductor (A_s/A).

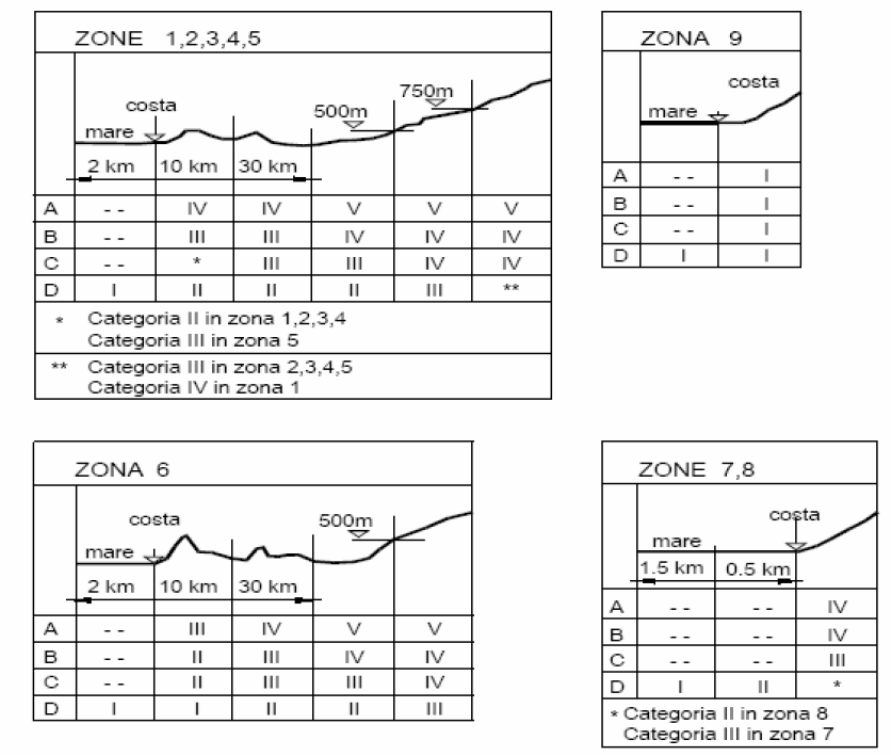


Figure 3.2: Definition of the zones [11]

For the calculation of the thermal expansion coefficient α, we have that:

$$\alpha_{cond} = \frac{E_a A_a \beta_a + E_s A_s \beta_s}{E_a A_a + E_s A_s} [1/^\circ C] \tag{3.10}$$

- α_{cond}: Coefficient of linear expansion of the complete conductor$[K^{-1}]$.
- β_a: Coefficient of linear expansion for aluminum, $[K^{-1}]$.
- β_s: Coefficient of linear expansion for steel (or aluminum-clad steel), $[K^{-1}]$.
- E_a: Modulus of elasticity of the aluminum wires,$[MPa]$.
- E_s: Modulus of elasticity of the steel wires, expressed in $[MPa]$.
- A_a: Cross-sectional area of the aluminum wires, [mm^2].
- A_s: Cross-sectional area of the steel wires, [mm^2].
- K_1: Relative stiffness of steel with respect to aluminum (used in the simplified version of the formula, where $K_1 = \frac{E_s A_s}{E_a A_a}$).

3.5 Calculation of transverse loads

The wind force expressed for any element is [11][10]:

$$Q_w = q_p(z) \cdot G_x \cdot C_x \cdot A \text{ [N]} \tag{3.11}$$

- A: area of the considered element, projected onto a plane perpendicular to the wind direction.$[m^2]$
- Q_w: Wind action [N].
- $q_p(z)$:Defined as the product of dynamic wind pressure q_b and $C_e((z)$calculated as in formula 3.8 $[N/m^2]$
- G_x: Dynamic factor. For conductors, we will replace the value of Gx with Gc of Tables 3.7 to 3.10
- C_x: Dynamic resistance (drag) factor, which depends on the shape of the element (for example, 1.00 for conductors).
- d: Cable diameter [m].

Drag coefficients (C_x):

- conductors ..... $C_x = 1.00$
- overhead stranded conductors ..... $C_x = 1.00$
- overhead cables ..... $C_x = 1.00$
- cylindrical objects (bars, tubular poles) ..... $C_x = 0.80$
- bar, tubular poles with more than six sides ..... $C_x = 1.20$
- bar, tubular poles with six sides ..... $C_x = 1.40$
- flat surfaces normal to wind direction (angles, rectangular poles) . $C_x = 1.80$
- spherical objects ..... $C_x = 0.35$
- insulators ..... $C_x = 1.20$

The process to calculate the transverse loads due to wind are presented in Figure 3.3

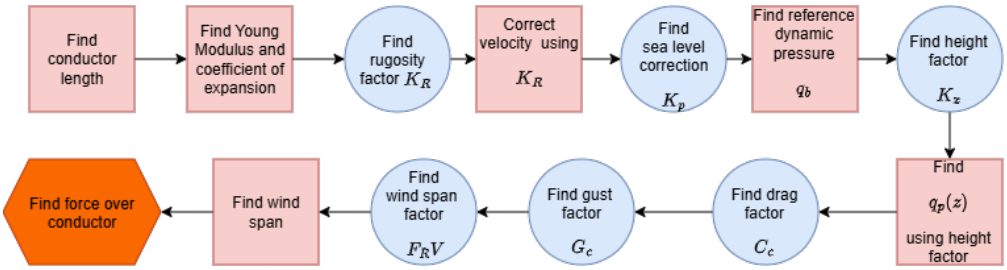


Figure 3.3: Process to find transverse loads over the conductor

The wind force on the conductors, assuming no deflection angle(then θ is 0):

$$F_c = q_p(z)\, G_{c,i}\, C_{c,i}\, d * \cos^2\left(\frac{\theta}{2}\right) F[N] \tag{3.12}$$

Where:

- $q_p(z)$: Is the peak wind pressure at height h. In Italian regulations, this is equivalent to the base pressure times the exposure coefficient: $q_p(z) = q_b \cdot C_e(z)$ $[N/m^2]$.
- $G_{c,i}$: Gust factor for conductors .
- $C_{c,i}$: Drag factor for the conductor [10].
- d: Conductor diameter [m].
- θ: Angle of line direction change [rad].
- F is the wind span in [m].

The factor $G_{C,i}$ is given by:

$$G_{C,i} = \frac{(1 + 2 \cdot k_p \cdot I_v(z) \cdot \sqrt{B^2 + R^2})}{1 + 7 \cdot I_v(z)} \tag{3.13}$$

In this relation, k_p represents the static peak factor of the gust, for which it is recommended to adopt a value of 3. The turbulence intensity is calculated as:

$$I_v(z) = \frac{1}{c_t \ln\left(\frac{z}{z_0}\right)} \tag{3.14}$$

where z is the height of the bracket and c_t is the topography coefficient, which is usually equal to 1.For its part, the background factor is determined by:

$$B^2 = \frac{1}{1 + \frac{3}{2} \cdot \frac{L_m}{L(z)}} \tag{3.15}$$

Within this calculation, L_m is the mean value of the two adjacent spans, defined as $L_m = \frac{L_1+L_2}{2}$.While $L(z)$ represents the integral scale of turbulence, whose formula is:

$$L(z) = 300 \cdot \left(\frac{z}{200}\right)^{0{,}67+0{,}05\cdot\ln(z_0)} \tag{3.16}$$

Finally, the resonance factor R^2 has a recommended value of 0.
We can also find these $G_{C,i}$ values through Tables 3.7, 3.8, 3.9, 3.10

Table 3.7: Values of $G_{C,i}$ for terrain category I [10]

Reference height h for conductor [m]												
z_0 **[m]**	L_m **[m]**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**≥ 60**
0.01	**100**	0.75	0.77	0.79	0.80	0.81	0.81	0.82	0.82	0.83	0.83	0.84
	200	0.69	0.72	0.73	0.74	0.75	0.76	0.77	0.77	0.78	0.78	0.79
	300	0.66	0.69	0.70	0.71	0.72	0.73	0.74	0.74	0.75	0.75	0.76
	400	0.64	0.67	0.68	0.69	0.70	0.71	0.72	0.72	0.73	0.73	0.74
	500	0.63	0.65	0.67	0.68	0.69	0.69	0.70	0.71	0.71	0.72	0.72
	600	0.62	0.64	0.66	0.67	0.68	0.68	0.69	0.70	0.70	0.70	0.71
	700	0.61	0.63	0.65	0.66	0.67	0.67	0.68	0.69	0.69	0.70	0.70
	800	0.60	0.63	0.64	0.65	0.66	0.67	0.67	0.68	0.68	0.69	0.69

Table 3.8: Values of $G_{C,i}$ for terrain category II [10]

Reference height h for conductor [m]												
z_0 **[m]**	L_m **[m]**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**≥ 60**
0.05	**100**	0.70	0.73	0.74	0.76	0.77	0.78	0.79	0.79	0.80	0.80	0.81
	200	0.63	0.66	0.68	0.70	0.71	0.72	0.73	0.74	0.74	0.75	0.75
	300	0.60	0.63	0.65	0.67	0.68	0.69	0.70	0.70	0.71	0.72	0.72
	400	0.58	0.61	0.63	0.64	0.66	0.66	0.67	0.68	0.69	0.69	0.70
	500	0.57	0.59	0.61	0.63	0.64	0.65	0.66	0.66	0.67	0.68	0.68
	600	0.56	0.58	0.60	0.61	0.63	0.64	0.64	0.65	0.66	0.66	0.67
	700	0.55	0.57	0.59	0.61	0.62	0.63	0.63	0.64	0.65	0.65	0.66
	800	0.54	0.57	0.58	0.60	0.61	0.62	0.63	0.63	0.64	0.64	0.65

Table 3.9: Values of $G_{C,i}$ for terrain category III [10]

Reference height h for conductor [m]												
z_0 **[m]**	L_m **[m]**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**≥ 60**
0.3	**100**	0.62	0.66	0.68	0.70	0.72	0.73	0.74	0.75	0.76	0.77	0.77
	200	0.55	0.59	0.61	0.63	0.65	0.66	0.67	0.68	0.69	0.70	0.71
	300	0.51	0.55	0.58	0.60	0.61	0.63	0.64	0.65	0.66	0.66	0.67
	400	0.49	0.53	0.55	0.57	0.59	0.60	0.61	0.62	0.63	0.64	0.65
	500	0.47	0.51	0.54	0.55	0.57	0.58	0.59	0.60	0.61	0.62	0.63
	600	0.46	0.50	0.52	0.54	0.56	0.57	0.58	0.59	0.60	0.61	0.61
	700	0.45	0.49	0.51	0.53	0.55	0.56	0.57	0.58	0.59	0.59	0.60
	800	0.45	0.48	0.50	0.52	0.54	0.55	0.56	0.57	0.58	0.58	0.59

Table 3.10: G_c values for terrain category IV [10]

		Reference height h for conductor [m]										
$\mathbf{z_0}$ **[m]**	$\mathbf{L_m}$ **[m]**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**≥ 60**
1.0	**100**	0.54	0.59	0.63	0.65	0.67	0.69	0.70	0.71	0.72	0.73	0.74
	200	0.47	0.52	0.55	0.58	0.60	0.61	0.63	0.64	0.65	0.66	0.67
	300	0.43	0.48	0.51	0.54	0.56	0.57	0.59	0.60	0.61	0.62	0.63
	400	0.41	0.45	0.49	0.51	0.53	0.55	0.56	0.57	0.58	0.59	0.60
	500	0.39	0.44	0.47	0.49	0.51	0.53	0.54	0.55	0.56	0.57	0.58
	600	0.38	0.42	0.45	0.48	0.50	0.51	0.52	0.54	0.55	0.56	0.56
	700	0.37	0.41	0.44	0.47	0.48	0.50	0.51	0.52	0.53	0.54	0.55
	800	0.36	0.41	0.43	0.46	0.47	0.49	0.50	0.51	0.52	0.53	0.54

To find the reference height for the conductor we can measure the distance of the cable to the ground, or use Table 3.11. For example, the method of individual height, center of gravity uses the reference height be at the lower third of the sag of the conductor.

To find the sag of the conductor, we will use the formula in Alberto Ortiz' book [6].

$$f = k \cdot \left[\cosh\left(\frac{L}{2k}\right) - 1\right] \tag{3.17}$$

Where

- k: catenary parameter from equation 3.3
- L: span from equation 3.3

For not leveled towers :

$$f_2 = f\left(1 + \frac{h}{4f}\right)^2 \tag{3.18}$$

Table 3.11: Determination of the reference height above ground [10]

Reference height above ground h	h_i	h_w	h_a
located at	$h = h_i$	$h = \frac{\sum n_i d_i h_i}{\sum n_i d_i}$	$h = \frac{\sum n_i h_i}{\sum n_i}$
centre of gravity (1)	1	2	3
attachment point at the insulator set	4	5	6
attachment point of the insulator set at the support	7	8	9

To determine wind forces on insulators we use Equation 3.19

$$Q_w = q_p(z) \cdot C_{i,i} \cdot G_{i,i} \cdot S_i \text{ [N]} \tag{3.19}$$

Where:

- $q_p(z)$ is the peak wind pressure at reference height [N/m^2].
- $C_{i,i}$ is the drag factor for the insulator set (the recommended value is 1.2 given by the NNA [11]).
- $G_{i,i}$ is the structural factor for the insulator set (the recommended value is 1.0 by the NNA [11]).
- S_i is the area of the insulator set projected horizontally on a vertical plane parallel to the axis of the string, [m^2].

Then, the process to find the wind force over insulators are shown in Figure 3.4

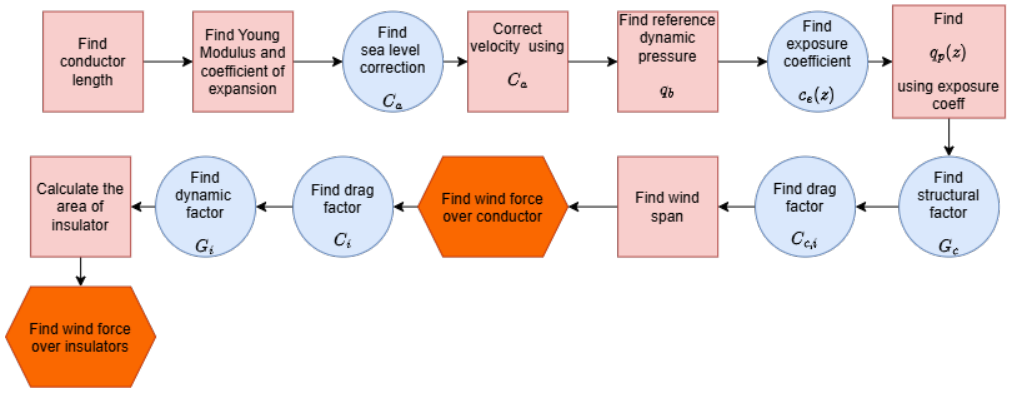


Figure 3.4: Process to find transverse loads over the insulator+conductor

To determine wind forces on lattice towers we use equation 3.20

$$Q_w = q_p(z) \cdot G_{t,i} \cdot C_t \cdot A \text{ [N]} \tag{3.20}$$

- $q_p(z)$ is the peak wind pressure at the reference height z of the structure, in [N/m^2].
- $G_{t,i}$ is the structural factor for the tower (the recommended conservative value is 1.0 [11]).
- C_t is the drag for the structure, which depends on its cross-sectional shape and solidity ratio.
- A is the effective area of the structure elements projected on a plane perpendicular to the wind direction, [m^2].

The drag coefficient $C_{t,i}$ is determined by

$$C_{t,i} = 3{,}96 \cdot (1 - 1{,}5\chi + \chi^2) \tag{3.21}$$

Where χ is the solidity ratio. It measures how "dense" the structure is and evaluates the airflow resistance of its individual steel members

The coefficient G_t is taken as 1, According to the NTC (Norme tecniche per costruzioni), we can conservatively assume a dynamic factor of 1.0 for regular structures up to 80 meters tall.

To get the area of each division, we can choose over two methods:

- Method 1: we divide the tower in sections, taking into account the sheltering effect.
- Method 2: we consider each member of the tower, without taking into account the sheltering effect.

According to the italian NNA, the method used is the second. Since we don't have a software to calculate each section of the tower, we will apply the first method which is more suitable for manual calculations.

According to the BS EN 50341-2-13:20 [11] standard, the partial factor that must be applied to wind actions is 1.

The final process to calculate the wind load over the different components are shown in Figure 3.5

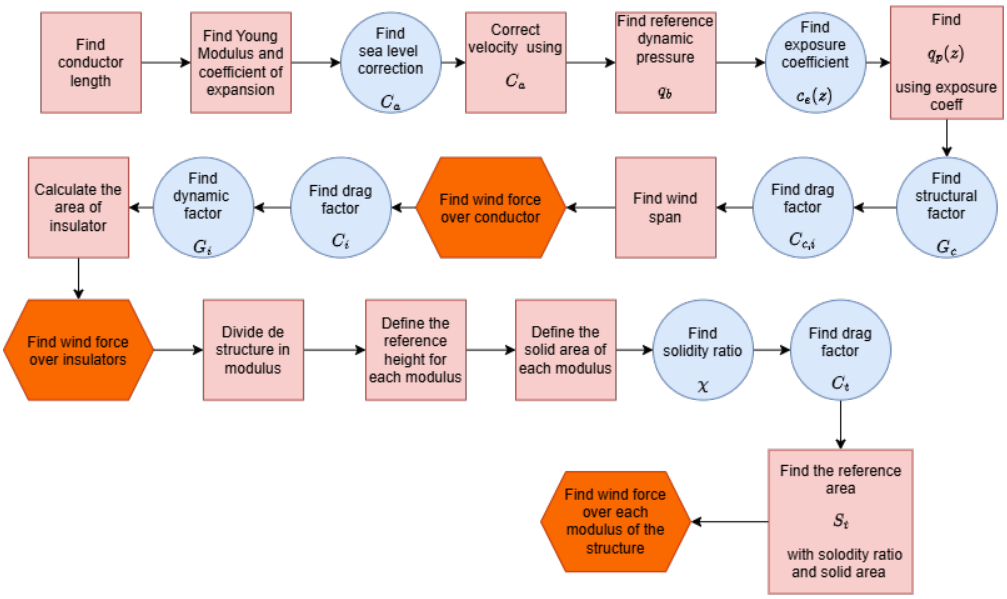


Figure 3.5: Process to find transverse loads over the structure+insulator+conductor

3.6 Calculation of vertical loads

For the vertical loads in normal conditions, according to normative BS50341-1:2012 [10], the permanent loads are due to the self-weight of the supports, insulators, and conductors of the adjacent spans, as well as the variable loads due to ice/snow in other conditions.

Although the standard does not define a calculation methodology for these loads, these calculations must be at the discretion of the engineer. To calculate the permanent loads, the methodology of N. Zoppetti and D. Andreuccetti in "Modellazione dei conduttori di un elettrodotto aereo: la catenaria," CNR - Istituto di Fisica Applicata "Nello Carrara", Florence, 2003 [12], can be used. In fact, the methodology of section 2.8 can also be used, which is much more detailed than the mentioned methodology, since it takes into account the thermal expansion due

to creep using the change of state equation. For illustrative purposes, since both standards are compared, the way to calculate the weight span with this reference from Italian authors will be mentioned; however, in the predefined calculations of the software, the same weight span calculation from section 2.8 will be used, in order to ensure that the observed differences come from the standards and not from the choice of the formula.

The process to calculate the vertical loads is shown in Figure 3.6. Again, the yellow node indicates the value that differs from colombian methodology.

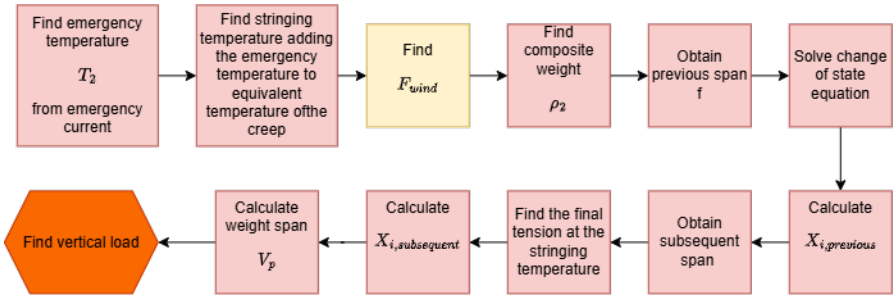


Figure 3.6: Process to find the vertical load

We apply the partial factors to formula 2.24.

$$C_v = \gamma_G \cdot [(\rho \cdot V_p \cdot NSC) + (NCA \cdot PCA)] \tag{3.22}$$

- CV_C: is the vertical load [N]
- ρ: is the unit weight of the conductor [N/m]
- V_p: is the weight span [m], which can be negative if the tower is subjected to uplift loads
- NSC: is the number of subconductors
- NCA: is the number of insulator strings
- PCA: is the weight of an insulator string
- γ_G: is the partial safety factor applied to permanent actions, according to Table 3.3 is 1,1 for equilibrium (EQUI)

The horizontal distance x_M of the lower support, which exists between the center of the union of the tower points and the midpoint of the catenary, is calculated.

$$x_M = -C \cdot atanh\left(\frac{h}{S}\right) \tag{3.23}$$

- S: Is the horizontal length of the span (the straight horizontal distance between the two supports) [m].

- C: Is the stringing parameter (or catenary parameter). It is a constant value along the cable and is calculated as the quotient between the horizontal tension of the cable (H) and the resultant weight per unit length (w).

- h: Is the difference in level (the vertical height difference) between the two attachment points [m].

To find the distance from the first tower to the minimum point of the catenary (blue color), the distance Xm and the span must be subtracted as seen in Figure 3.7.

- XI: It is the horizontal distance that exists between the lowest attachment (or suspension) point and the minimum point (the vertex) of the catenary [m].

- S: It is the horizontal length of the span (the straight horizontal distance between the two supports) [m].

- C: It is the tension parameter (or catenary parameter). It is a constant value along the cable and is calculated as the quotient between the horizontal tension of the cable (T) and the resulting weight per unit length (ρ) $C = \frac{T_0}{\rho}$

- h: It is the difference in elevation or drop (the vertical height difference) between the two attachment points [m].

- L: It is the effective length of the catenary (that is, the actual physical length of the suspended cable section in that span) [m].

$$XI = \frac{S}{2} - C \cdot atanh\left(\frac{h}{L}\right) \tag{3.24}$$

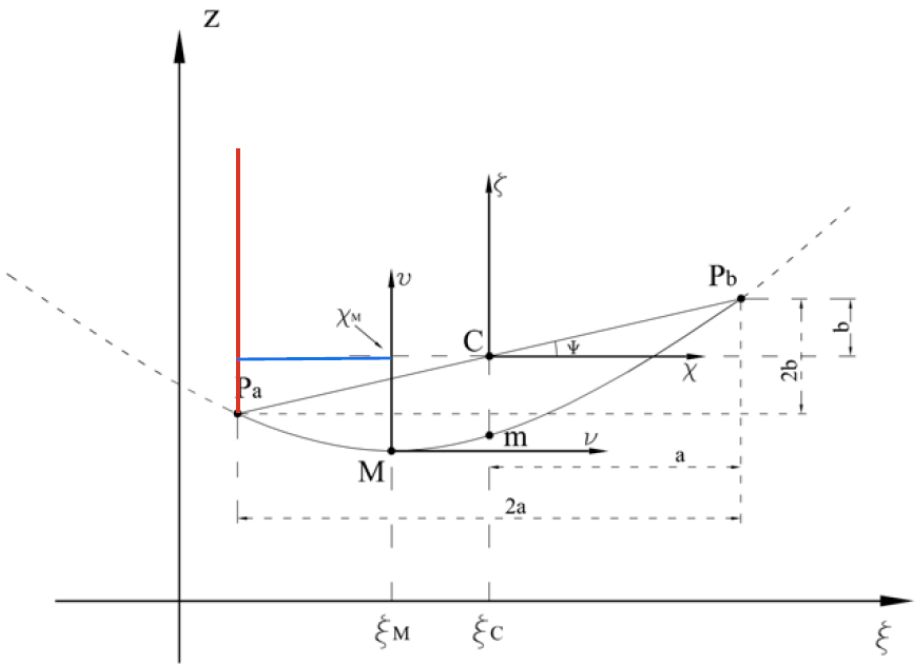


Figure 3.7: Graphical definition of the distance from the previous pole to the minimum point, XI

We obtain the weight span with equation 2.34

$$V_P = Previous\ span - XI_{(previous)} + XI_{(subsequent)} \tag{3.25}$$

The values γ_G according to the table of partial factors, must be taken as 1.1, while the partial factor for maintenance load γ_P must be considered as 1.5.

Chapter 4

Comparison of the used formulas

The Figures about the process to calculate transverse and vertical loads, 2.1, 2.3, 2.5, and 2.7 for the Colombian methodology, together with Figures 3.3, 3.4, 3.5, and 3.6 for the Italian methodology, show that both regulatory frameworks share the same calculation structure, even though they differ in how each step is parametrized.

For the wind-force of Figures 2.1, 2.3, 2.5 versus 3.3, 3.4, 3.5, both procedures start from the same reference-velocity concept and arrive at the same type of load, but every intermediate step relies on models suited to each country's environmental conditions (for instance, power-law versus logarithmic boundary-layer models, or gust responses derived from curve-fitting versus spectral approaches). This structural parallelism holds even at the lattice-tower stage (Figures 2.5 versus 3.5), where both codes convert an equivalent solidity ratio into a drag coefficient using a stepped table, confirming a shared aerodynamic origin despite the difference in notation (ϕ versus χ).

The vertical-load process (Figures 2.7 versus 3.6), on the other hand, is essentially identical between the two codes, since it draws on the same classical catenary and elasticity formulations. In fact, both flowcharts explicitly highlight a single node (F_{wind}) as their only point of disagreement. In other words, the sole difference in the vertical-load calculation comes from the transverse wind-force input, meaning that any discrepancy in vertical loads can be traced directly back to the differences already established in the wind-load parameters (Figures 2.1/2.3/2.5 and 3.3/3.4/3.5), rather than to any independent regulatory variation.

On Table 4.1, Colombia uses the probabilistic load and resistance factor method, while Italy has the European limit states theory with partial load factors. Both probabilistic methods use reduction and combination factors that affect the result of the structural analysis.

For the calculation of the basic wind pressure, the difference lies in how the velocity and the roughness and height correction coefficients are obtained. In the Italian case, the altitude and the geographic region of the country modify the wind speed $V_b = c_a * V_{b,0}$ before it enters the pressure equation $q_b = \frac{1}{2}\rho V_b^2$, adding an increment factor to it if the site altitude exceeds certain predefined thresholds by zone. In contrast, the Colombian methodology applies only a roughness coefficient $k_{r,c}$ to correct the initial wind speed $V_b = k_{r,c} * V_0$, but accounts for the altitude above sea level by directly modifying the dynamic pressure equation through the K_p factor as $q_b = k_p * V_b^2$.

For the case of the wind force on the conductor, Colombia explicitly includes in the same equation the span reduction factor FRV and the angle of incidence $\sin^2(\psi)$. Italy instead uses the angle of direction change θ without any wind span reduction factor.

The formulas to find the thermal expansion coefficient and Young's modulus are based on the same physical and mathematical principle. If the factor m in the Colombian equations is replaced and expanded algebraically, we obtain the same mathematical expression used by the Italian standard.

Starting with the Colombian standard equation, where m is defined as the area ratio of aluminum to steel ($m = \frac{A_A}{A_S}$):

$$E_{cond} = \frac{mE_A + E_S}{m+1} \tag{4.1}$$

Substituting into equation (1):

$$E_{cond} = \frac{\left(\frac{A_a}{A_s}\right) E_a + E_s}{\left(\frac{A_a}{A_s}\right) + 1} \tag{4.2}$$

We multiply the numerator and the denominator by A_s:

$$E_{cond} = \frac{A_a E_a + A_s E_s}{A_a + A_s} \tag{4.3}$$

We define the total area of the conductor as $A = A_a + A_s$, and separate the terms:

$$E_{cond} = E_a \left(\frac{A_a}{A}\right) + E_s \left(\frac{A_s}{A}\right) \tag{4.4}$$

According to the Italian standard, the area fractions are defined as $\alpha_a = \frac{A_a}{A}$ and $\alpha_s = \frac{A_s}{A}$. Substituting these fractions, we obtain exactly Equation (3.9) of the Italian standard:

$$E_{cond} = E_a \alpha_a + E_s \alpha_s \tag{4.5}$$

The thermal expansion coefficient of the composite conductor is defined as:

$$\alpha_{cond} = \frac{mE_A\alpha_A + E_S\alpha_S}{mE_A + E_S} \tag{4.6}$$

In addition to the area and elasticity variables already mentioned, we adapt the individual thermal coefficients to avoid confusion with the area fractions: $\alpha_A \rightarrow \beta_a$ (thermal expansion coefficient of aluminum) and $\alpha_S \rightarrow \beta_s$ (thermal expansion coefficient of steel).

Substituting $m = \frac{A_a}{A_s}$ and the other Italian variables into equation (6):

$$\alpha_{cond} = \frac{\left(\frac{A_a}{A_s}\right) E_a\beta_a + E_s\beta_s}{\left(\frac{A_a}{A_s}\right) E_a + E_s} \tag{4.7}$$

We multiply the numerator and the denominator of the main fraction by A_s:

$$\alpha_{cond} = \frac{A_aE_a\beta_a + A_sE_s\beta_s}{A_aE_a + A_sE_s} \tag{4.8}$$

This final expression is exactly Equation (3.10) stipulated in the Italian standard.

Table 4.1: Comparison of formulas used: Colombian Standard vs. Italian Standard

Concept	**Colombian Standard**	**Italian Standard**
Safety philosophy	**LRFD Method:** $\Phi R_c \geq \gamma Q_c$	**Limit States (ULS/SLS):** $\gamma_F \cdot F_k \leq \frac{R_k}{\gamma_M}$
Order of wind corrections (Altitude, Roughness, Height)	1. **Velocity:** Corrected by terrain roughness 2. **Base Pressure:** Corrected by altitude 3. **Final Pressure:** Corrected by height	1. **Velocity:** Corrected by altitude 2. **Final Pressure:** Corrected by height, terrain roughness and orography
Altitude correction factor	$K_p = 0.603 - 0.0514A$	c_a (Applied to basic wind velocity)
Basic dynamic wind pressure	$q_b = K_pV_b^2$	$q_b = \frac{1}{2}\rho V_b^2$
Corrected dynamic pressure	$q_p(z) = K_x \cdot q_b$	$q_p(z) = q_b \cdot c_e(z)$
Wind load / force on the conductor	$F_c = q_p(z) \cdot C_{c,c} \cdot G_{C,c} \cdot d \cdot F \cdot F_{RV} \cdot \sin^2\Psi$	$F_c = q_p(z) \cdot G_{c,i} \cdot C_{c,i} \cdot d \cdot \cos^2\left(\frac{\theta}{2}\right) \cdot F$

Concept	Colombian Standard	Italian Standard
Wind load on insulators	$F_i = q_p(z) \cdot C_{i,c} \cdot G_{i,c} \cdot S_i$	$Q_w = q_p(z) \cdot C_{i,i} \cdot G_{i,i} \cdot S_i$
Wind load on lattice towers	$F_t = q_p(z) \cdot C_f \cdot G_{t,c} \cdot S_t$	$Q_w = q_p(z) \cdot G_{t,i} \cdot C_{t,i} \cdot A$
Modulus of elasticity (Composite cable)	$E_{cond} = \frac{mE_A+E_S}{m+1}$ Where $m = \frac{A_A}{A_S}$	$E_{eq} = E_A \left(\frac{A_a}{A_A+A_S}\right) + E_S \left(\frac{A_S}{A_A+A_S}\right)$
Thermal expansion coefficient	$\alpha_{cond} = \frac{mE_a\alpha_a+E_s\alpha_s}{mE_a+E_s}$	$\alpha_{eq} = \alpha_A \left(\frac{E_A}{E_{eq}}\right)\left(\frac{A_A}{A_A+A_S}\right) + \alpha_S \left(\frac{E_S}{E_{eq}}\right)\left(\frac{A_S}{A_A+A_S}\right)$
Vertical loads in normal regime	$C_v = 1.1 \cdot \rho \cdot V_p \cdot NSC + 1.0 \cdot NCA \cdot PCA$	$C_v = \gamma_G \cdot [(\rho V_p NSC) + (NCA \cdot PCA)]$
Distance from the minimum point of the catenary to the support	$XI = \frac{S}{2} - \frac{T}{\rho} \sinh^{-1}\left[\frac{h}{2\frac{T}{\rho}\sinh\left(\frac{S}{2T/\rho}\right)}\right]$	$XI = \frac{S}{2} - C \cdot \operatorname{atanh}\left(\frac{h}{S}\right)$

Finally, the calculation of vertical loads in normal regime under both standards starts from the same physical principle, but differs fundamentally in the application of the safety factors and in the topographic calculation of the wind force F_{wind}, since it depends on V_b.

The Table 4.2 shows the equivalence between the coefficients used in both standards.

The most notable methodological difference lies in how each regulation constructs the mathematical model of the wind.

- Colombia (decoupled approach): They treat the physical phenomena multiplicating independently: the velocity is first corrected for terrain roughness $k_{r,c}$; the dynamic pressure is then modified for altitude K_p through a linear equation $0.603 - 0.0514A$; and finally the height correction is applied through the exposure coefficient K_x.

- Italy (integrated and logarithmic approach): The altitude correction is applied directly to the base velocity c_a through predefined thresholds, and the effects of height z and roughness $k_{r,i}$ are grouped into a single logarithmic exposure coefficient $c_e(z)$. This logarithmic formulation $c_e(z)$ represents with higher fidelity how ground friction slows the wind in reality, because it's derived from Prandtl's boundary layer theory, which establishes that wind shear near the surface follows a logarithmic curve strictly governed by the aerodynamic roughness.

Dynamic Gust Response (G Factors): Both regulations recognize that wind is

not constant and that cables and towers respond dynamically to gusts, but with different approaches:

- Factors $G_{c,c}, G_{i,c}, G_{t,c}$ (Colombia): The ISA methodology [5] is based on Davenport's model of wind turbulence. For practical design, the guide provides pre-calculated curves (Figures 2.4 and 2.6) parameterized by span length and effective height.

- Factors $G_{c,i}, G_{i,i}, G_{t,i}$: The conductor span factor $G_{c,i}$ is analytically determined from the local turbulence intensity $I_v(z)$, the turbulent length scale $L(z)$, and background and resonant response factors B^2, R^2.

Aerodynamic Drag Coefficients (C Factors): The way wind pressure affects physical profile

- Insulator Drag Coefficients (C_{xi}) vs. C_{ins}): Both methodologies converge on the same aerodynamic characterization for insulator sets, assigning an identical drag coefficient of 1.2 ($C_{xi} = 1.2$ under the Colombian ISA guide [5] and $C_{\text{ins}} = 1.20$ in the Italian NNA [11]).

- Lattice Structures (C_f vs. $C_{t,i}$): Colombia [5] applies a piecewise mathematical function (Table 2.6) for the force coefficient C_f based on the solidity ratio ϕ, which introduces minor step-like discontinuities on the intervals. On the contrary, Italy [10] adopts a continuous, smooth quadratic polynomial formulation from EN 1993-3-1, $C_{tn} = 3.96(1 - 1.5\chi + \times^2)$, based on the solidity ratio χ.

- Spatial Wind Correction (Factor F_{RV}): Colombia introduces an explicit wind span reduction factor (F_{RV}) for long spans, acknowledging that it is statistically unlikely for the peak of an extreme gust to hit simultaneously along a very long span (e.g., 500 m) with the same intensity. Italy does not use an explicit multiplicative reduction factor in the final force equation; instead, the European model absorbs the spatial correlation of gusts within the calculation of the integral turbulence scale $L(z)$ and the mean span L_m used to find $G_{C,i}$.

Table 4.2: Equivalence of coefficients

Coefficient	**Colombian standard**	**Italian standard**
Altitude correction factor	K_p	c_a
Exposure, Height and Terrain profile	K_x and $k_{r,c}$	$c_e(z)$ (incorporates $k_{r,i}$)
Terrain roughness coeff.	$k_{r,c}$	$k_{r,i}$
Gust factor (Conductors)	$G_{C,c}$	$G_{C,i}$
Gust factor (Insulators)	$G_{i,c}$	$G_{i,i}$
Gust factor (Towers)	$G_{t,c}$	$G_{t,i}$
Drag coeff. (Conductors)	$C_{c,c}$	$C_{c,i}$
Drag coeff. (Insulators)	$C_{i,c}$	$C_{i,i}$
Force coeff. (Structures)	C_f	$C_{t,i}$

Chapter 5

Application of regulations for the Val-Formazza project

The Val-Formazza project is a high-voltage grid rationalization initiative managed by Terna, Italy's national transmission grid operator. Located in the alpine terrain of the Piedmont region (Verbano-Cusio-Ossola province), the infrastructure traverses several municipalities, including Formazza, Premia, Montecrestese, and Crodo [16]. The primary objective of this project is to modernize the existing 220 kV and 132 kV transmission networks to ensure the security, reliability, and continuity of the national energy supply. Also, its purpose is to reduce the environmental and visual footprint in the valley through the strategic delocalization and undergrounding of historical power line segments. Due to its complex mountainous topography and exposure to severe alpine weather conditions, this project provides an ideal real-world case study. It supplies the necessary environmental and geographic data to evaluate and compare the practical application of the Colombian and Italian regulatory frameworks.

Specifically, the project's longitudinal profile [17] provides topographic and geometric parameters such as exact horizontal spans, elevation differences, and specific tower heights. We will analyse in this work the structures BP.24, BP.25 shown in Figure 5.1. We will analyze tower BP.25.

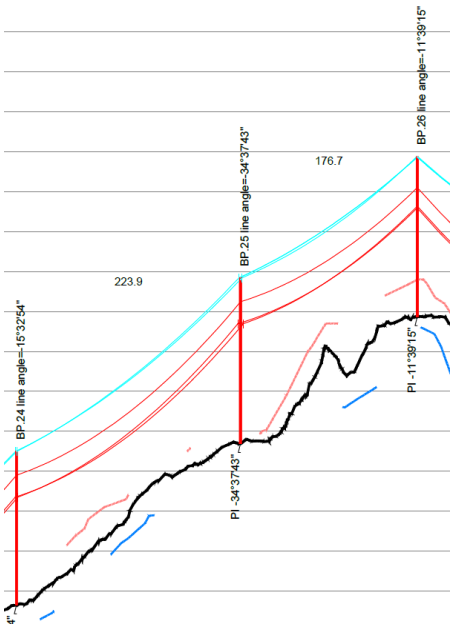


Figure 5.1: Supports BP.24, BP25 and BP.26. [17]

5.1 Colombian methodology

The data of the project adjusted for the Colombian normative are shown in Table 5.1.

Table 5.1: Transmission line design parameters (Colombian methodology)

Parameter	**Unit**	**Value**
1. Topographic and Environmental Data		
Gradient height (Z_g)	m	366
Horizontal span a (also previous span for X_I calculation)	m	223.94
Elevation difference h (Tower A-B)	m	40.41
Elevation difference h (Tower B-C)	m	31.73
Forward span (Tower B-C)	m	176.7
Tower A height	m	38.5
Tower B height	m	41.5
Effective conductor height	m	25
Terrain roughness factor (K_r)	-	0.85
2. Cable Mechanical and Physical Properties		

Table 5.1 –

Parameter	**Unit**	**Value**
Conductor code	-	1657-AL1/209-ST1A
Cable material type	-	Aluminum-Steel
Number of subconductors	-	1
External diameter	mm	56.3
Aluminum cross-section	mm^2	1656.7
Steel cross-section	mm^2	208.7
Total cross-section	mm^2	1865.4
Conductor unit weight (ρ)	kg/m	6.224
Modulus of Young (Aluminum)	GPa	55
Modulus of Young (Steel)	GPa	190
Thermal expansion coef. α (Aluminum)	1/°C	0.000024
Thermal expansion coef. α (Steel)	1/°C	0.000012
Nominal breaking load	N	532800
Horizontal cable tension (T_o)	kgf	8611
3. Thermal and Electrical Inputs		
Normal load current (I_1)	A	2309
Emergency current (I_2)	A	2886.25
DC resistance at 20°C	Ω/km	0.0175
Solar emissivity (ϵ_s)	-	0.2
Infrared emissivity (ϵ_l)	-	0.3
Thermal constant (M aluminum-copper)	-	228.1
Convective heat transfer coefficient (h)	$W/m^2 \cdot K$	20
4. Structures, Insulators, and Wind Coefficients		
Number of insulator strings	-	2
Insulator string weight	N	1500
Insulator string area	m^2	0.306
Top cross-arm base width	m	1.5
Bottom cross-arm base width	m	4.5
Upper middle body base width	m	9
Lower bottom body base width	m	10.96
Upper body solidity ratio	-	0.26
Middle body solidity ratio	-	0.24
Lower body solidity ratio	-	0.16
Wind gust factor for cable (G_c)	-	0.77
Cable drag coefficient (C_{xc})	-	1

Table 5.1 –

Parameter	**Unit**	**Value**
Cable directionality factor (Ψ)	rad	1.570796327
Resonant response factor (F_{rv})	-	1
Insulator drag coefficient (C_{xi})	-	1.2
Wind gust factor for insulator (G_i)	-	0.9
Force coefficient (C_f) on cross-arms	-	2.748
Force coefficient (C_f) on middle body	-	2.852
Force coefficient (C_f) on lower body	-	3.268
Topographic factor upper part ($G_{t,upper,c}$)	-	1.05
Topographic factor middle part ($G_{t,middle,c}$)	-	1.05
Topographic factor lower part ($G_{t,lower,c}$)	-	0.9
5. Creep Parameters		
Creep constant k	-	0.24
Creep exponent α	-	1
Creep exponent ϕ	-	1
Creep exponent μ	-	0.16
Tension to breaking strength ratio ($T/T_{rupture}$)	-	0.2
Test duration	hours	262800
Installation creep	mm/km	237.87

The 3-second gust wind speed was obtained using the velocity data from the Italian regulations. Since these velocities are 10-minute averages, they are multiplied by a factor of 1.55, according to Figure 5.2. This results in a design peak wind speed in Colombia of 46.5 m/s. The terrain category is type B according to Table 2.2, since these alps have an important amount of forests and is not a flat terrain. Information of the span of tower A-B and B-C, height of the towers A and B, effective height of the conductor are found in reference [17].

The mechanical properties of the cable is obtained on the standard [13]. Using reference [16] to search for the equivalent model, the model 657-AL1/209-ST1A fits the data.

To calculate the area of insulator we will use this formula of Alberto Ortiz' book [6]:

$$S_i = 0.6 \times (\text{string length} \times \text{insulator diameter}) \tag{5.1}$$

By applying this formula to a standard insulator string of 2.0 m in length with an insulator diameter of 255 mm (0.255 m), the resulting wind-exposed area is exactly:

$$S_i = 0.6 \times 2.0 \text{ m} \times 0.255 \text{ m} = 0.306[\text{ m}^2] \tag{5.2}$$

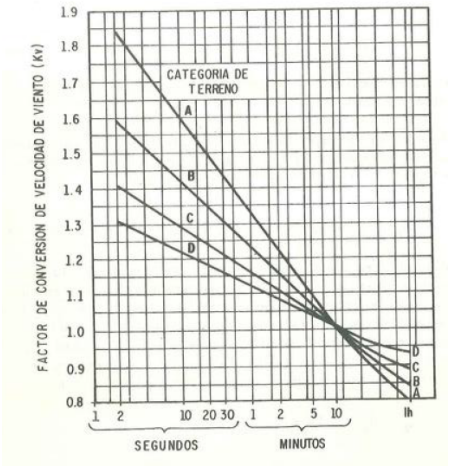


Figure 5.2: Factor of conversion of wind velocity

According to Table 2.3, for category B terrain, the roughness coefficient must be $K_r = 0.85$

The velocity corrected for terrain roughness is used with the formula 2.9.

$$V_b = 0.85 * 46.5 = 39.525[m/s] \tag{5.3}$$

Since the velocity was obtained from the Italian tables, which are defined at 10 m, the height correction factor is not applied.

Then next step is to find the conductor's length using equations 2.4 and 2.5.

$$C = \frac{8611}{6.224} \quad = 1383.52[m] \tag{5.4}$$

$$L = \sqrt{\left(2 * 1383.52 \sinh \frac{223.94}{2 * 1383.52}\right)^2 + 40.41^2} \quad = 227.8[m] \tag{5.5}$$

To find the equivalent Young's modulus and thermal expansion coefficient we will use equations 2.12 and 2.13

$$m = \frac{1656.7}{208.7} = 7.94 \tag{5.6}$$

$$E_{\text{conductor}} = \frac{7.94 * 55 + 190}{7.94 + 1} = 70.1[GPa] \tag{5.7}$$

$$\alpha_{\text{conductor}} = \frac{7.94 * 55 * 0.000024 + 190 * 0.000012}{7.94 * 55 + 190} = 2.03613 * 10^{-}5[1/°\text{C}] \tag{5.8}$$

The we proceed to calculate the transverse loads due to wind loads. To find the reference dynamic pressure we use kp from equation 2.15, velocity from equation 5.3 and the reference presssure from equation 2.14

$$K_p = 0.603 - 0.0514 * 2 = 0.5 \tag{5.9}$$

$$P_0 = 0.5 * 39.525^2 = 781.43[N/m^2] \tag{5.10}$$

Then we will correct this pressure to a specific height above ground level with equations 2.16 and 2.17.

$$K_x = \left(\frac{300}{10}\right)^{\frac{2}{7}} \left(\frac{25}{366}\right)^{\frac{2}{4.5}} = 0.802 \tag{5.11}$$

$$P_{oc} = 0.802 * 781.43 = 626.48 \quad [N/m^2] \tag{5.12}$$

To find the wind force over the conductor, we need to identify which wind span is higher between tower A and B.

$$L_{m,towerA} = (previousspan+subsequentspan)/2 = (142.3+223.94)/2 = 183.12 \quad [m] \tag{5.13}$$

$$L_{m,towerB} = (previousspan+subsequentspan)/2 = (223.94+176.7)/2 = 200.32 \quad [m] \tag{5.14}$$

Then we will choose the wind span of tower B for calculations. Then we apply it to the equation 2.18. Factor G_c is found in Figure 2.4 with a reference height of 25 meters and a span of 224 meters. FRV will be calculated according to Figure 2.2. The incidence angle will be perpendicular, so $\psi = \pi/2$

$$F_c = 1 * 0.77 * 56.3 * 10^-3 * 200.32 * 626.481 * \sin^2(\pi/2) \quad = 5440.36 \quad \text{[N]} \tag{5.15}$$

Then we will apply the 1.65 to the load according to the methodology

$$F_c = 5440.36 * 1.65 = 8976.59 \quad \text{[N]} \tag{5.16}$$

To calculate the force on the isolators we will use equation 2.21. Factor G_i is obtained with Figure 2.6.$S_i = 0.306m^2$

$$F_i = 1.2 * 0.9 * 0.306 * 626.48 = 207.037 \quad \text{[N]} \tag{5.17}$$

Then we will apply the 1.65 factor to this load

$$F_i = 207.037 * 1.65 = 341.61 \quad [\text{N}] \tag{5.18}$$

To calculate the wind load over the structure we divide the tower into three sections: the cross arms, the tower body and the base.

Since we don't have the specific data of the Val Formazza¡s towers, we will take the percentages of height of each section of a common tower of ISA guide at 230 kV shown in Figure 5.3

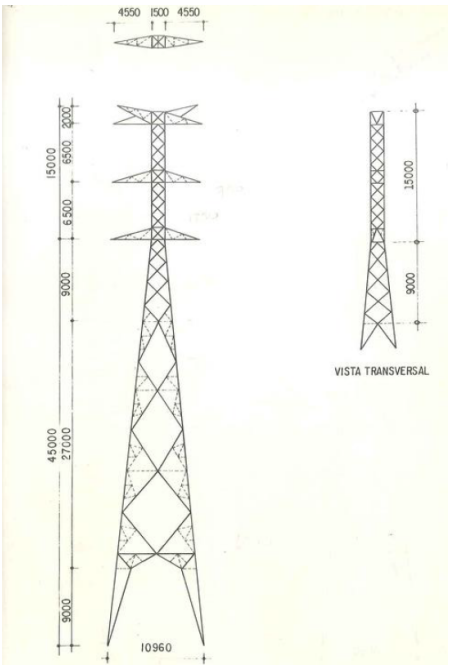


Figure 5.3: Tower of 230 kV of ISA guide [5]

Dividing into the three sections, we will get these percentages:

$$H_{\text{total}} = 15000 + 9000 + 27000 + 9000 = 60000 \tag{5.19}$$

$$P_{\text{upper}} = \left(\frac{15000}{60000}\right) \times 100 = 25\% \tag{5.20}$$

$$P_{\text{middle}} = \left(\frac{9000}{60000}\right) \times 100 = 15\% \tag{5.21}$$

$$P_{\text{base}} = \left(\frac{36000}{60000}\right) \times 100 = 60\% \tag{5.22}$$

Then we will apply these percentages to the actual height of the Val Formazza's tower

$$H_{\text{upper}} = 41.5 \times 0.25 = 10.375 \quad [m] \tag{5.23}$$

$$H_{\text{middle}} = 41.5 \times 0.15 = 6.225 \quad [m] \tag{5.24}$$

$$H_{\text{base}} = 41.5 \times 0.60 = 24.900 \quad [m] \tag{5.25}$$

Then we will define the solid area of the tower. In Figure 5.3, we have values of the trasversal face width of the tower, we will use them since we don't have exact data of the Val formazza's tower.

$$Area_{upper} = 10.375 * 1.5 = 15.56 \quad [m^2] \tag{5.26}$$

We don't have the exact upper width of the base structure for the Val Formazza's tower, so we calculate it using proportional triangles based on our adjusted heights. The boundary between the base and middle sections corresponds to an accumulated height of $h = 24.9$ m from the ground. Using the known base width $W_b = 10.96$ m, the top neck width $W_t = 1.5$ m, and the combined height of the pyramidal section (base + middle) $H = 24.9 + 6.225 = 31.125$ m, the proportional width reduction is governed by the equation:

$$W(h) = W_b - \left(\frac{W_b - W_t}{H}\right) h \tag{5.27}$$

By substituting our adjusted target height into the formula, we obtain exactly:

$$W(24.9) = 10.96 - \left(\frac{10.96 - 1.5}{31.125}\right) \times 24.9 = 3.392 \text{ m} \tag{5.28}$$

Then the middle area will be:

$$Area_{middle} = 6.225 * (1.5 + 3.392)/2 = 15.22 \quad [m^2] \tag{5.29}$$

An the area of the lower part will be

$$Area_{base} = 24.9 * (10.96 + 3.392)/2 = 178.68 \quad [m^2] \tag{5.30}$$

Having the solid area of the transversal face, we will apply the equation 2.23 to find the area of all elements in order to calculate the wind force over the structure

$$Area_{eff,upper} = \phi_{upper} * 15.56 = 4.04 \quad [m^2] \tag{5.31}$$

$$Area_{eff,middle} = \phi_{middle} * 15.22 = 3.65 \quad [m^2] \tag{5.32}$$

$$Area_{eff,lower} = \phi_{lowest} * 178.8 = 28.59 \quad [m^2] \tag{5.33}$$

Then we will find the centroid of each component as follows, measured to the ground level

$$Y_{centroid,upper} = \frac{10.375 \text{ m}}{2} + 6.225 \text{ m} + 24.9 \text{ m} = 36.31 \quad [\text{m}] \tag{5.34}$$

$$Y_{centroid,middle} = \frac{6.225 \text{ m}}{3} \times \left(\frac{3.392 \text{ m} + 2(1.5 \text{ m})}{3.392 \text{ m} + 1.5 \text{ m}} \right) + 24.9 \text{ m} = 27.61 \quad [\text{m}]$$

$$Y_{centroid,lower} = \frac{24.9 \text{ m}}{3} \times \left(\frac{10.96 \text{ m} + 2(3.392 \text{ m})}{10.96 \text{ m} + 3.392 \text{ m}} \right) = 10.26 \quad [\text{m}] \tag{5.36}$$

Then we must find the coefficient K_x from equation 2.17

$$K_{x,upper} = \left(\frac{300}{10} \right)^{\frac{2}{7}} \left(\frac{36.3125}{366} \right)^{\frac{2}{4.5}} = 0.946 \tag{5.37}$$

$$K_{x,middle} = \left(\frac{300}{10} \right)^{\frac{2}{7}} \left(\frac{27.61}{366} \right)^{\frac{2}{4.5}} = 0.837 \tag{5.38}$$

$$K_{x,lower} = \left(\frac{300}{10} \right)^{\frac{2}{7}} \left(\frac{10.26}{366} \right)^{\frac{2}{4.5}} = 0.539 \tag{5.39}$$

And with those coefficients we calculate the pressure over the centroid of each element.

$$P_{oc,upper} = 0.946 * 781.43 = 739.53 \quad [N/m^2] \tag{5.40}$$

$$P_{oc,middle} = 0.837 * 781.43 = 654.76 \quad [N/m^2] \tag{5.41}$$

$$P_{oc,lower} = 0.539 * 781.43 = 421.7 \quad [N/m^2] \tag{5.42}$$

Then we can calculate the force of the wind over the structure using equation 2.22. The factor $G_{t,c}$ for upper, middle and lower modulus are 1.05, 1.05 and 0.9 respectively.

$$F_{upper} = 739.52 * 2.748 * 1.05 * 4.04625 = 8634.04 \quad [\text{N}] \tag{5.43}$$

$$F_{middle} = 654.76 * 2.852 * 1.05 * 3.65 = 7165.15 \quad [\text{N}] \tag{5.44}$$

$$F_{lower} = 421.7 * 3.268 * 0.9 * 28.59 = 35461.19 \quad [\text{N}] \tag{5.45}$$

Then we multiply by the factor 1.65 to all forces

$$F_{upper} = 1.65 * 8634.04 = 14246.17 \quad [N] \tag{5.46}$$

$$F_{middle} = 1.65 * 7165.15 = 11822.51 \quad [N] \tag{5.47}$$

$$F_{lower} = 1.65 * 35461.19 = 58510.97 \quad [N] \tag{5.48}$$

To calculate the vertical load, we must find the stringing temperature which is calculated with the emergency current.

We found that the nominal current with 880 MVA and 220kV is 2309 A. Assuming an emergency current of 1.25 of nominal current, the emergency current is 2886.25 A.

Then we calculate the linearization factor as

$$E = 1.38 \times 10^8 + 1.39 \times 10^6 \cdot 20 = 165800000 \tag{5.49}$$

The DC resistance at 20°C was obtained with the BS EN 50182-2001 tables. Then, we must convert this resistance at 0°C with the formula according to normative IEC 60287-1-1:

$$R_{0^\circ\text{C}} = R_{20^\circ\text{C}} * (1 + \alpha * (T_0 - T_\infty)) \quad [\Omega/m] \tag{5.50}$$

Where α is the thermal coefficient for aulliminum.

$$R_{0^\circ\text{C}} = 0.0175 * (1 + 0.00403 * (0 - 20)) = 0.0160895 \quad [\Omega/m] \tag{5.51}$$

Then we calculate the equivalent AC resistance also with normative IEC 60287-1-1

$$x_s^2 = \frac{8\pi f}{R_{DC}} \times 10^{-7} \times k_s \tag{5.52}$$

where:

- x_s^2 = dimensionless auxiliary parameter for the skin effect
- f = frequency, in Hz
- R_{DC} = DC resistance of the conductor at operating temperature, in Ω/m

- k_s = coefficient depending on the conductor construction (solid, stranded, segmental, etc.)

$$x_s^2 = \frac{8\pi(50)}{1.60895 \times 10^{-5}} \times 10^{-7} \times 1 = 7.81 \tag{5.53}$$

$$x_s^4 = (x_s^2)^2 = (7.81)^2 = 61.00 \tag{5.54}$$

$$y_s = \frac{x_s^4}{192 + 0.8, x_s^4} \tag{5.55}$$

where:

- y_s = skin effect factor, representing the relative increase in resistance due to the non-uniform current distribution across the conductor cross-section

$$y_s = \frac{61.00}{192 + 0.8(61.00)} = \frac{61.00}{240.8} = 0.2533 \tag{5.56}$$

$$R_{AC} = R_{DC}\,(1 + y_s + y_p) \tag{5.57}$$

where:

- y_s = skin effect factor
- y_p = proximity effect factor, which depends on conductor spacing and diameter; assumed negligible ($y_p \approx 0$) for an overhead line with sufficiently separated phases

$$R_{AC} = 0.0160895 \times (1 + 0.2533) = 0.0160895 \times 1.2533 = 0.02016 \quad [\Omega/km] \tag{5.58}$$

$$R_{AC} = 2.016 \times 10^{-5} \quad [\Omega/m] \tag{5.59}$$

Then we find coefficients A,B and A' from equation

$$A = R_{AC} = 2.016 * 10^{-5} \quad [\Omega/m] \tag{5.60}$$

$$B = A/M = 8.838 * 10^{-8} \tag{5.61}$$

$$A' = A + BT_{\infty} = 2.016 * 10^{-5} + 8.83823 * 10^{-8}20 = 2.19^{-5} \tag{5.62}$$

In accordance with the IEEE Std 738-2023 standard [18], the specific solar heat intensity ($Q_{sun} = 1193$ W/m^2) was defined according to the local environmental conditions of the Val Formazza project. Specifically, this value corresponds to the elevation-corrected solar heat intensity (Q_{se}), which is determined by multiplying the solar heat intensity at sea level (Q_s) by an elevation correction factor (K_{solar}):

$$Q_{sun} = Q_{se} = K_{solar} \cdot Q_s \tag{5.63}$$

where Q_s is evaluated using a polynomial function based on the solar altitude for a clear atmosphere, and K_{solar} adjusts this baseline to account for the thinner atmosphere at the specific project altitude of 2000 m above sea level.

Solar emissivity $\epsilon_s = 0.2$ and infrared emissivity $\epsilon_l = 0.3$ are values assumed as the cable is without wear or surface aging. Convective heat transfer $h = 20$ was assumed as the calculation assumes soft winds.

Then we find emergency temperature T2 and normal operation T1 with formulas 2.25 and 2.26.

$$T_1 = 20 + \frac{2309^2 \cdot 2.19276 \times 10^{-5} + 0.2 \cdot \frac{56.3}{1000} \cdot 1193}{\pi \cdot 20 \cdot \frac{56.3}{1000} + 0.3 \cdot \pi \cdot \frac{56.3}{1000} \cdot \sigma \cdot 165800000 - 2309^2 \cdot 8.83823 \times 10^{-8}} \tag{5.64}$$

$$T_1 = 56.57[^{\circ}\mathrm{C}] \tag{5.65}$$

$$T_2 = 20 + \frac{2886.25^2 \cdot 2.19276 \times 10^{-5} + 0.2 \cdot \frac{56.3}{1000} \cdot 1193}{\pi \cdot 20 \cdot \frac{56.3}{1000} + 0.3 \cdot \pi \cdot \frac{56.3}{1000} \cdot \sigma \cdot 165800000 - 2886.25^2 \cdot 8.83823 \times 10^{-8}} \tag{5.66}$$

$$T_2 = 79.43[^{\circ}\mathrm{C}] \tag{5.67}$$

Then we must add to Equation 5.126 the temperature equivalent to the creep phenomenom, using equations 2.27, 2.29 and 2.30.

$$\varepsilon = 0.24\,(100 * 0.2)^1\, 20^1 262800^{0.16} = 706.99\ [\mathrm{mm/km}] \tag{5.68}$$

$$\varepsilon_T = 706.99 - 237.87 = 469.11[mm/km] \tag{5.69}$$

Then we will convert this creep into a virtual temperature:

$$\Delta t_{Eq} = \frac{469.11}{2.03613 * 10^{-5} * 1{,}000{,}000} = 23.04 \text{ [°C]} \tag{5.70}$$

The final stringing temperature is:

$$T_2 = 79.43 + 23.04 = 102.48 \text{ [°C]} \tag{5.71}$$

Then we need to calculate ρ_2 from Equation 2.35.The horizontal force extended by the wind is

$$F_{wind} = 0.0045 \cdot (39.525 \cdot 3.6)^2 \cdot 56.3/1000 = 5.13 \tag{5.72}$$

$$\rho_2 = \sqrt{6.224^2 + 5.13^2} = 8.07 \quad [kgf/m] \tag{5.73}$$

After getting the stringing temperature, we calculate the tension at the stringing temperature with the equation 2.35. We must calculate two tensions at the stringing temperature: the one of the previous span of tower A, and the subsequent span of the tower B. This equation has to be solved with numerical methods. Assuming T_1 as the everyday stress, as 20% of the nominal breaking load

$$T_{2,previous} = 78047.20 \quad [N] \tag{5.74}$$

$$T_{2,previous} = 7955.88 \quad [kgf] \tag{5.75}$$

$$T_{2,subsequent} = 67165.41 \quad [N] \tag{5.76}$$

$$T_{2,subsequent} = 6846.63 \quad [kgf] \tag{5.77}$$

After getting the two tensions we can find from Equation 2.33 the distance from the catenary vertex with respect to the preceding support

$$XI_{previous} = \frac{223.94}{2} - \frac{7955.88}{6.224} \sinh^{-1}\left(\frac{40.41}{2\left(\frac{7955.88}{6.224}\right)\sinh\left(\frac{223.94}{2\left(\frac{7955.88}{6.224}\right)}\right)}\right) \quad \text{[m]} \tag{5.78}$$

$$XI_{previous} = -117.17 \quad \text{[m]} \tag{5.79}$$

$$XI_{subsequent} = \frac{176.7}{2} - \frac{6846.63}{6.224} \sinh^{-1}\left(\frac{31.73}{2\left(\frac{6846.63}{6.224}\right)\sinh\left(\frac{176.7}{2\left(\frac{6846.63}{6.224}\right)}\right)}\right) \quad \text{[m]} \tag{5.80}$$

$$XI_{subsequent} = -107.92 \quad [\text{m}] \tag{5.81}$$

Then we can obtain the weight span with equation 2.34

$$V_P = 223.94 + 117.17 - 107.92 = 233.18 \quad [\text{m}] \tag{5.82}$$

Having all the data to calculate the vertical load, we use Equation 2.24

$$C_v = 1.1 \cdot 61.057 \cdot 233.18 \cdot 1 + 1.0 \cdot 2 \cdot 1500 = 18661.18 \quad [N] \tag{5.83}$$

5.2 Italian methodology

Having evaluated the structural behavior of the Val-Formazza transmission line under the Colombian LRFD framework, this section proceeds to analyze the identical scenario using the European and Italian regulatory framework. As established in Chapter 3, the structural design in Italy is governed by the CEI EN 50341-2-13 standard, which relies on the Limit State theory.

The data of the Val-Formazza project adjusted for Italian methodology is shown in Table 5.2

Table 5.2: Transmission line design parameters (Italian methodology)

Parameter	**Unit**	**Value**
1. Orographic and Environmental Data		
Altitude above sea level	m	2000
Tower A height	m	38.5
Tower B height	m	41.5
Horizontal span a (also previous span for X_I calculation)	m	223.94
Elevation difference h (Tower A-B)	m	40.41
Elevation difference h (Tower B-C)	m	31.73
Forward span (Tower B-C)	m	176.7
Effective height conductor	m	25
Terrain category	-	1
Exposure category	-	IV
Terrain roughness class	-	C
Air density	kg/m^3	1.25
Average ambient temperature (T_{inf})	°C	20
2. Conductor Specifications		

Table 5.2 –

Parameter	**Unit**	**Value**
Conductor code	-	1657-AL1/209-ST1A
Cable material type	-	Aluminum-Steel
Number of subconductors	-	1
Outer diameter	mm	56.3
Aluminum cross-section	mm^2	1656.7
Steel cross-section	mm^2	208.7
Total cross-section	mm^2	1865.4
3. Mechanical Properties and Creep		
Conductor unit weight (ρ)	kg/m	6.224
Cable horizontal tension (T_o)	kgf	8611
Ultimate Tensile Strength (UTS)	N	532800
Aluminum Young's modulus	GPa	55
Steel Young's modulus	GPa	190
Thermal expansion coef. α (aluminum)	1/°C	0.000024
Thermal expansion coef. α (steel)	1/°C	0.000012
k creep	-	0.24
α creep	-	1
ϕ creep	-	1
μ creep	-	0.16
T/t rupture	-	0.2
Test duration	hours	262800
Installation creep	mm/km	237.87
4. Tower Geometry		
Upper body solidity ratio	-	0.26
Middle body solidity ratio	-	0.24
Lower body solidity ratio	-	0.16
Upper body length	m	36
Upper body height	m	15
Upper body side	m	1.5
Middle body length	m	9
Base body upper width	m	3.392
Lower body lower width	m	10.96
5. Insulators		
Number of insulator strings	-	2
Insulator string area	m^2	0.51

Table 5.2 –

Parameter	**Unit**	**Value**
Weight of one insulator string	N	1500
6. Aerodynamic and Structural Coefficients		
$C_{t,i}$	-	1
$C_{c,i}$	-	1
$G_{c,i}$	-	0.63
$G_{t,i}$	-	1
$C_{i,i}$	-	1.2
$G_{i,i}$	-	1
7. Thermal and Electrical Parameters		
I_1 normal load current	A	2309
Emergency current (I_2)	A	2886.25
Q_{sun} incident solar energy	W/m^2	1193
Aluminum-copper M factor	-	228.1
ϵ_s conductor solar emissivity	-	0.2
ϵ_l infrared surface emissivity	-	0.3
h convective heat transfer coef.	W/m^{2}K	20
DC resistance at 20°C	Ω/km	0.0175

First we define the type of zone of Table 3.4, which is zone 1. Having then the values of $V_{b,0}$,a_0 and k_s

Since the height is higher than 1500, we will use an effective altitude of 1500 [m]; then, using Equation 3.4 we determine that coefficient c_a is 1.2.

Then we can calculate the velocity V_b using Equation 3.5.

$$V_b = 1.2 * 25 = 30 \quad [m/s] \tag{5.84}$$

Then we calculate the dynamic wind pressure according to equation 3.6

$$q_b = \frac{1}{2} 1.25 * 30^2 = 562.5 \quad [N/m^2] \tag{5.85}$$

Then we need to obtain coefficient $C_e(z)$ from equation 3.7 since z>zmin. To Obtain the coefficient k_r we will use the Tables 3.5, 3.6 and Figure 3.2.

We choose category C; according to Figure 3.2 for zone 1, at height higher than 750 it is category IV of exposure. We will get the values of $k_r = 0.22$, $z_0 = 0.3$ and $zmin = 8$.

Then we can determine coefficient $C_e(z)$

$$c_e(25) = (0.22)^2 \cdot 1 \cdot \ln\left(\frac{25}{0.3}\right)\left[7 + 1 \cdot \ln\left(\frac{25}{0.3}\right)\right] = 2.445242 \tag{5.86}$$

To obtain the Young Modulus and thermal expansion coefficient,

$$E = 55 * 0.89 + 190 * 0.111 = 70.103 \quad [GPa] \tag{5.87}$$

$$\alpha = \frac{55 * 1656.7 * .000024 + 190 * 208.7 * 0.000012}{55 * 1656.7 + 190 * 208.7} = 2.036 * 10^{-5} \quad [1/°C] \tag{5.88}$$

As mentioned on chapter 4, the value of the Young Modulus and the thermal expansion coefficient have the same approach and therefore, the same value.

Then we will calculate the length of the cable using equation 3.3. $K = H/w = 1383.51 \quad [m]$.

$$L = \sqrt{4 \cdot (1383.515424)^2 \cdot \sinh^2\left(\frac{111.97}{1383.515424}\right) + 4 \cdot (20.205)^2} = 227.80 \quad \text{[m]} \tag{5.89}$$

Then we will compare the wind spans of tower A and B same as equations 5.13 and 5.14

$$L_{m,towerA} = (previousspan + subsequentspan)/2 = (142.3 + 223.94)/2 = 183.12 \quad [m] \tag{5.90}$$

$$L_{m,towerB} = (previousspan + subsequentspan)/2 = (223.94 + 176.7)/2 = 200.32 \quad [m] \tag{5.91}$$

To calculate the wind force over the conductor we use equation 3.12:

$$QW_{cU} = 1375.45 \cdot 0.63 \cdot 1 \cdot 0.0563 \cdot \cos^2(0) \cdot 200.32 = 9772.77 \quad \text{[N]} \tag{5.92}$$

To calculate the wind force over the isolator we will use Equation 5.93 . While the Colombian standard applies a 0.6 form factor to reduce the insulator's total area by 40% accounting only for the "effective" area of the individual discs, the Italian standard [10] takes a more conservative, geometric approach by using the gross projected area (length × diameter).

$$Q_w = 562.5 \cdot 2.45 \cdot 1 \cdot 1.2 \cdot 0.51 = 841.77 \text{ [N]} \tag{5.93}$$

To determine the wind action on the lattice tower (Q_w), the structure is divided into distinct sections, keeping the same approach used in the Colombian methodology. Since detailed geometric data for the Val-Formazza tower are not

fully available, the proportional height distribution from the reference 230 kV ISA tower is adopted. The tower is divided into three main sections: the upper body (cross-arms), the middle body, and the base.

$$P_{\text{upper}} = 25\% \tag{5.94}$$

$$P_{\text{middle}} = 15\% \tag{5.95}$$

$$P_{\text{base}} = 60\% \tag{5.96}$$

Then the heights of the project are:

$$H_{\text{upper}} = 10.375 \quad [m] \tag{5.97}$$

$$H_{\text{middle}} = 6.225 \quad [m] \tag{5.98}$$

$$H_{\text{base}} = 24.900 \quad [m] \tag{5.99}$$

The solid area of each section is:

$$Area_{upper} = 15.56 \quad [m^2] \tag{5.100}$$

$$Area_{middle} = 15.22 \quad [m^2] \tag{5.101}$$

$$Area_{base} = 178.68 \quad [m^2] \tag{5.102}$$

Then the effective area is:

$$Area_{eff,upper} = 4.04 \quad [m^2] \tag{5.103}$$

$$Area_{eff,middle} = 3.65 \quad [m^2] \tag{5.104}$$

$$Area_{eff,lower} = 28.58 \quad [m^2] \tag{5.105}$$

We have to calculate $C_e(z)$ for each element: Upper, middle and lower part of the tower, according to equation 3.7.

$$c_{e,\text{upper}} = (0.22)^2 \cdot 1 \cdot \ln\left(\frac{36.31}{0.3}\right)\left[7 + 1 \cdot \ln\left(\frac{36.31}{0.3}\right)\right] = 2.74. \tag{5.106}$$

$$c_{e,\text{middle}} = (0.22)^2 \cdot 1 \cdot \ln\left(\frac{27.61}{0.3}\right)\left[7 + 1 \cdot \ln\left(\frac{27.61}{0.3}\right)\right] = 2.52 \tag{5.107}$$

$$c_{e,\text{lower}} = (0.22)^2 \cdot 1 \cdot \ln\left(\frac{10.26}{0.3}\right)\left[7 + 1 \cdot \ln\left(\frac{10.26}{0.3}\right)\right] = 1.8 \tag{5.108}$$

Then we need to find the coefficient C_t for each division also with equation 3.21

$$C_{t,\text{upper}} = 3.96 \cdot (1 - 1.5 \cdot 0.26 + 0.26^2) = 2.683 \tag{5.109}$$

$$C_{t,\text{middle}} = 3.96 \cdot (1 - 1.5 \cdot 0.24 + 0.24^2) = 2.762 \tag{5.110}$$

$$C_{t,\text{base}} = 3.96 \cdot (1 - 1.5 \cdot 0.16 + 0.16^2) = 3.111 \tag{5.111}$$

Then we can find the wind force over each part of the structure with equation 5.93

$$Q_{w,\text{upper}} = 562.5 \cdot 2.738 \cdot 1 \cdot 2.683 \cdot 4.04 = 16723.24 \text{ [N]} \tag{5.112}$$

$$Q_{w,\text{middle}} = 562.5 \cdot 2.522 \cdot 1 \cdot 2.762 \cdot 3.65 = 14320.6 \text{ [N]} \tag{5.113}$$

$$Q_{w,\text{base}} = 562.5 \cdot 1.801 \cdot 1 \cdot 3.111 \cdot 28.59 = 90086.82974 \text{ [N]} \tag{5.114}$$

Then, to calculate the vertical loads we must use Equation 3.22. We need to find also the weight span, using the stringing temperature as we did on Equations 5.49 to 5.81

$$E = 165800000 \tag{5.115}$$

$$R_{0^\circ\text{C}} = 0.0160895[\Omega/km] \tag{5.116}$$

$$x_s^2 = 7.81 \tag{5.117}$$

$$x_s^4 = 61.00 \tag{5.118}$$

$$y_s = 0.2533 \tag{5.119}$$

$$R_{AC} = 0.02016 \quad [\Omega/km] \tag{5.120}$$

$$R_{AC} = 2.016 \times 10^{-5} \quad [\Omega/m] \tag{5.121}$$

$$A = 2.016 * 10^{-5} \quad [\Omega/m] \tag{5.122}$$

$$B = 8.838 * 10^{-8} \tag{5.123}$$

$$A' = 2.19^{-5} \tag{5.124}$$

Using these coefficients in the heat balance equations, the steady-state conductor temperatures for normal operation (T_1) and emergency overload conditions (T_2) are found:

$$T_1 = 56.57 \quad [°\text{C}] \tag{5.125}$$

$$T_2 = 79.43 \quad [°\text{C}] \tag{5.126}$$

Finally, the permanent mechanical elongation (creep) developed over the conductor's lifespan is quantified.

$$\varepsilon = 706.99 \quad [\text{mm/km}] \tag{5.127}$$

$$\varepsilon_T = 469.11 \quad [mm/km] \tag{5.128}$$

$$\Delta t_{Eq} = 23.04 \quad [°\text{C}] \tag{5.129}$$

$$T_2 = 102.48 \quad [°\text{C}] \tag{5.130}$$

Then we find F_{vc} as same as formula 5.131.

$$F_{wind} = 0.0045 \cdot (30 \cdot 3.6)^2 \cdot 56.3/1000 = 2.955 \quad [N/m^2] \tag{5.131}$$

Then we will find ρ_2

$$\rho_2 = \sqrt{6.224^2 + 2.955^2} = 6.89 \quad [kgf/m] \tag{5.132}$$

Then we will find the tension T_2 at the stringing temperature with Equation 2.35.

$$T_{2,previous} = 67909.79 \quad [N] \tag{5.133}$$

$$T_{2,previous} = 6922.51 \quad [kgf] \tag{5.134}$$

$$T_{2,subsequent} = 58464.37 \quad [N] \tag{5.135}$$

$$T_{2,subsequent} = 5959.67 \quad [kgf] \tag{5.136}$$

Then we can calculate the distance from the catenary vertex with respect to the preceding support

$$XI_{previous} = \frac{223.94}{2} - \frac{6922.51}{6.224} \sinh^{-1}\left(\frac{40.41}{2\left(\frac{6922.51}{6.224}\right)\sinh\left(\frac{223.94}{2\left(\frac{6922.51}{6.224}\right)}\right)}\right) \quad [\text{m}] \tag{5.137}$$

$$XI_{previous} = -87.32 \quad [\text{m}] \tag{5.138}$$

$$XI_{subsequent} = \frac{176.7}{2} - \frac{5959.67}{6.224} \sinh^{-1}\left(\frac{31.73}{2\left(\frac{5959.67}{6.224}\right)\sinh\left(\frac{176.7}{2\left(\frac{5959.67}{6.224}\right)}\right)}\right) \quad [\text{m}] \tag{5.139}$$

$$XI_{subsequent} = -82.44 \quad [\text{m}] \tag{5.140}$$

Then the weight span is calculated as

$$V_P = 223.94 + 87.32 - 82.44 = 228.82 \quad [\text{m}] \tag{5.141}$$

And finally the vertical load will be calculated as Equation 3.22.

$$C_v = 1.1 \cdot [(61.057 \cdot 228.82 \cdot 1) + (2 \cdot 1500)] = 18668.41 \quad [N] \tag{5.142}$$

Chapter 6

Structural Verification for the Val Formazza project

Having established theoretical foundations and compared the mathematical formulations of the Colombian and Italian standards, this chapter performs the structural verification of the main components; it checks that, for every element, the resistance capacity is greater than or equal to the load effect produced by the most unfavourable load hypothesis.

6.1 Colombia: introduction

Following the reliability formula adopted by the ISA guide [5], the verification is expressed with the load and resistance factor design (LRFD) inequality already introduced in Equation 2.2:

$$\Phi\, R_c \;\geq\; \gamma\, Q_c \tag{6.1}$$

Reminding again, R_c is the characteristic resistance of the component, Φ the resistance reduction factor, Q_c the characteristic load effect and γ (equivalently the overload factor f_s) the load factor. A component is considered adequate when its *utilization factor*

$$U \;=\; \frac{\gamma\, Q_c}{\Phi\, R_c} \;\leq\; 1. \tag{6.2}$$

6.1.1 Conductors

For the conductor, the resistance is its ultimate tensile strength (UTS) and will be the nominal breaking load $R_c = \text{UTS} = 532{,}800\,\text{N}$ of the 1657-AL1/209-ST1A cable. The load effect Q_c is the maximum axial tension developed by the conductor. The verification therefore consists of three steps:

- definition of the critical load hypothesis
- computation of the maximum tension through the change-of-state equation
- application of the LRFD

6.1.2 Critical load hypothesis

Under the Colombian normal condition the maximum conductor tension is reached when thermal contraction (low temperature) is combined with the maximum design wind, which increases the resultant unit load acting on the cable. The coincident temperature is obtained from Equation 2.3 for the site altitude $H = 2{,}000\,\mathrm{m}$:

$$T_{\min} = \frac{2770 - H}{145} = \frac{2770 - 2000}{145} = 5.31 \quad [^{\circ}\mathrm{C}]. \tag{6.3}$$

The transverse wind adds a horizontal component to the conductor self-weight, so the composite unit load ρ_2 is the vector resultant of the vertical weight $\rho_1 = 6.224\,\mathrm{kg\,m^{-1}}$ and the wind force per unit length (Equation (2.24) and Equation (5.72)):

$$\rho_2 = \sqrt{\rho_1^2 + F_{\text{wind}}^2} = \sqrt{6.224^2 + 5.13^2} = 8.07 \quad [kg/m]. \tag{6.4}$$

6.1.3 Maximum tension: change of state

The maximum tension is obtained by moving from the reference state of the cable to the critical hypothesis with the change of state equation.

- The initial state 1 is taken as the every-day stress condition, $T_1 = 0.20\,\mathrm{UTS} = 106560[N]$ at $t_1 = 20\,^{\circ}\mathrm{C}$ with no wind ($\rho_1 = 6.224\,\mathrm{kg\,m^{-1}}$)
- The final state 2 corresponds to $t_2 = T_{\min} = 5.31\,^{\circ}\mathrm{C}$ and $\rho_2 = 8.07\,\mathrm{kg\,m^{-1}}$, giving a temperature increment $\Delta t = t_2 - t_1 = -14.69\,^{\circ}\mathrm{C}$.

Substituting these values in Equation 2.35 with the change of state equation with $E = 70.1\,\mathrm{GPa}$, $A = 1{,}865.4\,\mathrm{mm^2}$ and $\alpha = 2.036 \times 10^{-5}\,^{\circ}\mathrm{C}^{-1}$, $L = 223.94\,\mathrm{m}$ with an elevation difference $h = 40.41\,\mathrm{m}$ (Chapter 5), for which we have the results:

$$T_o = 141.45[kN] \tag{6.5}$$

$$C = \frac{T_0}{\rho_2} = 1788[m] \tag{6.6}$$

Because the span is inclined, the catenary vertex is not located at mid-span and the maximum tension occurs at the *upper* support. We will use section 2.3 to calculate the maximum tension.

$$T_{\max} = T_0 \cosh\frac{x_2}{C}, \qquad x_2 - x_1 = S, \tag{6.7}$$

where x_1 and x_2 are the horizontal distances from the vertex to the lower and upper supports, respectively. We calculate x_2 with equation 2.33, but instead of finding the preceding distance we find the subsequent distance, giving

$$XI = \frac{\mathrm{S}}{2} + \frac{T}{\rho}\sinh^{-1}\left(\frac{h}{2\frac{T}{\rho}\sinh\left(\frac{\mathrm{S}}{2\frac{T}{\rho}}\right)}\right) \quad [\mathrm{m}] \tag{6.8}$$

Calculating x_2 we obtain $x_2 = 432.7\,\mathrm{m}$

Using equation 6.7 we obtain the maximum tension:

$$T_{\max} = 145.66\,\mathrm{kN} = 27.3\%\ \mathrm{RTS}. \tag{6.9}$$

6.1.4 LRFD verification

Adopting the UTS as the characteristic resistance with a resistance factor $\Phi = 0.8$, value given by the normative ASCE 74 -1.4.4.4 [9], selection of strength factors, the design inequality (6.10) becomes:

$$\Phi\, R_c = 0.8 \times 538.2\,\mathrm{kN} \;\geq\; T_{\max} = 145.66\,\mathrm{kN}. \tag{6.10}$$

The corresponding utilization factor is

$$U = \frac{T_{\max}}{\Phi\, R_c} = \frac{145.66}{426.24} = 0.34 \;\leq\; 1. \tag{6.11}$$

The maximum tension equals 27.3% RTS and the every-day stress 34% RTS, both comfortably below the limits (according to Carlos Alberto's book [6], $\approx 50\%$ RTS for the maximum tension and $\approx$ 20–25% RTS for the EDS to control aeolian vibration).

6.2 Insulators

The suspension insulator string is verified against its specified mechanical load (SML), which plays the same role for the string that the RTS plays for the conductor: it is the characteristic mechanical resistance of the component. The verification again applies the LRFD inequality of equation 2.2, with the resistance R_c equal to the SML and the load effect Q_c equal to the resultant mechanical force that the conductor and the wind transfer to the string.

6.2.1 Load effect on the string

At a suspension support under the normal condition (all cables intact, no line angle, no longitudinal load), the string is subjected to two orthogonal actions, both already computed in Chapter 5 with their respective overload factors:

- A **vertical** component equal to the vertical load of Equation (2.24), i.e. the conductor weight over the weight span plus the self-weight of the string, $C_{V_c} = 18{,}661.18\,\text{N}$ (Equation (5.82));
- A **transverse** component equal to the sum of the wind load on the conductor and the wind load on the string itself, $F_c + F_i = 8976.59 + 341.61 = 9{,}318.20\,\text{N}$ (Equations (5.16) and (5.18)).

Because the string is free to swing, it aligns with the resultant of these two components, so the load effect is their vector sum:

$$Q_c = \sqrt{C_{V_c}^2 + (F_c + F_i)^2} = \sqrt{18661.18^2 + 9318.20^2} = 20.86 \quad [kN]. \tag{6.12}$$

6.2.2 Mechanical resistance

The line is verified with a standard toughened-glass cap-and-pin string of type U120B (data taken from IEC 60305 [19]), nominal disc diameter of 255 mm coincides with the insulator diameter used in Chapter 5 for the wind-area calculation (Equation 5.2).

Table 6.1: String insulator U120B [19]

Designation	**Specified mech. load (kN)**	**Max nominal diameter D (mm)**	**Nominal spacing P (mm)**	**Min nominal creepage dist. (mm)**	**Standard coupling (IEC 60120)**
U 120 B	120	255	146	295	16

6.2.3 LRFD verification

Unlike the conductor for which ASCE 74 recommends $\phi = 0.8$ when the nominal strength is taken as the RTS insulators and hardware are manufactured components with a very low strength coefficient of variation. Consequently, their probabilistic strength factor tends to unity. Taking the SML as the characteristic resistance with

a resistance factor $\Phi = 1.0$ and using the factored load effect of Equation (6.12), the design inequality 2.2 gives:

$$\Phi\, R_c = 1.0 \times 120\,\text{kN} \;\geq\; Q_c = 20.86\,\text{kN}, \tag{6.13}$$

so that the utilization factor, from Equation (6.2), is

$$U = \frac{Q_c}{\Phi\, R_c} = \frac{20.86}{120} = 0.17 \;\leq\; 1. \tag{6.14}$$

The string works at only 17% of its specified mechanical load.

The small percentage is expected as under the normal (intact) condition the string is governed not by strength but by electrical and swing requirements. Its mechanical capacity is instead dictated by exceptional load cases (broken-conductor and construction/maintenance hypotheses), which fall outside the normal condition analysed in this thesis. The U120B suspension string is therefore adequate for the analysed support.

6.3 Italian methodology

Under the Italian framework (CEI EN 50341-1 [10] with the National Normative Aspects EN 50341-2-13 [11])the verification is carried out with the limit-state format introduced in Chapter 3, Equation (3.1):

$$E_d \;\leq\; R_d, \qquad \text{or} \qquad \gamma_F\, F_k \;\leq\; \frac{R_k}{\gamma_M}, \tag{6.15}$$

where E_d is the design value of the action effect, R_d the design resistance, γ_F the partial factor on the action and γ_M the partial factor on the material. The limit-state method keeps the load essentially unfactored (for Italy the partial factor on wind is $\gamma_W = 1.0$, EN 50341-2-13, 4.13, IT.1[11]) and divides the characteristic resistance by γ_M. The utilization factor is $U = E_d/R_d \leq 1$.

6.3.1 Conductor

The conductor is verified against requirements defined by the Italian NNA [11].

Ultimate limit state (maximum tension). The characteristic resistance is the rated tensile strength $R_k = \text{RTS} = 532{,}800\,\text{N}$, and the partial factor for conductors is $\gamma_M = 1.25$ (EN 50341-1, 9.6.2), giving a design resistance

$$R_d = \frac{\text{RTS}}{\gamma_M} = \frac{532800}{1.25} = 426.24\,\text{kN}. \tag{6.16}$$

The maximum tension is obtained with the change-of-state equation 2.35

- For the initial state, the EDS reference state ($T = 106560[N]$, $t_1 = 15\,°C$, no wind).We used 15 °C because the Italian standard indicates that value on Table 3.1.
- For final tension, we calculated the wind force F_{VC} of the ρ_2 formula with equation 5.93 but instead of Newtons we calculate as [N/m] canceling the wind span, with equation $q_p(z)\, G_c\, C_c\, d$

Also, we are checking two cases:

- Case (c), wind action at −7 °C ($\rho_2 = 6.89\,\mathrm{kg\,m^{-1}}$, Equation (5.130))
- Case (b), minimum temperature. For the site altitude (2,000 m, Zone B) and the minimum temperature is −20 °C, combined with the reduced wind equation $V_b = 0.76 * \sqrt{c_e(z)}$ factor from Table 3.1) prescribed for that case.

The resulting tensions are given in Table 6.2.

Table 6.2: Conductor tension for the Italian load cases (span A–B, $L = 223.94\,\mathrm{m}$, $h = 40.41\,\mathrm{m}$).

Load case	T_H [kN]	$T_{\max}$ at upper support [kN] (% RTS)
Case (c): wind, −7 °C	149.802	154.057 (28.91%)
Case (b): min. temp., −20 °C	158.949	**163.055** (30.6%)

Consistently with the semi-probabilistic limit-state method, the partial factor is applied to the wind pressure, $q_d = \gamma_W\, q_b$ before the analysis, and the change-of-state equation is then solved with the factored wind load to obtain the design tension T_d. The factor is not applied to the resulting tension, because the conductor response is non-linear (Equation (2.24) is cubic in T).

For Italy $\gamma_W = 1.0$ (EN 50341-2-13, 4.13), so the factored wind equals the characteristic wind and the design tension coincides with the value of Table 6.2, $E_d = T_d = 163.055\,\mathrm{kN}$. The limit-state check (6.15) then gives

$$E_d = 163.055\,\mathrm{kN} \;\le\; R_d = 426.24\,\mathrm{kN}, \qquad U = \frac{163.055}{426.24} = 0.38 \le 1. \tag{6.17}$$

The conductor satisfies the ultimate limit states, working at 38% of its design tensile resistance.

6.3.2 Insulators

The suspension string is verified against its specified mechanical load (SML) divided by the insulator partial factor. Since the Italian NNA (10.7, IT.2) refers the value

of γ_M for suspended insulators back to EN 50341-1, which in turn adopts the value of section 11.6 which indicates when no value is given, the partial factor is $\gamma_M = 1.6$ (EN 50341-2-13, 11.6, IT.1). For the same U120B glass string (SML = 120 kN), the design resistance is

$$R_d = \frac{\text{SML}}{\gamma_M} = \frac{120}{1.6} = 75\,\text{kN}. \tag{6.18}$$

The design load effect is the resultant of the vertical load $C_v = 18.668\,\text{N}$ (Equation (5.140), with $\gamma_G = 1.1$) and the transverse wind, equal to the wind on the conductor plus the wind on the string, $\gamma_W\,(Q_{Wc} + Q_{Wi}) = 1.0\,(9772.77 + 841.80) =$ 10,614.5 N:

$$E_d = \sqrt{C_v^2 + \left[\gamma_W (Q_{Wc} + Q_{Wi})\right]^2} = \sqrt{18668.41^2 + 10614.5^2} = 21.48\,\text{kN}, \tag{6.19}$$

The limit-state check (6.15) gives

$$E_d = 21.48\,\text{kN} \;\leq\; R_d = 75\,\text{kN}, \qquad U = \frac{21.48}{75} = 0.29 \leq 1. \tag{6.20}$$

The string works at 29% of its design mechanical resistance and is therefore adequate. As with the Colombian check, the large reserve reflects the fact that the normal (intact) condition does not govern the insulator design.

6.3.3 Comparison of the two methodologies

Table 6.3 collects the design action, the design resistance and the utilization factor obtained for the conductor and the insulator string under each regulatory framework.

Table 6.3: Summary of the structural verification.

Component	**Methodology**	E_d	R_d	U
Conductor	Colombian (LRFD)	145.66 kN	532.80 kN	0.34
	Italian (limit states)	163.06 kN	426.24 kN	0.38
Insulators	Colombian (LRFD)	20.86 kN	120 kN	0.17
	Italian (limit states)	21.48 kN	75 kN	0.29

Both components satisfy the verification under the two standards, but the Italian framework proves more demanding in every case.

For the conductor, the Italian design action (163.06 kN) exceeds the Colombian one (145.66 kN), although the Colombian design wind speed is higher (39.5 m/s against 30 m/s), there is a bigger difference in the temperature used; the italian standard has a minimum temperature of $-20\,^\circ$C for the site (Zone B, load case b

of Table 3.1), while the Colombian coincident temperature of equation 2.3 yields a temperature of only 5.31 °C. This difference of roughly 25 °C in thermal contraction increases the axial tension more than the larger Colombian wind load does.

On the resistance side both methods now reduce the rated tensile strength, and by coincidence to the same value: the Italian method divides the RTS by $\gamma_M = 1.25$, while the Colombian method (ASCE 74, §1.4.4.4) applies a strength factor $\Phi = 0.80$ to the RTS when the nominal resistance is taken as the ultimate strength, so that $R_d = 0.80 \times 532.80 = 426.24$ kN in both cases. Consequently, the difference in the utilization factor arises solely from the design action that is, from thermal load and not from the treatment of the resistance.

For the insulator string the two design actions are almost identical (20.86 kN and 21.48 kN), so the difference in the utilization factor stems essentially from the resistance side. The Italian framework applies the partial factor $\gamma_M = 1.6$ to the specified mechanical load ($R_d = 120/1.6 = 75$ kN), whereas the Colombian method retains the full SML (120 kN). The Italian action is also larger because it adopts the gross projected area of the string (0.51 m^2) instead of the Colombian effective area, which is reduced by the 0.6 shape factor (0.306 m^2), and because the partial factor $\gamma_G = 1.1$ is applied to the self-weight of the string as well.

Chapter 7

Interface development and sensitivity analysis

The last chapters described the theoretical formulation of both standards, demonstrating their mathematical equivalences and differences, and applied them to the support that endures the greatest load of the Val Formazza example, the tower BP.25.

As mentioned in the second objective of this work, a graphical user interface (GUI) was developed. This GUI reproduces the calculation of both standards.

The interface therefore delivers two products: a static given tower (the load trees of Section 7.1) and a parametric sensitivity study (Section 7.2) that reveals how, and at which point, the two regulatory philosophies begin to disagree.

7.1 Main interface and load tree generation

The GUI groups every input required by the two standards (environmental conditions, terrain category, conductor and insulator properties, tower geometry, and the coefficients of each standard) in a single workspace, so that a change in any variable is propagated through both calculation paths.

Figure 7.1 shows the interface with the two load trees for each colombian and italian standard, generated for tower BP.25 of the Val Formazza case study. Each tree shows in yellow the upper, middle and lower parts of the structure, the transverse force generated by the wind; in red it shows the sum of the transverse wind load of conductor and insulator, and in green, the vertical load.

The two tables on the left show the individual contributions of the load tree: transverse load of conductor and insulator, each transverse load of the structure and the total transverse load which is the sum of all the previous forces. The string resultant force is the resulting force of transverse and vertical loads.

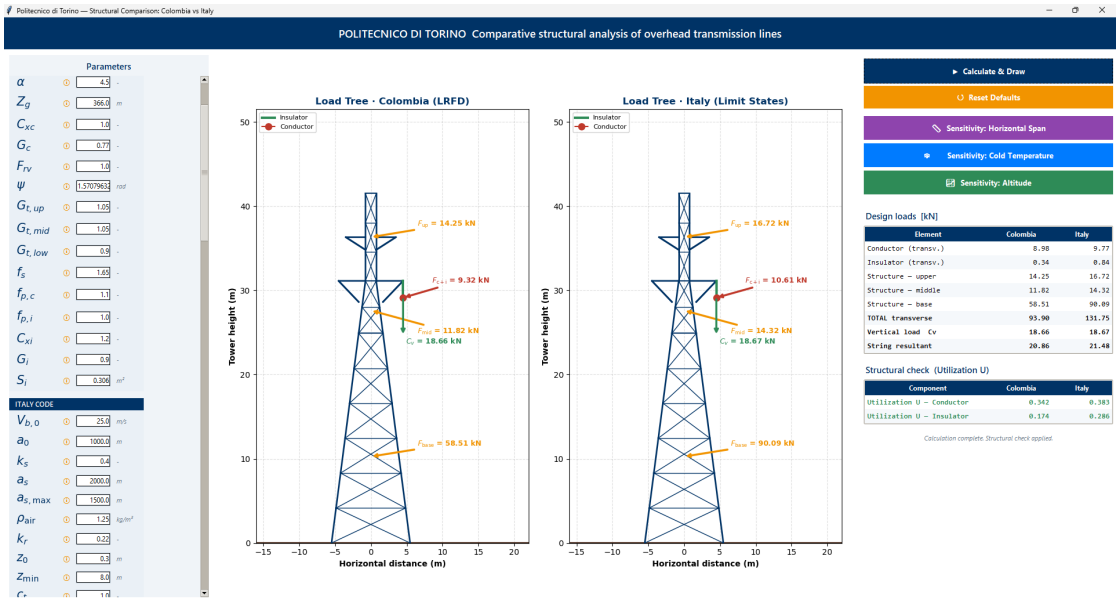


Figure 7.1: Main GUI

The values displayed reproduce exactly the manual verification of the previous chapter: a conductor utilization of 0.34 under the Colombian method against 0.38 under the Italian one, and an insulator utilization of 0.17 against 0.29.

7.2 Sensitivity Analysis

The sensitivity part keeps the geometry and materials of the tower fixed and varies one environmental or topographic parameter at a time (horizontal span, wind or altitude), while recomputing the whole load chain for both codes. For each swept value it plots six quantities: the transverse (wind) load, the total vertical load C_v, and the conductor and insulator utilization factors U, with the failure threshold $U = 1$ marked explicitly. Isolating one variable at a time makes it possible to attribute every difference between the two curves to a specific clause of each standard rather than to the combined effect of the whole hypothesis, which is precisely what a comparison aimed at judging extrapolability requires.

7.2.1 Sensitivity to Horizontal Span

Starting with the coefficients of subplot 6, the Colombian conductor gust factor $G_{c,c}$ decreases because we used the Davenport equation in 2.19, which contains the span in the fraction term as $(1 + 0.8\,S/L_s)^{-1}$. Once $0.8\,S$ grows large enough, the curve behaves as constant since this term will tend to 0.

The Italian structural factor $G_{c,i}$ has the same shape but lies lower and loses proportionally more over the range. Its span dependence comes from the background factor of Equation 3.15, $B^2 = \left(1 + \frac{3}{2}\,L_m/L(z)\right)^{-1}$, which is the same kind of decay but is scaled by the integral turbulence length $L(z)$ of Equation 3.16, instead of by the tabulated constant L_s of the Colombian curve fit.

The Colombian span reduction factor F_{RV} is the only coefficient of the panel that is not smooth, since it introduces breakpoints into the results. Equation 2.20 gives a linear function, $F_{RV} = 1.3 - 0.0012\,F$, bounded above by unity and below by 0.70.

The first subplot shows the sum of the transverse loads of conductor and insulator, $F_c + F_i$. In both standards, Equations 2.18 and 3.12, the wind force on the conductor grows linearly with the wind span and of coefficients that decrease with it. Also, the insulator contribution adds a constant offset that does not depend on the span at all as shown in equations 2.21 and 3.19.

The Italian curve is nearly straight because only one decreasing coefficient acts on it, $G_{c,i}$. The Colombian curve is segmented because two act on it, and one of them is piecewise, F_{RV} .

The second subplot is the wind force over the structure, and it returns two horizontal lines. This is the expected result, since the span does not appear in the wind force on the lattice tower, $F_t = q_p(z)\, C_f\, G_t\, S_t$, which is a function of the tower geometry, of the solidity ratios and of the pressure evaluated at the centroid of each module.

The third subplot shows the two vertical loads so close to each other that they cannot be distinguished at the scale of the plot. Comparing the two combinations of Table 4.1, the permanent load is $C_v = 1.1 \cdot \rho \cdot V_p \cdot NSC + 1.0 \cdot NCA \cdot PCA$ and $C_v = 1.1 \cdot [(\rho V_p NSC) + (NCA \cdot PCA)]$ in Italy. Both codes therefore apply the same factor to the conductor term, but have two main differences explained next:

- **The weight span.** Equations 2.33 and 2.34 define the vertex position XI and the weight span V_p. The vertex is located through the catenary parameter, which is fixed by the tension at the stringing state, and that tension is the solution of the change of state equation, in which each code introduces its own design wind through the composite unit load ρ_2. A heavier ρ_2 returns a higher tension, which displaces the vertex further outside the span and assigns a larger share of the cable weight to the upper support. Since the Colombian design is the higher of the two, its conductor term, is the larger.

- **The weight of the insulator strings.** It is multiplied by 1.00 in Colombia and by the partial factor $\gamma_G = 1.1$ in Italy. As both calculations share the same N_{CA} and P_{CA}, the Italian string term exceeds the Colombian one by exactly ten per cent at every span.

Part of this closeness is also a consequence of the methodology adopted here. Neither the Colombian guide nor the Italian standard prescribes a procedure for locating the catenary vertex, so the same geometric treatment was applied in both branches.

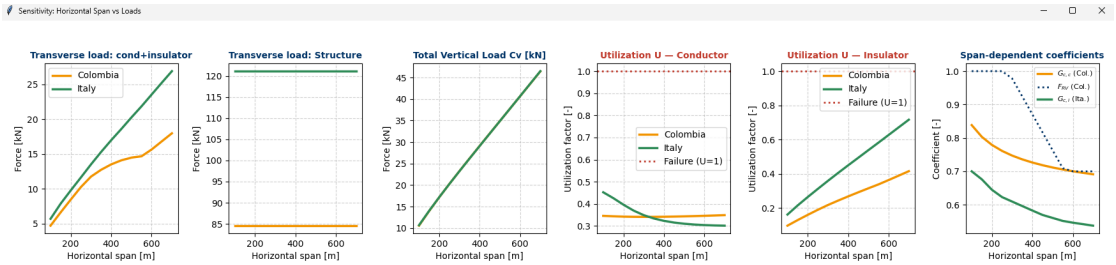


Figure 7.2: Sensitivity analysis for horizontal spans

The fourth subplot contains the utilization factor of the conductor. The colombian utilization factor varies very little over the whole sweep while the Italian factor

falls monotonically. Both behaviors are given by the structure of the change of state equation, which with the span admits two limits.

$$T_2^3 + T_2^2 \left[EA\alpha\Delta t - T_1 + \frac{EAS^2\rho_1^2}{24\,T_1^2} \right] = \frac{EAS^2\rho_2^2}{24} \tag{7.1}$$

When span tends to 0, $T_2 \to T_1 + EA\alpha|\Delta t|$: the cable behaves as a rigid tie and the tension depends only on the thermal contraction. When span tends to infinity, those terms dominate and $T_2 \to T_1\,\rho_2/\rho_1$: the thermal term becomes negligible and the tension depends only on the wind (ρ_2).

The shape of each curve is decided by how far apart its two limits of the function are: when the gap between them is small the tension is nearly the same in both regimes and the curve is almost constant. Analyzing the thermal increment $EA\alpha|\Delta t|$ with Table 5.1, multiplying by $\Delta t| = 14.69$ we see that it contributes to the initial limit 39.1 kN while ρ_2 load of Section 6.1.2 contributes 31.6 k to the final limit, proving that the two differ by less than a quarter, almost constant behavior.

For the italian case, under load case (b) of Table 3.1 the drop to the minimum temperature of Zone B contributes 93.2 kN and Table 6. 2confirms the imbalance The Italian limits are therefore far apart and the curve falls from one to the other.

The fifth subplot shows the utilization factor for insulators. The linearity follows from the design action $E_d = \sqrt{C_v^2 + (F_c + F_i)^2}$: the vertical component is several times the transverse one, so the resultant is governed by C_v and the Colombian transverse load is almost invisible here.

Also, the divergence between the two lines is a matter of resistance rather than of action. The design resistance is the specified mechanical load itself in Colombia, where the strength factor for manufactured components is taken as unity, and the same load divided by $\gamma_M = 1.6$ in Italy, while the two design actions differ only through the gross projected area of the string against the Colombian effective area reduced by the 0.6 shape factor, and the application of γ_G to its self-weight.

7.2.2 Sensitivity to altitude

The subplot of the transverse load, we have the Colombian curve which is a straight, monotonically decreasing line, from 11.23 kN at sea level to 6.92 kN at 4,500 m. This behavior is because of the reference pressure that has coefficient K_p:

$$q_b = K_p \cdot V_b^2$$

Since every parameter is not changing, only the altitude, the final curve inherits the exact linearity of Equation 2.15, $K_p = 0.603 - 0.0514A$, where A is the altitude above sea level in kilometers. The italian transverse load inherits the shape of Equation 3.4, $c_a = 1$ for $a_s \le a_0$; $\quad c_a = 1 + k_s(a_s/a_0 - 1)$ for $a_s > a_0$, $\quad$ with $a_s = \min(A, 1500\text{ m})$,

The subplot of the force over the structures repeats the shape of the transverse load over the conductor.The reason is that the total structural force is a sum of three terms, each of them linear with q_b , while none of the remaining factors responds to elevation: the drag coefficients $C_f(\phi)$ and $C_t(\chi)$ depend only on the solidity ratio, the effective areas only on the geometry of the tower.

For the total vertical load subplot, the Colombian curve is exactly horizontal at 18.66 kN, and the Italian one moves from 18.58 kN to 18.67 kN The vertical load is therefore, to all practical purposes, insensitive to elevation in both codes. The reason is structural rather than numerical. Equation 2.24 gives

$$C_v = 1.1 \cdot P_{UC} \cdot V_p \cdot NSC + 1.0NCA \cdot P_{CA}$$

in which the only quantity that could feel the wind is the weight span V_p through ρ_2 . In the Colombian formulation the ρ_2 is calculated with $0.0045 \cdot (V_b \cdot 3.6)^2 \cdot d$, and since the velocity is a fixed value for colombia, the value of ρ_2 is constant, and for the case of Italy, the altitude coefficient c_a scales the reference wind speed directly, such that $V_b = c_a \cdot V_{b,0}$. As altitude changes, V_b changes, causing the wind force and ρ_2 to vary.

On the subplot of utilization curve of the conductor, the Colombian growth is entirely thermal; the design action is the cable tension at the upper support, obtained with the change of state Equation 2.35 is using the coincident temperature that changes with altitude H: $t_{\min} = (2770 - H)/145$

The Italian curve is almost flat because Table 3.1 fixes the minimum temperature of load case (b) at -20 °C for Zone B irrespective of elevation, and the reduced wind $0.76(c_e(z))^{1/2}V_b$ is the only altitude-dependent term left (because V_b depends on c_a but the contribution of the total variation is only 1.9% .

On the subplot of utilization factor of the insulator, the attenuation of the slopes with respect to the subplot of transverse load, is a consequence of the quadratic composition of the design action. The string is verified against the resultant

$$Q_c = (C_v^2 + Q_{\text{transv}}^2)^{1/2}$$

Since the vertical weight (C_v) is larger than the transverse wind force (Q_{transv}), the vertical component dictates the magnitude of the quadratic sum. Even drastic reductions in the transverse wind load across the altitude sweep translate into minimal changes in the overall utilization factor

The fifth subplot shows two curves: K_p and c_a which are the only coefficients of the whole model that respond to elevation. K_p decays linearly from 0.603 to 0.372, losing 38% of its value over the sweep; c_a is unity up to 1,000 m, ramps to 1.20 at 1,500 m and stays there.

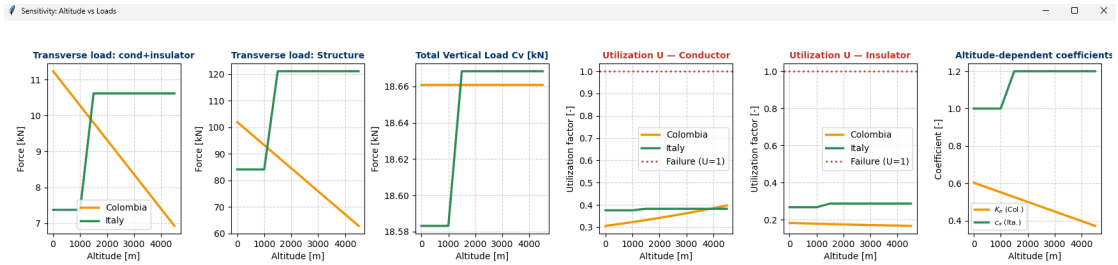


Figure 7.3: Sensitivity analysis for altitude.

7.2.3 Sensitivity to wind speed

Unlike span and altitude, wind speed cannot be swept by writing the same number for the calculation because the two codes don't start from the same meteorological quantity, the Italian standard defines the reference velocity $V_{b,0}$ as a ten-minute mean at 10 m above ground, and the Colombian guide starts from $V_{b,0}$, a three-second gust.

The only coefficient of the whole model that responds to the wind speed is the Colombian gust response factor $G_{c,c}$, through the term $V^3 s^{2/3}$ of Equation 2.19.

The first subplot shows the transverse load on conductor and string insulator. It shows a quadratic behavior because of Equations 2.18 and 3.12: the velocity enters only through the reference pressure, and the pressure is quadratic in the velocity in both formulations, $q_b = K_p V^2$ for colombia and $q_b = \frac{1}{2}\rho V_b^2$ for italy; every remaining factor multiplies that pressure by a constant.

The Italian curve is above the Colombian one over the whole range, although Colombia is driven by a gust of 46.5 m/s against an Italian of 30 m/s, but overall, Italy is higher because of the height correction. At the reference height of the conductor, $z = 25$ m, the Italian exposure coefficient amplifies the base pressure, $c_e = 2.445$, while the Colombian K_x of Equation 2.16 reduces it, $K_x = 0.802$, because the Colombian pressure is referred to the gradient height through $(Z/Z_g)^{2/\alpha}$.

For the vertical load, although wind acts as a transverse force, an increase in wind speed elevates the vertical load (C_v) due to the conductor's catenary. Again, it increases ρ_2 because wind speed increases, and so T_2, making XI to shift outward and further away from the preceding support and finally expands the weight span V_p making a higher C_v

Furthermore, the Colombian curve ascends more steeply because its methodology uses a 3-second wind gust as input obtained by multiplying the Italian 10-minute mean velocity by a conversion factor of 1.55. Since the wind force is a function of the velocity squared, this higher input exponentially magnifies the impact on the tension, the weight span, and ultimately, the vertical load.

The transverse load on the structure (third subplot) shows two parabolas,

because the velocity appears in equation 3.20 and 3.20 through the pressure; both loads are of the form (constant) $\times V_{b,0}^2$. According to the methodologies, the Colombian structural force is defined as $F_t = q_p(z) \cdot C_f \cdot G_{t,c} \cdot S_t$, while the Italian load is defined as $Q_w = q_p(z) \cdot G_{t,i} \cdot C_t \cdot A$. Since the tower's geometry is not altered during the sweep, all geometric areas and solidity ratios remain strictly constant. Second, although the Colombian 3-second gust speed is numerically higher than the Italian 10-minute mean velocity, the Italian structural load turns out to be much higher due to the height correction. The Italian standard uses a logarithmic exposure coefficient, $c_e(z)$, modeled as:

$$c_e(z) = k_{r,i}^2 \cdot c_t \cdot \ln\left(\frac{z}{z_0}\right) \cdot \left[7 + c_t \ln\left(\frac{z}{z_0}\right)\right]$$

This amplifies the base pressure reaching a multiplier of 2.445 in the case study. In contrast, the Colombian coefficient K_x evaluates the tower's height (Z) in proportion to a very high gradient height (Z_g), formulated as:

$$K_x = \left(\frac{300}{10}\right)^{\frac{2}{7}} \cdot \left(\frac{Z}{Z_g}\right)^{\frac{2}{\alpha}}$$

This mathematically ends up attenuating the base pressure by yielding reduction factors, such as 0.802 for the evaluated sections.

The conductor utilization (fourth subplot) has an increasing slope dictated by the structure of the composite unit load, $\rho_2 = \sqrt{\rho_1^2 + F_{\text{wind}}^2}$. Once the wind force overtakes the conductor's self-weight ($F_{\text{wind}} > \rho_1$), the resultant becomes wind-dominated. Since the wind force is proportional to the velocity squared ($\propto V^2$), and the change-of-state equation is cubic with respect to tension, the resulting tension grows asymptotically proportionally to $V^{4/3}$. This rapid scaling explains the steep acceleration of the curve at higher velocities.

The insulator's utilization factor exhibits a similar quadratic shape for the same reasons, but involving a different pair of components. The design action on the string is the resultant of the vertical load and the transverse wind: $E_d = \sqrt{C_v^2 + Q_{\text{transv}}^2}$. At lower speeds, the vertical load (C_v) heavily dominates the vector sum, maintaining a flat utilization slope. However, as velocity increases, the sensitivity of the resultant to the transverse action—weighted by the fraction $Q_{\text{transv}}^2/(Q_{\text{transv}}^2 + C_v^2)$—shifts dramatically.

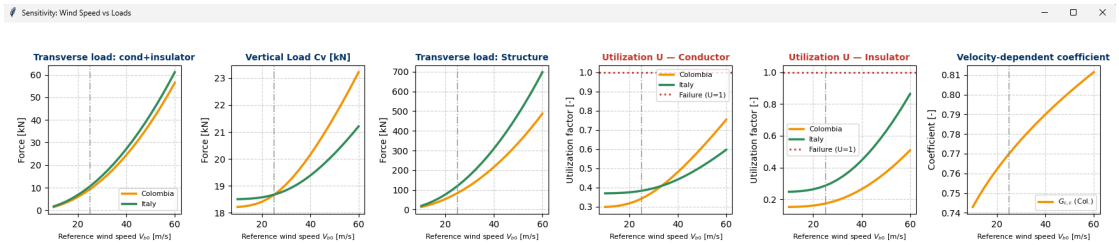


Figure 7.4: Sensitivity analysis for wind speed.

Chapter 8

Conclusions and future work

This thesis compared the Colombian and the Italian regulatory frameworks for the structural design of overhead transmission lines, applied both of them to the support of the Val Formazza project (tower BP.25), and implemented a graphical interface that allows the topographic and climatic parameters to be varied one at a time.

8.1 On the comparison of the two regulatory frameworks

The first conclusion is that the two codes are not two different theories, but two different parameterizations of the same theory. Both build the wind action along an identical sequence: reference velocity, correction for terrain and altitude, dynamic pressure, correction for height, and finally a force obtained as the product of pressure, drag coefficient, gust factor and projected area, and both close the vertical load through the classical catenary and change-of-state formulation. The flowcharts of Chapters 2 and 3 make this more explicit: in the vertical load process the only node that differs between the two methodologies is the wind input F_{wind}, so that every discrepancy in vertical loads is inherited from the transverse-load parameters rather than generated independently.

It was demonstrated for the material model by substituting $m = A_a/A_s$ in the Colombian expressions for the equivalent Young's modulus and for the thermal expansion coefficient, the Italian formulations $E_{cond} = E_a\alpha_a + E_s\alpha_s$ and $\alpha_{cond} = (E_aA_a\beta_a + E_sA_s\beta_s)/(E_aA_a + E_sA_s)$ are recovered exactly. The mechanical characterisation of the conductor is therefore not different between the two standards,so the differences are to be attributed to the climatic and safety parameters.

The methodological differences are concentrated in three points:

- **Safety philosophy.** Colombia applies the LRFD format $\Phi R_c \geq \gamma Q_c$ with a single overload factor. In this case is choosen $f_s = 1.65$ (class 1, $P_f = 0.0005$, $\beta = 3.5$, return period of 1000 years) amplifying every climatic action, and a resistance factor Φ applied to the characteristic strength. Italy applies the limit-state format $\gamma_F F_k \leq R_k/\gamma_M$, in which the wind action is left essentially unfactored ($\gamma_W = 1.0$) and the safety margin is transferred to the resistance side through material factors ($\gamma_M = 1.25$ for conductors, $\gamma_M = 1.6$ for insulators). The two philosophies therefore place the margin at opposite ends of the inequality.

- **Structure of the wind model.** The Colombian model is decoupled and algebraic: roughness corrects the velocity through $k_{r,c}$, altitude corrects the pressure through the linear factor $K_p = 0.603 - 0.0514A$, and height is introduced through a power law referred to the gradient height, K_x. The Italian model is integrated and logarithmic: altitude corrects the velocity through c_a, while height and roughness are put together into a single exposure coefficient $c_e(z)$. At the reference height of the conductor of the case study ($z = 25$ m) the Italian coefficient amplifies the base pressure ($c_e = 2.445$) whereas the Colombian coefficient attenuates it ($K_x = 0.802$), because the Colombian pressure is referred to a gradient height of the order of a few hundred metres.

- **Treatment of gust and of spatial correlation.** Colombia determines the gust response factor using the analytical Davenport model, parametrized by terrain category, span and effective height, and introduces an explicit and piecewise wind-span reduction factor F_{RV}. Italy determines the structural factor analytically from the local turbulence intensity $I_v(z)$, the integral turbulence length $L(z)$ and the background factor B^2, absorbing the spatial correlation of gusts inside those quantities instead of applying a separate multiplier. The duality of discrete versus continuous formulations also appears in the lattice tower, where the Colombian force coefficient is a stepped table of the solidity ratio and the Italian one is a continuous quadratic polynomial.

8.2 On the structural verification of the Val Formazza support

Both components satisfy the verification under both standards, but the Italian framework is the more demanding one in every case. For the conductor the design actions are 145.66 kN (Colombia) against 163.06 kN (Italy), giving utilisation factors of 0.34 and 0.38 respectively. The most instructive aspect of this result is that the two design resistances coincide numerically ($0.80 \times \text{RTS} = \text{RTS}/1.25 = 426.24$ kN),

so the entire difference comes from the action and the action is dominated by temperature, not by wind. The Colombian design wind is in fact the larger of the two (39.5 m/s against 30 m/s), but the coincident temperature obtained from $t_{min} = (2770 - H)/145$ gives only 5.31 °C at the site altitude, whereas the Italian standard prescribes −20 °C for Zone B. The resulting gap of 25 °C in thermal contraction surpases the Colombian wind.

For the insulator string the two design actions are almost identical (20.86 kN and 21.48 kN) and the difference in utilisation (0.17 against 0.29) is produced on the resistance side by the partial factor $\gamma_M = 1.6$, with a secondary contribution from the Italian use of the gross projected area of the string (0.51 m^2) instead of the Colombian effective area reduced by the 0.6 shape factor (0.306 m^2), and from the application of $\gamma_G = 1.1$ to its self-weight.

8.3 On the interface and the sensitivity analysis

Span. The Colombian conductor utilisation is almost insensitive to the span while the Italian one decreases monotonically. The explanation lies in the two asymptotic limits of the change-of-state equation: for short spans the tension tends to $T_1 + EA\alpha|\Delta t|$ (thermally dominated) and for long spans to $T_1\rho_2/\rho_1$ (wind dominated). In the Colombian case the two limits differ by less than a quarter, which produces a flat curve; in the Italian case the drop to the minimum temperature of Zone B makes the thermal limit dominant, and the curve falls steeply from one regime to the other.

Altitude. This is the most significant divergence found in the whole study, because the two codes move in opposite directions. The Colombian transverse load decreases linearly with elevation, through K_p, since the model only recognizes the reduction of air density. The Italian load increases with elevation through c_a, which is unity up to a_0, ramps up to 1.20 at 1500 m and is then constant, recognizing the orographic intensification of the wind. The two curves intersect in the transition band between 1000 and 1500 m. Below that band the Colombian criterion is conservative; above it, it becomes progressively unconservative for the same site.

Wind speed. Both transverse loads grow quadratically with the reference velocity, as expected, but the Italian curve lies above the Colombian one over the entire range despite starting from a lower reference velocity. Once again the cause is the height correction: the logarithmic amplification of $c_e(z)$ compensates the higher Colombian wind. The utilisation factors accelerate at high velocity because, once the wind force exceeds the conductor self-weight, the composite load becomes wind-dominated and the tension scales approximately as $V^{4/3}$.

8.4 Limitations of the study

The conclusions above must be read within the boundaries adopted in Chapter 1. The analysis is restricted to the normal, intact condition on suspension supports with no line deflection angle, so longitudinal and torsional actions were not considered; ice and snow hypotheses (cases 2 and 3 of the Italian framework) and the security cases (case 4) were excluded. The geometry of the Val Formazza tower was not fully available and was reconstructed by applying the proportional height distribution of the reference 230 kV ISA tower, with solidity ratios taken from typical values of ASCE 74; the wind on the lattice was evaluated by sections (Method 1) instead of the member-by-member approach prescribed by the Italian NNA. The same geometric treatment was deliberately applied to both branches, so that the observed differences originate in the standards and not in the choice of formula.

8.5 Future work

The natural continuations of this work follow directly from those limitations:

1. **Extension to ice and snow hypotheses.** Load cases 2 and 3 of EN 50341 are the part of the Alpine design envelope that the Colombian framework cannot represent at all. Quantifying how large that unrepresented fraction is would complete the answer on extrapolability.

2. **Exceptional and security load cases.** Broken-conductor, torsional, longitudinal, construction and maintenance hypotheses should be added, since the low utilisations obtained for the insulator string (0.17 and 0.29) show that the normal condition does not govern its design.

3. **Tension and angle supports.** Introducing the deflection angle and the longitudinal unbalance would extend the comparison from suspension towers to the full range of support types.

4. **Verification of the lattice structure itself.** Coupling the load tree with a finite-element model of the tower would allow member and foundation verification, and would make it possible to apply Method 2 (member by member) as required by the Italian NNA, quantifying the error introduced here by the sectional approach.

5. **Validation of the gust conversion.** The factor of 1.55 that links the two meteorological definitions should be verified against anemometric records from Alpine stations, since it conditions the whole comparison of wind actions.

6. **Reverse case study.** Applying the Italian methodology to an Andean line would test whether the conclusions are symmetric, and would allow the inclusion of hazards that are decisive in Colombia and absent here, such as seismic action and slope instability.

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