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Assessment and Impact of CO2 Emissions Attributable to Rebar Used in Building Columns to Withstand Climatic Loads

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Abstract

The location of a building dictates the climatic loads to which it will be subjected during the use phase. To design building columns, wind and snow loads must be taken into consideration. This study analyzes the amount of rebar necessary depending on the building location. To this end, a nine-floor building is modeled with waffle slabs and pillars. The entire structure is made of reinforced concrete. The study covers 135 locations: wherein the wind zone, terrain category and topographic altitude vary. The structural analysis indicates the different amounts of rebar necessary and these quantities are compared with a reference location. The results corresponding to the different rebar quantities are analyzed according to location. The variation between the locations examined and the reference building site ranges from 4.5% to 74.9%. Based on this analysis, conclusions are drawn regarding the economic costs and CO_2 emissions incurred by building columns (terrain category IV). The construction process is analyzed and the transportation of rebar to the building site is identified as a primary source of CO_2 emissions. Design guidelines are presented to address wind and snow action, and minimize costs and emissions. Given the looming challenges of climate change, these aspects take on greater relevance.

Keywords: Building; concrete structures; construction materials; environmental effect; reinforced concrete (RC)

1. Introduction

Columns are a structural element subjected to a variety of stresses. The traditional stresses are axial loads (weight of the structure and use loads) and horizontal loads (wind loads and occasionally earthquake loads). The magnitudes of design loads depend on the typology of the structure where the columns are located. Columns are primarily utilized in bridges and buildings. Let us discuss some significant aspects of both typologies, as certain aspects of design are related to our case study of columns in residential buildings.

The study and optimization of bridge columns has revealed significant findings, and different aspects have been examined. For example, Martínez *et al.* conducted a cost analysis study including materials and formwork in the optimization algorithm (Martínez *et al*., 2011). By considering execution costs, alternative reinforcement configurations can be evaluated. Kim *et al.* analyze the performance of innovative reinforcements that are economically viable and facilitate shorter construction periods (Kim *et al.*, 2015). Standardizing dimensions and reinforcement of columns in residential buildings also affects the pace of construction.

Bridge columns, given their role in places of vehicle transit, are designed to support lateral impact loads. A study conducted by Liu *et al.* with finite element analysis simulates axially-loaded circular reinforced concrete columns subjected to lateral impact load (Liu *et al*., 2017) Give the difficulty and expense involved in performing a parametric study of column impact scenarios, Yi *et al.* use finite element analysis to propose an evaluation procedure utilizing a probabilistic approach (Yi *et al*., 2015). In the case of residential construction, vehicle transit inside a garage does not reach high speeds, which justifies not including such actions in column design for these structures. Adaptive models are necessary for bridge columns to simulate the nonlinear interactive behavior under the combined action of shear, bending moment, and variable axial load. An adaptive finite element model can be found in the work of Xu and Zhang. Another study using finite elements, in this case by Gao *et al.* (2013), found that the deformation capacities obtained coincide with experimental results (Xu and Zhang, 2012). Finite element modeling is often used to incorporate a variety of parameters in complex problems, a condition that is not essential in the design of residential building columns.

The design of rigid and monolithic structures subject to extremely heavy loads sometimes leads to problems in execution due to excessive reinforcement. As pointed out by Niwa *et al*., the use of fibers in specific cases has not been ruled out for the future. Comparable structural responses can be obtained by combining steel fibers and a smaller amount of steel rebar (Niwa *et al*., 2012). There are other proposals for fiber reinforcement, such as the case of fiber-reinforced polymer, which is an alternative solution to tackle corrosion problems in harsh environments. The research of Farghaly *et al.* and Mohamed *et al.* concludes that columns designed with fiber-reinforced polymer can withstand loads similar or superior to columns reinforced with steel (Farghaly, Tobbi and Benmokrane, 2012) (Mohamed, Afifi and Benmokrane, 2014). Regarding columns used in residential construction, adequate dimensions for the concrete section and suitable coatings provide viable designs that meet durability requirements without resorting to fibers.

After analyzing the guidelines for column design in buildings, we have found that numerous studies examine high-rise buildings. The results obtained by Cao and Zhao demonstrate that economically optimal designs are constrained by loads: axial loads for the columns in lower floors, and the combination of axial and horizontal loads for the columns in the higher floors (Cao and Zhao, 2015). Column design for high-rise buildings must address the combined action of all the structural elements for the initial design, as highlighted by the research of Hoenderkamp *et al.* (Hoenderkamp, Snijder and Hofmeyer, 2012). Regarding wooden buildings, Kim *et al.* highlight the relevant role played by the rigid action of horizontal elements (slabs) in structural responses, (Kim, Ko and Cho, 2016). This theory makes sense when the roof and rafters restrict column rotation, as in the case of reinforced concrete buildings. Olmati *et al.* point out that residential and industrial facilities are often flat slab concrete structures and underscore that such structures can progressively collapse from accidental loads (Olmati *et al*., 2017) Thus, punching shear analysis should be incorporated into structural performance modeling of slab-column connections. Another factor that modeling must take into account is the presence of eccentric loads. Tian and Li analyze the influence of vertical loads on reinforced concrete columns. American and Chinese design codes for reinforced concrete also advocate column design that incorporates the combination of vertical and horizontal loads (Tian and Li, 2013). Youbao *et al.* emphasize that eccentricity produced by a vertical load is an important parameter to consider (Jiang *et al*., 2015). Eurocodes also address this issue. For the case of high-rise buildings, it is important to perform a second-order structural analysis of wind loads, as can be observed in the work of Kimura *et al*. In this study of an 80-floors building, the stress generated by the level-2 wind load was almost half that of the level-2 earthquake load (Kimura *et al*., 2007). However, for residential construction, this circumstance need not be considered given that these buildings are not so slender. As noted in the work of Beck *et al*., hazard probabilities and performance should be evaluated as factors to be incorporated into design optimization (Beck, Kougioumtzoglou and dos Santos, 2014). Current regulations underscore the importance of taking into account the wind action on a building in the four principal directions.

Other studies, such as that of Osorio *et al.* regarding horizontal earthquake loads, aim to develop a model that incorporates the plastic response of columns (Osorio, Bairán and Marí, 2017). If the objective is to analyze the behavior of a structure during the phases prior to collapse, the plastic hinge response must be incorporated in the model. This can be achieved by means of specific analysis tools as can be appreciated in the work of Visintin *et al.* on the non-linear analysis of reinforced concrete columns and beams with small axial loads under severe dynamic loads (Visintin *et al*., 2012). Murugesan and Thirugnanam analyze the plastic response of column designed with fiberglass reinforced plastic (Murugesan and Thirugnanam, 2014). Yuan *et al.* insist that results and models based on simulations using finite elements are inherently provisional by nature (Yuan, Wu and Li, 2017). In the case of columns in residential buildings, the load history regarding wind provides only static information and the use of fiberglass reinforced plastic is not economically viable. The use of fibers is only recommended for the reinforcement and repair of existing columns due to their high cost, as highlighted by Shraideh and Aboutaha, (Shraideh and Aboutaha, 2013). For the case of bridge columns, Sun *et al.* propose a new form of reinforcement for concrete structural elements: steel-fiber-reinforced polymer bars (Sun *et al*., 2014). This option is currently in the experimental phase.

Numerous studies examine the reliability of structural analysis models. For instance, Baji and Ronagh study the effects of cross-sectional shape and rebar configuration on the reliability indices of concrete columns. The results of the reliability analysis affirm the importance of sectional shape, especially at low load eccentricities (Baji and Ronagh, 2011). Jiang and Yang demonstrate that in terms of applicability the load partial factors in American and British codes are correct (Jiang and Yang, 2012). An analysis conducted by Hussain *et al.* of loads using the ACI code for a 15-floors building exhibits a strong correlation in the results (Hussain, Wasim and Hasan, 2016). In order to take into account and model wind loads, the model of ultimate limit state proposed by Eurocodes and the use of conventional reinforcing framework is adequate.

Nowadays, structural designs must fulfill other requirements in addition to structural ones. For example, environmental, social and economic factors play a strong role. Relevant research regarding these requirements is referenced below.

Optimization in concrete design is important considering the limited resources, environmental impacts and technological competition. Poluraju *et al.* proposes a methodology to obtain the optimal design for building elements using the concept of mix design and judicious selection of materials during the initial stages of the design phase (Poluraju *et al*., 2012). The design phase directly impacts cost and must be carefully examined. Ferreiro-Cabello *et al.* emphasize that the production stage for materials incorporated into a structure (concrete and steel rebar) represents 85.5% of total emissions (Ferreiro-Cabello *et al*., 2016). It is important to understand the impact decisions made during the initial phase of a project have on emissions generated afterwards. Medeiros and Kripka make a proposal to optimize the monetary and environmental costs associated with pieces of rectangular reinforced concrete columns. To this end, several indicators are used to minimize environmental costs. The results are compared with those obtained from conventional sizing processes. This study concludes that minimizing monetary costs leads to reductions in environmental cost, regardless of the indicator used for impact analysis (de Medeiros and Kripka, 2014). Cost and emissions must always be considered during the design phase: determining where and how they are produced can guide designers in their decision-making process.

In the past, high strength steel reinforcement in buildings was limited to specialized applications. Thomas *et al.* conclude that economic cost factors must be supplemented by those corresponding to execution (Thomas et al., 2013). As Jarkas explains in his research, reinforced concrete columns are among the main elements developed "in situ". Buildability is one of the most important factors influencing labor productivity (Jarkas, 2012). And factors such as symmetric solutions in the concrete section and the position of reinforcements ensure fewer errors during execution. The use of prefabricated columns requires standardized connections to support horizontal loads; a study by Zalewski *et al.* presents a solution using steel plates. The precast concrete industry has responded to the presence of horizontal loads by introducing reinforcing fibers to replace the traditional reinforcements (Zalewski *et al*., 2013). A study conducted by Quang *et al.* concludes that fibers must be high performance (HPFRCC) in order to achieve responses similar to that of traditional reinforcements (Quang *et al*., 2016). Prefabricating columns makes sense for projects where duration and cost are critical factors. However, CO_2 emissions are greater for prefabricated columns than for those made in situ. For example, a study by Jeong *et al.* compares the performance of a form-latticed prefabricated steel reinforced concrete column (Form-LPSRC) as a substitute for a conventional steel reinforced concrete column (SRC) (Jeong *et al*., 2017). In residential construction, only a small minority of projects are made with prefabricated columns.

García-Segura *et al.* studied the CO_2 emissions generated during the production of reinforced concrete. The capture of CO_2 (carbonation) is an interesting process in terms of emissions balance and is limited by durability requirements (inhibiting the corrosion of the reinforcing frame) (García-Segura, Yepes and Alcalá, 2014). We concur with the statement of Choi *et al.* that reducing CO_2 emissions during the design and construction phases is increasingly important, especially in the case of buildings with almost zero consumption (Choi *et al*., 2016).

Emissions balance sheets must take into account the impact generated by reinforcing framework. This study aims determine the repercussions of CO_2 emissions attributable to rebar, depending on wind loads in residential building columns. In the future, column design will be done with computer tools that incorporate in-depth information on material production processes, element execution, and a structure's use and even its demolition. Environmental product declarations will provide information on the production phase, but technicians must also be aware of the consequences of their decisions made during the design phase on the subsequent design of reinforced concrete structures.

2. Materials and Methods

This study quantifies and evaluates the design parameters of columns in residential buildings. With this objective, a typical Spanish building is modeled and subjected to different wind and snow loads.

The structure has 9 floors (the top two are the roof and the penthouse). The ground floor has a height of 4 m and the rest of floors measure 3 m. Hence, the total height of the building is 28 m. The dimensions of each floor of the structure are 25 meters wide by 25 meters long, with a distance of 5 meters between columns in both directions (Figure 1). Each floor has: 6 apartments, a flight of stairs, an elevator shaft and a common area.

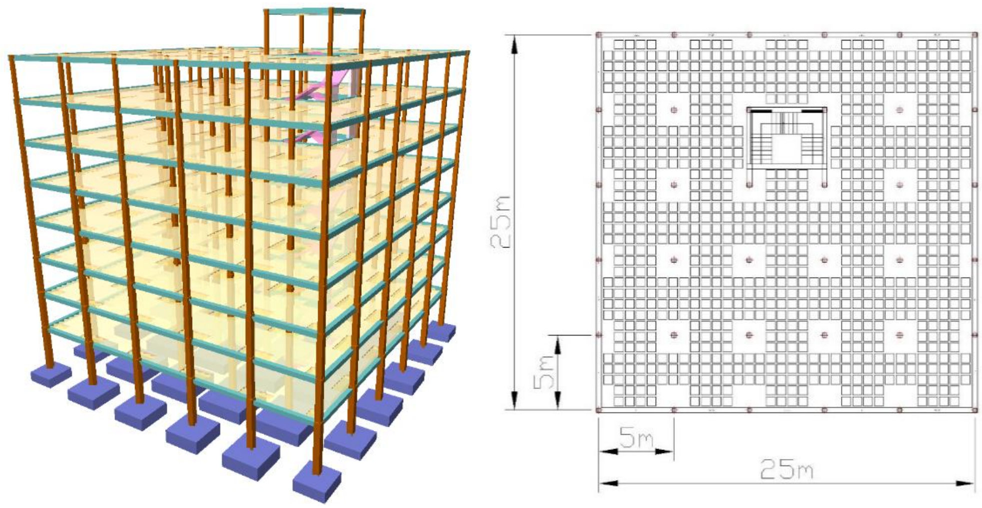

Figure 1. Floors and section of modeled residential building.

Furthermore, the structural elements that remain constant are: 35x35 cm perimeter beams; waffle slabs with a 12 cm rib and an interaxis of 72 cm; and permanent penthouse made of expanded polystyrene (Figure 2). The staircase has 3 landings on each floor, and the following dimensions: a width of 1.4 m, a tread of 0.28 m, riser of 0.17 m, 24 steps on the first floor, 18 steps on the rest of the floors, and a 2x2 m central shaft where the elevator is located. Regarding the column dimensions, the concrete section remains constant in all the columns on each floor; but the concrete section decreases on the higher floors. The dimensions of the concrete sections were selected based on the design of the most popular building. Thus, all the modeled buildings have the following dimensions:

- 1st and 2nd floors: 45x45 cm
- 3rd and 4th floors: 40x40 cm
- 5th and 6th floors: 35x35 cm
- 7th , 8th , 9th floors: 30x30 cm

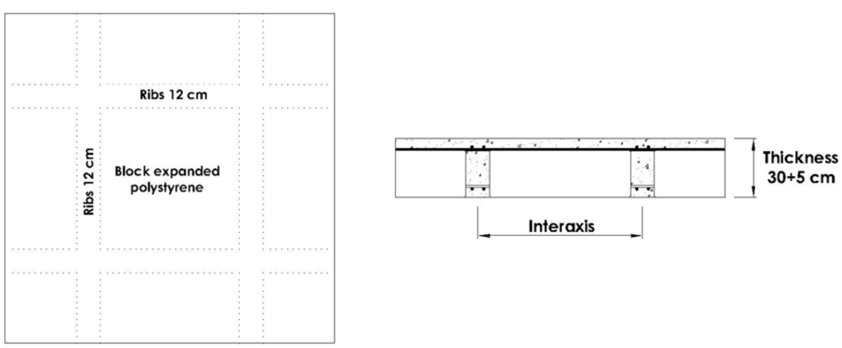

Figure 2. Typology and geometry of waffle slab.

2.1. Modeling of loads

According to Eurocode-2 (BS EN 1992-1-1, 2004), compliance with structural safety requirements (bearing capacity and stability) and serviceability must be verified. Different types of actions are taken into consideration for buildings and they are classified in three groups, as follows: 1. Permanent actions: the fixed elements in a building (constants in all the cases studied); 2. Variable Actions: actions that can change over the service life of a building (service overload, snow load and wind load); 3. Accidental Actions: those triggered by external unforeseeable causes. In this study the loads corresponding to wind and snow are varied, while the rest of the loads remain constant.

Herein, the slab weight is 4.1 kN/m^2, superficial loads were considered: "imposed loads" of 2 kN/m² and "permanent loads" of 2 kN/m². Exterior walls loads were also considered with a characteristic value of 8 kN/m, located in the perimeter of the defined geometry. In the case of the roof and penthouse, 1 kN/m² was considered as the service overload for roof maintenance and 1 kN/m² as the permanent load.

The distribution and value of the pressure exerted by wind on a building and the resulting forces depend on the shape and dimensions of the structure, its characteristics, and the permeability of its surface, as well as the direction and intensity of wind storms. Therefore, it is important to distinguish between the different wind actions addressed in the regulations. Wind actions are classified according to wind zone and terrain category. The wind zones in Spain are divided according to 3 basic wind speeds. Specifically: zone A (26 m/s), zone B (27 m/s) and zone C (29 m/s). Furthermore, regulations describe five terrain categories, as shown below:

- I: Sea, coastal area exposed to the open sea.
- II: Lakes or area with negligible vegetation and without obstacles.
- III: Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights.
- IV: Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest).
- V: Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m.

The distribution and intensity of the snow load on a building, or in particular on a roof, depends on the location climate, the type of precipitation, the landscape, the shape of the roof, the effects of the wind, and on thermal exchange in the exterior walls. The snowpack per unit area (pN) is calculated as follows:

$$p_N = \mu \cdot s_k \tag{1}$$

Where: μ is the shape coefficient and Sk the characteristic value of the snow load.

The snow load was examined for the following topographic altitudes: 0, 200, 400, 600, 800, 1000, 1200, 1500 and 2000 meters. Regulations identify several characteristic values (Sk) according to altitude and winter zone. To cover all cases, the most restrictive values were selected for each of the altitudes studied (Table 1):

Table 1. Snow overload on horizontal terrain (kN/m²).

Altitude (m)	Sk	Snow load (kN/m²)	Snow load (kN/m²) coef exp. +20%
0	0.4	0.4	0.48
200	0.5	0.5	0.60
400	0.6	0.6	0.72
600	0.9	0.9	1.08
800	1.2	1.2	1.44
1000	1.7	1.7	2.04
1200	2.3	2.3	2.76
1500	5.5	5.5	6.60
2000	9.3	9.3	11.16

When a building is protected from wind action, the snow load value can decrease by 20%. If the structure is located in a heavily exposed area, the value increases by 20%.

2.2. Case Classification

Given that the objective of this study is to comprehend the relationship between cost and environmental impact according to the amount of steel incorporated into columns in the 135 modeled structures, columns of equal dimensions were chosen for all cases. Thus, the variations among the different cases were analyzed.

Each structure was analyzed under different load conditions depending on the location. Based on the structural analysis, different results were obtained for the column design depending on the conditions to which each structure was subjected. Each of these resulting structures represents a case to be analyzed. The classification of wind action incorporates 15 possible locations (combination of wind and terrain category). Snow loads are a function of the topographic altitude and seven winter weather zones. This last factor forced us to make a discrete selection of the snow loads analyzed. Thus, the study analyzed 135 cases, broken down as follows:

- 9 cases according to altitude: 0, 200, 400, 600, 800, 1000, 1200, 1500 and 2000 m. For each case, the snow loads reflected in Table 1 were considered.
- 3 cases according to wind zone: zone A, zone B and zone C.
- 5 cases according to terrain category: I, II, III, IV and V.

Now let us explain the combination of one of the cases and the terminology. Here is an example of the terminology used to characterize each case: A-I-800 → The structure is located in wind zone A, in terrain category I, and at 800 m altitude.

2.3. Structural Analysis and Determining the Amount of Rebar

Reinforced concrete columns are designed in compliance with structural safety requirements (bearing capacity and stability) and serviceability. To this end, the specific calculation software Cypecad was utilized (CYPE Ingenieros S.A., 2017). Therefore, after the structural analysis and subsequent dimensioning, the total quantities of steel were determined for each building. As explained above, the amount of concrete remains constant.

Making columns on site involves five factors identified below in the traditional units: formwork labor (€/m^2), concrete pouring labor (€/m3), formwork materials (€/m^2), concrete materials (€/m3), steel materials (kg/m3). The sum of these items determines the cost incurred by making columns on site. To establish column dimensions, all the items except steel materials (kg/m3) remained constant in all the cases to be analyzed. When conducting the structural analysis, different stress maps were obtained for the columns. The column design was only adapted by modifying the amount of rebar. Thus, the steel reinforcement of the columns is what varies depending on the case studied, while the concrete section remains constant in all cases.

To determine the cost and CO_2 emissions (of the steel needed to reinforce the columns), values of €/kg Fe were obtained including installment and a value for kg CO_2/kg Fe. For the cost, databases of specific prices from the construction sector were consulted (CYPE Ingenieros S.A., 2017), and the value of 1.21 €/kg Fe was established for rebar produced and installed on site. In the case of steel, the emissions corresponding to the production phase (A1-A2-A3) were obtained from the environmental product declaration 1: 0.546 kg CO_2/kg Fe. The transport phase to the building site (A4) and on-site installment (A5) were estimated with average values of 1.054 kg CO2/kg Fe and 0.272 kg CO_2/kg Fe. We have also accounted for the emissions generated by truck transportation, which consumes fossil fuels, from the steelworks to the reinforcement manufacture facility, and from there to the construction site. After adding up the emissions, an accumulated value of 1.872 kg CO_2/kg Fe was obtained.

To incorporate a reference value in the subsequent comparison, the structural analysis of the building was performed without considering either wind loads or snow loads. Thus, the amount of rebar necessary for columns to withstand the fixed axial loads was obtained. This represents a reference value of the consumption of rebar in the columns. At this point, based on the data recorded for costs and unitary CO_2 emissions, we can proceed to conduct an economic and environmental assessment of the costs incurred by the column design for each case. Thus, variations in both costs and emissions are attributed to the production and installment of the different amounts of rebar.

$$Cost\ (€) = M_i \cdot \gamma \tag{2}$$

$$Emissions(kg\ CO_2Eq) = M_i \cdot \varphi \tag{3}$$

Where: Mi is the amount of rebar used to make the columns, γ the unit costs of the rebar, including installment and φ the equivalent CO_2 emissions corresponding to the production, transport and installment of rebar in column molds at the construction site.

The results obtained for each of the cases studied are given as a percentage variation from the reference case. The data obtained reveals the amount of rebar that should be used in the modeled building considering the wind and snow actions. This information clarifies the costs and environmental impacts involved in tackling climate actions.

3. Results and discussion

This section details the amount of steel necessary for columns in all the cases studied, and the CO_2 emissions and the cost of these emissions attributable to reinforcing framework. In order to compare the steel quantities of the columns to an initial or reference value, a reference building was calculated. This reference structure is characterized by the following environmental conditions: snow load for an altitude of 0 m and no wind load. After conducting the structural analysis and utilizing the same dimensions in the concrete sections of the columns, a reference amount of steel consumption of 10023 (kg) was obtained, resulting in 96.38 (kg/m3) of rebar in the columns. The table below summarizes the rebar necessary for the column design (Table 2).

It can be observed in the table that the quantity of rebar increases as the topographic altitude rises, and the same occurs with the wind zone. On the contrary, when the terrain category increases, the need for rebar decreases. These variations are in accordance with the magnitudes of the horizontal and vertical loads to which the buildings are subject. The costs and emissions are proportional to the amount of rebar necessary. In order to better visualize the results, the percentage variations of rebar necessary for each climatic wind zone are presented graphically (A-B-C).

Table 2. Quantities of rebar necessary for columns (kg).

	Topographic Altitude (m)								
	0	200	400	600	800	1000	1200	1500	2000
A-I	12627	12647	12681	12645	12624	12678	12693	13317	15712
A-II	12216	12216	12216	12228	12228	12447	12469	12813	14804
A-III	11764	11764	11764	11764	11764	11727	11894	12145	14033
A-IV	11340	11340	11340	11403	11468	11468	11468	11718	12739
A-V	10473	10473	10473	10640	10640	10873	11028	11276	12454
B-I	13853	13853	13853	13853	13853	13853	13962	14619	15840
B-II	12328	12328	12363	12494	12691	12921	13041	13925	15028
B-III	11786	11786	11786	11786	11786	11956	12075	12730	14317
B-IV	11403	11403	11468	11420	11468	11468	11568	11914	13267
B-V	11096	11096	11096	11096	11165	11229	11357	11576	12626
C-I	15618	15645	15645	15746	15746	15833	15873	16550	17531
C-II	14516	14582	14643	14749	14896	14996	15329	15967	17030
C-III	12609	12857	12857	12987	13022	13158	13538	14174	15822
C-IV	11764	11764	11764	11764	11764	11764	11821	12136	14039
C-V	11107	11276	11276	11340	11403	11468	11468	11588	12702

Thus, Figure 3 shows the variations for wind zone A. As one can see, the percentage values range from 4.49% for terrain category V at an altitude between 0 and 400 m, up to 56.76% for terrain category I at an altitude of 2000 m. It should be noted that for any given terrain category the rebar amount remains almost constant up to an altitude of 1200 m, and then from this point on the need for rebar in the columns increases considerably. It is also remarkable that the values for terrain category V are far below the other categories, ranging between 4.49% and 10% in the area below 1200 m.

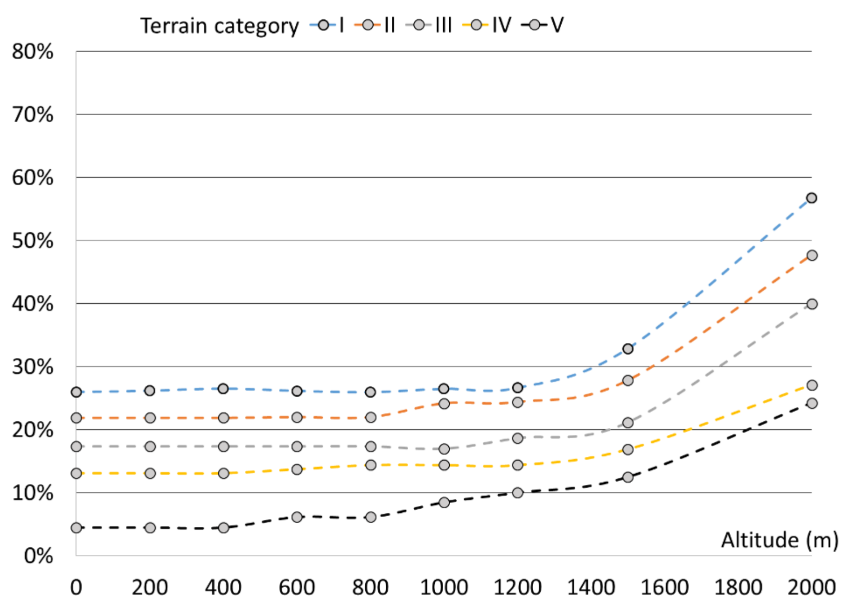

Figure 3. Percentage variations in rebar necessary for wind zone A.

Figure 4 displays the variations in wind zone B. As one can see, the percentage values range from 10.71% for terrain category V at an altitude between 0 and 600 m, up to 58.04% for terrain category I at an altitude of 2000 m. The minimum value is greater than that of wind zone A; and the maximum value is similar to that of wind zone A. It should be noted that for any given terrain category, the rebar amount remains constant up to an altitude of 800 m, except in terrain category II where it increases by 3.62%, and then from this point on, the need for rebar in columns greatly increases. Terrain category I is clearly above the other categories.

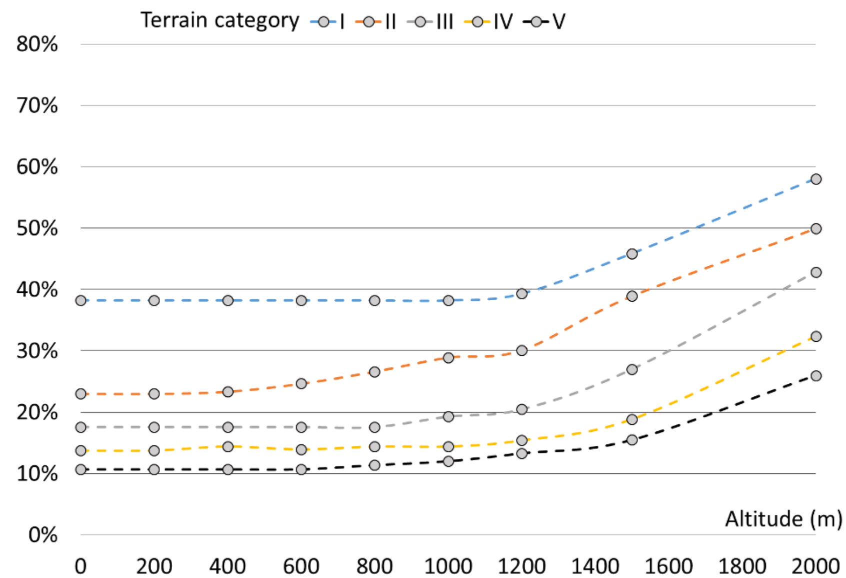

Figure 4. Percentage variation in rebar necessary for wind zone B.

The percentage variations for wind zone C are depicted in Figure 5. As one can see, the percentage values range from 10.82% for terrain category V and an altitude between 0 and 0 m, up to 71.91% for terrain category I at an altitude of 2000 m. The values increase slightly as altitude rises, except in category IV which remains constant up to an altitude of 1000 m. The minimum value is greater than that of wind zone A, and similar to that of wind zone B. On the contrary, the maximum value increases substantially for all terrain categories. In this wind zone there is a substantial jump from terrain category II to IV.

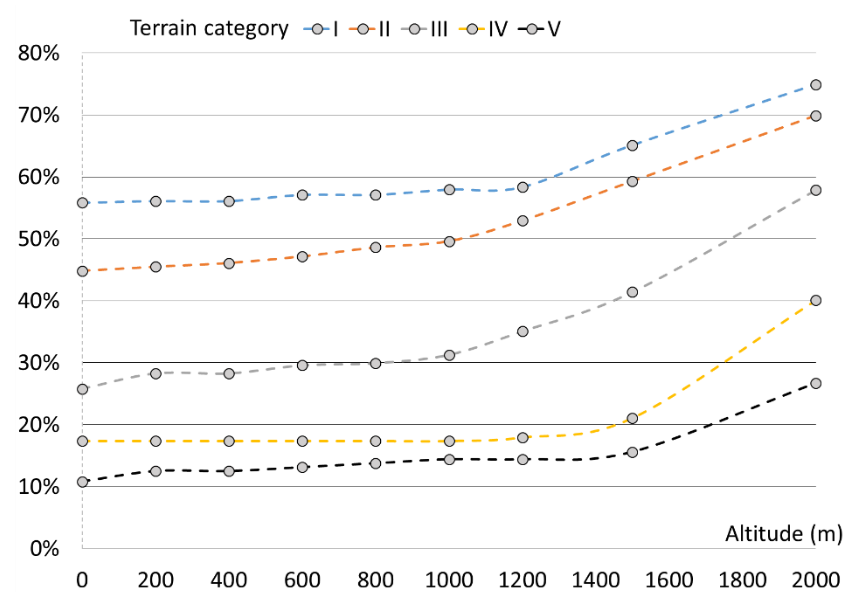

Figure 5. Percentage variations in rebar necessary for wind zone C.

Analyzing the lowest topographic altitude zone (between 0-800m), the percentage variations prove to be more marked in wind zone C where they range from 10.8% to 57.1%. In zone B, this range shrinks to between 10.7% and 38.2%. And finally, in zone A, which registered the lowest basic wind velocity, values range between 4.5% and 26.5%.

To better comprehend these values, the results for terrain category IV (general, industrial or forested urban area) are presented in relative values of cost and emissions in their corresponding monetary unit and equivalent CO_2 emissions. These values of costs and emissions for the reference building are €12127 and 18763 kg CO_2. Table 3 lists the results.

Table 3. Summary of increasing amount of rebar necessary for columns in terrain category IV.

Case	Δ Rebar (kg)	Δ (€)	Δ (kg CO_2)	Case	Δ Rebar (kg)	Δ (€)	Δ (kg CO_2)	Case	Δ Rebar (kg)	Δ (€)	Δ (kg CO_2)
A-IV-0	1317	1594	2465	B-IV-0	1380	1670	2583	C-IV-0	1741	2107	3259
A-IV-200	1317	1594	2465	B-IV-200	1380	1670	2583	C-IV-200	1741	2107	3259
A-IV-400	1317	1594	2465	B-IV-400	1445	1748	2705	C-IV-400	1741	2107	3259
A-IV-600	1380	1670	2583	B-IV-600	1397	1690	2615	C-IV-600	1741	2107	3259
A-IV-800	1445	1748	2705	B-IV-800	1445	1748	2705	C-IV-800	1741	2107	3259
A-IV-1000	1445	1748	2705	B-IV-1000	1445	1748	2705	C-IV-1000	1741	2107	3259
A-IV-1200	1445	1748	2705	B-IV-1200	1545	1869	2892	C-IV-1200	1798	2176	3366
A-IV-1500	1695	2051	3173	B-IV-1500	1891	2288	3540	C-IV-1500	2113	2557	3956
A-IV-2000	2716	3286	5084	B-IV-2000	3244	3925	6073	C-IV-2000	4016	4859	7518

Thus, it is confirmed that the maximum amount necessary corresponds to wind zone C at an altitude of 2000 meters. The need for rebar increases by 4016 kg, which raises the cost by €4859 and emissions by 7518 kg CO_2 in comparison to the reference building (40.07%). The minimum value corresponds to wind zone A at an altitude of 0 meters, where the rebar necessary increases by 1317 kg, cost by €1594 and emissions by 2465 kg CO_2 (13.14%). Comparing wind zones A and B at up to 1200 meters, there is less than 1.28% of a difference, but between A and C that difference reaches 4.23%. At topographic altitudes above 1200 m, the difference increase to 5.27% between zones A and B, and 12.97% between zones A and C.

4. Conclusions

This study provides information on the variations in the amount of rebar necessary for in situ column design attributable to wind and snow factors. Such variations entail economic and environmental costs that, depending on the location of the building, can increase by up to 74.91%. The concept of sustainability is founded on a three-part commitment: social, economic and environmental. In 2017, global emissions of carbon dioxide (CO_2) grew by 1.4% after three years of stagnation. All industry sectors must strive to control and minimize the emissions they generate.

The results of this study provide information on the effect of climatic loads on column design for residential buildings. The results indicate that the optimal areas for the location of residential buildings are within terrain category V. In the future, urban planning should consider this observation, given that the effect of topographic altitude is also lesser in this terrain category as compared to other terrain categories.

The values of horizontal loads (wind) in combination with high values of axial loads (snow) trigger huge increases in the need for rebar. Roofs with slopes that minimize axial loads are recommended for topographic altitudes above 800 m.

The greatest source of emissions involved in rebar is its transportation to the building site (A4) which represents 56.30%. In the future, employing means of transport that generate fewer emissions would reduce this value. For terrain category IV at topographic altitudes below 800 m, which is the most common location for residential buildings, emissions attributable to climatic loads (wind and snow) increase in zones A and C by 2705 and 3259 kg CO_2, respectively. The most extreme case is terrain category I where emissions range from 4869 (zone A) to 10713 kg CO_2 (Zone C).

The World Meteorological Organization (WMO) warns of extreme weather conditions in the future. This situation underscores the importance of protecting buildings from the action of climatic loads, which at the same time can reduce economic costs and emissions generated during construction.

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