XLVI CILAMCE
VITÓRIA - ES - BRAZIL - 2025
XLVI IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING

CO_2 mitigation strategy for concrete slabs in Brazil: a reliability-based approach at negative cost

Gustavo K. Tamura[1], André T. Beck[1]

[1]*Dept. of Structural Engineering, University of São Paulo*
Av. Trabalhador São-carlense, 400, 13566-590, São Carlos, SP, Brazil.
kenzotamura@usp.br, atbeck@sc.usp.br

Abstract. In recent years, extreme climate events such as floods, wildfires, heatwaves, and prolonged droughts have been observed with increasing frequency, intensity, and geographical spread. Due to this, there has been growing interest in sustainability, particularly in structures, since the construction and operation of buildings account for approximately 37% of global CO_2 emissions. Thus, dematerialization is an extremely relevant topic for the conscious and rational use of natural resources in buildings. However, current Brazilian technical standards do not reflect this concern, being potentially conservative without significant gains in structural safety. To align these two interests, reliability theory can be applied, ensuring structural safety while reducing the environmental impact of constructions. The initial goal of the reliability-based calibration of partial safety factors was to achieve more uniform safety levels across different structural designs. As an additional benefit, it was possible to observe a reduction in design loads and, consequently, in construction material consumption. In this study, CO_2 emission reductions in slabs were evaluated by comparing a design using standard safety factors from design codes and using reliability-based calibrated factors. The Brazilian tool Sidac was employed to estimate CO_2 emissions. Using the calibrated partial factors, an average 7.65% reduction in CO_2 emissions and a 7.41% cost reduction were achieved in the design of case-study slabs.

Keywords: greenhouse gas emissions, partial safety factors, reinforced concrete slabs, structural reliability, sustainability

1 Introduction

According to the most recent report from the Intergovernmental Panel on Climate Change, future climate change is dependent on the future greenhouse gas (GHG) emission, with cumulative CO_2 emissions being the dominant factor [1]. Limiting the global warming to 1.5°C, as stablished in the Paris Agreement [2] requires a deep, rapid and sustained reduction on GHG emissions. One of the consequences of reaching the 1.5°C warming is the occurrence of more frequent and intense extreme events [1]. The recent floods in the south region of Brazil, for example, have led to at least 176 deaths, 39 missing, 806 injured and over 400 thousand people were made homeless [3]. The World Economic Forum reports studies showing that every dollar invested in resilience and adaptation returns four dollars in reduced damage costs [4]. In this panorama, we need to actively adapt our infrastructure to be resilient to the impacts of climate change.

The construction industry has a great responsibility, since it is one of the largest sources of greenhouse gas emissions [5]. Considering direct and indirect emissions, the use or operation of buildings accounts for approximately 30% of global energy use and 27% of carbon dioxide (CO_2) emissions in 2021, according to the International Energy Agency (IEA) [6]. Furthermore, according to the Global Cement and Concrete Association (GCCA), the cement manufacture is responsible for between 5%-8% of global GHG emissions [7], having a massive responsibility mainly in reducing its CO_2 emissions. This data shows the enormous carbon footprint of concrete, with approximately 30 billion tons emitted annually [8].

The same report from The World Economic Forum (2022) indicates that green structures have an average of

3% addition cost, with a payback period of 3 years [4]. Although the cost increase may appear negligible from a global perspective, it can become significant within the increasingly competitive construction industry, where even minor cost variations may influence decision-making and project viability.

There are many different strategies to reduce the carbon footprint of structures, but most come with a price. The use of fly-ash geopolymer concrete, a feasible decarbonization strategy in concrete and cement, has an estimated cost of 55 USD/tCO_2 in China's demonstration project [9]. Other decarbonization strategies were analyzed by Hills *et al.* showing a cost avoidance of 88 to 161 USD/tCO_2 in other countries [10].

On the other hand, optimizing structural design has negative cost, since it focusses on reducing material consumption (dematerialization). The GCCA roadmap outlines seven key areas that must contribute to achieving net-zero carbon emissions in cement and concrete. Among these, improved efficiency in both the design and construction phases stands out as a critical strategy, accounting for an estimated 22% reduction in greenhouse gas emissions [11]. However, structural design optimization has a scaling problem, unless the reduction is used for a multiple number of buildings. Yet, the reliability-based revision of partial safety factors has an immediate impact country-wise. Given that the structural design methodology is not modified, its replicability is facilitated, representing a valuable opportunity to concurrently promote structural safety and reduce greenhouse gas emissions. This study was focused on the design factors of Brazilian concrete structures, since they are long outdated, but it may be useful for other countries like India, which uses similar partial safety factors.

2 The Reliability-based calibration of Brazilian partial safety factors

This study was focused on the calibration of partial design factors presented on Brazilian codes such as ABNT NBR 6118:2014 (design code for concrete structures) [12] and ABNT NBR 8681:2003 (design code for structural safety and design loads) [13].

2.1 The background of ABNT NBR 6118 partial safety factors

The Allowable Stress Design methodology, once widely adopted in structural engineering practice, was gradually replaced by the Limit State Design approach, which incorporates partial safety factors to account for uncertainties in loads and material resistance. The shift towards the use of partial safety factors represented a significant advancement in structural safety, as it allowed for a more accurate representation of the individual uncertainties associated with both loading and resistance components [14]. In the United States, this methodological evolution was guided by a reliability-based calibration framework, as demonstrated in foundational studies by Ellingwood and Galambos [15] and later refined by Szerszen and Nowak [16]

The Brazilian design code NB1 was among the earliest to adopt a rupture-based design, recommending the design of reinforced concrete (RC) beams in Stage III [17]. With the replacement of NB1 (1960) by the first edition of NBR 6118 in 1978, the original global rupture factor of 2 was decomposed into two separate partial factors: 1.4 for material strength and 1.4 for actions, resulting in a combined safety margin of 1.96 [18]. In parallel, the design factor for steel rupture was reformulated as $1.4 \times 1.15 = 1.61$, with 1.15 introduced as the partial factor for steel strength. This decomposition, although empirical, appears to have been an interim solution adopted prior to the formal implementation of a reliability-based partial safety factor framework.

The partial safety factors adopted in the Brazilian design standards NBR 8681 and NBR 6118 were originally defined through a purely empirical approach, involving the decomposition of the global safety factor of 2 previously used in the design of reinforced concrete structures. However, this approach overlooks a key aspect: the significantly higher variability associated with live and wind loads compared to dead loads. Applying increased partial factors to variable loads and reduced factors to permanent loads not only promotes a more consistent level of structural reliability, but also enables reductions in greenhouse gas emissions of up to 10%, as demonstrated in a recent study by Tamura & Beck [19].

2.2 Reliability-based calibration

The research group of Prof. André T. Beck at USP has an extensive background and expertise in reliability-based calibration of Brazilian design codes. Its first studies, published by Beck & Souza Jr in 2010, suggest

increasing the partial safety factors associated with accidental loads (γ_q), while simultaneously reducing the combination factors for secondary actions (ψ_w and ψ_q), which leads to significantly lower design load values [20]. The research group also has studies on Brazilian concrete conformity [21], studies on Brazilian wind loads [22][23] and studies on live loads models for buildings [24]. The most recent calibration studies were published by Santiago *et al.* [25][26] and Costa *et al.* [24], which incorporated previous studies on concrete conformity and statistical Brazilian loads adjusting partial safety factors with stablished values for loads used by the country's design codes.

The calibration studies used a reliability-based design optimization (RBDO) approach, minimizing a target reliability index (β_T) with reliability indexes obtained by designing different structures using the partial safety factors. The RBDO problem is formally expressed as:

$$Find: \qquad \boldsymbol{\Gamma} = \{\gamma_g, \gamma_q, \gamma_w, \psi_q, \psi_w, \gamma_c, \gamma_s, \gamma_{a1}\ e\ \gamma_{a2}\}$$

$$which\ minimizes: \qquad \Psi = \sum_{g=1}^{mat.} \sum_{h=1}^{conf.} \sum_{i=1}^{\frac{Q}{D}} \sum_{j=1}^{\frac{W}{D}} \{[\beta_T - min_k(\beta_{ghijk}(\boldsymbol{\Gamma}))]^2 \times w_{ij}\} \times \xi_h \times \xi_g \ . \tag{1}$$

It should be noted that the calibration process did not incorporate considerations of sustainability or greenhouse gas emissions. Its primary objective was to reduce the dispersion between the target reliability index and the reliability levels derived from structural calculations. The partial safety factors obtained in the most recent study [24] are presented in Table 1.

Table 1. Partial safety factors obtained by reliability-based calibration

Factor	NBR 6118:2014 [12]	First calibration $\beta_T = 3{,}0$ [26]	Most recent calibration $\beta_T = 3{,}17$ [24]
γ_c	1,40	1,40	1,40
γ_s	1,15	1,15	1,15
γ_g	1,40	1,25	1,20
γ_q	1,40	1,70	1,50
γ_w	1,40	1,65	1,50
ψ_q	0,50 / 0,70 / 0,80	0,35	0,45
ψ_w	0,60	0,30	0,35
$\gamma_q \times \psi_q$	0,70 / 0,98 / 1,12	0,60	0,68
$\gamma_w \times \psi_w$	0,84	0,50	0,53

The result of this study shows that the partial safety factors associated with the material strengths of concrete and steel (γ_c and γ_s) were retained without modification, however the safety factor associated with dead loads (γ_g) was significantly reduced. Also, safety factors associated with live loads (γ_q) and wind loads (γ_w) were increased, due to their higher variability. Finally, the combination factors for secondary actions (ψ_w and ψ_q) were decreased. It is worth to note that the target reliability index used in Costa *et al.* [24] is an average of reliability indexes of different structures designed with NBR 6118.

3 Methodology

The evaluation of greenhouse gas emission and cost reductions in this study was conducted using the methodological framework depicted in Fig. 1.



Figure 1. Methodological framework of the study.

3.1 Define initial parameters and a reference floor plan

The slab design was based on conventional concrete strength (f_{ck}) of 35 MPa and an environmental exposure class II, corresponding to an urban environment, and with a reinforcement cover of 2,5 cm. Steel strength (f_{yk}) was considered 500 MPa.

Among the various types of buildings designed in Brazil, it is notably challenging to define a "standard" building that adequately represents the country's broad architectural diversity, particularly due to the lack of statistical data regarding typical building geometries. Therefore, to establish a representative floor plan, the present study adopts the dataset compiled in the master's dissertation of Rodrigues [27], which gathered geometric information from constructed buildings.

The reference floor plan is presented in Fig. 2a, with a square shape, featuring five columns spaced at 5-meter intervals, yielding a total area of 400 m^2. Also, future studies will evaluate RC beams and columns of a 10-story building, as a perspective view is shown in Fig. 2b.

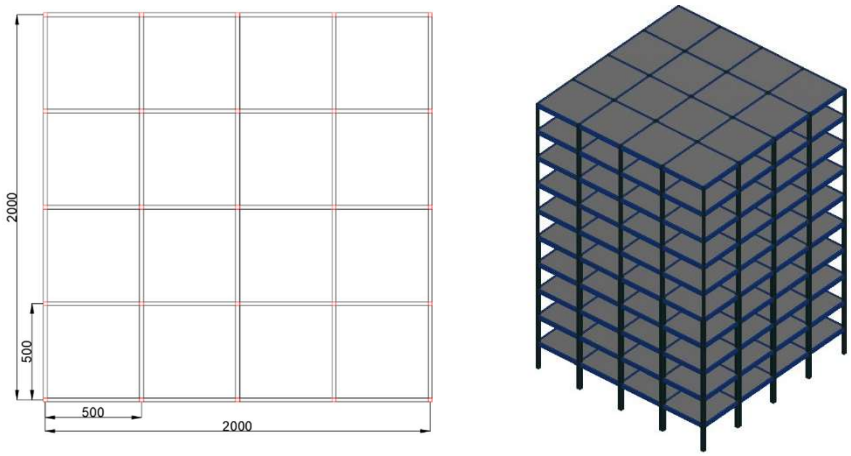


Figure 2. Reference floor plan, units in cm (a) and perspective view of studied building (b).

3.2 Selection of partial safety factors

The partial safety factor for dead loads (γ_g) adopted in this study differs from the value proposed by Costa *et al.* [24]. While the original calibration suggested a reduction from 1.4 to 1.2, this study adopts a more conservative value of $\gamma_g = 1.3$ to address potential concerns within the Brazilian engineering community regarding structural safety. Despite this adjustment, the results still indicate a significant reduction in environmental impact, suggesting that meaningful sustainability gains can be achieved without compromising perceived safety. The remaining partial safety factors were kept unchanged.

3.3 Design of structural concrete slabs

This study used recommendations from Brazilian design codes for concrete structures NBR 6118:2023 [28] and for design loads NBR 8681:2003 [13]. Using the TQS structural analysis software - commonly adopted by Brazilian designers - reinforced concrete slabs were dimensioned for the reference floor plan, considering thickness variations between 8 cm and 20 cm. Two distinct design scenarios were developed: one employing the partial safety factors prescribed by current design codes, and the other using the factors derived from the reliability-based calibration proposed in by Costa *et al.* [24]. Furthermore, the material requirements were determined at this stage, including the volume of concrete (m^3) and the mass of steel (kg).

3.4 Estimate of CO_2 emissions

This study used the Information System for Environmental Performance in Construction (Sidac) to estimate CO_2 emissions. Sidac is a Brazilian tool that applies a streamlined life cycle assessment (LCA) approach that evaluates cradle-to-gate embodied carbon and energy. Its system is composed of a lifecycle inventory (LCI) database, including generic Brazilian data and specific information provided by manufactures [29], thus making it a valuable tool for estimating CO_2 emissions within the national context.

The analysis focused exclusively on CO_2 rather than CO_2-equivalent due to the availability of reliable national data and the fact that CO_2 accounts for over 90% of the global warming potential of concrete and steel [30]. Also, the system allows making an assessment covering stages A1-A4 of EN 15978 [31]. Nevertheless, herein we opted to consider only stages A1-A3. This is justified by the scope of the study, which centers on the percentage reduction of material use (dematerialization), a factor fully captured within the A1–A3 stages. Stage A4, which refers to the transportation of materials from concrete and steel plants to the construction site, was excluded, as its associated CO_2 emissions are expected to scale proportionally with the improvements in environmental performance observed in the earlier stages. Furthermore, A1-A3 stages typically represents more than 60% of a structure's total embodied carbon [32].

Thus, the environmental performance indicator calculates structural embodied CO_2 (SEC) using Eq. (2), where q_i is the quantity of material (in the corresponding unit) "i", ECC_i is the embodied CO_2 coefficient of material "i" (kg CO_2/unit), and A is the total structured area of typical floors (m^2).

$$SEC = \frac{\sum_i (q_i * ECC_i)}{A} \tag{2}$$

3.5 Estimate of material costs

To estimate the total material costs (TMC), this study used the National System of Civil Construction Costs and Indices (SINAPI) which contains Brazilian references for costs and engineering services. Based on the defined material quantities, the unit costs available in the SINAPI database were employed to calculate the total cost of construction materials, as shown in Eq. (3), where MC_i is the material cost coefficient of material "i" (R$/unit).

$$\text{TMC} = \frac{\sum_i (q_i * MC_i)}{A} \tag{3}$$

3.6 Limitations

This study has an exploratory nature and represents the first attempt to assess CO_2 emission reductions resulting from the reliability-based calibration of partial safety factors. Accordingly, its limitations are presented below.

a) Only materials used in the structure of typical floors were considered, excluding foundation, podium and roofs.
b) Only product stage was considered in the LCA (A1-A3), disregarding other life cycle stages.
c) Only CO_2 emissions were accounted for, other greenhouse gases were not considered.
d) Only gravitational loads were considered. Wind loads are reported to influence the structural embodied carbon [33] and should be considered in future studies.
e) Only one reference floor plan was considered. Other floor plans should be considered in future studies.

4 Results and discussion

Figure 3 presents the average reinforcement ratios of concrete slabs obtained using the TQS structural analysis software: Fig. 3a refers to results based on code-prescribed partial safety factors, while Fig. 3b shows those derived from calibrated values. Considering the slab dimensions, required concrete cover, and reinforcement bar diameters, it was observed that a thickness of 8 cm does not allow for the proper placement of all reinforcement layers. These constraints lead to software errors, resulting in reinforcement arrangements that are not feasible.

Slabs with thicknesses of 19 cm and 20 cm were excluded from the study, as the average calculated reinforcement ratio was lower than the minimum required by the design code.

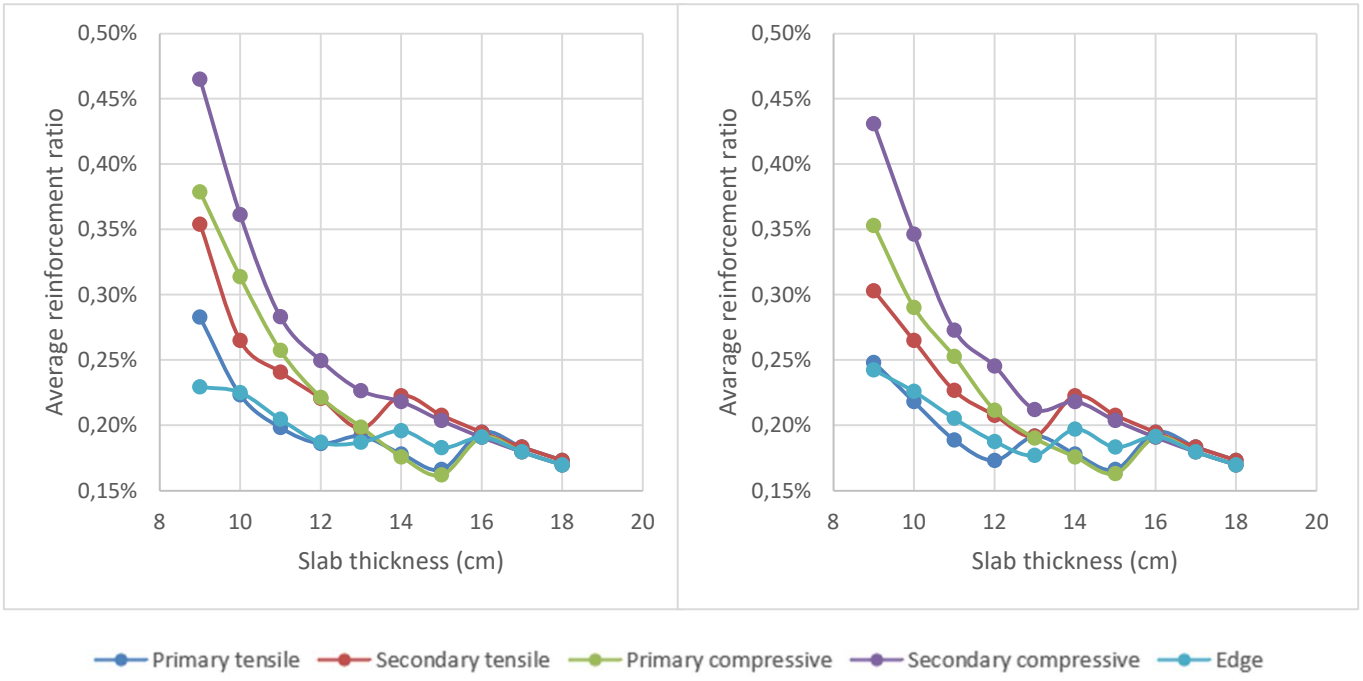


Figure 3. Average reinforcement ratio dimensioned with design code safety factors (a) and with calibrated safety factors (b).

To compare environmental performance, three slab thicknesses were selected from the designs based on code-prescribed safety factors, and then selecting those with the smallest variation in reinforcement ratio between the code-based and the calibrated safety factor scenarios. The selected thicknesses represent three reinforcement ratios: the maximum and minimum values allowed by the design code, and a conventional value based on preliminary sizing according to Lorrigio *et al.* [34]. As a result, slab thicknesses of 9, 13, and 18 cm were adopted for the design based on design code partial safety factors, while 9, 12, and 18 cm were selected for the design incorporating calibrated factors. It is worth noting that the use of calibrated partial safety factors led to reductions in the factored design load of 1.43%, 5.42%, and 2.94% for the configurations with maximum, conventional, and minimum reinforcement ratios, respectively.

Owing to the diversity of methodologies adopted in the manufacturing of construction inputs, the Sidac system reports environmental performance indicators as ranges, defined by minimum and maximum values within a 95% confidence interval. Fig 4 illustrates the embodied CO_2 (in kg CO_2/m^2) associated with each average reinforcement ratio, along with their respective variability ranges. The structural embodied carbon exhibited an average reduction of 7.65% for the conventional reinforcement ratio, as it was the only case with variation in concrete consumption. In contrast, the other two scenarios showed negligible changes in steel consumption and no variation in concrete usage, resulting in minimal differences in embodied carbon.

Table 2 presents the estimated total material costs (in R$/m²) for each reinforcement ratio analyzed, considering slab designs using both code-prescribed partial safety factors and the calibrated factors. For the minimum reinforcement ratio, a negligible cost increase of 0.06% was observed. In contrast, the maximum ratio resulted in a 1.94% cost reduction, while the conventional ratio led to the highest reduction, at 7.41%, primarily due to the simultaneous decrease in both concrete and steel consumption.

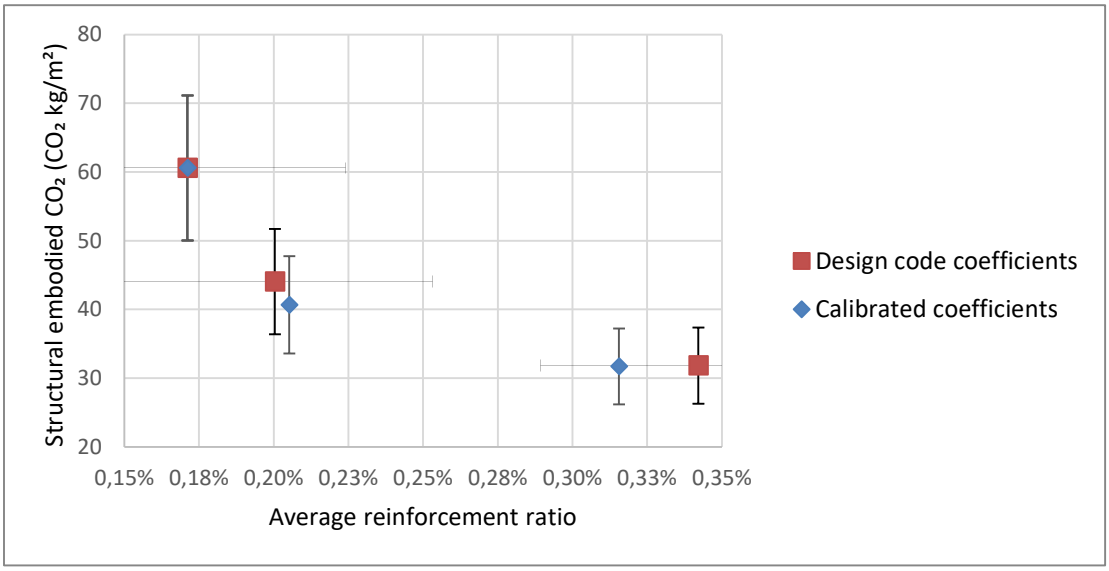


Figure 4. Structural embodied CO_2 by average reinforcement ratio

Table 2. Estimated total material cost for each reinforcement ratio analyzed.

Factor	Minimum	Conventional	Maximum
Design code	125,02	93,57	79,19
Calibrated	125,10	86,64	77,65

5 Conclusions

This study represents an initial attempt to reduce structural embodied carbon through the use of reliability-based calibrated partial safety factors. The results indicate that even when adopting a more conservative value of 1.3 for the partial safety factor for dead loads (γ_g) as opposed to the original calibrated value of 1.2, a reduction of 7.65% in CO_2 emissions can still be achieved. This finding is specific to conventional reinforcement ratios; however, it remains relevant, as designers rarely aim to use reinforcement ratios close to the maximum or minimum limits defined by design codes.

Furthermore, in a highly competitive sector such as construction, any cost reduction is considered valuable, provided it does not compromise structural safety. The primary objective of the reliability-based calibration was to reduce the variability of the reliability index in structures designed using partial safety factors. In this context, the use of calibrated safety factors not only enhances structural reliability but may also lead to material cost savings ranging from 1.94% to 7.41%.

Finally, this study shows that the use of calibrated partial safety factors can be a powerful tool and ally to reduce the enormous carbon footprint of constructions, while improving safety and reducing material costs. The dematerialization achieved can be replicated with an immediate effect since it doesn't modify the structural design methodology. The authors encourage future research to replicate and refine these findings, overcoming the limitations that were beyond the scope of this study.

Acknowledgements. Funding of this research project by Brazilian agencies CAPES (Brazilian Higher Education Council), CNPq (Brazilian National Council for Research, grant n. 309107/2020-2) and joint FAPESP-ANID (São Paulo State Foundation for Research - Chilean National Agency for Research and Development, grant n. 2019/13080-9) is also acknowledged.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] International Panel for Climate Change, "AR6 Synthesis Report: Climate Change 2022 — IPCC," 2022. [Online]. Available: https://www.ipcc.ch/report/sixth-assessment-report-cycle/

[2] C. A. Horowitz, "Paris Agreement," *International Legal Materials*, vol. 55, no. 4, 2016, doi: 10.1017/s0020782900004253.

[3] Estado do Rio Grande do Sul, "Defesa Civil atualiza balanço das enchentes no RS – 14/6, 9h," https://www.estado.rs.gov.br/defesa-civil-atualiza-balanco-das-enchentes-no-rs-14-6-9h.

[4] World Economic Forum, "How to build climate resilience into the construction industry," https://www.weforum.org/stories/2022/03/heres-how-to-build-climate-resilience-into-the-construction-industry/.

[5] M. Röck *et al.*, "Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation," *Appl Energy*, vol. 258, 2020, doi: 10.1016/j.apenergy.2019.114107.

[6] International energy agency, "Tracking Clean Energy Progress 2023," https://www.iea.org/reports/tracking-clean-energy-progress-2023.

[7] GCCA, "Key Facts : GCCA," gccassociation.

[8] "Concrete needs to lose its colossal carbon footprint," 2021. doi: 10.1038/d41586-021-02612-5.

[9] C. Luan, A. Zhou, Y. Li, D. Zou, P. Gao, and T. Liu, "CO2 avoidance cost of fly ash geopolymer concrete," *Constr Build Mater*, vol. 416, 2024, doi: 10.1016/j.conbuildmat.2024.135193.

[10] T. Hills, D. Leeson, N. Florin, and P. Fennell, "Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting," *Environ Sci Technol*, vol. 50, no. 1, 2016, doi: 10.1021/acs.est.5b03508.

[11] Global Cement and Concrete Association, "Concrete Future - The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete," Global Cement and Concrete Association. [Online]. Available: https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap.pdf

[12] ABNT, "NBR 6118: Projeto de Estruturas de Concreto - Procedimento," 2014.

[13] Associação Brasileira de Normas Técnicas, "ABNT NBR 8681:2003 - Ações e segurança nas estruturas," *Associação Brasileira de Normas Técnicas*, 2003.

[14] B. Ellingwood *et al.*, "Development of methods of structural reliability," *Structural Safety*, vol. 113, p. 102474, Mar. 2025, doi: 10.1016/j.strusafe.2024.102474.

[15] B. Ellingwood and T. V. Galambos, "Probability-based criteria for structural design," *Structural Safety*, vol. 1, no. 1, 1982, doi: 10.1016/0167-4730(82)90012-1.

[16] M. M. Szerszen and A. S. Nowak, "Calibration of design code for buildings (ACI 318): Part 2 - Reliability analysis and resistance factors," *ACI Struct J*, vol. 100, no. 3, 2003, doi: 10.14359/12614.

[17] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, "NB 1: Cálculo e execução de obras de concreto armado," 1960.

[18] A. Cheung, A. Beck, P. Nobrega, F. Stucchi, and S. Santos, "Ações e Segurança," in *Estruturas de Concreto Armado*, vol. 1, Kimura AE, Parsekian GA, Almeida LC, Santos SHC, and Bittencourt TN, Eds., São Paulo: Instituto Brasileiro do Concreto (IBRACON), 2022, ch. B04.

[19] G. K. Tamura, "Redução das emissões de gases de efeito estufa pelo ambiente construído a partir da calibração baseada em confiabilidade dos coeficientes parciais de segurança em estruturas de concreto armado," Universidade de São Paulo, São Carlos, 2025. doi: 10.11606/D.18.2025.tde-17062025-161102.

[20] A. T. Beck and A. C. De Souza, "A first attempt towards reliabilitybased calibration of brazilian structural design codes," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 32, no. 2, 2010, doi: 10.1590/S1678-58782010000200004.

[21] W. C. Santiago, "Estudo da (não-)conformidade de concretos produzidos no Brasil e sua influência na confiabilidade estrutural," Universidade de São Paulo, São Carlos, 2011. doi: 10.11606/D.18.2011.tde-06022012-081447.

[22] A. T. Beck and M. R. S. Corrêa, "New design chart for basic wind speeds in Brazil," *Latin American Journal of Solids and Structures*, vol. 10, no. 4, 2013, doi: 10.1590/S1679-78252013000400003.

[23] A. M. Loredo-Souza, M. S. Pfeil, E. de Lima Nascimento, J. D. Riera, G. F. Fisch, and A. T. Beck, "A climatology-based wind speed map for NBR 6123," *Revista IBRACON de Estruturas e Materiais*, vol. 16, no. 4, 2023, doi: 10.1590/S1983-41952023000400001.

[24] L. G. L. Costa, W. C. Santiago, and A. T. Beck, "Probabilistic models for live loads in buildings: critical review, comparison to Brazilian design standards and calibration of partial safety factors," *Revista IBRACON de Estruturas e Materiais*, vol. 16, no. 2, 2023, doi: 10.1590/S1983-41952023000200004.

[25] W. C. Santiago, "Calibração baseada em confiabilidade dos coeficientes parciais de segurança das principais normas brasileiras de projeto estrutural," Universidade de São Paulo, São Carlos, 2019. doi: 10.11606/T.18.2019.tde-03042019-092619.

[26] W. C. Santiago, H. M. Kroetz, S. H. de C. Santos, F. R. Stucchi, and A. T. Beck, "Reliability-based calibration of main brazilian structural design codes," *Latin American Journal of Solids and Structures*, vol. 17, no. 1, 2020, doi: 10.1590/1679-78255754.

[27] I. D. Rodrigues, "Avaliação da vulnerabilidade sísmica de edificações regulares em concreto armado no Brasil através da elaboração de curvas de fragilidade," UNICAMP , Campinas, 2021.

[28] A. NBR, "ABNT NBR 6118 - Projeto de estruturas de concreto - Procedimento," *Associação Brasileira de Normas Técnicas*, vol. 16501, 2023.

[29] F. Belizario-Silva *et al.*, "The Sidac system: Streamlining the assessment of the embodied energy and CO2 of Brazilian construction products," *J Clean Prod*, vol. 421, 2023, doi: 10.1016/j.jclepro.2023.138461.

[30] F. B. Silva *et al.*, "Primary data priorities for the life cycle inventory of construction products: focus on foreground processes," *International Journal of Life Cycle Assessment*, vol. 25, no. 6, 2020, doi: 10.1007/s11367-020-01762-4.

[31] British Standards Institution, "BS EN 15978:2011 - Sustainability of construction works : assessment of environmental performance of buildings : calculation method.," 2011.

[32] J. Hart, B. D'Amico, and F. Pomponi, "Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures," *J Ind Ecol*, vol. 25, no. 2, 2021, doi: 10.1111/jiec.13139.

[33] F. Belizario-Silva, D. Costa Reis, M. Carvalho, R. Leopoldo e Silva França, and V. M. John, "Material intensity and embodied CO2 benchmark for reinforced concrete structures in Brazil," *Journal of Building Engineering*, vol. 82, 2024, doi: 10.1016/j.jobe.2023.108234.

[34] D. D. Loriggio, P. M. Lazzari, P. G. B. de Nóbrega, F. P. Milani, and G. A. Parsekian, "Análise de Sistemas Estruturais," in *Estruturas de Concreto Armado*, 1st ed., vol. 1, A. E. Kimura, G. A. Parsekian, L. C. de Almeida, S. H. de C. Santos, and T. N. Bittencourt, Eds., São Paulo: Instituto Brasileiro do Concreto (IBRACON), 2022, ch. B03.