Periódico Técnico e Científico Cidades Verdes
Technical and Scientific Journal Green Cities
ISSN 2317-8604 Suporte Online / *Online Support*

Edição em Português e Inglês / *Edition in Portuguese and English* - Vol. 14, N. 50, 2026

Numerical Analysis of the Effects of Ascending and Descending Corrosion on Steel Columns of Industrial Portal Frames

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Submissão: 14/11/2025
Aceite 06/01/2026
CARVALHO, Camila Souza; BRANQUINHO, Maria Ávila. Análise Numérica dos Efeitos da Corrosão Ascendente e Descendente em Pilares Metálicos de Pórticos de Galpões. **Periódico Técnico e Científico Cidades Verdes**, *[S. l.]*, v. 14, n. 50, p. e2601, 2026. DOI: 10.17271/23178604145020266243. Disponível em: https://publicacoes.amigosdanatureza.org.br/index.php/cidades_verdes/article/view/6243

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Análise Numérica dos Efeitos da Corrosão Ascendente e Descendente em Pilares Metálicos de Pórticos de Galpões

RESUMO

Objetivo - Avaliar numericamente o impacto da corrosão atmosférica no comportamento mecânico de pilares metálicos integrantes de pórticos de aço, considerando diferentes alturas e direções de propagação da deterioração. O estudo busca compreender como a perda de espessura influencia a rigidez e a estabilidade da estrutura, subsidiando decisões de projeto e manutenção preventiva.

Metodologia – A pesquisa foi conduzida por meio de modelagem numérica utilizando o *software* Abaqus, com base no modelo teórico de Vogel (1985). As simulações foram realizadas com elementos finitos tipo B21, adotando uma malha de 200 mm. Foram considerados cenários de corrosão com reduções de espessura progressivas ao longo dos períodos de exposição de 7, 15, 25 e 50 anos, conforme diretrizes da ABNT NBR ISO 9223 (2024).

Originalidade/relevância – O trabalho propõe uma abordagem que correlaciona a altura e direção da corrosão à perda de desempenho estrutural, destacando regiões críticas e padrões de deterioração típicos em pilares metálicos.

Resultados - Os resultados indicam que a corrosão ascendente apresenta efeitos graduais, tornando-se significativa apenas quando atinge cerca de 1,0 m de altura, enquanto a corrosão descendente provoca deterioração perceptível já com 0,4 m de extensão. Observou-se redução da rigidez e antecipação da falha da estrutura, ainda que com variações de deslocamento em pequenas grandezas.

Contribuições teóricas/metodológicas - O estudo aprimora a compreensão do efeito localizado da corrosão em elementos metálicos estruturais, apresentando um método replicável de simulação via método dos elementos finitos.

Contribuições sociais e ambientais - A pesquisa reforça a importância da durabilidade e sustentabilidade em construções metálicas, promovendo o uso racional de recursos por meio de estratégias de manutenção preventiva e extensão da vida útil das estruturas. A aplicação prática dos resultados pode reduzir custos de reabilitação, minimizar o desperdício de material e contribuir para edificações mais resilientes e ambientalmente responsáveis.

PALAVRAS-CHAVE: Corrosão. Estrutura Metálica. Modelagem Computacional. Simulação. Manutenção preventiva.

Numerical Analysis of the Effects of Ascending and Descending Corrosion on Steel Columns of Industrial Portal Frames

ABSTRACT

Objective - To numerically evaluate the impact of atmospheric corrosion on the mechanical behavior of steel columns in portal frames, considering different heights and directions of deterioration propagation. The study aims to understand how thickness loss influences the stiffness and stability of the structure, supporting design and preventive maintenance decisions.

Methodology - The research was carried out through numerical modeling using the Abaqus® software, based on the theoretical model proposed by Vogel (1985). Simulations were performed with B21 beam elements, using a 200 mm mesh size. Corrosion scenarios with progressive thickness reductions were considered over exposure periods of 7, 15, 25, and 50 years, according to the guidelines of ABNT NBR ISO 9223 (2024).

Originality/Relevance - The work proposes an approach that correlates the height and direction of corrosion with the loss of structural performance, highlighting critical regions and typical deterioration patterns in steel columns.

Results - The results show that ascending corrosion exhibits gradual effects, becoming significant only when it reaches approximately 1.0 m in height, whereas descending corrosion causes noticeable deterioration with extensions as small as 0.4 m. A reduction in stiffness and an earlier onset of structural instability were observed, even with small displacement variations.

Theoretical/Methodological Contributions - The study enhances the understanding of localized corrosion effects in structural steel members, presenting a replicable finite element–based simulation method.

Social and Environmental Contributions - The research reinforces the importance of durability and sustainability in steel structures, promoting the rational use of resources through preventive maintenance strategies and extension of service life. The practical application of the results may reduce rehabilitation costs, minimize material waste, and contribute to more resilient and environmentally responsible buildings.

KEYWORDS: Corrosion. Steel Structure. Computational Modeling. Simulation.

Análisis Numérico de los Efectos de la Corrosión Ascendente y Descendente en Pilares Metálicos de Pórticos de Naves Industriales

RESUMEN

Objetivo - Evaluar numéricamente el impacto de la corrosión atmosférica en el comportamiento mecánico de los pilares metálicos que integran pórticos de acero, considerando diferentes alturas y direcciones de propagación del deterioro. El estudio busca comprender cómo la pérdida de espesor influye en la rigidez y la estabilidad de la estructura, sirviendo de base para la toma de decisiones de diseño y mantenimiento preventivo.

Metodología - La investigación se desarrolló mediante modelado numérico utilizando el software Abaqus®, basado en el modelo teórico propuesto por Vogel (1985). Las simulaciones se realizaron con elementos tipo B21, adoptando una malla de 200 mm. Se consideraron escenarios de corrosión con reducciones progresivas de espesor a lo largo de períodos de exposición de 7, 15, 25 y 50 años, de acuerdo con las directrices de la norma ABNT NBR ISO 9223 (2024).

Originalidad/Relevancia - El trabajo propone un enfoque que correlaciona la altura y la dirección de la corrosión con la pérdida de desempeño estructural, destacando regiones críticas y patrones típicos de deterioro en pilares metálicos.

Resultados - Los resultados indican que la corrosión ascendente presenta efectos graduales, volviéndose significativa solo cuando alcanza aproximadamente 1,0 m de altura, mientras que la corrosión descendente provoca deterioro perceptible con extensiones de apenas 0,4 m. Se observó una reducción de la rigidez y una anticipación del fallo estructural, aunque con variaciones de desplazamiento de pequeña magnitud.

Contribuciones Teóricas/Metodológicas - El estudio mejora la comprensión del efecto localizado de la corrosión en los elementos estructurales metálicos, presentando un método de simulación reproducible basado en el método de los elementos finitos.

Contribuciones Sociales y Ambientales - La investigación refuerza la importancia de la durabilidad y la sostenibilidad en las construcciones metálicas, promoviendo el uso racional de los recursos mediante estrategias de mantenimiento preventivo y extensión de la vida útil de las estructuras. La aplicación práctica de los resultados puede reducir los costos de rehabilitación, minimizar el desperdicio de material y contribuir a edificaciones más resilientes y ambientalmente responsables.

PALABRAS CLAVE: Corrosión. Estructura Metálica. Modelado Computacional. Simulación. Mantenimiento preventivo.

1 INTRODUCTION

In Brazil, the incorporation of steel into civil construction occurred relatively late, since the conventional system of reinforced concrete with masonry infill became consolidated over decades due to its technical familiarity, wide availability of labor, and accessible materials. However, in line with global trends in innovation, the use of steel structures has been gradually increasing, driven by the pursuit of more agile, lightweight, and sustainable construction processes. In this context, steel has come to be valued not only for its structural properties, but also for the greater formal freedom it affords to architectural design, the reduction of construction time, the achievement of higher construction precision, and the possibility of disassembly and reuse. These characteristics reinforce its relevance within a sustainability-oriented framework and in response to transformations in the built environment (Cortez, 2017).

Nevertheless, the durability of such structures depends strongly on the interaction between steel and the environment in which it is placed. Corrosion is defined in the literature as a destructive and unintentional attack on metals, resulting in their deterioration over time. This phenomenon may occur through electrochemical mechanisms or oxidation processes and generally manifests from the material surface (Pannoni; Silva, 2010; Gentil, 2022; Callister Jr., 2015). It is the primary agent of degradation in steel structures, responsible for thickness loss, reduction of the load-bearing cross-section, and, in extreme cases, compromise of the global stability of the structural system. Moreover, in industrialized countries, losses resulting from corrosion account on average for approximately 3.5% of the Gross Domestic Product (GDP). It is estimated that between 30% and 50% of these losses could be prevented through the appropriate adoption of corrosion control techniques already well established in the sector (Pannoni, 2017). The identification and accurate diagnosis of such pathologies provide essential technical support for structural maintenance and rehabilitation. In this context, the use of advanced mapping and diagnostic approaches enables a comprehensive assessment of building conditions, facilitating decision-making for more efficient interventions and contributing to increased durability, safety, and preservation of structures over time (Teixeira et al., 2024; Albuquerque et al., 2024). Corrosion is also a factor leading to the premature replacement of steel structural components, and this early loss of functionality not only increases the consumption of new materials and energy for the production of replacement parts, but also generates significant volumes of metallic waste. In this regard, the adoption of strategies that enable the extension of the service life of steel structures becomes fundamental. Such an approach is aligned with the principles of the circular economy and contributes to the reduction of environmental impacts by minimizing the demand for raw materials and mitigating the generation of solid waste in civil construction (Vale et al., 2021).

According to Pannoni (2017), corrosion affects not only structural safety, but also increases maintenance costs and reduces the service life of steel structures. Therefore, understanding its mechanisms and predicting its progression are essential to ensure durability and sustainability. In this context, computational modeling based on the Finite Element Method (FEM) proves to be an effective tool for simulating thickness loss and evaluating the impact of deterioration on structural performance (Wei et al., 2019; Liu et al., 2020; Deringer, 2020). The Vogel model (1985) was adopted as a reference for the development of this research due to its wide application in studies of steel frames, providing a consolidated theoretical basis and enabling the validation of the results obtained in this study.

2 OBJECTIVE

The present study aims to numerically analyze the impact of atmospheric corrosion on the stiffness and structural performance of steel portal frames used in industrial sheds, with a particular focus on the influence of corrosion height along the columns on the global behavior of the structure. To this end, a numerical model of a steel portal frame composed of IPE 360 sections was developed and validated using the Abaqus® software, taking the experimental model proposed by Vogel (1985) as a reference. The results obtained make it possible to identify the regions most sensitive to thickness loss and to understand how deterioration affects structural stability, thereby providing technical support for the planning of preventive maintenance strategies.

3 CORROSION IN STEEL STRUCTURES

The steel industry represents, on a global scale, the industrial sector with the highest level of carbon dioxide (CO_2) emissions into the atmosphere, accounting for approximately 7% to 9% of global emissions, according to data from the World Steel Association. In this context, assessing the service life of steel structures becomes essential, as extending their durability contributes to reducing the need for the production of new steel components. This approach is directly aligned with decarbonization targets and the pursuit of more sustainable construction practices, in which structural efficiency and the rational use of materials play a strategic role (AGRIMIDIA, 2022).

In Brazil, the use of steel encompasses several construction typologies. In infrastructure works, such as bridges and viaducts, steel stands out for enabling the spanning of large clear distances; in commercial developments, airports, and multi-storey buildings, its use is associated with the feasibility of large-scale roofs and the optimization of costs and construction schedules; in industrial sheds, steel is employed in large-span roofing systems; and in sports facilities, the use of trusses and slender columns is favored to achieve wide internal spaces (Melo, 2021). From an environmental perspective, steel constitutes a strategic alternative, as it is 100% recyclable and can be reused indefinitely without loss of properties (Moliterno; Brasil, 2015). In terms of durability, it is characterized by high mechanical strength and structural stability, provided that it is adequately protected against corrosive processes (Silva; Mei, 2010). However, certain limitations must be considered, such as its susceptibility to corrosion—which requires periodic maintenance and the application of protective coatings—the need for integration with other materials for the execution of non-linear elements, such as slabs, and market restrictions in certain regions of Brazil (Pannoni; Silva, 2010).

With regard to performance, the Brazilian standard NBR 15575-1/2013 defines pathology as a nonconformity that manifests in a product as a result of failures in design, manufacturing, installation, execution, assembly, use, or maintenance, as well as problems not associated with the natural aging of materials (ABNT, 2013). According to Cândido (2005) and Melo (2021), pathological manifestations in steel structures can be grouped into three categories: acquired, transmitted, and atavistic. Acquired pathologies are related to the lack of maintenance and to design flaws that favor the accumulation of aggressive agents, such as corrosive gases, industrial liquids, moisture, and excessive vibrations. Transmitted pathologies, in turn, result from construction defects, generally associated with deficiencies in execution and insufficient technical qualification of assembly teams. Atavistic pathologies originate from structural design errors, inadequate conceptual design, or incompatibilities between materials, compromising the structure from its initial stages and requiring technical rigor from design through execution. It is noteworthy that the latter occur more frequently (Garcia, 2025).

3.1 Corrosion

As one of the main pathologies found in steel structures, corrosion consists of the degradation of metals resulting from chemical or electrochemical reactions with the environment and may occur regardless of the presence of mechanical loading. This process alters the microstructure and compromises the physical properties of the material, reducing its structural integrity (Gentil, 2022). In the case of steel, corrosion manifests through the formation of rust, a porous product with low adhesion whose volume can be up to ten times greater than that of the original metal. This expansion generates internal stresses that affect not only exposed components but also elements embedded in reinforced concrete (Weimer; Thomas; Dresch, 2018). The main issue with rust is that, unlike a patina adhered to the base metal, it does not form a stable and adherent layer; instead, it detaches over time, promoting the progressive loss of mass of the original material and accelerating the structural degradation process (Jr., 2020).

Most metals tend to react spontaneously with the environment, giving rise to corrosion processes such as the tarnishing of silver and the rusting of iron. This phenomenon can be understood as the reverse of steelmaking: while metallurgy reduces ores to obtain the metal, corrosion oxidizes it, returning it to a stable condition similar to that of its mineral origin. In the case of iron, for example, rust corresponds to hydrated iron oxide ($Fe_2O_3 \cdot nH_2O$), which is very close to the mineral hematite (Fe_2O_3), evidencing its natural tendency to revert to its original state (Gentil, 2022). Strategies for mitigating corrosion can be grouped into four categories: modification of the manufacturing process, alteration of the corrosive environment, improvement of the metal’s characteristics, and, most importantly, the application of protective coatings. In general, protection systems consist of three layers: a primer, responsible for adhesion and initial protection; an intermediate layer, which increases thickness and acts as a sealant; and a finishing layer, which ensures chemical resistance and defines the final appearance (Gentil, 2022).

Atmospheric corrosion can be classified according to the mass loss of steel, in accordance with the guidelines of ABNT NBR ISO 9223 (2024), which establishes procedures for determining corrosion rates in different natural environments. This standard defines aggressiveness categories ranging from very low (C1) to extreme (CX), relating environmental factors—such as humidity, presence of chlorides, pollutants, and temperature—to the rate of material deterioration, thereby enabling the estimation of residual service life. Dry indoor environments (C1) exhibit negligible losses, whereas severe industrial and coastal atmospheres (C5–CX) require more robust anticorrosive protection systems due to the acceleration of degradation processes (ABNT NBR ISO 12944, 2018). The corrosion rates associated with each category are summarized in Table 1, which provides important support for maintenance planning, coating selection, and the calibration of numerical models that represent the gradual reduction in thickness of steel profiles, enabling realistic analyses of durability and structural reuse.

Table 1 - Classification of corrosion rates in different scenarios, according to NBR ISO 9223:2024

Atmospheric aggressiveness category	Typical environmental conditions	Reference corrosion rate of carbon steel (µm/year)	Examples of environments
Very low (C1)	Dry indoor environments, low relative humidity	≤ 1,3	Dry industrial warehouses, indoor residential buildings
Low (C2)	Urban areas with low pollution, moderate humidity	> 1,3 a 25	Rural environments, ventilated warehouses
Moderate (C3)	Urban and industrial environments with moderate pollution and/or proximity to coastal inland areas	> 25 a 50	Industrial cities, regions with frequent rainfall
High (C4)	Industrial or coastal environments with high humidity and pollution	> 50 a 80	Ports, humid coastal regions, urban industrial zones
Very high (C5)	Severe industrial environments or tropical coastal areas with high salinity	> 80 a 200	Port areas with intense marine atmosphere
Extreme (CX)	Highly aggressive atmospheres with continuous presence of salts, humidity, and industrial contaminants	> 200 a 700	Severe industrial regions, offshore zones

Source: Adapted from ABNT NBR ISO 9223 (2024).

The determination of atmospheric corrosion rates is essential for assessing the durability of metallic components, especially in roofing structures, where material integrity is critical to the safety and functionality of the building. Knowledge of these data makes it possible to estimate thickness loss over time, providing the basis for calculating the residual service life of components and defining appropriate maintenance or replacement intervals. In addition, quantifying corrosion rates enables the identification of scenarios of accelerated degradation, supporting decisions related to anticorrosive protection and reuse strategies. Thus, incorporating corrosion rate information into structural analyses contributes not only to safety and cost efficiency, but also to the adoption of sustainable practices in civil construction, by extending the life cycle of materials and reducing the unnecessary disposal of steel components (Cândido, 2005).

Beyond the degree of classification, corrosion in steel structures may manifest in different forms, each with its own characteristics and distinct impacts on structural performance. Uniform corrosion leads to homogeneous thickness loss over the entire exposed surface, whereas pitting and alveolar corrosion occur in a localized manner, forming cavities or grooves of varying proportions. Plate corrosion and exfoliation affect specific regions, causing progressive material detachment or the separation of parallel layers, thereby severely compromising structural integrity. Galvanic corrosion results from the contact between dissimilar metals in the presence of an electrolyte, leading to the degradation of the less noble metal. Crevice corrosion, which is difficult to detect, develops in poorly accessible regions due to differences in oxygen concentration, while filiform corrosion appears in the form of thread-like filaments, especially in column stiffeners. In addition, weld seams and the bases of steel columns constitute critical points, as residual stresses, surface irregularities, moisture, and aggressive agents favor accelerated corrosive processes, requiring specific care in detailing, surface preparation, and protection (Gentil, 2022; Neto; Cunha, 2025).

3.2 Main Occurrences of Corrosion in Steel Industrial Sheds

Corrosion represents one of the main degradation mechanisms in steel structures and is often associated with deficiencies in design, execution, or maintenance. At column bases with base plates, the corrosive process may affect weld seams, leading to partial loss of the protective coating and surface oxidation, which is aggravated by the accumulation of rainwater, constant moisture, and the execution of column bases at floor level. Columns, in general, show high susceptibility to ascending corrosion caused by water accumulation at their bases; intermediate corrosion due to direct exposure to weathering; and descending corrosion resulting from failures in gutters and drainage systems at the roof level (Mendes et al., 2020). This observation is consistent with Gentil (2012), who reports that ascending corrosion can reach heights of up to 1 meter. Roof steel beams, in turn, tend to exhibit localized corrosion in welded regions as a result of degradation of the paint system, accumulation of impurities, and failures in waterproofing of roofing systems or connections. These pathological manifestations highlight the importance of proper constructive detailing, the specification of preventive solutions, and the performance of periodic inspections to ensure the durability and safety of steel structures (Santos, 2016). Factors that further aggravate the problem include inadequate surface preparation, the use of low-quality materials, the absence of periodic maintenance, and the lack of appropriate constructive detailing, all of which reduce the protective capacity of the structure. According to Rahgozar (2009), in a study on the evaluation of the capacity of I-shaped beams subjected to corrosion, mass loss within the same profile may manifest differently along the web. The literature indicates that thickness reduction tends to be more pronounced in regions close to the flanges due to the accumulation of impurities and moisture retention at the corners. Regarding the flanges, deterioration also varies according to the beam position, with the upper flange—being more exposed—generally more susceptible to thickness loss than the lower flange.

Figure 1 presents a summary of the areas most susceptible to corrosion in a steel portal frame, according to the reviewed literature.

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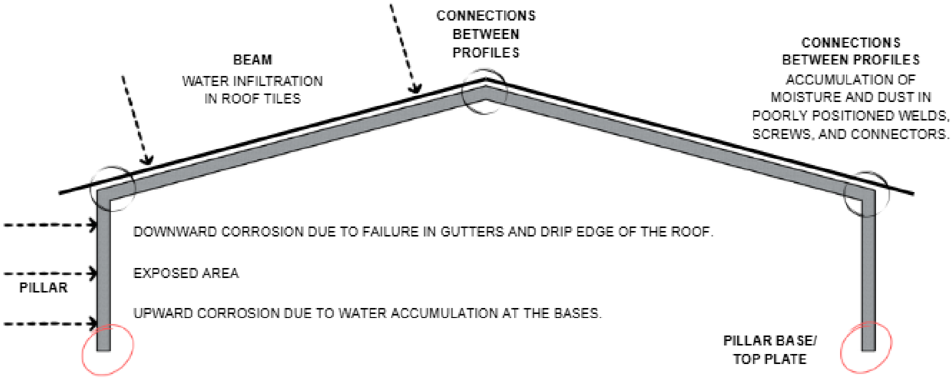
Figure 1 - Schematic summary of the points most susceptible to corrosion in roof steel portal frames



Source: Prepared by the authors (2025).

In summary, it is observed that column bases are particularly susceptible to the accumulation of moisture and impurities, favoring the initiation and propagation of corrosion from the base of the column section. The central region of the column, which is widely exposed to the external environment, also exhibits significant vulnerability. The upper extremity, in tum, may be affected by corrosion resulting from deficiencies in the execution or maintenance of roof gutters and drip edges. In the body of the upper beams, water infiltration from the roofing system can increase moisture levels, while all structural connections—including flat connectors, unsealed bolts, and weld seams—become critical points when inadequately designed or executed, promoting water accumulation and intensifying corrosive processes.

4 METHODOLOGY

The methodology adopted in this study is based on a comprehensive theoretical framework comprising scientific articles, books, and technical standards addressing steel structures in civil construction, corrosion, sustainability, and structural analysis methods based on the Finite Element Method. Based on this conceptual foundation, a steel portal frame was modeled (Figure 2), taking as reference the theoretical model developed by Vogel (1985) for a roof structure composed of IPE 360 steel profiles. This model serves as the basis for defining structural parameters and for carrying out the computational simulations required for the proposed investigation. The selection of this model is justified by its representativeness within the field of steel structural engineering, as well as by the relevance of the author’s classical study, which provides well-established parameters for evaluating the mechanical behavior of such elements. The analyses performed considered both geometric and material nonlinearities typical of these structures, as addressed by Vogel (1985).

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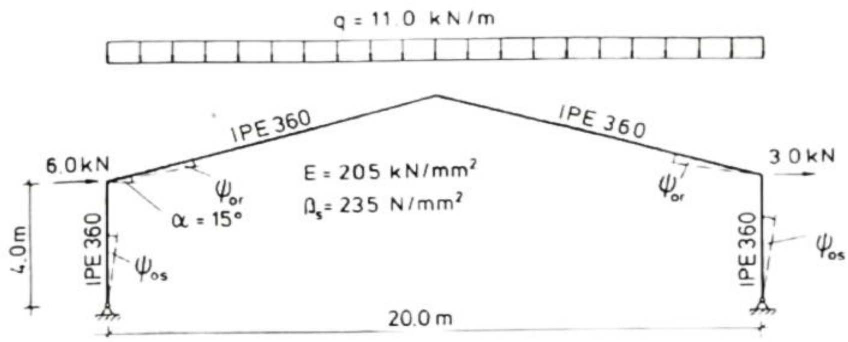
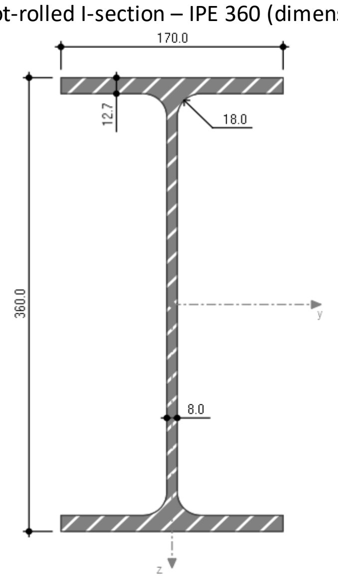
Figure 2 - Portal frame model developed by Vogel (1985)



Source: Vogel (1985)

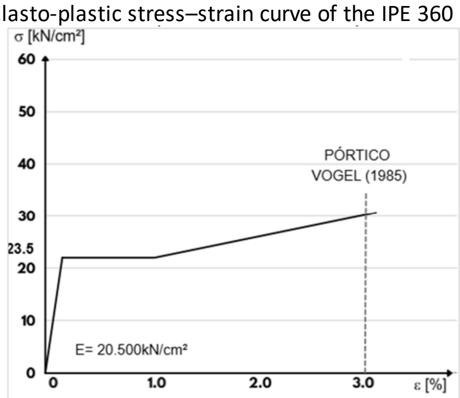
The adopted structural model corresponds to a steel portal frame composed of IPE 360 profiles (hot-rolled structural steel sections, as shown in Figure 3), with a span of 20.0 meters and column heights of 4.0 meters. The roof slope was assumed to be 15° relative to the horizontal, with rigid connections between columns and beams. The material employed was structural steel, defined with a modulus of elasticity of 205 GPa and a yield strength of 235 MPa, as presented in Figure 4.

Figure 3 - Hot-rolled I-section – IPE 360 (dimensions in mm)



Source: Adapted from ArcelorMittal (2018).

Figure 4 - Elasto-plastic stress–strain curve of the IPE 360 steel profile



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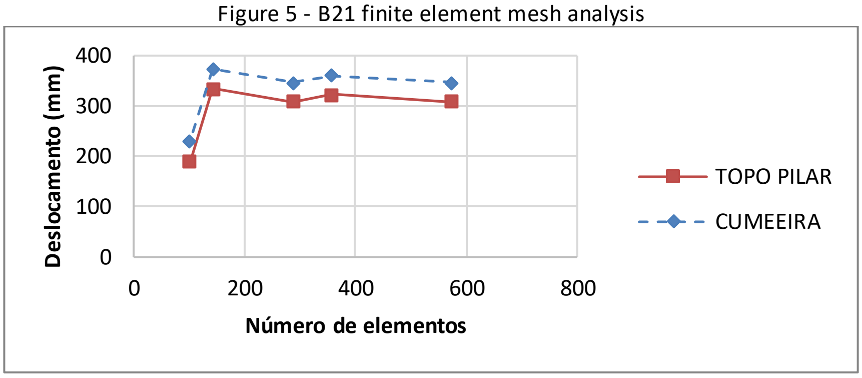
Source: Adapted from Vogel (1985).

Regarding the boundary conditions, the supports were modeled at the column bases, ensuring restraint only against translational displacements. The loading consists of a uniformly distributed load of q = 11.0 kN/m applied along the roof, in addition to concentrated loads of 6.0 kN and 3.0 kN at the beam–column joints.

For the modeling of the steel portal frame in the Abaqus software, the B21 finite element was adopted, belonging to the family of one-dimensional beam elements. The choice of this element was motivated by its computational efficiency and its compatibility with the boundary conditions and loading defined in the study by Vogel (1985), which facilitates the validation of the numerical model through comparison of the obtained load–displacement curves. To ensure the accuracy and numerical stability of the results, a mesh refinement study was performed for the portal frame model (Figure 5). Based on these analyses, it was verified that a mesh with an element size of 200 mm, corresponding to 144 elements discretizing the structure, exhibited satisfactory convergence of the parameters of interest, including displacements and internal forces, without unnecessary increases in computational time.

Figure 5 - B21 finite element mesh analysis



Source: Prepared by the authors (2025).

Based on the information obtained from the theoretical review (summarized in Figure 1), it was possible to identify that steel columns constitute regions particularly susceptible to corrosion, especially at their bases, where moisture accumulation occurs, and in the upper zones near the beam–column connections, where sealing deficiencies may accelerate the deterioration process. Accordingly, the numerical model was partitioned into 200 mm "parts," corresponding to the size of the adopted finite element, enabling a segmented analysis of the column under different corrosion conditions. Corrosion heights of 200, 800, 1000, and 2000 mm from the base were considered, representing the upward progression of deterioration, as well as heights of 200 and 400 mm from the top, simulating descending corrosion (left column). This modeling strategy allows for a detailed assessment of the influence of corrosion height on the global behavior of the portal frame, as illustrated in Figure 6, which presents the layout and numbering of the analyzed points.

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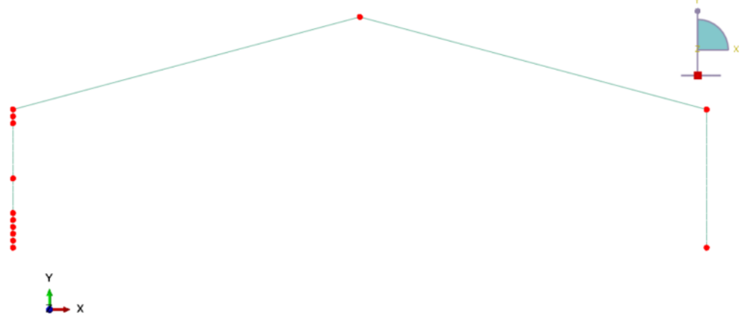
Figure 6 - Discretization of the Abaqus model according to the corrosion points



Source: Prepared by the authors (2025).

The corrosion scenario adopted in this study represents uniform corrosion, characterized by a proportional and simultaneous reduction in thickness of both the flanges and the web of the steel profile. Time horizons of 7, 15, 25, and 50 years were considered, in accordance with the durability ranges of anticorrosive protection systems established by ABNT NBR ISO 12944 (2018), in order to analyze the progressive evolution of deterioration over time. The simulations were initially conducted under the C3 environmental scenario, which corresponds to moderately aggressive urban and industrial environments, where steel portal frames are widely used, allowing for a more realistic representation of the most common exposure conditions for this type of structure. According to ABNT NBR ISO 9223 (2024), the estimated thickness loss under the C3 scenario is 0.026 mm/year.

Table 1 presents the corresponding estimates of mass and thickness loss for the different exposure periods considered in this study.

Table 1 - Estimated thickness loss of steel profiles

Cenário	Rate (mm/ano)	7 years (mm)	15 years (mm)	25 years (mm)	50 years (mm)
C3 (moderate urban)	0,026	0,182	0,39	0,65	1,3

Source: Prepared by the authors (2025).

Considering the web and flange thicknesses of the IPE 360 profile, it is possible to estimate the corresponding thickness loss values for each degree of corrosivity classification as a function of exposure time (Table 2).

Table 2 - Estimativa de espessura residual do perfil IPE360 ao longo dos anos

Cenário / horizonte	Loss (mm)	Residual web thickness (mm)	Residual flange thickness (mm)
Original (no corrosion)	0,00	8,00	12,70
C3 – 7 years	0,18	7,82	12,52
C3 – 15 years	0,39	7,61	12,31
C3 – 25 years	0,65	7,35	12,05
C3 – 50 years	1,30	6,70	11,40

Source: Prepared by the authors (2025).

Thus, the methodology adopted in this study establishes a solid basis for analyzing the effects of corrosion on steel columns, integrating numerical modeling, normative criteria, and progressive simulations of thickness loss.

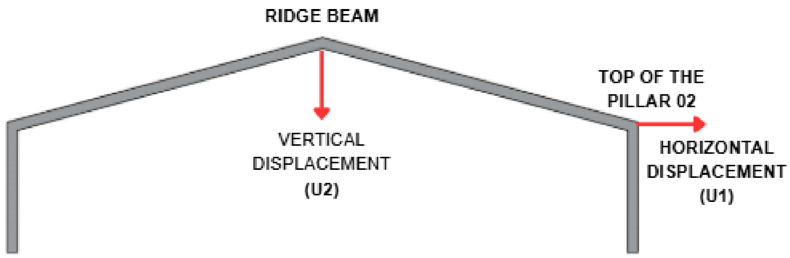
5 RESULTS

This section initially presents the validation of the model developed in the Abaqus software, seeking compatibility between the numerical response and the experimental results obtained by Vogel (1985) in terms of load-bearing capacity and displacement behavior. The stability parameters of the portal frame were evaluated, and two-dimensional displacement simulations were performed, enabling the generation of comparative graphs among the previously defined points, with the aim of identifying the regions that exhibit the greatest deformation under loading.

5.1 Validation of the reference model

For the calibration and validation of the numerical model, data obtained from the simulations performed in Abaqus were exported, allowing the construction of a load–displacement curve representative of the behavior of the steel portal frame. This curve was compared with that presented by Vogel (1985) in the reference experimental study, enabling the assessment of the model's fidelity in reproducing the observed structural performance. For the development of the graph, data for the Load Proportionality Factor (LPF) — a parameter that represents the gradual amplification factor of the applied loads up to the point of instability or structural colapse — and the displacements at the ridge and at the top of the right column were exported, as performed by Vogel (1985) and indicated in Figure 7.

Figure 7 – Identification of the analyzed points according to Vogel (1985)



Source: Prepared by the authors (2025).

Figure 8 presents the comparison between the curves obtained from the theoretical model proposed by Vogel (1985), represented by the black lines, and those derived from the computational modeling developed in Abaqus, indicated by the gray lines. It can be observed that the curves of the numerical model exhibit slightly lower LPF values in the initial loading stages, particularly in the ridge region, suggesting a lower initial stiffness when compared to the theoretical model. However, as displacement increases, the curves tend to converge, indicating that, despite the simplifications assumed in Vogel's theoretical model, it satisfactorily represents the global behavior of the structure. The discrepancy observed at the failure stage was only 7.5%.

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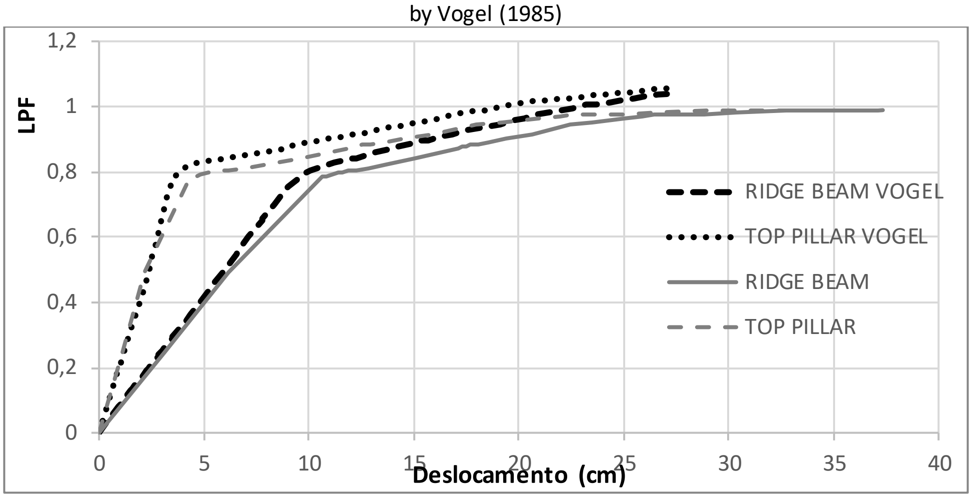
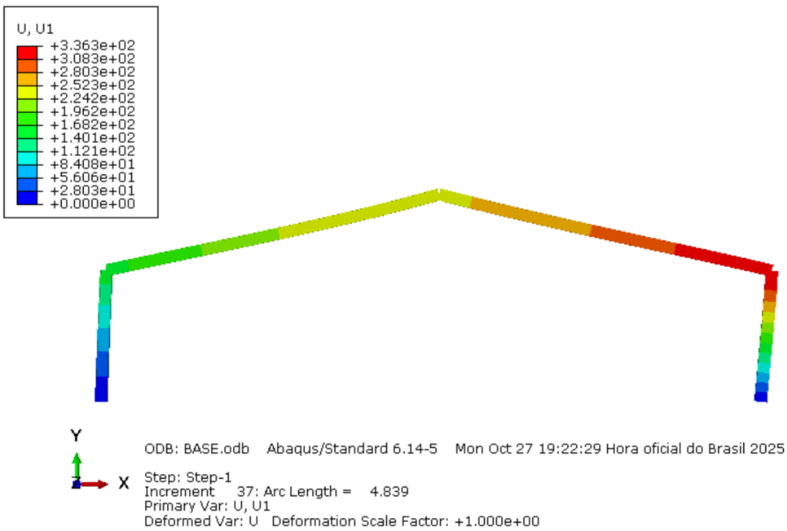
Figure 8 - Comparison of displacement data obtained from the model developed in Abaqus and the data reported by Vogel (1985)



Source: Prepared by the authors (2025).

The identified differences can be attributed to the consideration, in the computational model, of additional factors such as residual stresses in the steel profiles. The validation stage confirms that the model is suitable for subsequent analyses, including simulations of thickness reduction to represent different corrosion scenarios, ensuring that the results realistically reflect the structural behavior of the components. Figure 9 presents the horizontal displacement behavior (U1, in millimeters) of the portal frame in the Reference Model, without thickness loss, highlighting greater displacements in the beam–column connection regions, which are typical of structural bending. Figure 10, in turn, shows the vertical displacement (U2), in millimeters, with maximum deformation occurring at mid-span, a characteristic behavior of simply supported structures. These results represent the intact behavior of the structure and serve as a reference for comparison with the simulated corrosion scenarios.

Figure 9 - Diagram of horizontal displacements (U1) in mm of the portal frame.



Source: Prepared by the authors (2025).

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ISSN 2317-8604 Suporte Online / Online Support
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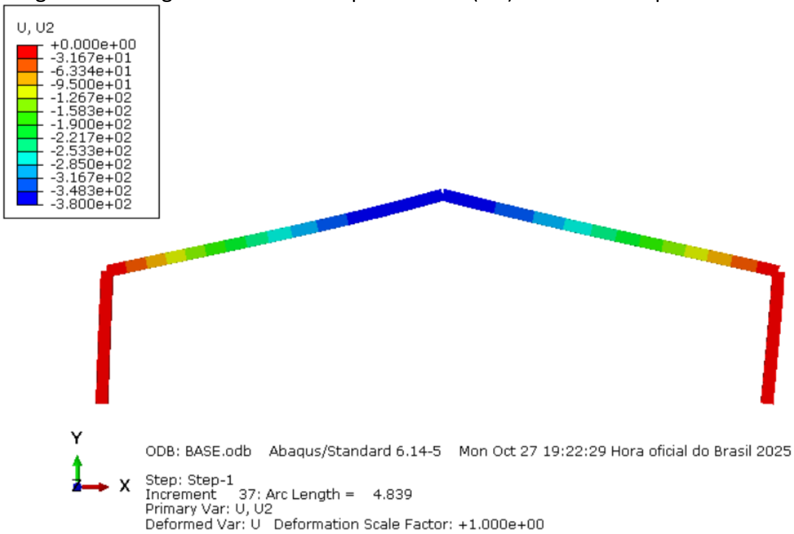
Figure 10 - Diagram of vertical displacements (U2) in mm of the portal frame.



Source: Prepared by the authors (2025).

Overall, the results presented for the reference case confirm the expected structural behavior of an intact steel portal frame, with no influence from corrosive processes. The displacement distributions in the horizontal and vertical directions indicate a response consistent with the theoretical model proposed by Vogel (1985), with greater deformation concentrated in the transition regions between beams and columns and at the central span of the roof.

5.2 Simulation – Moderately Aggressive Urban Scenario (C3)

This section presents a preliminary study carried out in the Abaqus software to evaluate the structural behavior of the portal frame under uniform thickness loss of the IPE 360 profile, according to the data presented in Table 3. The simulation, based on the C3 corrosion scenario (ABNT NBR ISO 9223, 2024), was conducted incrementally by varying the affected height in 200 mm intervals, in order to identify the point at which deterioration begins to significantly influence the structural performance.

The analyses considered the vertical displacement at the roof ridge and the horizontal displacement at the top of column 02 (right), in accordance with Vogel (1985), allowing for direct comparison of the obtained results. The graphs presented in Figures 11, 12, and 13, which relate displacement to the load proportionality factor (LPF), enable the comparison of the impact of progressive corrosion on the structural performance of the steel portal frame over time.

Figure 11 – LPF – displacement graphs of the structure considering mass loss due to corrosion over the years, from the base to the top

GRÁFICO LPF X DESLOCAMENTO - CUMEEIRA	GRÁFICO LPF X DESLOCAMENTO – TOPO PILAR 02

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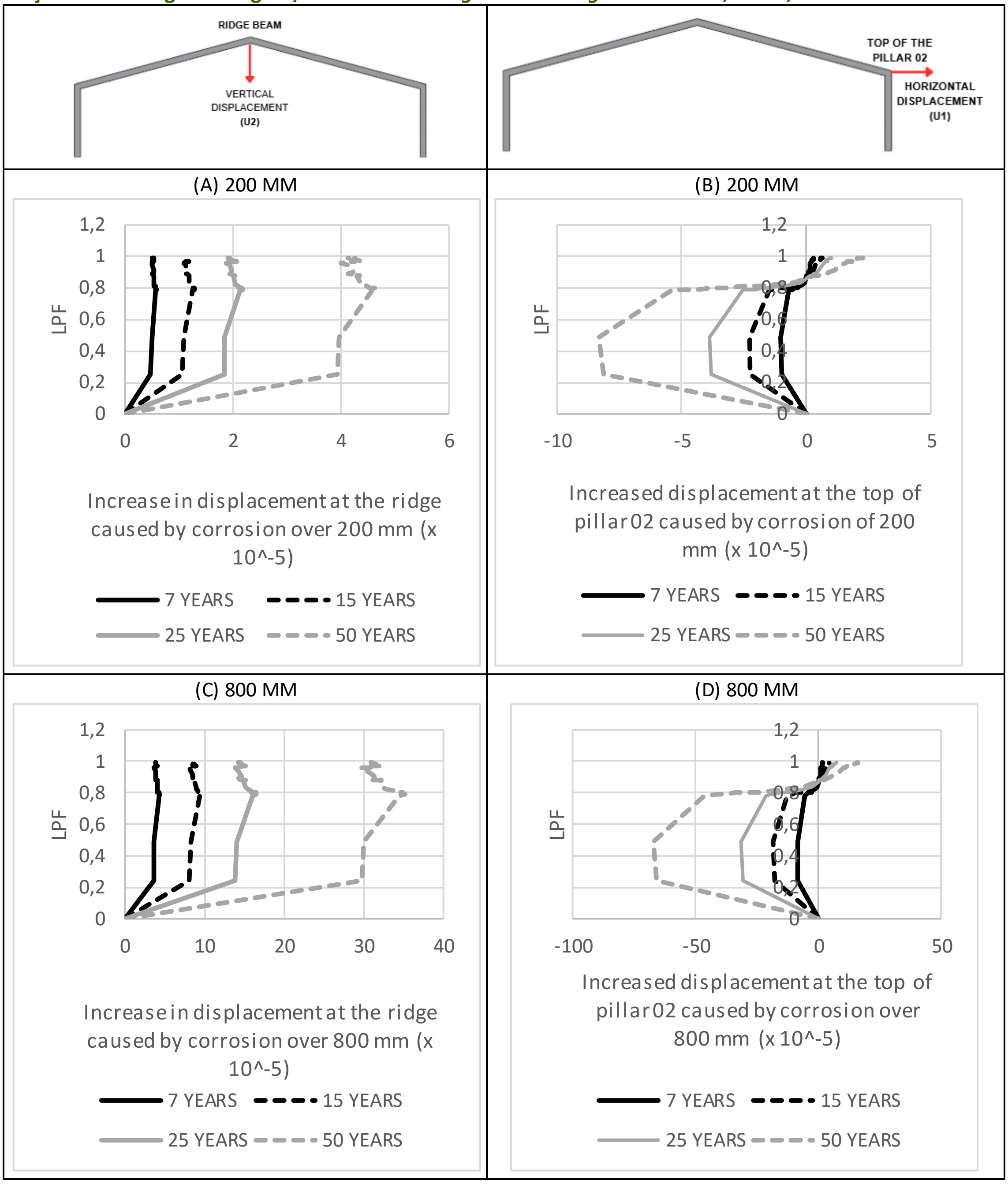
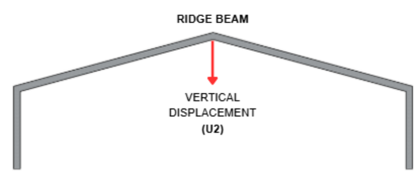


Source: Prepared by the authors (2025).

Figure 12 - LPF – displacement graphs of the structure considering mass loss due to corrosion over the years, from the base to the top

GRÁFICO LPF X DESLOCAMENTO - CUMEEIRA	GRÁFICO LPF X DESLOCAMENTO – TOPO PILAR 02
	

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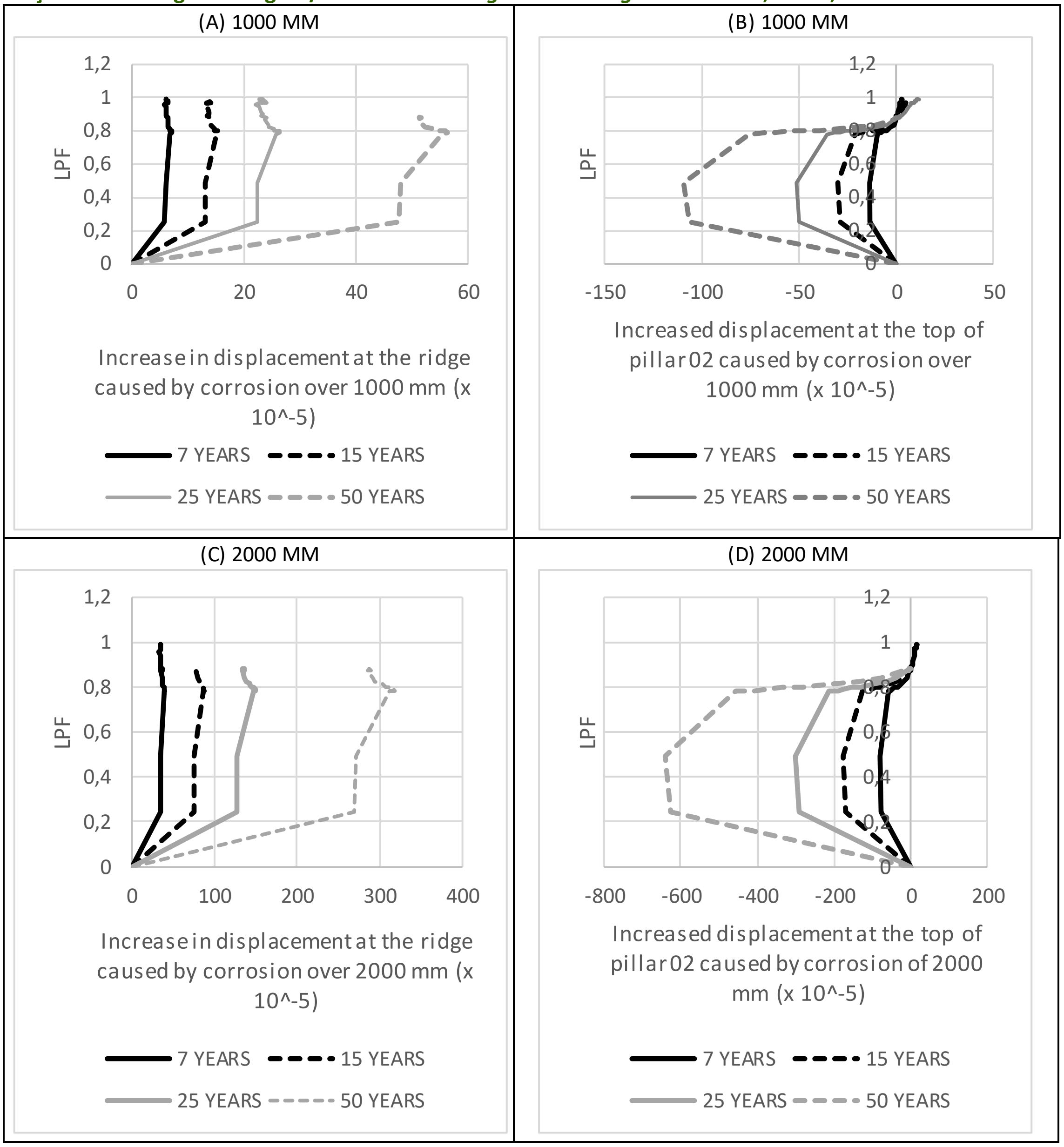
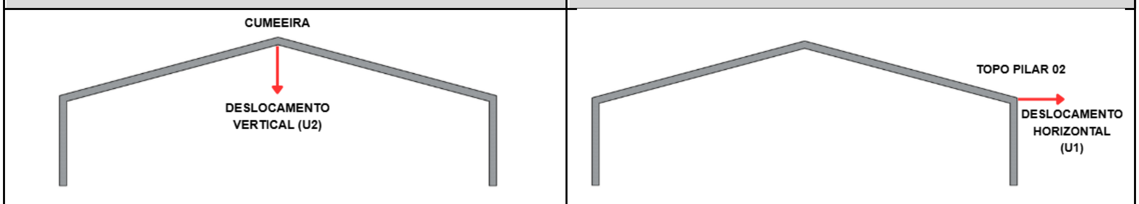


Source: Prepared by the authors (2025).

Figure 13 – LPF – displacement graphs of the structure considering mass loss due to corrosion over the years, from the top to the base

GRÁFICO LPF X DESLOCAMENTO - CUMEEIRA	GRÁFICO LPF X DESLOCAMENTO – TOPO PILAR 02



(A) 200 MM TOPO	(B) 200 MM TOPO

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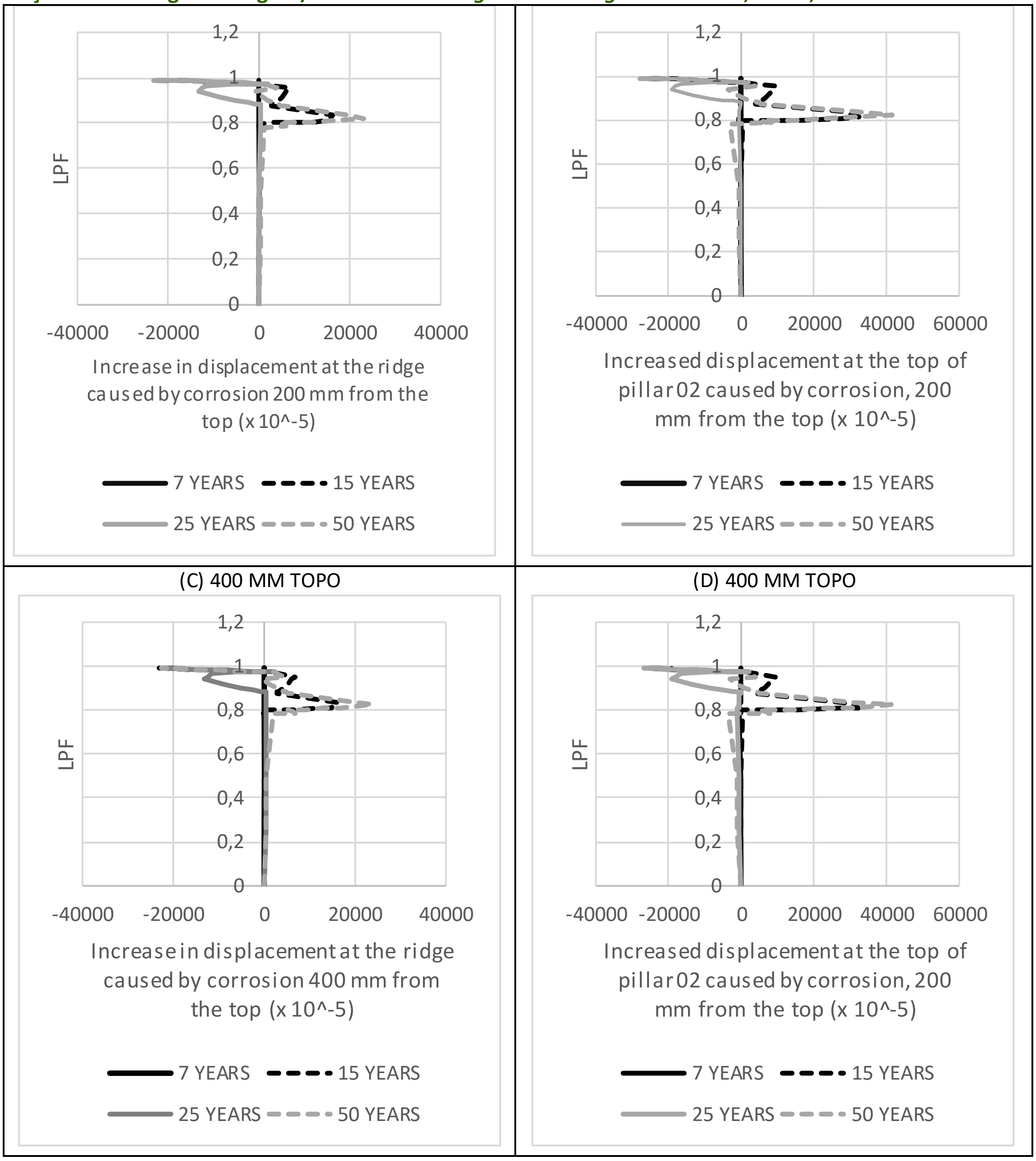

Source: Prepared by the authors (2025).

The results indicate that the progression of corrosion, according to the exposure periods considered (7, 15, 25, and 50 years), causes a gradual increase in vertical displacements at the roof ridge, indicating a loss of stiffness and load-bearing capacity—although the variations remain of small magnitude. In cases of ascending corrosion, displacements increase discretely up to approximately 800 mm in height (Graphs 11C and 11D), becoming more pronounced from 1000 mm onward (Graphs 12A and 12B), reaching up to 0.006 mm when deterioration affects critical stress regions. This behavior is consistent with Gentil (2022), who associates moisture-induced ascending corrosion with the bases of columns. In contrast, descending corrosion exhibits a more sensitive structural response: even small extents of deterioration (200–400 mm) result in displacement increases of up to 0.01 mm, indicating greater vulnerability in the beam–column connection regions (graphs in Figure 13).

It is therefore concluded that the structural behavior is strongly dependent on both the location and the extent of corrosion. Ascending corrosion produces gradual effects, whereas descending corrosion leads to faster and more significant degradation. Consequently, upper regions should be prioritized in maintenance actions, reinforcing the importance of proper constructive detailing and preventive maintenance at the interfaces between columns and beams.

6 CONCLUSION

Based on the results obtained, it is concluded that corrosion influences the structural behavior of steel columns even in situations involving small thickness losses. It was verified that the location of deterioration is a determining factor. While ascending corrosion at the column bases tends to produce gradual effects, descending corrosion in the upper regions leads to more immediate reductions in stiffness and structural performance. The top of the column proved to be a particularly sensitive region to deterioration, requiring greater attention in inspection and maintenance routines, especially in situations associated with gutter failures, water infiltration, or moisture accumulation at beam–column connections.

These findings reinforce the importance of considering the distribution of corrosion along the height of structural elements when assessing the durability of steel structures. In addition, the relevance of extending this analysis to other regions susceptible to deterioration—such as connections and points along the beam body (as indicated in Figure 1) —is highlighted, since the interaction between different corrosion locations may intensify the overall effects on structural performance. In this way, the study contributes to the improvement of design practices and preventive maintenance strategies, promoting greater durability, safety, and sustainability in steel constructions.

Acknowledgments

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 (2025).

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Technical and Scientific Journal Green Cities
ISSN 2317-8604 Suporte Online / *Online Support*

Edição em Português e Inglês / *Edition in Portuguese and English* - Vol. 14, N. 50, 2026

DECLARAÇÕES

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Ao descrever a participação de cada autor no manuscrito, utilize os seguintes critérios:

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- **Redação - Revisão Crítica**: Camila Souza Carvalho; Maria Ávila Branquinho.
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DECLARAÇÃO DE CONFLITOS DE INTERESSE

Nós, **CAMILA SOUZA CARVALHO E MARIA ÁVILA BRANQUINHO,** declaramos que o manuscrito intitulado "**Análise Numérica dos Efeitos da Corrosão Ascendente e Descendente em Pilares Metálicos de Pórticos de Galpões**":

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