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Research article

Structural Analysis of the Deck of a Deck-Cargo Barge using the Finite Element Method to Predict the Effects of Corrosion and Fatigue on Collapse Stress

Análisis Estructural de la Cubierta de una Barcaza de Carga sobre Cubierta, mediante el Método de Elementos Finitos para Predecir los efectos de la Corrosión y la Fatiga en el Esfuerzo de Colapso

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Abstract: This paper analyzes the risk of collapse in the hull structures of barges used in commercial river navigation, specifically due to the effects of corrosion and fatigue. Although documented cases are scarce in Colombia, significant incidents have been reported internationally, such as those in Paraguay and Serbia, where barge hull structures collapsed due to these factors. The study focuses on the application of finite element analysis (FEA) to model the structure of a barge operating on the Meta River in Colombia. Three specific objectives were established: to create a mathematical model of the barge hull considering the nonlinear behavior of the material, to simulate the impact of fatigue and corrosion on the collapse stresses of the structure, and to evaluate the combined influence of both phenomena on the service life of the vessel. To achieve this, SHELL181 and BEAM188 elements were used in ANSYS software, allowing for detailed simulation of structural behavior under extreme conditions. Corrosion reduces the thickness of structural sections, decreasing their strength and accelerating plastic collapse under loads. Results showed that fatigue, combined with corrosion, significantly reduces the barge's service life and increases the risk of structural failure. The analysis revealed that thickness reduction due to corrosion leads to increases in equivalent stresses, compromising structural integrity and leading to plastic collapse when stresses reach critical levels. This study highlights the importance of considering both corrosion and fatigue in the design and maintenance of river barges to avoid catastrophic failures.

Keywords: Structural collapse; Corrosion; Fatigue; Finite elements; River barges

Resumen: Este artículo analiza el riesgo de colapso en las estructuras de casco de barcazas destinadas a la navegación comercial fluvial, específicamente debido a los efectos de la corrosión y la fatiga. Si bien en Colombia existen pocos casos documentados, a nivel internacional se han registrado incidentes significativos, como los ocurridos en Paraguay y Serbia, donde las estructuras de barcazas colapsaron a causa de dichos factores. El estudio se centra en la aplicación del método de elementos finitos (EF) para modelar la estructura de una barcaza que opera en el río Meta, Colombia. Se establecieron tres objetivos específicos: crear un modelo matemático del casco de la barcaza considerando el comportamiento no lineal del material, simular el impacto de la fatiga y la corrosión en los esfuerzos de colapso de la estructura, y evaluar la influencia conjunta de ambos fenómenos en la vida útil de la embarcación. Para ello, se emplearon los elementos SHELL181 y BEAM188 en el software ANSYS, lo que permitió simular detalladamente el comportamiento estructural bajo condiciones extremas. La corrosión reduce el espesor de las secciones estructurales, lo que disminuye su resistencia y acelera el colapso plástico bajo cargas. Los resultados mostraron que la fatiga, combinada con la corrosión, reduce significativamente la vida útil de la barcaza e incrementa el riesgo de falla estructural. El análisis reveló que la reducción del espesor debida a la corrosión genera incrementos en los esfuerzos equivalentes, comprometiendo la integridad de la estructura y conduciendo al colapso plástico cuando los esfuerzos alcanzan niveles críticos. Este estudio destaca la importancia de considerar tanto la corrosión como la fatiga en el diseño y mantenimiento de las barcazas fluviales para evitar fallas catastróficas.

Palabras clave: Colapso estructural; Corrosión; Fatiga; Elementos finitos; Barcazas fluviales

1. Introduction

The technological bulletin published by the Superintendencia de Industria y Comercio de Colombia [18], titled "Barcazas," highlights the urgent need to expand and modernize the country's river barge fleet in order to meet the sector's growing demands. A 400% increase in freight transport along inland waterways is projected, which requires improving both the capacity and the safety of vessels. Colombia currently operates approximately 208 single-hull barges that, pursuant to Article 5 of Resolution 1918 of 2015, must be replaced by double-hull barges. This transition aims to optimize operational efficiency and enhance safety in the transport of petrochemical products, asphalt, hydrocarbons, and their derivatives along the Magdalena River, a key corridor connecting production centers such as Barrancabermeja with the Caribbean coast. The Plan Maestro Fluvial [14] underscores Colombia's vast potential in river navigation, recognizing it as an essential sector for the country's economic development. It also identifies, however, a notable absence of policies and programs directed at fleet modernization, environmental sustainability, and operational optimization. Accordingly, it is imperative to implement measures that improve the constructive and structural efficiency of barges in order to ensure sustainable and competitive growth.

Although Colombia's river transport sector presents significant opportunities for expansion, its development depends largely on improvements to vessel construction processes. Barge construction must therefore adhere to more rigorous standards that ensure greater structural resistance against dynamic loads, impacts, and adverse environmental conditions. Furthermore, the adoption of new design and manufacturing technologies including advanced structural simulation software, corrosion-resistant materials, and optimized welding techniques, will contribute to the production of safer and more durable vessels.

A critical challenge facing the industry is the risk of unforeseen structural failures in barges, which can have severe human, material, and environmental consequences. It is therefore essential to analyze structural collapse resistance by accounting for the effects of corrosion and material fatigue. The implementation of inspection and maintenance methodologies based on continuous structural monitoring will enable failure prediction and the extension of vessel service life, thereby improving operational safety.

This research ultimately seeks to contribute to the optimization of barge design and construction in Colombia by providing key data to enhance structural performance. To that end, a domestically built barge, the largest operating on the Meta River waterway, constructed using traditional methods on its banks, was selected as the reference vessel. Analysis of its structure will make it possible to identify potential improvements to construction processes, with the goal of strengthening the safety, efficiency, and sustainability of the country's river fleet.

The remainder of this paper is organized as follows. Section 2 presents the main contributions of this research to the structural assessment and modernization of river barge design in Colombia. Section 3 reviews previous studies related to ultimate strength, corrosion, fatigue, and finite element analysis applied to marine and river structures. Section 4 describes the methodological approach, the selected barge, the finite element model, the material properties, the loading conditions, and the corrosion and fatigue models considered in the analysis. Section 5 presents the numerical results obtained from the structural simulations. Section 6 discusses the influence of corrosion and fatigue on stress distribution, deflection, buckling behavior, and plastic collapse. Finally, Section 7 summarizes the main findings and highlights the implications for the design, inspection, and maintenance of deck-cargo river barges.

2. Contributions

This research contributes to the modernization of river vessel design and construction in Colombia by providing technical evidence on the structural performance of traditionally built deck-cargo barges. In particular, the study addresses the effects of corrosion and fatigue on structural integrity, safety, and collapse stress, offering a basis for improving design practices, maintenance strategies, and construction standards in the inland waterway sector.

The main contributions of this work are summarized as follows:

i. Modernization of river vessel construction in Colombia: This study provides relevant technical information to support the improvement of barge design and construction standards, contributing to the modernization of the national river navigation sector.
ii. Identification of structural weaknesses in traditionally built barges: The research evaluates the effects of corrosion and material fatigue on the structural performance of a deck-cargo barge built using conventional methods on the Meta River.
iii. Contribution to safer and more durable vessel designs: The findings highlight the need to incorporate advanced engineering tools, corrosion-resistant materials, and optimized welding techniques to improve structural resistance, safety, and service life.
iv. Application of finite element analysis to river barge assessment: The study demonstrates the usefulness of finite element analysis as a technical tool for predicting critical stress conditions and potential collapse scenarios.
v. Promotion of preventive maintenance strategies: The research emphasizes the importance of continuous structural monitoring and predictive maintenance to reduce the risk of unexpected failures and accidents.
vi. Reduction of operational and economic risks: By supporting the early detection of structural deterioration, this study contributes to lowering costs associated with emergency repairs, downtime, and structural failures.
vii. Technical foundation for sector modernization: The results provide a basis for implementing innovative solutions in naval construction and strengthening Colombia’s inland waterway infrastructure.
viii. Contribution to a safer, more competitive, and sustainable river transport industry: This work supports a development model focused on safety, efficiency, and sustainability in navigation along Colombia’s rivers.

3. Related Works

Cameron, Nadeau, and Losciuto [6], address the ultimate strength analysis of barges, an aspect directly related to the structural resistance focus of the present work. Both studies center on improving the design and operation of river barges to prevent collapse, with particular emphasis on structural elements, especially the deck, and on the influence of loading on stability. Their methodology for analyzing critical stresses, including the validation of methods proposed by the classification society, aligns with the finite element approach used in the present research to predict structural failures.

Meinken and Schluter [13], in their work titled “Collapse Behaviour of a Push-Barge,” investigate the structural behavior of barges by accounting for the impact of corrosion and collisions on structural deformation. Nonlinear analysis using the finite element method and the study of corrosion as a determining factor in structural collapse represent key points of convergence between that work and the present investigation.

Salazar, L., Hernández, J., Rosas Huerta, R., Iturbe, A., and Herrera, A. [17], examine structural failures in the midship section of barges due to corrosion and wave loading. Although this article shares with the present work an interest in the influence of corrosion, its scope is limited to midship sections and wave effects, whereas the present study addresses the overall structural collapse of a deck-cargo barge.

Kalyanasundaram [10], in the thesis "Hull Girder Ultimate Strength of a Ship Using Nonlinear FE Method," analyzes the structural capacity of the hull girder of an open-deck container ship exceeding 150 meters in length, with emphasis on how vertical bending moments affect its overall resistance. The author employs iterative methods to calculate the ship's capacity, treats vertical moments as the critical load case, applies safety factors to account for uncertainties in material properties and corrosion-induced dimensional reductions, and uses a nonlinear finite element approach to improve the interpretation of results under combined loading conditions. The present work bears notable similarities to this thesis, particularly in the analytical methods employed and the focus on structural resistance. The primary distinction lies in the type of vessel analyzed: while that thesis examines large open-deck container ships, the present project determines the deck load capable of inducing collapse in a river barge.

Leheta, H. W., Elhewy, A. M., and El Sayed Mohamed, W. [11], in "Finite Element Simulation of Barge Impact into a Rigid Wall," address vessel-to-bridge collisions, a phenomenon that, although infrequent, has occurred with some regularity throughout history. Available records document bridge failures caused by ship impacts dating back to 1850, and statistics reveal an increase in the number of collisions in the late 1970s and early 1980s, followed by a temporary decline and a renewed rise from the early 1990s onward, particularly in regions such as Germany. The consequences of such events can be devastating, as illustrated by the 2005 incident in Krems, Austria, where a collision displaced a bridge pier by more than two meters, and the 2007 accident in China, where a vessel impact caused a bridge to collapse.

Garbatov, Y., and Guedes Soares, C. [8], in "Fatigue Reliability Assessment of Welded Joints of Very Fast Ferries Accounting for Vehicle Load" (Journal of Marine Structures, 18(1), 1–23), address fatigue in high-speed ferries. The parallels with the present work lie in the structural fatigue analysis: both studies apply the finite element method to model fatigue and corrosion, identify critical locations within the structure, and assess cumulative fatigue damage.

Ayyub, B. M., Stambaugh, K. A., McAllister, T. A., de Souza, G. F., and Webb, D. [3], in "Structural Life Expectancy of Marine Vessels: Ultimate Strength, Corrosion, Fatigue, Fracture, and Systems", provide a comprehensive analysis of the structural service life of marine vessels, with emphasis on fatigue, corrosion, and fracture. Their methodology is closely aligned with that of the present work, as both focus on structural reliability and the factors affecting barge integrity, and both employ numerical simulations to model these degradation processes.

Royani, A., Prifiharni, S., Priyotomo, G., Triwardono, J., and Sundjono [16], in "Corrosion Rate and Life Expectancy of Carbon Steel in Freshwater", focus on the corrosion rate of carbon steel in freshwater, a factor of direct relevance to the present study. Their findings support the corrosion analysis conducted here, given that freshwater river conditions directly influence the rate of deterioration of steel structures.

Bureau Veritas [5], in its guidelines for corrosion protection applicable to inland navigation vessels, provides recommendations of high relevance to the present study, which likewise addresses the mitigation of corrosion effects. Both works share the objective of extending barge service life through maintenance strategies and corrosion protection measures.

4. Materials and Methods

Given the approach and procedures required, the research was conducted using a quantitative and exploratory approach. The quantitative methodology involves the collection and analysis of data obtained from various sources.

The methodological steps followed to achieve the results are as follows:

- Review of background information, state of the art, and theoretical framework: This step focused on the collection of information related to the collapse of river barges or similar structures, in order to provide a solid foundation for the research.

- Acquisition of barge plans: A “Deck Cargo” type barge operating on the Meta River was selected due to its high prevalence in Colombian rivers and its low flexural rigidity, resulting from its high beam-to-depth ratio. It is important to note that the developed simulation model is applicable to all types of barges, with the only variation being the cross-sectional configuration.
- Development of a finite element model using 1D and 2D Shell-type elements: This model is spatially positioned and incorporates the stress–strain curve that summarizes the elastoplastic behavior of the material. It enabled the simulation of the structural collapse of a “Deck Cargo” type barge while considering the influence of corrosion. The analysis is geometrically nonlinear due to the lateral deformation that reduces the resistance of elements subjected to compression and materially nonlinear, since the deformations could take the material beyond its proportional limit.
- Development of a finite element model to simulate the effect of fatigue: This model made it possible to evaluate the potential collapse of the structure of the “Deck Cargo” river barge under a scenario in which corrosion is also present, which is essential for understanding the structural behavior under adverse conditions.

5. Results

The present research was developed within the theoretical and conceptual framework of nonlinear structural analysis, taking fatigue and corrosion as determining factors in the plastic collapse process of naval and river structures. To achieve the expected results, a "Load on Deck" type barge of national construction was analyzed, in which the effects of corrosion and fatigue were simulated in order to determine their influence on the plastic collapse of the structure. The collapse is a failure that could occur in the middle of the life cycle of the vessel, a period in which, according to Meinken and Schluter [13], the first effects of corrosion begin to manifest themselves, which deteriorate the dimensions of the structural components.

5.1. Plastic Collapse

Gaylord and Gaylord [9] describe the kinematic mechanism of collapse as the state in which a structure develops a sufficient number of plastic ball joints, arranged in such a way as to make it an unstable system, unable to maintain equilibrium under any circumstances. The failure process that leads to collapse is complex and does not allow predicting the order in which the triggering events will occur.

5.2. Sagging and critical load

Sagging in columns is determined by factors such as flexural stiffness and slenderness of the element. This phenomenon occurs when a centered axial load causes the element to become unstable and begin to deflect laterally [15]. The centered load that triggers this behavior is called critical load. In the case of slender columns, once the load has been removed, the element recovers its original shape without permanent deformation, and the forces generated are below the yield limit (see Figure 1).

The linear behavior described above can be expressed by Euler’s classical analytic equation [15]:

$$\mathbf{P_{Cr}} = \frac{\pi^2 EI}{L^2} \tag{1}$$

Where:

- E is the elastic modulus of the material.
- I is the moment of inertia of the cross-section of a column.
- L is its length.

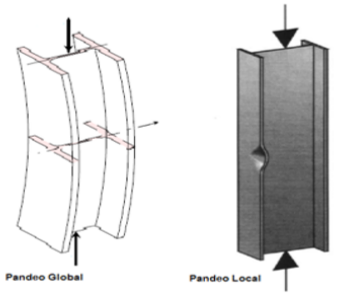

Figure 1. Global Buckling and Local Buckling in Compression Members. Marmolejo C.A. (2014)
Source: The authors.

5.3. Elasto-plastic behavior

The dynamics of collapse are explained by the elastoplastic behavior of the material. To understand elastoplasticity, it is necessary to describe the elastic and plastic properties of a material, as well as the transition between the two zones. Therefore, the use of a material characterization graph is required, as is usual in engineering, where each material has distinctive properties. The curve that represents this behavior is obtained from experimental tests of simple tension, in which key points are identified that reveal the specific properties of the material, as shown in Figure 2. The yielding effort, which marks the limit of the elastic zone, is one of the most important points.

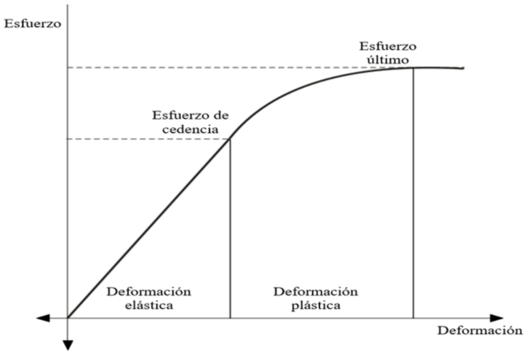

Figure 2. Elastoplastic behavior of a steel, Juárez O.M. (2011)
Source: The authors.

5.4. Bending limbs

Gaylord and Gaylord [9] point out that buckling can occur in elements subjected to bending, being caused by the compressive stresses derived from this state of load. This phenomenon can present itself in three different ways:

- Local sag on skids (inelastic).
- Pandeo lateral torsional.
- Inelastic torsional lateral buckling.

The various types of buckling, both in compression and flexural elements, are part of the collapse mechanism of a structure, as illustrated in Figure 3.

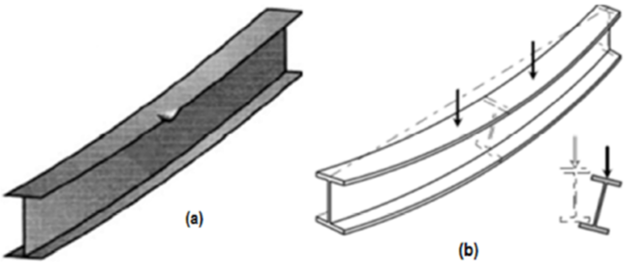

Figure 3. Local Buckling and Torsional Lateral Buckling, Carlos Amador Marmolejo Castro (2014)
Source: The authors.

5.5. Plate buckling

Plates are fundamental components present in deck ironing, in beam skids and webs, and in the columns of a barge structure; therefore, the study of their structural behavior is essential. Creep failure, elastic buckling and inelastic buckling can develop in a plate, for reasons similar to those analysed in column buckling. Unlike the latter, plates are governed by the ratio of the length of the loaded side to the thickness, rather than the ratio of slenderness (Blodgett, 1976). Plate buckling can occur when excessive compression is applied along two opposite sides, as shown in Figure 4. The value of the critical stress of a rectangular plate can be obtained by the following expression:

$$\sigma_{cr} = \frac{K\pi^2 E}{12(1-\nu^2)} \left(\frac{t}{b}\right)^2 \tag{2}$$

Where:

- E = Modulus of elasticity in compression (steel=30000 psi)
- t = thickness of the plate, inches.
- b = plate width, inches
- a = plate length, inches
- v = Poisson ratio (for steel is = 3.0)
- K = depends on bale form factor b/a

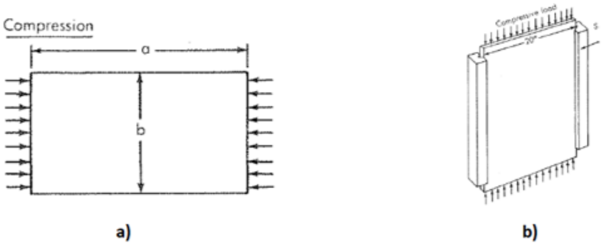

Figure 4. Flat Plate to Compression Design of Welded Structures O. W. Blodgett
Source: The authors.

5.6. Fatigue in structures

López Matus [12], in his work "Fatigue Analysis of a Flotation Hull of an Ocean System during Transportation", points out that the growing activity of oil and gas exploration in offshore areas has significantly boosted research on the fatigue response of offshore structures, which are constantly subjected to loads generated by waves. wind and sea currents. Fatigue is a critical phenomenon that causes the failure of mechanical components exposed to cyclic loads. Unlike other types of failure, it does not require a high load or cause immediate damage; Instead, failure manifests itself after prolonged exposure to repetitive loads, resulting in cumulative damage that progresses to a critical point. The stages of the fatigue process are illustrated in Figure 5.

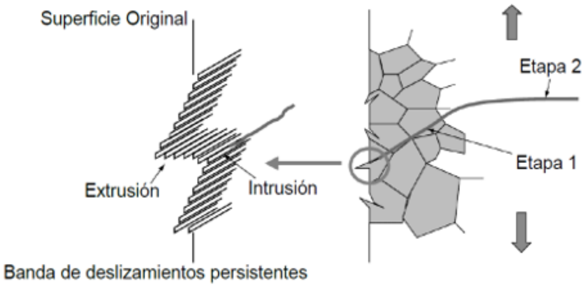

Figure 5. Stages of fatigue on a thin plate under cyclic stress face showing stages 1 and 2. I. López Matus (2016).

Figure 6 shows the phenomenon of crack initiation in steel.

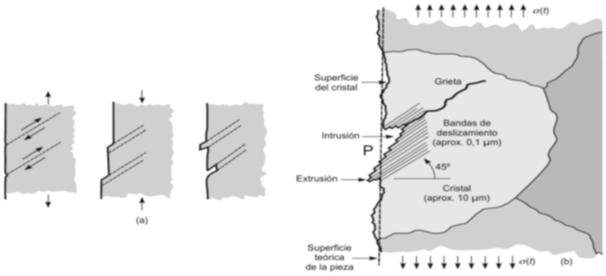

Figure 6. Figure 6 Representation of the Initiation or Nucleation of Cracks in Metals: (a) Initial Landslides, Intrusions and Extrusions, (b) Cracking of a Grain. te: I. López Matus (2016)

5.7. Structural Corrosion and Corrosion Control in River Vessels

Although there is abundant information on corrosion models and processes in marine vessels, specific knowledge on river vessels is limited. Given this lack of data, a corrosion model applied to low-carbon steel pipes in contact with fresh water was taken as a reference [16]. The results indicate that the corrosion rate of carbon steel in freshwater ranges from 0.41 to 0.76 MPY (thousandths of an inch per year). From this rate it is possible to estimate the residual service life of the steel. Based on this model, a thickness loss of 0.5 mm in the sheets of the vessel is estimated over a period of 25 years. It should be noted that this rate could be higher if additional factors such as river temperature, salinity levels, pollution, and the presence of specific bacteria are considered. An additional objective of this work is to provide criteria for the development of corrosion control methodologies in the structure of barges. Anti-corrosion protection is a determining factor for the safety and longevity of river vessels; A proper approach to design, material selection, maintenance, and inspection reduces operating costs and prevents structural failures. In this area, Bureau Veritas [5] has published the "Guidelines for Corrosion Protection Applicable to Inland Navigation Vessels".

5.8. Types of barges

There are four types of barges, Table 1 shows the types of barges, and in Figure 7, you can see barges that operate in the Meta River waterway.

Figure 7. Typical barges operating on the Meta River
Source: The authors.

Table 1. Types of barges

Item	Types
1	Type of Load on Deck
2	Hopper Type
3	Tank Type
4	Dual Type

5.9. Barge data sheet

The barge selected as the object of study is of the "Cargo on Deck" type and operates in the waterway of the Meta River, in the Llanos of Colombia.

Table 2. Barge Dimensional Parameters

Item	Description	Unit	Magnitude
1	Length overall	m	62
2	Beam	m	15
3	Depth	m	2.13
4	Maximum draft	m	1.83
5	Freeboard	m	0.30
6	Lightweight	t	297.64
7	Deadweight	t	1322.19
8	Block coefficient	n.a.	0.97

Table 3. Characteristics of structural elements.

Item	Description	Material	Quantity [m^2/unit]
1	Liner or hull, 3/8 in thick	A-36	2,131.8 m^2
2	Bow and stern plates, 3/8 in thick	A-36	50 units
3	Typical frames in 3/8 in plate	A-36	40 units
4	4 in × 4 in × 3/8 in angled vertical struts	A-36	80 units
5	4 in × 4 in × 3/8 in angled longitudinal bottom reinforcements	A-36	30 units
6	4 in × 4 in × 3/8 in angled longitudinal deck reinforcements	A-36	30 units
7	3 in × 3 in × 1/4 in angled frame cross diagonals	A-36	80 units
8	3 in × 3 in × 1/4 in angled longitudinal diagonals	A-36	100 units
9	Longitudinal bulkhead in 3/8 in sheet	A-36	2 units
10	Collision bulkhead in 3/8 in sheet	A-36	2 units
11	Medium frames in 3/8 in plate	A-36	2 units
12	Small frames in 3/8 in plate	A-36	2 units

Figure 8 shows the structural arrangement of the barge under study.

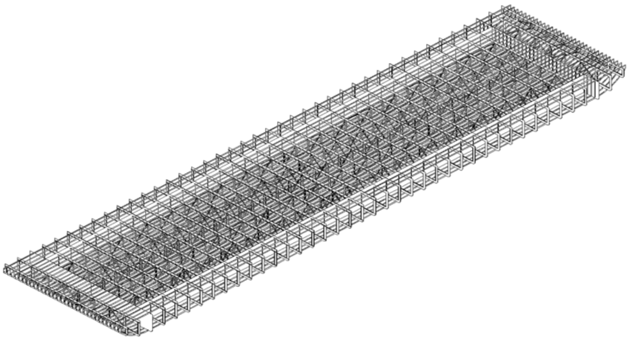

Figure 8. Structural arrangement of the barge
Source: The authors.

5.10. Model Description

The model implemented for the simulations corresponds to the fourth part of the "Deck Load" type barge. This decision is based on the fact that the barge has two planes of symmetry: one longitudinal in the bay and another transverse in the master section, which allows a significant reduction in computational cost (see Figure 9).

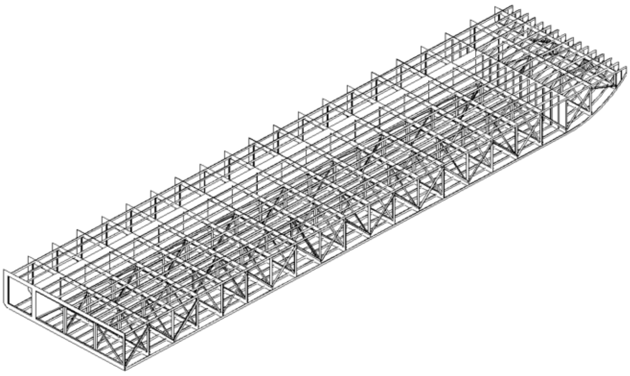

Figure 9. Optimized Model (1/4 Barge)
Source: The authors.

5.11. Design pressures

The design pressures applied to the model were obtained from Lloyd's Register regulations for special vessels, adapted for a river vessel with a wave height of 0.6 m, a vertical speed of 2.61 kt, a draft of 1.8 m and a total displacement of 1 620 tonnes. The resulting values are presented in Table 4.

Table 4. Design pressures.

Item	Description	Value [kg/m^2]
1	Hydrostatic pressure	31.6
2	Hydrodynamic pressure	18.0
3	Pressure on exposed deck	34.1
4	Deck load pressure	8.1

5.12. Acceptance criteria for the levels of efforts obtained

The acceptance criteria refer to the characteristics that the vessel must have to be considered safe in accordance with regulatory requirements. For the hull, these criteria correspond to the levels of permissible stresses, classified as equivalent Von Mises stresses, direct stresses (normal in all directions), and shear stresses. Axial stresses are applied to elements subjected to stress-compression, such as struts.

To define the acceptance criteria for the vessel's design, the parameters suggested by the Lloyd's Register regulations for direct analysis were used as a reference, in which maximum values are defined for longitudinal, transverse and prop elements (see Table 5).

Table 5. Acceptable equivalent forces.

Item	Description of the Structural Element	Permissible Stress [MPa]
1	Longitudinal elements	220
2	Transverse elements	165
3	Struts	157

Note. Lloyd's Register ShipRight Design and Construction.

Table 6 presents the equivalences between the commercial structural profiles and the profiles adopted in the model, in order to facilitate the implementation of the 2D Shell-type elements.

Table 6. Equivalences between commercial and equivalent structural profiles.

Item	Commercial Profile	Equivalent Profile	Property
1	4 in × 4 in × 3/8 in angle as longitudinal deck and bottom reinforcement	Plate 101.6 mm × 18.25 mm	Weight per unit length
2	4 in × 4 in × 3/8 in angle as longitudinal deck and bottom reinforcement in the bay	Plate 101.6 mm × 18.25 mm	Weight per unit length
3	4 in × 4 in × 3/8 in angle as vertical strut	Round or square bar of 18.6 cm^2	Weight per unit length
4	3 in × 3 in × 1/4 in angle as longitudinal and transverse diagonal reinforcement	Round or square bar of 9.1 cm^2	Weight per unit length
5	3 in × 3 in × 1/4 in angle as longitudinal diagonal reinforcement in the bay	Round or square bar of 9.1 cm^2	Weight per unit length

5.13. Model Boundary Conditions

The boundary conditions in a finite element structural analysis define the context of the analysis, and include supports, embedments, constraints, forces, accelerations, and moments acting on the structural element studied. In the model, movement restrictions were configured in the three degrees of freedom in the bow, stern and bay bulkheads. In addition, symmetry conditions were configured on two axes, so that only a quarter of the barge was modeled.

5.14. Model Contacts

In the geometry of the developed model, "Bonded" type contacts were used. This type of contact completely restricts any relative movement between the parts, analogous to a welded joint, and is the most widely used and easiest type to configure.

The bonded contact allows the transmission of compressive and tensile forces, but does not support relative tangential slippage, so friction does not need to be considered. Its formulation is, linear it does not require nonlinear iterations and is based on multipoint constraints (MPC) applied between neighboring nodes in the contact zone, as illustrated in Figure 10. To verify the correct configuration of these contacts, a modal analysis was performed.

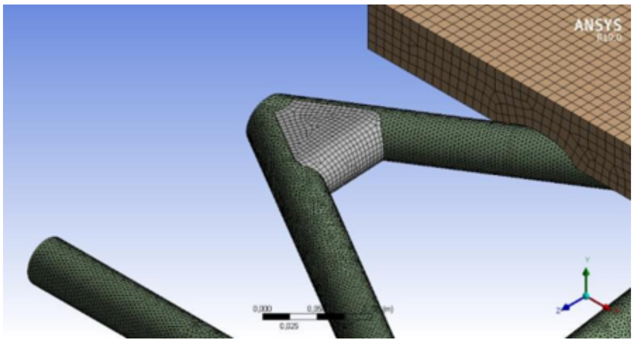

Figure 10. Bonded contact (Cadavis, 2018)

5.15. Loading conditions on the model

The barge under study supports a load of 1,620 tons on its deck. It is also subjected to thrust pressure (hydrostatic pressure on the hull) and moderate waves; these conditions were replicated in the model.

5.16. Ramberg-Osgood nonlinear material model

To describe the nonlinear behavior of structural steel A-36, the Ramberg-Osgood equation was used, a nonlinear expression that relates stress and unit strain in the vicinity of the yield strength of the material.

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{S_{ty}}\right)^{\frac{1}{n}} \tag{3}$$

The first term of the equation describes the elastic part of the deformation and the second term represents the plastic behavior.

- : Unit strain
- : Stress [N/m2]
- E: Young's Modulus [N/m2]
- Sty: Ultimate Effort [N/m2]
- n: Constant depending on the material

The terms of the Ramberg-Osgood equation can be seen in Tables 7, 8 and 9, and in Figure 11 we can see the relationship between real stress vs unit deformation.

Table 7. Ramberg–Osgood equation terms.

Item	Description	Value [MPa] / Dimensionless
1	S_y – Yield stress	250
2	S_u – Ultimate tensile strength	400
3	E – Modulus of elasticity, Young's modulus	200,000
4	ε_L – Total elongation strain, elongation to fracture	20%
5	ε_p – Plastic strain at yield, 0.2% offset	0.2%
6	n – Material constant	0.10206

Table 8. Data for the true stress–strain curve.

Strain [mm/mm] ($\varepsilon_{\text{true}}$)	**Stress [MPa]** (S_{true})
0	0
0.0002	20
0.000300002	40
0.000300002	60
0.000400028	80
0.000500252	100
0.000601506	120
0.000706819	140
0.000825232	160
0.000980011	180
0.001224642	200
0.001671561	220
0.002540666	240
0.00325	250.00
0.005601295	270.00
0.010012481	290.00
0.018008509	310.00
0.032019142	330.00
0.055802488	350.00
0.09502112	370.00
0.158011391	390.00
0.256794098	410.00

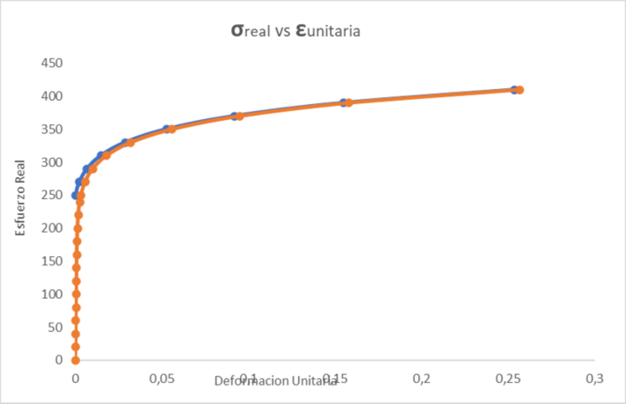

Figure 11. Graph of real stress vs unit strain
Source: The authors.

5.17. Mechanical Properties of A-36 Structural Steel

A-36 steel sheets were selected for the construction of the vessel. This material is a mild carbon steel, characterized by its low carbon content, high ductility and excellent weldability, which makes it ideal for structural applications and shipbuilding for river use.

Table 9. Mechanical properties of A36 steel.

Item	Property	Value	Unit
1	Yield strength	235	MPa
2	Density	7,850	kg/m^3
3	Elastic modulus	200	GPa
4	Ultimate tensile strength	460	MPa
5	Poisson's ratio	0.30	–

5.18. Boundary condition

Movement restrictions were set up in the three degrees of freedom in the bow and aft bulkheads, and a two-axis symmetry condition was established, so that only a quarter of the barge was modeled (see Figures 12 and 13).

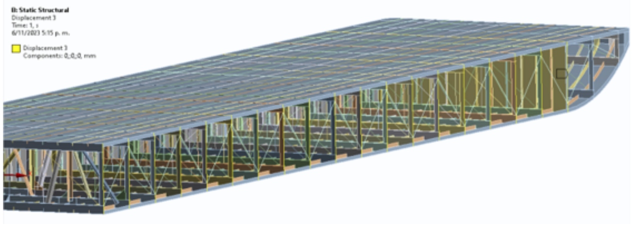

Figure 12. Travel Constraints on Model-01
Source: The authors.

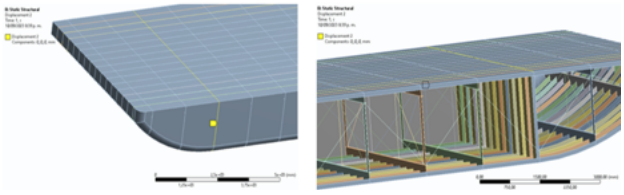

Figure 13. Travel Constraints in Model-02
Source: The authors.

5.19. Corrosion Model for Fatigue Analysis

The plastic collapse of a "Deck Load" river barge can be significantly influenced by the effects of corrosion on carbon steel, the main component of its structure. Corrosion of steel in contact with water is a complex phenomenon, affected by the water quality, temperature and operating conditions of the vessel, factors that can progressively weaken structural strength. In a river environment, where water conditions vary considerably in terms of chemical composition and temperature, corrosion becomes a critical factor capable of accelerating structural deterioration.

Mass loss due to corrosion, especially when not properly controlled, can lead to material thinning that compromises the structure's ability to withstand operational loads. This is especially relevant in the context of plastic collapse, where a reduction in steel thickness can precipitate structural failure under extreme load conditions. Therefore, corrosion not only affects the longevity of the barge, but also plays a critical role in structural integrity and in preventing catastrophic failures.

A thickness loss of 0.5 mm in the boat sheets is estimated over a period of 25 years. However, this rate could increase if additional factors such as river temperature, salinity levels, pollution, and the presence of certain types of bacteria are considered (see Figure 14).

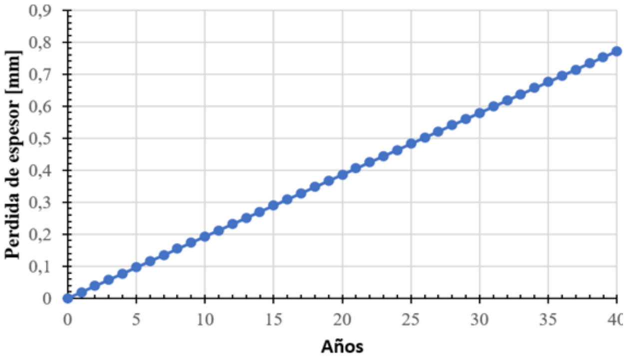

Figure 14. Estimation of sheet thickness losses due to corrosion
Source: The authors.

5.20. Static Resistance Model

For the static resistance model, the Von Mises elastic distortion energy criterion was adopted, in which normal and shear stresses are integrated into the determination of an equivalent stress.

$$\sigma_{VM} = \sqrt{\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 + 3\tau_{xy}^2} \tag{4}$$

5.21. Fatigue estimation model

The evaluation of the fatigue life of the material was carried out using the S-N curve for A-36 steel, using Goodman's failure theory, a stress ratio of 0 and an amplitude ratio of 1.0. A loading pattern was defined based on the loading and unloading cycle of the barge (see Figure 39). Figures 15 and 16 show the S-N curves of A-36 steel.

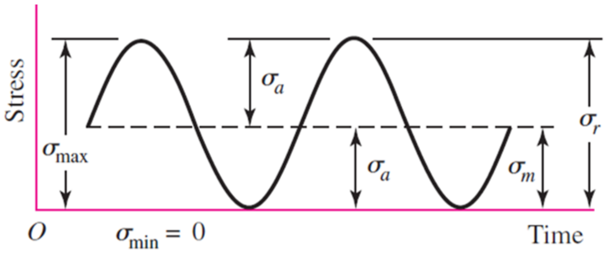

Figure 15. Sinusoidal variation of stress, Shigley's Mechanical Engineering Design.
Source: Richard G. Budynas and J. Keith Nisbett [4].

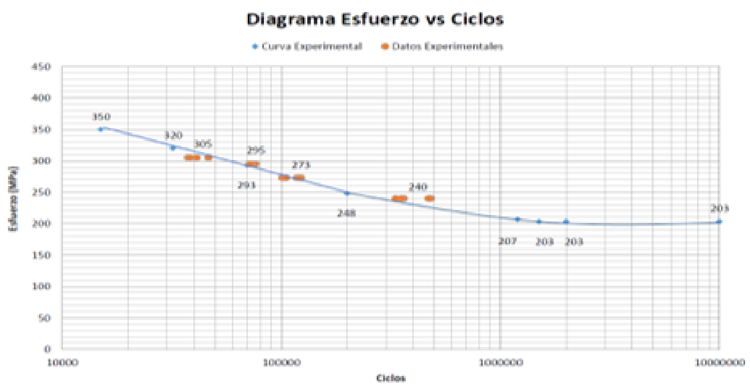

Figure 16. Curve S-N A36 steel.
Source: Alfonso A. Celleri Calle [7]

6. Discussion

The model was built using the BEAM188 and SHELL181 elements, which incorporate the effects of corrosion and fatigue. This approach allows the thicknesses of the cross-sections of all components of the structure to be reduced, which directly affects the ability of the barge to support loads. Corrosion decreases structural strength and accelerates plastic collapse under extreme loads.

The simulation includes the gradual application of loads until the plastic collapse state is reached, which facilitates the evaluation of the barge's response to extreme stresses under conditions of corrosion deterioration. Accurate modelling of the material, which must incorporate elastoplastic properties, is essential to capture the non-linear behaviour of the steel used in the construction of the barge.

The use of symmetry in the model optimizes computational resources and allows a detailed analysis of structural behavior in critical situations, considering the additional weakening caused by corrosion. This goal was effectively achieved (see Figures 17 and 18).

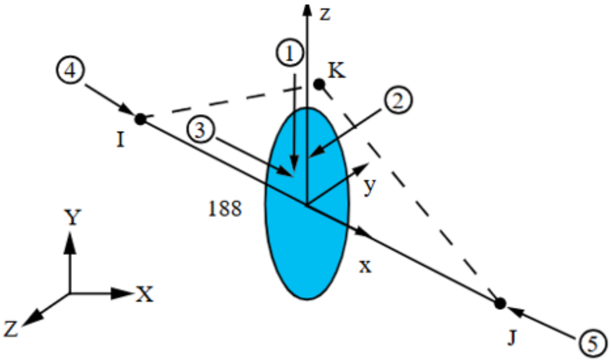

Figure 17. Geometry and node configuration of the BEAM188 element, adapted from ANSYS, Inc. [1].

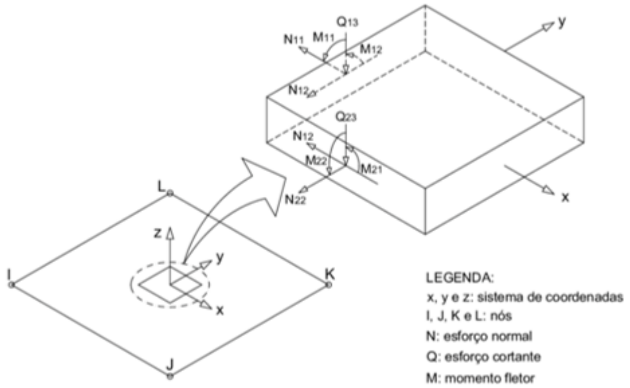

Figure 18. Geometry and node configuration of the SHELL181 element, adapted from ANSYS, Inc. [2].

In relation to the simulation of the model to evaluate the effect of fatigue and its impact on the collapse stress of the structure, it was identified that fatigue failures generally occur in structural details. Therefore, the fatigue life of the previously identified details was evaluated and the most critical was selected as a reference to analyze the effect of thickness reduction due to corrosion (see Figure 19).

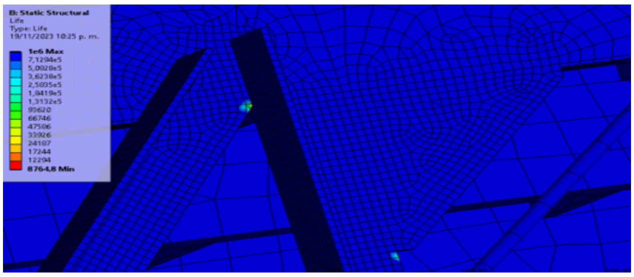

Figure 19. Fatigue life of joints or structural details under cover
Source: The authors.

Fatigue analysis applied to the bottom of the barge, using Goodman's criteria, reveals the presence of significant stress concentrations in this area, which increases its susceptibility to cumulative fatigue damage. This phenomenon is intensified by the reduction of the thickness of the material. As for the equivalent forces on the bottom, the values on the bow are less than 50 MPa; Values above this threshold correspond to singularities of the model. Consequently, a safety factor close to 4.7 is obtained (see Figure 20).

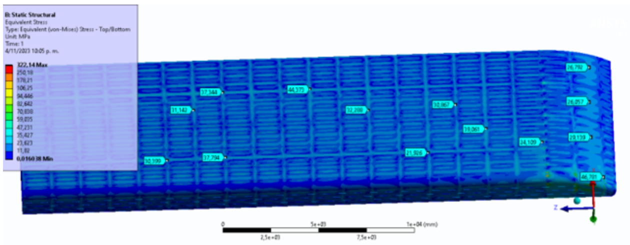

Figure 20. Stresses on the bottom of the barge
Source: The authors.

In the internal reinforcements of the bow region, values close to 160 MPa are recorded in the frames, with a safety factor of 1.5. The longitudinal bottom reinforcements have forces close to 100 MPa, with an associated safety factor of 2.3. On the other hand, the longitudinal deck reinforcements located in the area near the bow plate register forces close to 120 MPa (see Figure 21).

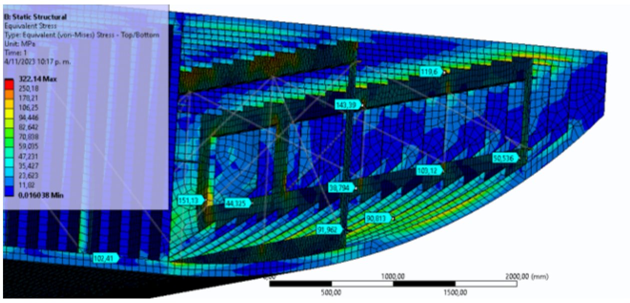

Figure 21. Bottom stress level with simplified braces as one-dimensional elements
Source: The authors.

The bottom reinforcements have average values below 70 MPa; however, in the region of the junction of the braces, the stresses in the varengas amount to 170 MPa. This behavior is due to the fact that the modeling of the braces is performed as one-dimensional elements joined at a single point (see Figure 22).

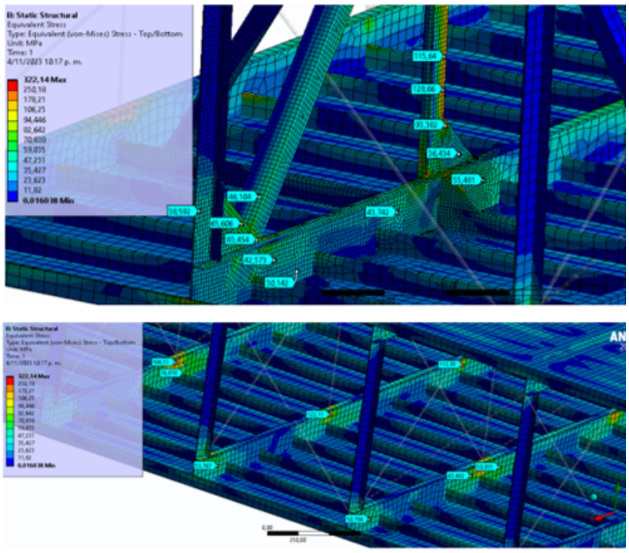

Figure 22. Level of stresses at the bottom of braces modelled as surface
Source: The authors.

The roof, subjected to the environmental and operational loads described in the regulations, has forces on the sheet of less than 40 MPa, resulting in a safety factor of 5.8 (see Figure 23).

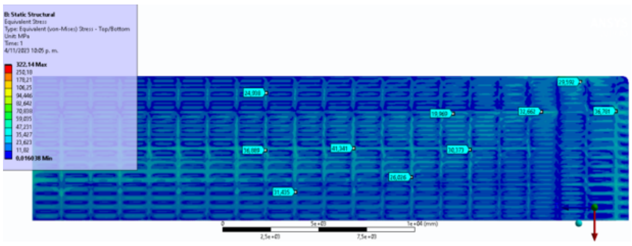

Figure 23. Deck stresses
Source: The authors.

The structural behavior of the roof differs from that observed at the bottom. The variations in stresses seem to be related to the distribution of the load and to the structural response to cyclic stresses. Although fatigue is not the main failure mechanism in this area, the loss of thickness increases the possibility of cumulative damage. In addition, the combination of fluctuating stresses and corrosion could accelerate degradation, compromising long-term structural strength.

Underdeck baths experience stresses close to 150 MPa, especially in the area of connection with the braces, which generates a safety factor of 1.5 (see Figure 24).

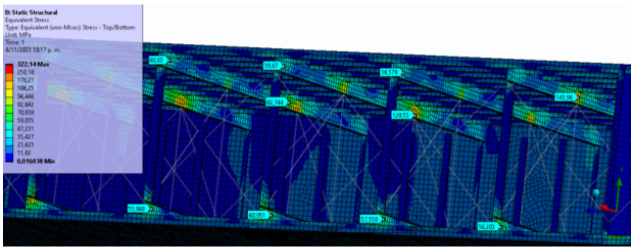

Figure 24. Roof stresses on internal reinforcements with simplified braces as elements
Source: The authors.

When modeling in greater detail the union of the braces with the beams, it was observed that the stresses on the latter, initially close to 150 MPa, decrease to values between 80 and 115 MPa. However, some structural details show stresses close to 125 MPa and 240 MPa. Given their local character, plastic deformation in these areas would not significantly affect the structural arrangement of the vessel (see Figures 25, 26, 27, and 28).

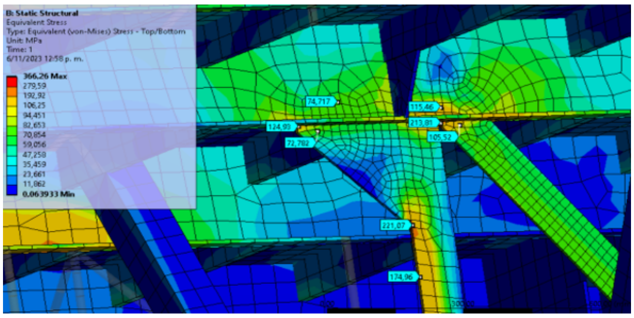

Figure 25. Detailed connection of the braces with the bao
Source: The authors.

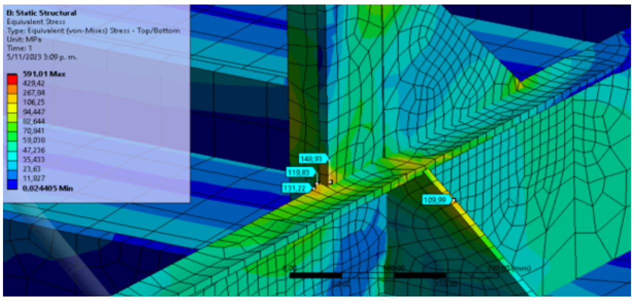

Figure 26. Connection in detail of the braces with the bottom
Source: The authors.

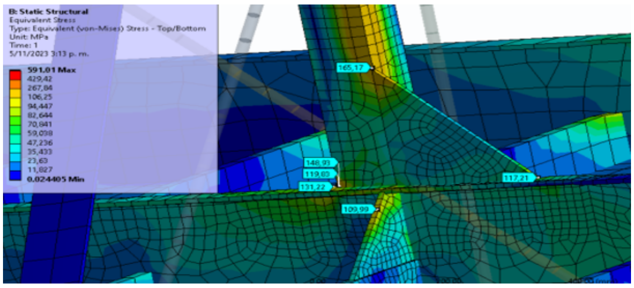

Figure 27. Connection in detail of the braces with the bottom
Source: The authors.

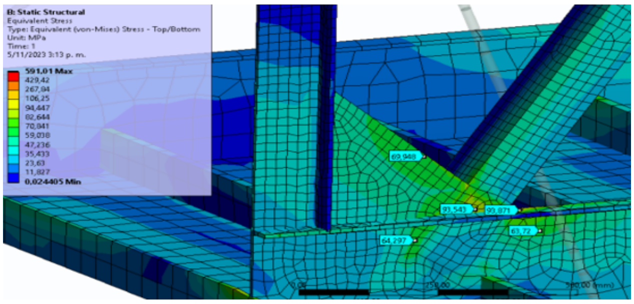

Figure 28. Detailed connection of the braces with the bottom towards the bay
Source: The authors.

The study confirms that fatigue is a determining factor in the plastic collapse of the barge, especially on the bottom, where the combination of high stresses and corrosion severely compromises structural strength. Although the roof has lower criticality, it remains vulnerable under adverse conditions. Therefore, it is essential to implement inspection and maintenance measures to prevent premature failures and ensure the durability of the structure.

The following images illustrate the deflections in the center of the barge under the rub, both with the pressures applied and with its original thickness. It is observed that the center of the barge would experience deflections close to 61 mm, which are within the elastic regime, according to the distribution of stresses presented below (see Figures 29 and 30).

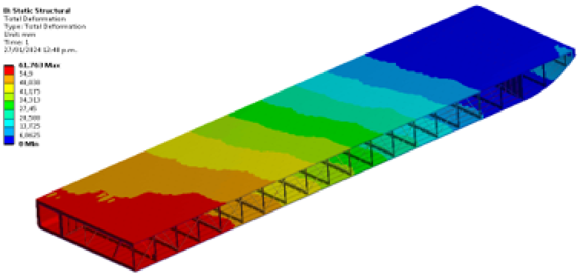

Figure 29. Deflection of the model with its original thickness
Source: The authors.

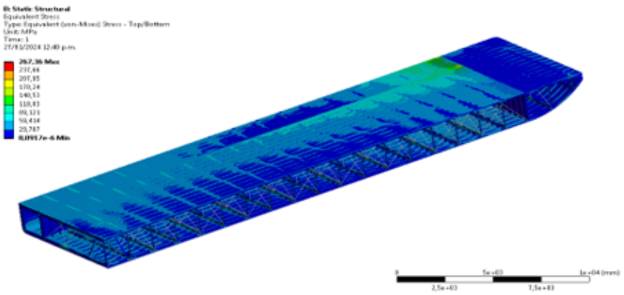

Figure 30. Equivalent stress of the barge model with the original thickness
Source: The authors.

When analyzing the interior of the barge in the middle area, it is observed that the deck presents forces close to 70 MPa, while the reinforcements exhibit a nominal stress close to 65 MPa. Some stress concentrators close to the connection details reach values close to 200 MPa. In this context, it can be concluded that the barge is in a linear-elastic deformation regime (see Figures 31 and 32).

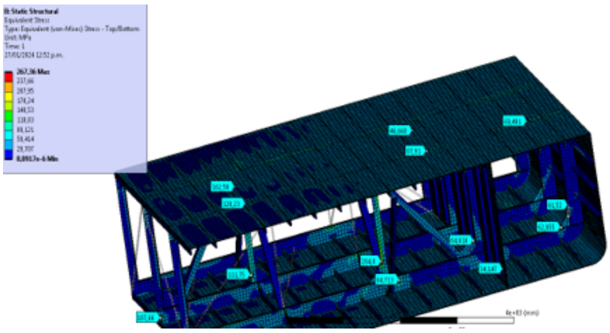

Figure 31. Equivalent stress on the midsection of the barge with the original thickness
Source: The authors.

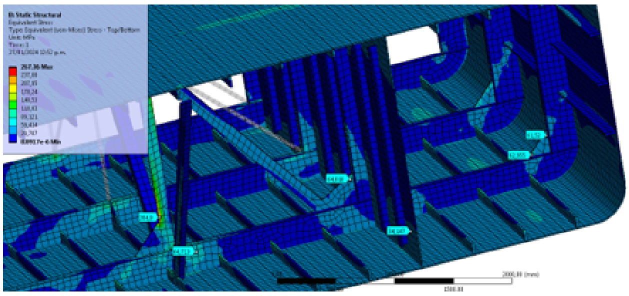

Figure 32. Equivalent stress of elements in the midsection of the barge with the original thickness
Source: The authors.

By reducing the thickness of the structural panels to 8.5 mm, the deflections in the midsection of the vessel increase to 75 mm. The equivalent stresses on the roof are increased to 90 MPa, while the stresses on the internal structure amount to about 100 MPa. Stress concentrations close to certain structural details reach 235 MPa, which corresponds to the yield limit of the material (see Figures 33 and 34).

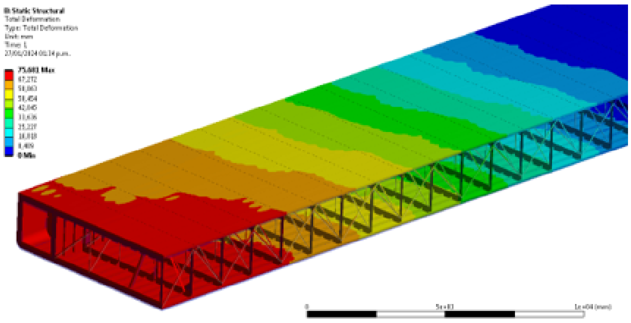

Figure 33. Model deflection with 8.5mm panel thickness
Source: The authors.

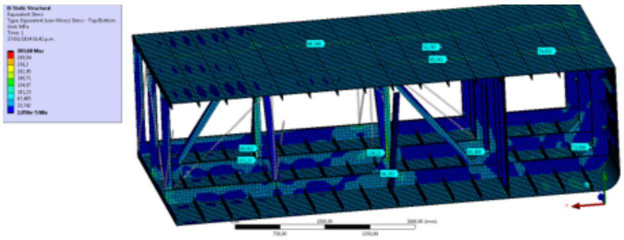

Figure 34. Equivalent stress of elements in the midsection with a thickness of 8.5 mm
Source: The authors.

With a panel thickness of 7.5 mm, the deflection in the midsection of the barge reaches 86 mm and the equivalent stresses on the deck increase to 103 MPa; in some structural details, values of up to 235 MPa are recorded. Once the elastic regime is exceeded, the deformations and stresses cease to maintain a linear relationship; consequently, high deformations produce relatively low increases in stress (see Figures 35 and 36).

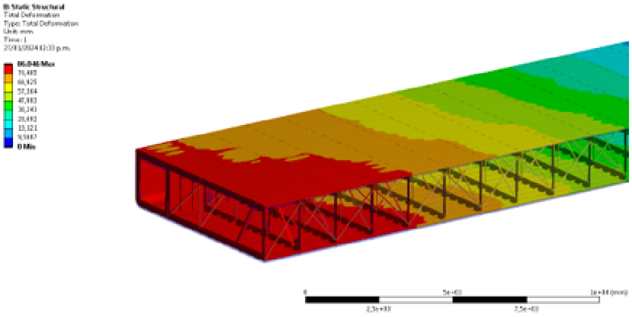

Figure 35. Model deflection with 7.5 mm panel thickness
Source: The authors.

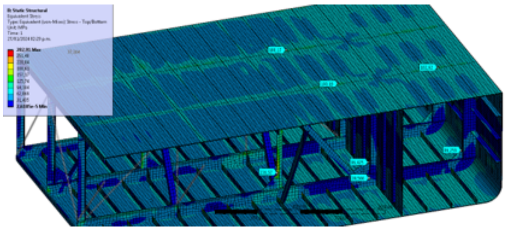

Figure 36. Equivalent stress of elements in the midsection of the barge with a thickness of 7.5 mm
Source: The authors.

By reducing the thickness of the panels to 3.5 mm, the deflections in the middle area of the boat reach up to 300 mm. The general stresses are around 170 MPa, a value that exceeds the equivalent permissible stress for the transverse elements. In addition, a significant proportion of the longitudinal elements experience stresses greater than 220 MPa (see Figures 37 and 38).

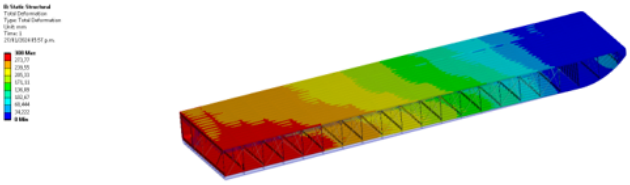

Figure 37. Model deflection with 3.5 mm panel thickness
Source: The authors.

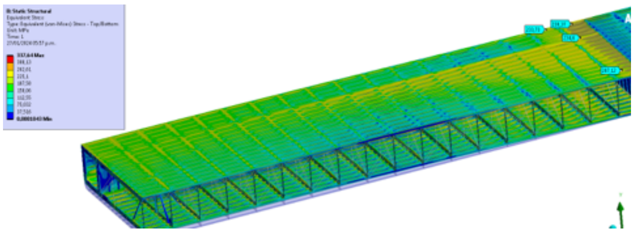

Figure 38. Equivalent Stress of the Barge Model with 3.5 mm Thickness
Source: The authors.

The study determines that the decrease in thickness has a significant impact on structural integrity. It was identified that for every millimeter of reduction in thickness, the equivalent Von Mises stress increases by 14%, indicating that the structure must withstand greater resilient demand in the face of loss of structural capacity. This reduction also has a negative impact on the service life of the barge, reducing it by approximately 9,000 cycles (see Figure 39).

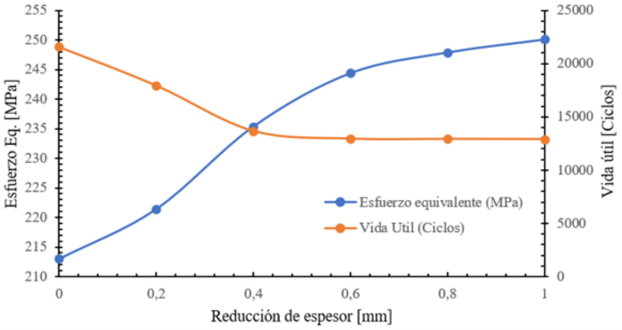

Figure 39. Stress vs. Thickness Reduction & Stress vs. Tool Life
Source: The authors.

7. Conclusions

The study confirms that fatigue is a determining factor in the plastic collapse of the barge, especially on the bottom, where the combination of high stresses and corrosion severely compromises structural strength. Although the roof has lower criticality, it remains vulnerable under adverse conditions. Therefore, it is essential to implement inspection and maintenance measures to prevent premature failures and ensure the durability of the structure.

As the thickness of the structural elements decreases, the barge experiences a progressive increase in deformations and internal stresses. With a thickness of 8.5 mm, the deflection in the midsection increases to 75 mm and the stresses on the structure reach values of up to 235 MPa, which practically coincides with the yield limit of the material. This result indicates that, in such a state of corrosion deterioration, the structure is at the threshold of plastic deformation, a condition that could compromise its integrity if the deterioration continues or the loads increase.

When corrosion reduces the thickness to 7.5 mm, the deformations increase to 86 mm and the internal stresses begin to exceed 235 MPa in certain structural details. At this point, the relationship between stress and deformation ceases to be linear, evidencing a change in the mechanical behavior of the material when it enters the plastic zone: although deformations increase significantly, stresses do not grow in the same proportion. This phenomenon is characteristic of materials that have reached their plastic limit, implying that the structure has lost much of its ability to support additional loads without suffering permanent damage.

The structure of the barge enters the plastic zone when it has lost 21.25% of its original thickness. In the most extreme case – thickness reduced to 3.5 mm – the deflection in the middle zone reaches 300 mm, representing a drastic increase compared to the initial conditions. The general stresses exceed 170 MPa, far exceeding the permissible values for the transverse elements, while the longitudinal elements register stresses above 220 MPa. This scenario confirms that, with such a reduced thickness, the structure enters a critical state of deformation that could lead to the total collapse of the vessel.

Simultaneously, fatigue contributes to cumulative damage that could accelerate vessel collapse.

Regarding the linear analysis of buckling in relation to collapse, the following conclusion is reached:

i. For a thickness of 5mm, the buckle load factor is less than 1, indicating that the structure cannot withstand the applied load without failing.
ii. For a thickness of 7 mm, the factor is 0.96, which still indicates that buckling occurs, although with greater resistance compared to the previous case.
iii. From 7.5mm, the factor is greater than 1, which means that the panels can withstand without buckling failure within the evaluated load range.

This behavior is due to the fact that the thickness directly influences the flexural rigidity of the panels, which determines their ability to withstand loads without presenting excessive deformations.

In conclusion, the reduction of structural thickness has a significant impact on the mechanical response of the barge. If not carefully considered in the design and maintenance stages, it can lead to a drastic decrease in the service life and operational safety of the vessel. Therefore, any modification in the design must be accompanied by a detailed analysis that ensures an appropriate balance between structural efficiency, strength and safety.

Author Contributions: **Arrieta, A.:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization.
All authors have read and agreed to the published version of the manuscript. Refer to the taxonomía CRediT for term explanations. Authorship should be limited to those who have contributed substantially to the work reported.

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Institutional Review Board Statement: Not applicable, since the present study does not involvehuman personnel or animals.

Informed Consent Statement: This study is limited to the use of technological resources, so nohuman personnel or animals are involved.

Conflicts of Interest: Under the authorship of this research, it is declared that there is no conflict of interest with the present research.

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