Aesthetic Integration of Structural Elements: Joaquim Cardozo's Legacy in Modern Architecture

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Abstract. In established architectural projects, the structure serves as a guiding parameter, meaning architecture is designed simultaneously with the structure. "Once the structure is complete, the architecture is already present, simple, and beautiful" (NIEMEYER, 2002). In modern Brazilian architecture, the role of structure in the composition of buildings is particularly noteworthy. Structural elements are often incorporated in an apparent manner, directly linked to the building's aesthetics. Engineer Joaquim Cardozo's works highlight several structural elements with these features, including the arches of the Alberto Torres Rural School in Recife (1935), the shells of the *Igreja de São Francisco de Assis* in Pampulha (1943), and the columns of the *Igrejinha Nossa Senhora de Fátima* in Brasilia (1957). In this study, we analyze these and other structural elements calculated by Joaquim Cardozo, using the software SAP2000. Our goal is to identify the significant contribution of the engineer and his structural solutions to modern Brazilian architecture, while also highlighting the relationship between structural systems and architectural aesthetics.

Keywords: Structural Elements; Modern Architecture; Numerical Analysis; Joaquim Cardozo

1 Introduction

Brazilian architecture has been recognized worldwide for its unique blend of modernist Brazilian architecture is renowned for its blend of modernist and regional vernacular influences [1]. This synthesis is exemplified in the works of architects like Oscar Niemeyer, who sought to harmonize structure and form [2].

Engineer Joaquim Cardozo was a key figure in integrating structural and architectural elements, collaborating extensively with Niemeyer and others [3]. Cardozo actively elevated structure as an integral aesthetic component, rather than just a functional necessity. Cardozo's multifaceted talents as a poet, artist, and engineer enabled him to uniquely integrate the technical and artistic aspects of his work, elevating the aesthetic expression of architecture through his distinctive structural designs [4].

Cardozo was recognized and celebrated by his peers, including renowned figures such as Jorge Amado, Oscar Niemeyer, and Candido Portinari. In 1961, Modulo magazine dedicated an entire issue to Joaquim Cardozo, featuring contributions that exalted his career as a Master of Works and arts, highlighting his significant contributions to engineering, poetry, architecture, and historical heritage preservation.[5][6]

This research paper aims to analyze the role of structural elements in the aesthetic composition of modern Brazilian architecture, with a particular focus on the work of Joaquim Cardozo.

2 Joaquim Cardozo - Engineer of Poetry

Joaquim Cardozo, known as the "Engineer of Poetry", was a highly cultured individual, according to Oscar Niemeyer, the most cultured man he had ever known. Cardozo had diverse intellectual interests, serving as a poet, writer, engineer, and more [7]. He was a key figure in the modernist movement that shaped modern Brazilian architecture, working alongside Luís Nunes and Roberto Burle Marx in the 1930s, in the Directory of Architecture and Urbanism in Recife-PE.

Cardozo also played a crucial role in enabling the realization of various works by architect Oscar Niemeyer, including the design of the Pampulha Complex in Belo Horizonte, considered a milestone in Brazilian Modernist Architecture. He also contributed to the design of major buildings in Brasília, such as the Alvorada Palace, the Planalto Palace, the Cathedral, and the National Congress [8].

Cardozo's educational path was unconventional - he interrupted his engineering studies in 1919 to serve in the army and work as a surveyor, only resuming and completing his studies in 1930. During this period, he actively participated in the modernist movements of the *Semana de Arte Moderna*, showcasing his talents in artistic and intellectual circles. Cardozo's work reflected his political and social stance, championing the underprivileged and criticizing elites whose actions perpetuated the "drought industry" in the Northeast. This stance led to his imprisonment on two occasions, including in 1939 by the Estado Novo regime.

Cardozo's diverse intellectual interests and engineering background were evident in his poetic production, which demonstrated his ability to fuse art and science. His poetry, described as "crystalline" by Jorge Amado, also revealed his social consciousness and commitment to the people of the Northeast. [6].

2.1 Structural Expressiveness in Modern Brazilian Architecture

Structural elements as aesthetic features define modern Brazilian architecture [9]. Key architects like Oscar Niemeyer consciously highlighted the building's structure, integrating it into the overall design. This was influenced by Joaquim Cardozo, who developed innovative structural solutions that were technically efficient and visually striking. Cardozo enabled architects like Luiz Nunes and Niemeyer to seamlessly integrate structure and architecture. His approach elevated the functional aspects of the artistic realm, shaping the visual language of modern Brazilian architecture. Cardozo's structural solutions were not just technically efficient, but also visually striking, making his work prominent in the Brazilian modernist movement. [10]

In the Alberto Torres Rural School in Recife, Luiz Nunes' design incorporated Cardozo's expressive use of reinforced concrete arches, which served a structural function and became a defining architectural element [11]. Similarly, in Oscar Niemeyer's iconic *Igreja de São Francisco de Assis* in Pampulha, Cardozo's intricate calculations and design of the thin, sinuous concrete shells that form the roof and walls directly contributed to the building's sculptural aesthetic [2]. Likewise, in Niemeyer's *Igrejinha Nossa Senhora de Fátima* in Brasília, Cardozo's elegant column design, with flared bases and tapered tops, is a defining feature that imbues the structure with a sense of lightness and grace.

Cardozo's structural contributions are also evident in other iconic Brasília buildings, such as the Cathedral of Brasília and the National Congress building, where the integration of key structural elements into the overall aesthetic composition is discernible, further exemplifying his impact on the architectural character of the city.[12]

Cardozo's ability to seamlessly integrate structural and aesthetic considerations in his engineering solutions played a pivotal role in shaping the distinctive visual language of modern Brazilian architecture. By elevating the functional aspects of construction to the realm of the artistic, Cardozo's work fundamentally influenced how architects of his time approached the design process, allowing them to create buildings that were not only technically sound but also expressive.[12]

3 Numerical Analysis of Structural Elements

To better understand the structural and aesthetic contributions of Joaquim Cardozo, we have conducted a numerical analysis of several of his key works using the SAP2000 software.

3.1 Arches of the Alberto Torres Rural School - Recife

The Alberto Torres Rural School in Recife (Fig. 1), designed by Luiz Nunes in 1933, features a series of three reinforced concrete arches spanning the length of the building's façade. These arches, engineered by Joaquim Cardozo, have a span of 13.30 meters and a height of 6.55 meters. The arches support the ramps providing access to the school's second floor through concrete tie rods.

Figure 1. Escola Rural Alberto Torres Recife-PE, projeto do Arq. Luiz Nunes, construído em 1935-36. Source: Escola Alberto Torres (escolalbertotorres.wixsite.com)

Using the SAP2000 software, we have modeled the arches and analyzed their structural behavior. Our analysis reveals that the displacement diagram (Fig. 2) clearly shows significant displacement of the roof on the upper landing of the ramp - at the arrival to the second floor - reaching -9.21 cm. This excessive displacement would not be considered acceptable by today's engineering standards, but at the time, NB1 - first Brazilian code for concrete construction was still under development.

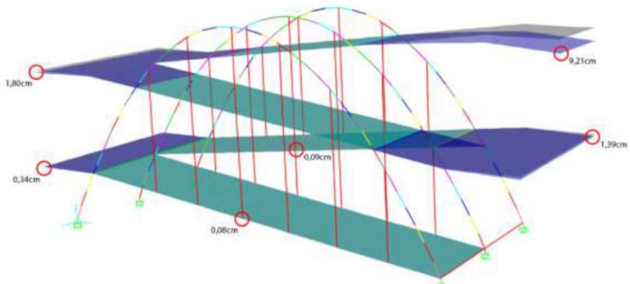

Figure 2. Diagrama de deslocamentos da rampa de acesso da Escola Rural Alberto Torres. Source: Desenho do Autor, Programa SAP 2000 [4]

The slab in this section has a thickness of only 8 cm at the final edge, creating a sense of lightness that deserves notice. In contrast, the displacements in the sections contained within the arches, supported not only by the arches but also by the concrete tie rods, exhibit negligible displacements, in the order of -0.13 cm. [4]

From this numerical analysis, it becomes evident that Cardozo's structural solutions, while innovative and expressive, also pushed the boundaries of engineering at the time.

More importantly, the arched structure not only served a practical structural purpose but also became a defining aesthetic element of the building, exemplifying Cardozo's ability to seamlessly integrate engineering and architecture.[4]

3.2 Shells of the Church of São Francisco - Pampulha

The Church of São Francisco de Assis in Pampulha, designed by Oscar Niemeyer in 1943, is widely regarded as one of Niemeyer's most iconic works. Joaquim Cardozo was responsible for the structural design of the church's distinctive thin concrete shells that form the roof and walls. [2]

The *Igreja de São Francisco de Assis* features a complex structural composition, including a reinforced concrete shell forming the parabolic dome roof of the main nave, supported on a radial slab, with a variable height ranging from approximately 8.5 to 15.5 meters over a length of 19.9 meters. Additionally, the structure incorporates a set of three arched concrete shells for the sacristy, with a constant height of 7.2 meters, contrasting with the lateral arches. The marquee and bell tower further complement the structure.[4]

The structural analysis of the *Igreja de São Francisco de Assis* reveals that the main shell is under pure compression, a condition well-suited for its arch-like design. The compressive forces range from -6.8 to -16.8 Tonf (Fig. 3). The gradual reduction in the arches' cross-section helps mitigate "edge disturbances" and potential bending stresses. The vault shell exhibits high rigidity, as evidenced by the displacement diagram (Fig. X) for the main structure, and displays very small displacements, ranging between 0 and 0.03 centimeters.

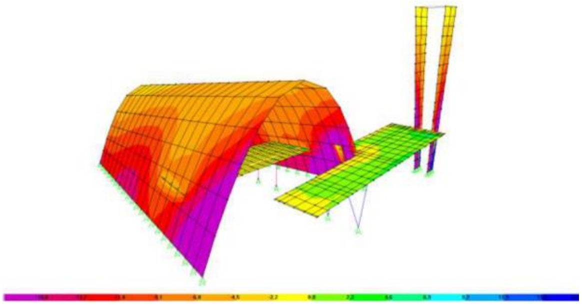

Figure 3. Normal Forces Diagram for *Igreja São Francisco de Assis* SAP 2000. Fonte: PEREIRA, 2012 [2].

The numerical analysis highlights how Cardozo's innovative structural design directly contributed to the expressive and sculptural aesthetic of the church, creating a seamless integration of architecture and engineering.[2].

3.3 Columns of the *Igrejinha Nossa Senhora de Fátima* - Brasília

In the design of the *Igrejinha Nossa Senhora de Fátima*, also by Oscar Niemeyer in Brasília, Cardozo's structural solutions were again instrumental in shaping the building's aesthetic.

The architecture of the *Igrejinha Nossa Senhora de Fátima* (Fig. 4) is characterized by its simplicity, featuring only three basic elements: two structural walls, three external columns, and a curved roof. The three columns, with their wide bases and slender tops, support the church's roof, creating a simple and welcoming environment for the congregation.

Figure 4. Front view of the Igrejinha Nossa Senhora de Fátima. Source: Photo by Author.

The structure, entirely made of reinforced concrete, consists of a variable-thickness triangular curved roof, supported by five curved beams of varying heights, resting on the three wide-based columns as well as two structural walls. The ingenuity of Engineer Joaquim Cardozo's structural solutions was instrumental in shaping the building's distinctive aesthetic.

Observing the Bending Moment Diagrams (Fig. 5) of the structural system of the *Igrejinha*, we can see that the form of the *Igrejinha* is directly related to its structural system. We need to notice how the design of the Bending Moment diagram in the column resembles the form the architect used in this element.

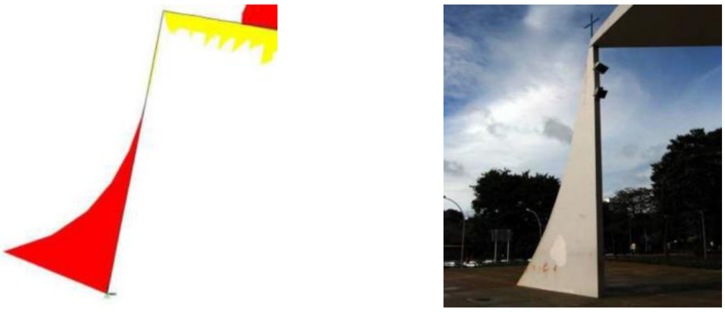

Figure 5. Bending Moment Diagram compared to the built column of the *Igrejinha Nossa Senhora de Fátima*. Sources: Author´s design, SAP 2000. Photo by Authors.

The *Igrejinha Nossa Senhora de Fátima* presents a characteristic formal simplicity, which makes it unique and recognized worldwide. This simplicity was achieved through a complete harmony between the adopted structural system and the intended architectural design, from the beginning of the design process [8].

3.4 Columns of the Palácio da Alvorada – Brasília

In the design of the Palácio da Alvorada, the official residence of the President of Brazil in Brasília, Cardozo's structural solutions were again instrumental in shaping the building's aesthetic.

The Palácio da Alvorada (Fig. X), constructed in 1956, was the first palace built in Brasília. Its distinctive column supports, which appear to barely touch the ground, were the result of engineer Joaquim Cardozo's ingenious solutions.

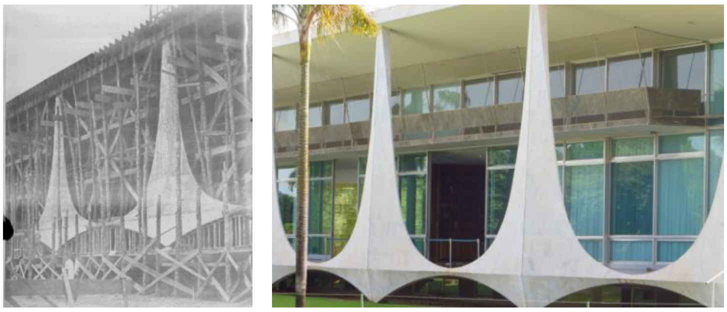

Figure 6. Columns of the Alvorada Palace, during construction in 1956 and on actual days. Sources: Modulo Magazine, 1961, Vol. 26, p. 7 and Folha de São Paulo (by Pedro Ladeira).

Cardozo designed internal supports to carry the bulk of the loads, reducing the visual impact of the external columns. Additionally, the roof slab is discontinuous in the veranda section, gradually decreasing in thickness towards the columns, further minimizing the load transferred to the facade columns.

The palace's design features a robust central body and a lighter, curved external veranda, with the external columns sustaining only the loads of the roof slab and veranda floor slab. Cardozo also concealed the structural supports within the main volume to create the impression that the columns are resting on the ground by recessing the true column supports and burying them after backfilling [12].

A simplified structural analysis using the Ftool program, as shown in Figure 7, reveals that despite their striking visual appeal, the columns of the Palácio da Alvorada adhere to a coherent structural system, as evidenced by the bending moment diagram. Using these structural engineering techniques, Cardozo was able to create the impression of elegant, almost weightless columns, as proposed by the architect Oscar Niemeyer, while ensuring the building's structural integrity.

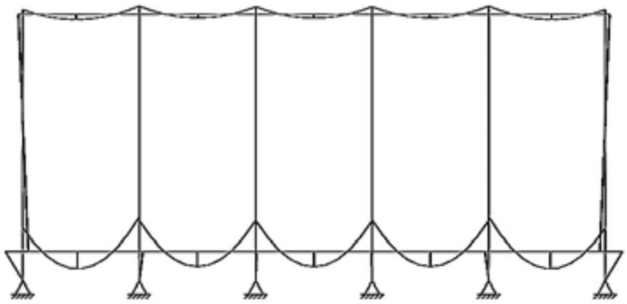

Figure 7. Bending moment diagram for a simplification of the façade of the Alvorada Palace. Source: Author's drawing. Software FTOOL.

Cardozo's structural solution for the innovative column design became emblematic of Brasília's architectural style, exemplifying his pivotal influence on modern Brazilian architecture. Moreover, this structural configuration imparted a sense of visual lightness to the building's aesthetic [1].

3.5 Museu da Cidade - Brasília

The City Museum (Fig. 8), is the oldest museum in Brasília, the capital of Brazil. Designed by Oscar Niemeyer in 1958, the museum was built to document the construction of Brasília and has since been recognized as historical heritage by the government.

Figure 8. The City Museum, in Brasília. Source: Photo by Júnior Aragão.

The museum structure is a longitudinal reinforced concrete block measuring 5.00 m x 35.00 m, formed by two C-shaped beams. The block is supported by a cube structure, composed of two pillars, which house the staircase access and service areas. The design of this apparent monolithic form, resting on a single supporting element, gives rise to two visually striking cantilevers.[13]

Figure 9 indicates the displacements at the ends of the "C" beam that forms the main block of the City Museum. The analysis shows that the maximum displacement at the end of the largest cantilever is approximately 1 cm, a value well below the current allowable standards. Additionally, the analysis reveals a moment concentration at the intersection of the beams and the support column, where the moment reaches 30,517 kN.m. Furthermore, a maximum compressive stress of 7,115 kN is observed at the base of the columns.

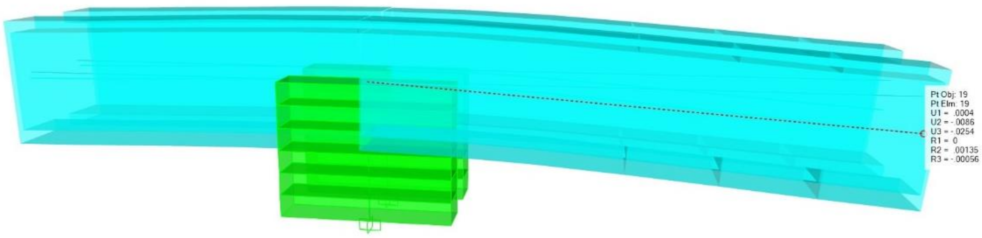

Figure 9. Displacements Diagram for the City Museum. Developed by the authors (SAP 2000)

The analyzed data show that the structural elements of the City Museum building are larger than the minimum required by current standards under the conditions surveyed. This demonstrates Cardozo's ingenious structural solutions that enabled Niemeyer's architectural vision, characterized by bold cantilevers and an apparent structural simplicity.

3.6 Columns of the Cathedral of Brasília – Brasília

The Cathedral of Brasília, designed by Oscar Niemeyer and inaugurated in 1970, is one of the most iconic examples of Niemeyer's architectural style. In the design of the Cathedral of Brasília Cardozo's structural engineering solutions were once again instrumental in shaping the building's distinctive aesthetic.

While the architectural program and floor plan of the ensemble may appear simple, the structural solution adopted is remarkably complex and it remains the Cathedral's defining highlight.

The structural design of the Cathedral consists of 16 hyperbolic paraboloid columns arranged in a 60-meter diameter circle. The columns are supported by two reinforced concrete rings: the first, surrounding the base, functions as a tension tie to absorb horizontal stresses; the second, in compression, passes through the columns at their juncture and prevents inward closing. The roof slab serves solely as a cladding element without structural function.

Figure 10 presents the shear force diagrams along the vertical Y-axis and the bending moment diagrams, as determined by PESSOA in 2002 using the SAP 2000 program [14]. These diagrams demonstrate that the variations in the Cathedral's column cross-sections are directly related to the increasing stresses acting on the structure. The columns are designed with larger cross-sections in the regions experiencing higher bending moments and shear forces, in order to provide the necessary structural capacity and safely support the loads acting on the building.

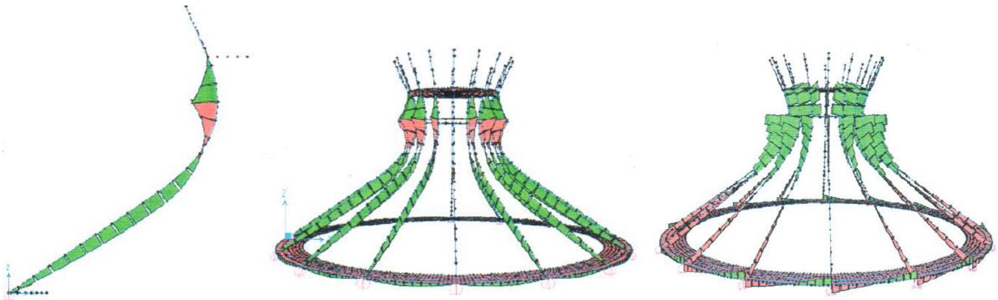

Figure 10. Bending Moment Diagram and Sheer Forces Diagram for the Cathedral of Brasília. Source: PESSOA, 2002, SAP 2000 [14].

Brasilia´s Cathedral is a distinguished building, its innovative form has no relation to any other building in the world, It is one of the most remarkable achievements of modern Brazilian architecture. Cardozo's structural solutions were fundamental in allowing Niemeyer to realize his bold architectural vision, “When the structure is complete, the architecture is already present.” Niemeyer *appud* [8]

3.7 Inverted Dome of the National Congress - Brasília

In Brasília, the National Congress building designed by Oscar Niemeyer also prominently features Joaquim Cardozo's innovative structural solutions, particularly in the design of the inverted dome that crowns the Deputies Chambers. Figure 11 shows a design drawing of the dome, published in Modulo Magazine [5].

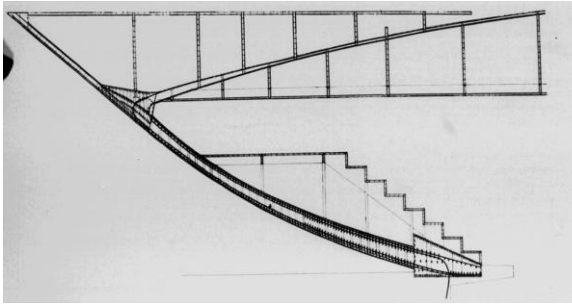

Figure 11. Drawing of the structural design of the inverted dome of National Congress, published in Modulo Magazine. Source: Modulo Magazine, 1961, Vol. 26, p. 18.

The structural system designed by Joaquim Cardozo to enable Niemeyer's architectural vision for the inverted dome is composed of three concrete shells. The first shell is a surface of a "zone of a revolution ellipsoid, below the equator" (Cardozo appud [15]). Resting on this first shell is a second shell, a surface of an inverted truncated cone, which, by meeting the first shell at a point of tangency, creates a seamless visual continuity, appearing as a single structural element. At the junction of these two shells, an intermediate concrete ring supports the third shell, an extremely lowered concave spherical cap that in turn supports two slabs - a horizontal ceiling slab and an upper, flat slab with a circular void at the center. This final system of the third shell, ceiling slab, and upper slab is interconnected through a series of 10x10cm square reinforced concrete columns and tie rods, which hold the upper slab in place and support the ceiling slab. This innovative structural configuration spans a 62-meter diameter, leaving the entire plenary hall below unobstructed[8].

Our numerical analyses, using the SAP 2000 software to model the structural system, reveal that the Normal Force diagram of the inverted dome indicates a concentration of forces in the first shell, the base of the inverted dome. In contrast, the stresses are much lower in the region of the second shell, which is tangentially connected to the first at the point where the intermediate ring is located.

Furthermore, the Bending Moment diagram, depicted in Figure 12, shows that the moment is greater in the first shell and decreases considerably in the second shell. We also observe a significant increase in the moment near the junction of the two shells and at the base of the first shell, where the intermediate and lower rings are positioned to provide the necessary structural support [15].

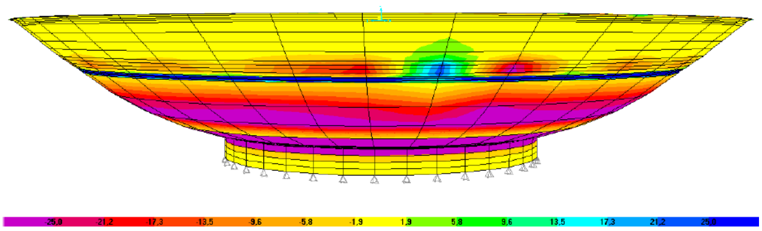

Figure 12. Bending Moment Diagram for the Inverted Dome of the National Congress. Source: Author´s design, SAP 2000.

The structural analysis reveals how Cardozo's innovative solutions enabled Niemeyer's architectural vision for the inverted dome, a defining feature of the National Congress building. Cardozo's ingenious structural system not only provided the necessary support for the inverted dome but also contributed to its striking visual expression, which has become an iconic symbol of Brasília's architectural identity.

4 Conclusions

Through our numerical analysis of several key architectural works engineered by Joaquim Cardozo, it is clear that Cardozo's innovative structural solutions played a pivotal role in shaping the visual expression and aesthetic quality of modern Brazilian architecture.

Cardozo's structures, whether arches, shells, columns, or inverted domes, were not merely functional elements, but were seamlessly integrated with the architectural design to create buildings of remarkable beauty and grace. Cardozo's ability to reconcile the demands of structure and the aspirations of architecture was instrumental in the development of a distinctive Brazilian modernist aesthetic [16]

Joaquim Cardozo was a pivotal figure in shaping the cultural landscape of Brazil during the Modern Movement. He made significant contributions not only in the fields of poetry and literature but also through his socially-oriented political involvement. However, his most profound impact was in the realm of architecture, where his innovative structural solutions played a crucial role in the creation of a distinct and celebrated Brazilian modernist aesthetic during the 1950s and 1960s. Cardozo's structural designs, seamlessly integrated with the architectural vision, were instrumental in the development of some of Brazil's most prominent modernist buildings, solidifying well-known Brazilian Architecture.[10].

A comprehensive numerical examination of the innovative structural components designed by Joaquim Cardozo is essential for fully comprehending and appreciating the exceptional quality, technical sophistication, and engineering excellence that underpinned the iconic modernist buildings he contributed to.

Such in-depth structural assessment illuminates how Cardozo's ingenious solutions harmoniously integrated structure and architecture, enabling the actualization of visually compelling and functionally resilient designs that have become emblematic of Brazil's modernist architectural heritage. This rigorous analysis sheds light on the central protagonism that Cardozo's structural innovations played in shaping the aesthetics and technical prowess of modern Brazilian architecture during its formative period.

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