Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Contribution of structural intuition at early conceptual stage in efficient workflow: A precedent study of Oscar Niemeyer

Irem SEREFOGLU[*], Luiza Souza WANDERLEY[a], Remo PEDRESCHI[b], Miguel Paredes MALDONADO[b]

[*] The University of Edinburgh
iserefog@ed.ac.uk

[a] Bouygues TP
[b] University of Edinburgh

Abstract

Complex forms necessitate a detailed understanding of form, structure, and architecture through a multi-disciplinary collaboration of the core players of the design team. The impact of design changes on the project's total cost becomes more detrimental as the project develops. The desired design efficiency is a result that is aesthetically pleasing, structurally efficient and easy to build for sustainable and innovative structures that comply with the budget [1]. Some scholars state that to optimise form, the designers need structural intuition, a skill that is explained as an innate understanding of the functional requirements of a structure [2]. This paper will explore how structural intuition affects design efficiency from an architectural point of view by looking at the work of the world-renown Brazilian architect Oscar Niemeyer. His work stands out with intrinsic detail to fine architecture, early-stage contribution of structural intuition and interdisciplinary design development. This paper identifies the critical elements of his design workflow which are exemplified through two case studies of his works: The University of Constantine (1972) and the National Congress (1960). Qualitative and quantitative analysis is conducted through a structured precedent analysis involving computational modelling, literature review and 3D printing to prove structurally intuitive design methods. The output of this evaluation demonstrates efficient workflow through learning from precedent studies and the application of parametric modelling.

Keywords: conceptual design, morphology, form finding, parametric design, digital fabrication, optimisation, concrete shells, precedent-based design, efficiency, workflow

1. Introduction

The disciplines of architecture and engineering have been inextricably linked throughout the history of the built environment. The evolution of new technologies, encompassing advanced tools, materials, and production techniques, has consistently spurred changes in these domains [3]. Moving away from the rectilinear paradigm, modern architectural trends push the limits of material and expression. The interaction between the two disciplines spans a broad range, from a cohesive vision of structure and architecture to a complete disregard for structural performance in favour of aesthetics [4]. This interplay is reflected in the collaborative relationship between architects and engineers during the design process.

The inseparable nature of the two disciplines merged within the work of master builders, single handedly designed, managed, and executed. In earlier times, architects or builders possessed only limited knowledge of construction but were ultimately responsible for all aspects of the building process. This required a multifaceted skill set, including artistic talent, materials expertise and an understanding of structural behaviour [5].

Despite the integration of complex forms and efficient design workflows, a prevailing trend exists where structural engineering considerations are seldom the primary focus at the beginning of an architectural design process, owing to the multitude of other concerns that need to be addressed. Conversely, architectural considerations are often not prioritized in structural engineering projects [6]. Key discussions within this interdisciplinary tension involve material selection, form and structure exploration, and proportion determination.

By incorporating complex forms and adopting efficient design workflows, architects and engineers can cultivate a stronger collaboration and develop more comprehensive solutions that effectively balance aesthetics, structural performance, and constructability [7]. This integrative approach has the potential to reshape the future of the built environment, as professionals from both disciplines work together to push the boundaries of design and engineering.

2. Workflow from the conceptual design phase

Modern construction projects often involve a linear design workflow where stakeholders possess separate goals and complications, leading to fragmented development of the project [8]. This fragmented process results in over-budget and inefficient buildings, particularly in large-scale complex projects where many stakeholders, materials, design challenges, and environmental impacts are involved [9].

Architects, structural engineers, civil engineers, and building services engineers have declared their commitment to addressing climate and biodiversity emergencies [10] [11]. However, achieving these common goals is challenging due to the fragmented nature of traditional linear workflow. Historically, architects and engineers have been associated with different parts of the building industry, leading to a lack of common design language [6] [12]. This fragmentation is reinforced by education and specialization of disciplines [13]. Despite advancements in modern digital tools and construction techniques, linear workflow fails to achieve a balance between aesthetic, structural, functional, and construction-related objectives. A more efficient and collaborative workflow model is required.

Modern architecture has introduced new dimensions to the traditional methods of construction, and it has had a tremendous effect on introducing new approaches to the aesthetic understanding of the built environment. Complex geometric forms in modern architecture can be designed more efficiently, more cost-effectively, and construction-friendly whilst minimising material usage when carefully considered structural intuition is accepted into the conceptual design phase. Careful and thoughtful consideration is need to ensure that project remains true to the early conceptual design decisions. Additionally, incorporating environmental considerations as early as the conceptual design phase can reduce the cost of later changes, as indicated by the MacLeamy Curve, shown in Figure 1.

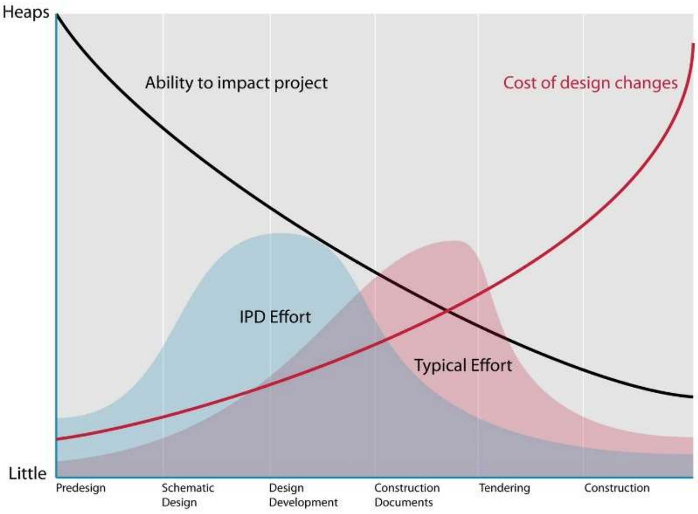

Figure 1. The MacLeamy Diagram [14]

The MacLeamy Design Effort/Effect Curve is a chart used to demonstrate the need to optimize the design process of complex design projects. According to the curve, the earlier in the design process that key decisions (such as structural concept) are made, the more efficient the design process will be. Conversely the curve also suggests that the later in the design process that changes are made, the more costly and time-consuming they become.

Digital form-finding tools can facilitate efficient design of complex forms, but they require a change in workflow approach and seamless collaboration between architects and engineers. The Foundation Louis Vuitton by Frank Gehry, which exceeded its budget eight times, exemplifies the inefficiency that can result from post-rationalization of form despite using modern digital tools [15] [16].

3. Methodology and case study analysis

This paper focuses on Oscar Niemeyer and his works as contemporary examples of efficient design workflow, which incorporate structural intuitions early in the conceptual design that is demonstrated through an examination of the development of the structural design of some of his distinguished projects. This study is a part of a broader research agenda that introduces a novel approach on how precedent and case studies can be used to address the issues that define efficient design, development, and production. The approach uses computational modelling and qualitative analysis of precedent case studies to determine the design workflow. A range of MEng Structural Engineering with Architecture (SEA) dissertation students was involved in understanding the possible impact of using digital tools combined with a careful analysis of precedent studies to identify and highlight the relationship between architecture, structure, and construction. This part of the research concentrates on the consistent collaboration between the architect Oscar Niemeyer and a small group of engineers throughout his career in the conceptual design stages and re-evaultaion through exploring digital trends to re-appraise case studies of his work

The two selected projects from Niemeyer demonstrate slightly different versions of Niemeyer's preferred workflow. The first one is the National Congress of Brasilia (1956) which relied on the expertise of the structural engineer Joaquim Cardozo [17]. The Congress was only one of the many buildings within the large-scale project that was the construction of the Brazilian capital, and due to its importance, it is also one of Niemeyer's most well-known projects. The second project is perhaps less well known, the Auditorium of the University of Constantine 2 (1969) in Algeria. The university project is interesting as a whole because it is not one that immediately comes to mind when thinking of Niemeyer, but the story behind it contains valuable clues into Niemeyer's working dynamic with engineers.

4. Oscar Niemeyer

Oscar Niemeyer (1907-2012) is arguably Brazil's most renowned architect, with over 600 projects completed around the globe during a very long career. [18]. He is widely considered one of the most significant names in modern architecture, with his use form and concrete and glass.

These works , not unexpectedly areviewed through a primarily aesthetic lens. However, to fully understand his style and workflow, there are some important details in his early career that illustrate important aspects not often mentioned, most notably a deep concern for both structure and construction.

4.1. Influences

4.1.1. Studies

Going as far back as his time in university the first insight comes from the courses he completed while studying at Escola Nacional de Belas Artes (ENBA), or National School of Fine Arts, 1930-34 [19] While the curriculum changed during his time as a student , the courses on construction, material sciences and applied physics were always present with advanced mathematics a later addition [20]. Niemeyer engaged with structural an material sciences from the start of his career. From interviews and correspondence with collaborating engineers, where they mention having long discussions on structural form and behaviour, further developed f his inherent interest in the opportunities of structure in the evolving conceptual development of his projects. [21]. . The pragmatic aspects of construction, materials and structure, in the eyes of Niemeyer were not constraints to architectural but offered both guidance and opprotunities.

4.1.2. Concrete Revolution

The next major influence to be considered is the material Niemeyer used, which throughout his career was mostly reinforced concrete. The context required to understand the connection is both in the international and Brazilian scenarios of the time. The development of concrete began in the later years of the 18th Century in France but by mid-19th Century it had already become widespread with the evolution of reinforced concrete [18]. This new material could take advantage of the flexibility of concrete being moulded into varying shapes but also counted on the steel reinforcement taking the tensile stresses that concrete was weak against. Through this time several experiments and systems were developed finally in the 20th Century many key names in architecture and engineering were largely associated with the material, a few examples being Robert Maillart, Pier Luigi Nervi, Eugène Freyssinet amongst many others the work [22]. Meanwhile in Brazil, the document stating the standard for the calculation of reinforced concrete was first published in 1931, during Niemeyer's studies, therefore it would likely have been something discussed within his courses.

4.1.3. Le Corbusier

Finally, it is nearly impossible to talk of modern architecture without there being some reference to the Swiss-French architect, Le Corbusier (1887-1965) [18]. Niemeyer had the opportunity to work with Le Corbusier soon after graduating, and his influence can be seen in the subsequent projects. Niemeyer, much like Le Corbusier gave importance to light, air, and space in his works, using the same five elements of Le Corbusier as the base of his early style. An example is the Obra do Berço (1938), where Niemeyer re-worked his preliminary study from 1935 after having worked on the building for Ministry of Health and Education in Rio de Janeiro with Le Corbusier [23]. However, it is also important to know that from those early works, Niemeyer developed his own language which he describes as being more suitable to Brazil, with curves and spaces to meld and reflect the curves of the country's rivers and mountains. In the documentary about his life and career titled "Life is a Breath", Niemeyer says: "Our architecture is very different from Le Corbusier's. We evolved to an architecture that has more to do with our weather: it's lighter, has more hollowed surfaces, more empty space." [24] Architecture should be contextual to location culture and climate.

4.2. Style and workflow

This evolution from having Le Corbusier's five elements as a base to developing his own form of language in architecture can be seen through the different periods of Niemeyer's career. A study in which thirty of his buildings traversing his career, , ranging from 1943 to 2003, were analysed and one of the trends showed that through the years the control mechanisms he used became more sophisticated as he gained experience [25]. José Carlos Sussekind, a structural engineer that often worked with Niemeyer, noted that despite not being an engineer, Niemeyer had an innate knowledge of structure in addition to his many years of experience [26].

These events all explain how Niemeyer arrived at the aesthetic expression of his work, but these projects wouldn't be possible without the aid of structural engineers to fill in with their expertise on structural behaviour. Curiously, the architect himself recognised the importance of the engineers to the realisation of his projects and admitted in his own books that he would accept sacrifices to aesthetics for best result [27]. Furthermore, he has repeatedly stated the sentiment that "once the structure is ready, the architecture is already there" [26]. Because of his long career it was inevitable that Niemeyer worked with many engineers on the hundreds of projects he completed, but there are also certain names that keep recurring in the list of collaborators. Early in his career it was Joaquim Cardozo, Bruno Contarini for his years in exile and return to Brazil and José Carlos Sussekind in the second half of his career [21] [26]. Niemeyer's long-standing connections to these engineers can be seen as an indication of cohesiveness of the unit of the design team and is often talked about by these people in their writings. Some examples are taken from Contarini's biography, and the collection of letters exchanged between Sussekind and Niemeyer himself where they discuss Niemeyer's preferred workflow [21] [28].

5. Case Studies

5.1 National Congress, Brasília, Brazil, 1960

Figure 2. National Congress, Brasília, Brazil, 1960 [29]

The National Congress, shown in Figure 2, was one of the buildings commissioned in 1956 by President Juscelino Kubitschek within the larger scheme of what was to become the new capital of Brazil, Brasilia [30]. At the time, Niemeyer, with Lucio Costa (French-Brazilian architect and urban planner), prepared a plan that was eventually nicknamed the 'Monumental Axis' [31]. The congress is central to this plan, as the access ramp and the gap between the two towers align with the main axis of the city.

Niemeyer describes the design concept of the buildings in Brasilia as his search for structural purity, where structure and form are unified, a recurring theme in his work. The National Congress has in itself a few different parts to it: the two chambers (Federal Senate and Chamber of Deputies) shaped as a dome and a bowl sitting on a long horizontal building and the two office towers beside it.

Cardozo had already been working with Niemeyer for approximately a decade at this point and was considered an expert in the reinforced concrete within the country [17]. From Niemeyer's original sketches to the engineer's drawings some differences in shape can be noted, the main one being the inverted dome chamber, where the original intention was a paraboloid, but ultimately became an ellipsoid with a tangent of an inverted cone [32]. Precedent study did play a part here, as Cardozo introduced layers to the structure that resemble some of Robert Maillart's works [17].

Due to the magnitude of the project and the limited information released, there is no confirmed cost associated to the construction of Brasilia, although many scholars have made estimates, and this does therefore limit what can be said about the efficiency of the methods employed. However, there is some information on the workflow between Niemeyer and Cardozo related specifically to the congress, for example the story of Cardozo's morning call to Niemeyer to say he had found the ideal tangent to the inverted dome that would best suit Niemeyer's vision [21].

The congress building has been modelled in 3D multiple times using multiple softwares, but going through the process based solely on the notes of the architect and engineer allow for a more practical insight into how the structure works. As mentioned before, the structure has several individual elements defined by Cardozo, these are shown in Table 1 and Figure 3:

Table 1. Structural Elements of the Chamber of Deputies as Defined by Joaquim Cardozo, see *[32]*

Number	**Element**
1	Lower Pillars
2	Concrete Curtains
3	Supporting Beams
4	Lower Compression Ring
5	First Shell
6	Intermediate Ring
7	Second Shell
8	Lining Slab
9	Ceiling Pillars
10	Third Shell
11	Upper Pillars
12	Upper Ring
13	Upper Slab

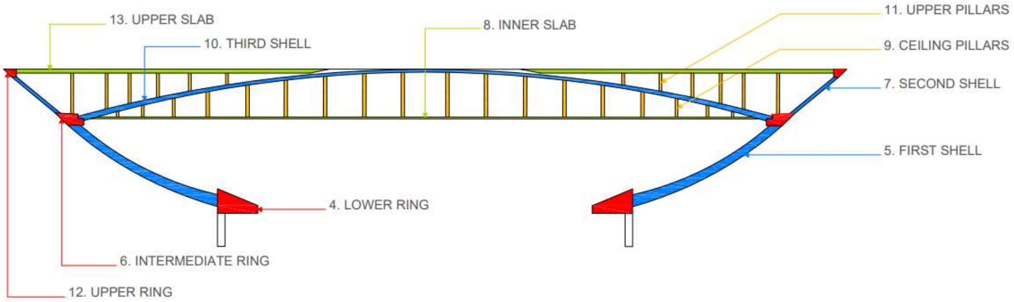

Figure 3. Section of the Chamber of Deputies with labelled elements corresponding to Table 1 [33]

Due to limitations in the modelling software (Rhino3D and Grasshopper) used certain aspects of the geometry had to be adapted and additional assumptions had to be made, and Figure *4* was the final result. For example, the software couldn't map the grid of pillars onto the surface of the third shell, and in their place imaginary support points were mapped onto the surfaces of the upper slab and third shell. Furthermore, the compression and intermediate rings also were divided into 1m segments and were called beams in the software. Lastly, the load cases were determined following the British Standard EN 1991-1-1 [33].

Figure 4. Rotated shape of the section of Figure 3 [33]

Elements 10 and 11 form a structure that resembles Maillart's Schwandbach Bridge (1933), with the thin bridge arch being equivalent to the inner shell and the stiff deck to be the upper slab. Therefore, when it came to analysing the structure, it was expected for these to act in a similar manner, where the deck (or upper slab) would have a smaller deflection than the arch (or third shell). The results from the model confirm this, with the worst-case scenario having a deflection of 0.075cm in the upper slab and 0.567cm in the third shell [33].

From the results of the 3D model analysis, the other interesting occurrence was the behaviour of the intermediate ring. The deflection results of the third shell, show that the deflection was in the vertical direction, which is reasonable as the support conditions were set to be at the interface with the intermediate ring which restrained it from deflecting to the sides [33]. This resulted in the ring, defined as beams in the model, acted differently than it would have under pure gravity. Under normal conditions, the beams would sag, showing compression in the upper fibres and tension in the lower fibres. However due to the third shell pushing outwards, the opposite was observed, with upper fibres of the rings being under tension and the lower rings under compression.

5.2. University of Constantine, Constantine, Algeria, 1969

Commissioned by President Houari Boumediene, the Constantine University, now called Université Frères Mentouri de Constantine, is a large collection of educational and administrative buildings. Niemeyer was committed to reduce the number of buildings from what was originally over twenty buildings to a simplified plan of only seven [24].

Figure 5. University of Constantine Auditorium, Constantine, Algeria, 1969 [34]

The auditorium, shown in Figure 5, is the most distinct looking of these buildings with the thin shell-like roofs, resembling a bird's wings or an open book, which meet in the middle with a single beam between them and contain no interior support. The 60 m long beam in the middle can be seen over the seam where the shells meet, while these span 30 m outwards. Niemeyer admits that he enjoyed pushing the limits of his preferred material of reinforced concrete.

One factor that seemed to be against Niemeyer's vision was the difference in technological advancements between Algeria and Brazil, which could have potentially set the construction back. However, the projects were designed in such a way that in addition with the cooperation between the Algerian and Brazilian workers it resulted in a smoother execution [35].

The information available on Niemeyer's process for the auditorium specifically is scarce as most of the literature available is surrounding the main classroom building. The story goes that when Niemeyer proposed the 50m span between columns the French engineers completing the calculations stated that a 1.5m thick wall would be required for structural stability. Niemeyer, unsatisfied with this, called in the Brazilian engineer Bruno Contarini who had worked with him in previous projects. Contarini then determined that only 0.3m thick walls were required and thus he was brought into the project [28].

The lack of information on this building meant that modelling it was a challenge and without anything to compare it to two versions were made, one following the tapering section as built in Constantine and a hypothetical version where the shell remains at a constant thickness. The tapering shell has a thickness ranging from 3m where it meets the ground and 30cm at its highest point, while the uniform shell was chosen to be 30cm throughout [33].

The modelling software caused another limitation for this model where the program could not create the tapered shell as was designed, therefore the shell was broken up into strips with the average thickness of what it would have been. This seemed to have worked appropriately as the calculated mass of the adapted tapered shell was only 0.2% smaller than that of the hand calculated original tapered shell [33]. Once again, the load cases were determined following the British Standards EN 1991-1-1, and summarised in Table 2.

Table 2. Loading conditions for the tapered shell [33]

Load #	Name	Category	Eurocode	Value	Safety Factor
1, 2, 3	Self-Weight	Dead Load	-	Calculated from mass	1.35
2	Wind (x-dir)	Live Load	EN 1991-1-4	0.7 kN/m^2	1.5
3	Access	Live Load	Roof category H from EN 1991-1-4	0.4 kN/m^2	1.5

Figure 6. Complete model of the auditorium [33]

Since the two designs were so similar, the largest difference within the analysis was the self-weight of the tapered shell being larger than that of the shell with constant thickness. This proved to have a difference in deflection where the heavier, tapered shell had a deflection of 1 cm while the hypothetical shell only deflected 0.82 cm [33].

The more significant difference however is in the stress distribution across the shells. The wings become narrower on the side where it meets the ground, they go from 50 m wide in the middle where they meet the beam to 12m where it meets the ground [33]. This variation means that the stresses become more concentrated thus the expectation is that the model will show darker colours towards the foundations. This turns out to be true in the case of the shell with constant thickness, however the shell with tapered cross section, has a thicker section where it meets the ground which then counteracts the narrowing width [33].

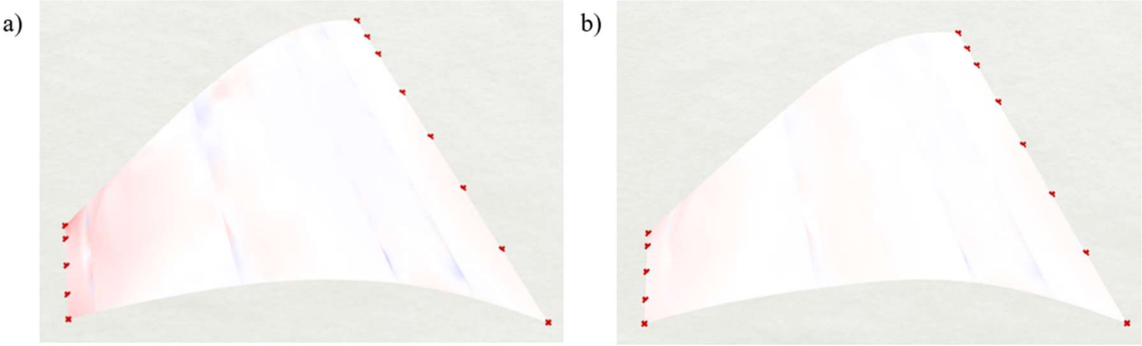

Figure 7 Principal stresses on the different shells a) constant 30cm thick shell b) variable thickness Shell [33]

Following this, the next point of concern would be the buckling of the constant thickness shell as the moments reach -81kNm/m, while the tapered section has a maximum bending moment of 27kNm/m at its thinnest point [33].

Unsurprisingly, the beams behave as would be expected, with displacement being at its highest in the middle of the beam, Figure 8.a , and compression on the top fibres and tension in the bottom fibres, Figure 8.b.

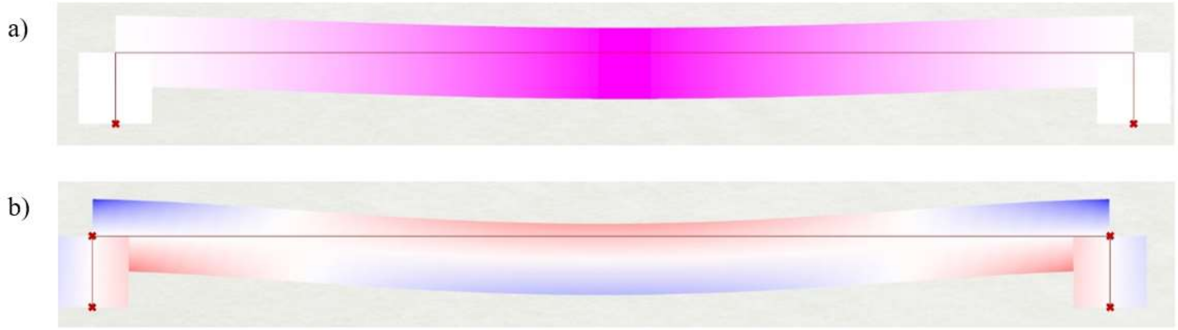

Figure 8 a) Displacement of beam b) Principal stresses on the beam. [33]

Recreating the 3D digital model of the case study and 3D printing of the structure provides great insights into design, behaviour and construction. In this case, individual shells and beam sections are printed separately giving clues in the complex nature of the tapered shells. The structure is designed for stability when the two shells work together. The beam stiffens as the tapered shells are attached to complete the two wings.

6. Discussion

"That in good architecture, when the structure is ready, architecture is already present." – Oscar Niemeyer [36]

This quote succinctly surmises Niemeyer's philosophy of design, where the structure and architecture are born together and coexist as a single entity. The engineers that worked with him, such as Contarini and Sussekind both repeatedly reaffirm this attitude in interviews and this is an example of Niemeyer's structural intuition at play [21] [28].

The structures observed in the case studies are visually different, however they do have similarities in terms of the rationalisation of their geometries. For the Congress, Niemeyer's design originally called for a parabola but he conceded to Cardozo's change to a revolved ellipsoid and tangential inverted cone, demonstrating Niemeyer's willingness to compromise his original idea for a more structurally intuitive option.

The way that Niemeyer designed these two buildings at the time used more conventional type of the design with hand calculations and drawings, while nowadays there are more advanced tools and softwares that allow for new ways of form-finding and faster iterative process. In this study the software used was Rhino3D, with the Grashopper, Karamba3D and other plugins to investigate how digital tools can be used to understand conventional structures with today's opportunities.

Despite the advancement in available tools there are still limitations to these that will affect the outcome and possibilities of the designs. In this particular set of case studies, there limitations with the software revolved around the geometric properties of the elements of the structure. For the National Congress the rings that had to be broken into 1m segments for the software to analyse them as beams, and for the auditorium, the tapered shell that had to be filleted into sections to show different thicknesses rather than a single continuous shell.

Whilst trying to understand the construction sequence and the rationalisation of form, the 3D model was useful to visualise and prove that the rationalised geometry was easy to build, thus fulfilling the ease of construction criteria of efficient design.

7. Conclusion

Ultimately, the examples of today's design explorations demonstrate that a more efficient and collaborative workflow is essential for modern construction projects. By addressing the fragmented nature of traditional linear workflow, stakeholders can work together to create buildings that simultaneously satisfy aesthetic, structural, functional, and construction-related objectives, while also contributing to climate change mitigation and sustainability.

Oscar Niemeyer, through his comprehensive education and his concern for structure prioritised this in his projects, maintaining a similar workflow throughout his career. He had a strong relationship and design collaboration with his engineers which allowed for cutting edge designs with the relatively new materials and techniques of the time. His innovation and precision to intrinsic detail rooted from the structurally intuitive nature of his design workflow.

There are many quotes from Niemeyer and his engineers on their collaboration process, perhaps one of the most insightful sources of these is the book with the collection of letters exchanged between Niemeyer and Sussekind [21]. In these Niemeyer writes: *"I attentively followed your explanations to the structural problems, not rarely caused by myself, certain that you always solve them in a masterful way."* and then continues *"I have felt how important you have been to me, in the development of my projects, a friendship that has seemed to do us both a lot of good."* [21]. The engineer also mentions a few projects where he and Niemeyer would discuss a design and come to a solution before submitting the final design to the client [21].

The structured analysis of two case studies have been demonstrated to provide an insight into a successful example of a collaborative workflow of aesthetically pleasing, structurally efficient and construction aware approach that results in Iconic architecture. Through physical modelling in this study, the fundamental principle behind the design and construction related challenges were identified. It was decided that 3D printing can serve as a valuable tool for feedback on the design at the early conceptual stages. Its implementation in the design workflow is recommended as it has been one of the earliest a tool for architectural design.

From the qualitative analysis in this study, it is seen that Niemeyer valued the engineers' point of view seeing them as a part of the initial design team to derive the concept. In the traditional design workflow where the architect receives the glory, often the engineer is responsible from facilitating the post-rationalisation of form to realisation where manufacturing becomes cumbersome and costly. Research into collaborative design strategies, learning from precedent and emphasis on practices with efficient design workflows becomes even more important when we consider the advantages of advanced digital opportunities in response to climate emergency.

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