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RESEARCH ARTICLE

The Role of Earthquake-Resistant Building Elements in Parametric Architecture Design; Balancing Aesthetics and Performance

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ABSTRACT

While traditional methods prioritise structural strength but limit design flexibility, parametric design provides a data-driven method that can maximise seismic performance and aesthetics. This article analyzes the core principles of earthquake-resistant buildings and discusses how seismic braces and critical structural components can be integrated aesthetically into parametric designs.
Furthermore, this paper explores various parametric design parameters that contribute to aesthetics, including form, texture, light, repetition, and variation. In addition to analysing the parameters of architecture and parametric design and taking a general look at the structure of the theoretical foundations of this contemporary artistic realm, this classification emphasises the importance of prioritising structural integrity while strategically using these parameters for visual appeal.
Finally, by highlighting the transformative potential of parametric design in earthquake-prone areas, this paper tries to show that parametric design can pave the way for creating visually captivating architectural wonders and flexible seismic architecture. This represents a significant advancement in the design process, offering a path towards safer, stronger, and more aesthetically pleasing structures in earthquake-prone regions.

Keywords: Earthquake-resistant design, Parametric architecture, Parametric aesthetics, Seismic bracing

1. Introduction

In the dynamic world of architecture, the advent of parametric design has marked a revolutionary shift, redefining the boundaries of what is possible in architectural design and construction. At its core, parametric design is a process that utilises algorithms and computational thinking to generate complex forms and structures that are both aesthetically groundbreaking and functionally innovative.

This approach, steeped in the fusion of art and technology, is not only reshaping our skylines but also the very way architects approach the creative process (Schumacher, 2009).

Earthquakes pose a constant threat to communities globally, causing devastating loss of life and infrastructure damage. Building design plays a crucial role in mitigating these consequences by prioritising structural integrity and occupant safety (Schumacher, 2009). However, traditional methods often struggle to balance these needs with design flexibility and adaptation to specific site conditions. This article explores a holistic and adaptable approach to the potential of parametric architecture to revolutionise the use of earthquake-resistant building elements to obtain aesthetic and safety parameters, based on the parametric architecture approach.

Parametric architecture offers exciting possibilities for creating earthquake-resistant structures that are not only safe but also visually compelling. This paper delves into the architectural aspects of parametric design, specifically focusing on its potential to enhance building aesthetics and safety in seismically active areas by integrating performance-based design with unique form generation and optimisation capabilities. The focus of this paper is to investigate how parametric architecture can improve building aesthetics and safety from an architectural perspective.

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2. Background

The term “parametric architecture” itself emerged in the late 20th century, signalling a new era in which design complexity could be managed and fine-tuned through algorithms. Traditional earthquake-resistant building design relies on established engineering principles, prioritising structural strength through robust materials and systems such as shear walls and braced frames. However, this approach often limits design flexibility and the ability to optimise for specific site conditions or architectural aspirations.

Parametric architecture offers a compelling alternative and can trace its lineage to the pioneering works of Antonio Gaudi (Figure 1) and Frei Otto (Figure 2), as it embraces natural forms and intricate structures. Gaudi’s use of geometric rules and Otto’s lightweight, tensile structures exemplify early examples of parametric thinking. The advent of powerful computing has since propelled parametricism into a more widely applicable design approach.

Figure 1. Sagrada Familia (started 1882) by Antoni Gaudi, Available at: https://www.archdaily.com.br/br/787647/classicos-da-arquitetura-la-sagrada-familia-antoni-gaudi

Figure 2. International and Universal Expo, 1967 (Montreal, Canada), by Frei Otto https://hyperallergic.com/189699/frei-otto-master-of-tensile-structures-dies-day-before-winning-pritzker-prize/

In recent years, there has been an increasing focus on innovative design approaches to address these limitations. As a background review, two notable case studies—the Nanjing International Youth Olympic Sports Centre (Figure 3) and The Bosco Verticale (Figure 4) exemplify this trend.

Figure 3. The Nanjing International Youth Olympic Sports Centre, 2002 (Nanjing, China) by Arup Architects https://sportsmatik.com/sports-corner/sports-venue/nanjing-olympic-sports-center

The Nanjing International Youth Olympic Sports Centre utilizes parametric design tools to optimise a complex, curvilinear roof structure. The roof spans a large open area without columns, creating a visually striking architectural form (Figure 3). The parametric design process considered seismic loads during optimisation. The resulting structure is lightweight yet robust and can withstand the significant horizontal forces exerted by earthquakes. The integration of performance-based design with a unique architectural form exemplifies the potential of parametric architecture in earthquake engineering.

The Bosco Verticale incorporates natural elements like vegetation into the building's facade. A parametric design was used to optimise the structural support for the additional weight of the trees and planters while maintaining the building's aesthetics (Figure 4). In this project, the analysis considered the extra weight and wind resistance due to the vegetation. The resulting structure is strong and flexible and can withstand the lateral forces of earthquakes. Bosco Verticale demonstrates how parametric design can be used to create earthquake-resistant buildings that integrate with the natural environment.

These projects showcase the potential for innovative design strategies that balance structural performance with architectural expression. However, a critical gap exists in the research dedicated to exploring the intersection of aesthetic parameters in parametric architecture and earthquake-resistant building design. We try to fill a part of this gap in the literature by presenting a few examples of this interdisciplinary field.

Figure 4. The Bosco Verticale, 2014 (Milan, Italy) by Stefano Boeri Architects. https://milano.repubblica.it/cronaca/2019/10/09/news/bosco_verticale_milano_tra_50_grattacieli_piu_iconici_al_mondo-238111573/ www.Google.com

3. Principles and Definitions of Parametricism

Schumacher initially introduced the idea of Parametricism in his work Parametricism Manifesto (Schumacher, 2008), and (Schumacher, 2009), as well as in another book (Schumacher, 2011), he presented two approaches to this idea called Dogmas to follow this concept and Things to avoid known as Taboos (Al-Azzawi & Al-Majidi, 2020).

The use of scripts instead of models, Inter-articulating, Hyperdizing, and Utilising Splines and Nurbs were among the Taboos in his paper (Schumacher, 2008), whereas the use of Platonic objects, Straight lines, Right angles, and other well-known topologies was among the Dogmas. The Dogmas were further defined in Schumacher's work Parametricism; a New Global Style for Architecture & Urban Design (Schumacher, 2009), in which all forms must be parametrically malleable, inflected, or connected systematically and distinctive gradually. Meanwhile, Schumacher introduced new principles for the Taboos, including Simple Repetition and the Juxtaposition of Unrelated systems and elements, and incorporated hermetic forms within the platonic forms mentioned in his previous paper (Schumacher, 2008).

Finally, Schumacher repeated the same Dogmas and Taboos in his book Autopoiesis of Architecture (Schumacher, 2011), highlighting the process of producing forms and integrated systems inside it. He also used the phrase Rigid Geometric Primitives for Taboos instead of "Platonic" or "hermetic" forms (Al-Azzawi & Al-Majidi, 2020).

In an overview, parametricism is a defining approach in architecture, where design incorporates dynamic characteristics and overcomes rigid restrictions (Figure 5). This signifies the beginning of a paradigm shift in which responsiveness and adaptability drive the evolution of architectural expression. Parametricism, in contrast to traditional methods, promotes a fluid design process in which variables determine form, thus bringing about a new era of inventive and flexible architecture.

Complexity and flexibility are fundamental concepts in parametricity. Avoiding minimalism in favour of complex and dynamic designs, it moves through a space where each architectural component is interrelated and ready to adjust to contextual or environmental changes. The theory emphasises the dynamic interaction between volume, function, and the surrounding context, generating a developed environment that promotes harmony with the surrounding environment (Isabella, 2024).

Figure 5. Ray and Maria Stata Centre (Massachusetts, USA) (2004) by Frank Gehry https://farm4.staticflickr.com/3624/3351701515_baabf8128e_o.jpg

3.1. Parametric Architecture

Luigi Moretti used the term parametric architecture in the early 1940s to describe the study of architectural systems based on the identification of connections between various parameters and their dimensions. This is where the term parametric in architecture first appeared. However, a study published by Maurice Ruiter in 1988 with the title "Parametric design" may be the first usage of this phrase in the discipline (Al-Azzawi & Al-Majidi, 2020).

Parametric design is a concept supported by the increasing availability of computer-aided techniques and the development of manufacturing processes that facilitate the achievement of complex forms. As an approach, parametric design relies on defining variables; whenever a parameter changes, the results also change. Thus, it has been used in recent decades as part of computational design to support the design process and achieve unique design products. Architectural practise has experienced significant changes because of working parametrically, which converts all programming decisions into design decisions and raises the need for architects to acquire new skills to become proficient in new techniques (Isabella, 2024) (Figure 6).

Figure 6. Hyder Aliyev Centre (Baku, Azerbaijan) by Zaha Hadid Architects, (www.parametric-architecture.com)

At the edge of the frontiers of architectural innovation is parametric architecture, defined by its computational flexibility, fluidity of forms, and variety. The primary use of computational tools in the architectural design process has been parametric design in architecture. However, this approach was not popular until the late 20th and early 21st centuries. The proliferation of advanced computer technology and software has been a key driver, enabling architects to explore new forms and structures that were previously unimaginable or more complex. The elements and concepts of parametric architecture inspiration often originate from natural and organic forms. A unique aspect of this method is the conversion of natural structures and patterns into design elements for architecture. The complex geometry of patterns and fluid curves evokes images of chaos and order in natural settings.

Using algorithms as guidelines, designers create structures that dynamically balance form and function in response to shifting conditions. Parametric design includes complexity and drives beyond conventional limits to create complex forms that arouse curiosity. Within this field, structures appear as manifestations of mathematical elegance and technical mastery, altering the landscape of the constructed surroundings of the future (Isabella, 2024).

Parametric architecture offers a new threshold to the world of unique design characterised by adaptability and the ability to create curved and flowing shapes that are reminiscent of nature. This fluidity in form and content allows architects to integrate aesthetics with functional needs. However, this would not be possible without the deep integration of digital tools and software.

Parametric design software utilizes parameters, as well as variables, to describe and connect multiple elements in a design. This allows substantial flexibility and consistency throughout the design process. Modifying a single parameter may cause automated alterations across the model to ensure consistency and coherence in the outcome.

3.2. Aesthetically Effective Parameters in Parametric Architecture

The parametric architecture, with its data-driven design and algorithmic control, offers a unique approach to aesthetics. Here are the key parameters, Form-Geometry, Materiality-Texture, Light-Shadow Play, and Repetition-Variation in Design, that contribute to the aesthetic impact of parametric buildings to explore further:

- **Form and Geometry**
- Organic Shapes and Complexity: Parametric design allows for creating intricate, nonlinear forms that deviate from traditional geometric shapes. These forms can be visually striking and create a sense of dynamism and movement (Kolarevic, 2009).
- Curvature and Variation: The ability to define and manipulate curves within design software allows architects to explore flowing lines, tapered elements, and varying thicknesses. This approach creates visual interest and helps to break away from the monotony of straight lines and sharp corners (Oxman, 2010).
- Optimisation and Efficiency: The underlying concepts of parametric design often result in visually beautiful shapes. By optimising structures for performance and material utilisation, the resulting shapes can seem attractive and efficient, demonstrating a harmonic balance between functionality and aesthetics.

- **Materiality and Texture**
- Differentiation and Customisation: Parametric design allows for precise control of material properties and textures across different parts of a building. This allows architects to create buildings with unique material expressions, using variations in colour, texture, and even translucency (Kolarevic, 2009).
- Integration with Structure: The integration of structural elements into the overall design scheme can represent a purposeful aesthetic approach. Architects may achieve a coherent and visually cohesive design by modifying the form and texture of the columns, beams, and support systems.
- Sustainability and Innovation: Parametric design can facilitate the incorporation of sustainable and innovative materials. This can include the use of recycled materials with unique textures or the exploration of new materials with specific visual properties.
- **Light and Shadow Play**
- Dynamic Effects: The complex geometries and varied material properties created through parametric design can interact with light in unique ways. This can lead to dynamic effects like shifting shadows or the creation of moiré patterns on the building's façade (Eltaweel & SU, 2017).
- Environmental Control and Daylight Optimisation: Parametric design tools can be used to optimise the building's form and façade elements to control the amount of natural light entering the building. This can create a more comfortable and visually interesting interior environment (Baker & Steemers, 2013).
- **Repetition and Variation in Design**
- Rhythm and Pattern: Parametric design allows for creating intricate patterns and rhythmic elements across a building's facade or other components. This can create a sense of order and visual interest, even in complex geometries (Burry, 2013; Schumacher, 2009).
- Fractals and Natural Patterns: Parametric tools can generate natural patterns, such as fractals and branching structures. These patterns can create a sense of harmony and organic beauty in a building (Schumacher, 2009).
- Uniqueness within Repetition: The ability to define variations within a repeating pattern allows architects to create a sense of visual complexity while maintaining a cohesive overall design.

4. Earthquake-Resistant building design with braces for aesthetic purposes

During a ground shake, an earthquake-resistant structure should be able to provide all of its seismic resistance concurrently. If not, the stepping happens, putting the building at risk of collapse (Giuliani, 2000).

Therefore, the goals of earthquake-resistant architecture are to prevent buildings from stepping during earthquakes and to ensure that all elements interact positively during an earthquake.

Traditional earthquake-resistant building design relies on several core principles:

- Structural Strength: Utilizing robust materials (e.g., steel-reinforced concrete) and structural systems (e.g., shear walls, braced frames) capable of absorbing and distributing earthquake forces.
- Seismic isolation: Employ base isolation systems to decouple buildings from the ground, reducing the transfer of seismic energy and minimising damage.
- Energy Dissipation: Integrating elements such as dampers or fuses that absorb and dissipate earthquake energy and protect the primary structural elements.

4.1. Integration of Seismic Bracing and Elements

Seismic Bracing is one of the most essential structural components utilized in parametric architecture projects. Structural characteristics based on seismic bracing used in parametric architecturally designed structures play a significant role in earthquake resistance and maintaining optimal structural performance. These elements, in cooperation with other structural members of the building, can create a suitable platform for greater flexibility and fluidity of the volume and overall structure of the building. Also, to give architects and engineers the possibility of more confidently designing higher, more complex, and finally more beautiful buildings in harmony with the aesthetic paradigms of contemporary architecture (Figure 7).

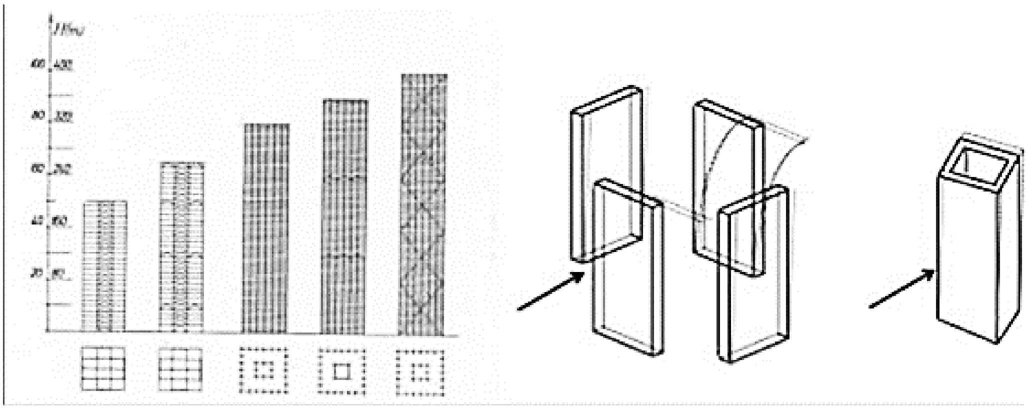

Figure 7. On the left: structural systems for tall buildings. On the right: wall versus tube behaviour (Laghi & Palermo, 2017).

Although seismic bracing is not strictly a parametric element, it can be strategically incorporated to complement its overall form. This creates a unified aesthetic and demonstrates a harmonious relationship between structure and aesthetics (Figure 8).

Figure 8. From the top left, clockwise: John Hancock Building; Sears Tower; Onterie Centre; Agbar Tower, Barcelona; CCTV, Beijing; 30 St. Mary's Axe, London (Laghi & Palermo, 2017).

The installation of seismic bracing can provide several benefits:

1. Enhanced Structural Stability (ASCE standard, ASCE/SEI, 2017, p.41-17).
2. Improved Performance During Seismic Events (NEHRP, FEMA P-1051, 2016).
3. Mitigating Non-Structural Damage (Lorant, 2016).
4. Compatibility with the aesthetics of parametric design (Bento & Simões, 2021).
5. Adaptability to specific building design needs, such as high building height and special design due to general building uses, as well as geographical or climatic constraints.

Seismic bracing should be considered in conjunction with the inherent strengths of parametric design for earthquake resistance. This combined approach can lead to the creation of highly resilient and visually striking buildings in earthquake-prone areas.

4.2. The Role of Parametric Architecture in Earthquake-Resistant Building Design

Architecture is quickly being transformed by parametric design. This design methodology uses computational methods to produce innovative, fluid, and efficient structures. On the other hand, parametric architecture may play a crucial role in reducing the danger of earthquakes, which makes designing structures in seismically active locations a big challenge for architects and engineers (Figure 9).

Figure 9. CCTV Headquarters (Beijing, China) by Rem Koolhaas (www.parametric-architecture.com)

Parametric design can enhance earthquake-resistant building design in several ways such as (Figure 10):

1. Automated Structural Analysis (ETABS-SAP2000-RISA-3D-Grasshopper (with Rhino 3D).
2. Form-Finding for Seismic Performance (Rhino 3D- Revit).
3. Integrated Design for Efficiency (BIM (Building Information Modelling) - Parametric Design Integration).

Figure 10. CCTV Headquarters (Beijing, China) by Rem Koolhaas (www.parametric-architecture.com)

5. Result and Suggestions

While seismic bracing prioritises structural integrity, some parametric design parameters can be strategically chosen to achieve both aesthetic appeal and seismic performance. In the following sections, the main aesthetic parameters mentioned in the previous section, Form-Geometry, Materiality-Texture, Light-Shadow Play and Repetition-Variation in Design, which seismic bracing can affect their production and creation have been analysed in order.

- **Form and Geometry**
- Organic Shapes and Complexity: While these parameters can be aesthetically appealing and fall into the category of parametric architecture, they may not always translate well into optimal seismic performance. Complex geometries can lead to tension concentrations and require detailed structural analysis (Figure 11).

Figure 11. Guangzhou Opera House (Guangzhou, China) by Zaha Hadid Architects, (www.parametric-architecture.com)

- Curvature and Variation: Curved elements, such as arcs, shells, and various surfaces, can provide intrinsic strength and efficient load distribution under seismic loads while meeting aesthetic requirements in design.
- Optimisation and Efficiency: The parametric design allows for the exploration and analysis of various forms to achieve optimal performance under seismic loads. This analysis of various shapes and volumes using parametric architecture software continues to achieve the best performance for the desired form of designers (Figure 12).

Figure 12. Guangzhou Opera House (Guangzhou, China) by Zaha Hadid Architects, (www.parametric-architecture.com)

- **Materiality and Texture**
- Differentiation and customisation: While this can enhance aesthetics, it may not directly contribute to seismic bracing. However, using parametric design standards to optimise material placement based on stress analysis can be beneficial (Figure 13).

Figure 13. Broad Museum (Los Angeles, USA) (Material: GFRC-Glass Fibre Reinforced Concrete) by Diller Scofidio + Renfro (www.whereisthenorth.com)

- Integration with the structure: This is critical for seismic performance. Parametric design can be used based on its theoretical foundations which emphasise the use of curve designs, repetitive surfaces, and shells to combine integrated structural elements in the overall form, creating a unified and efficient system.
- Sustainability and Innovation: Stable materials with good seismic performance, such as high-performance concrete or engineered wood, can be examined using parametric design to achieve a good level of strength and approved structural performance. This can meet the goals of architects and designers in complex designs in the realm of parametric design.
- **Light and Shadow Play**
- Dynamic Effects, Environmental Control, and Daylight Optimisation: While important for occupant comfort and energy efficiency, it does not impact seismic performance.
- **Repetition and Variation in Design**
- Rhythm, Pattern, and Uniqueness within Repetition: Patterns and styles and in general parametric architectural design that can be applied aesthetically are challenging in many aspects for earthquake-resistant design because, for seismic performance, the focus on regularity and symmetry in the structural system is often useful for efficient load distribution. However, with the help of today's computational software, a well-proportioned and well-balanced architectural designer can achieve good results against different loads simultaneously with complex designs (Figure 14).

Figure 14. Galaxy Soho (Beijing, China) by Zaha Hadid Architects, (www.parametric-architecture.com)

- Fractals and natural patterns: Although they can be visually intriguing, they may not always translate to optimal seismic performance due to the presence of potential stress concentrations.

6. Conclusion

By strategically utilising parametric design capabilities, architects and engineers can enhance the collaboration between aesthetics and seismic performance. While prioritising the structural integrity of today's buildings remains a priority, by focusing on parameters such as curvature, optimised geometry, strategic material placement, and integrated structural integration, parametric design empowers the creation of buildings that are both visually captivating and seismically resilient. The interaction between the theoretical and aesthetic foundations of the parametric world paves the way for a future in which seismic safety and visual appeal co-exist in architectural wonders.

Parametric architecture exemplifies the progression of the design process by combining creative vision with computational methodologies, as well as representing a transition away from traditional architectural practice and towards computational design. Due to its high degree of adaptability and customisation, it creates settings that are responsive to its surroundings and the needs of its users. The use of algorithms and computational design allows parametric architecture to achieve unprecedented levels of depth and complexity in design expressions, optimise structural aspects, and increase sustainability.

Parametric architecture represents a possible route to improving earthquake-resistant building design. This technique, by taking advantage of its capacity to improve performance, combine various design requirements, and develop novel forms, can result in safer, stronger, and visually appealing structures. More studies are needed to create established methods and case studies that show the full potential of parametric design in this vital subject.

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