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EXPLORING THE TECTONIC DIMENSION: PAST, PRESENT AND FUTURES OF THE USE OF TECHNOLOGY IN ARCHITECTURE

Tobias Danielmeier

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EXPLORING THE TECTONIC DIMENSION: PAST, PRESENT AND FUTURES OF THE USE OF TECHNOLOGY IN ARCHITECTURE

Tobias Danielmeier

Architecture production is foremost a tectonic process: vital elements for the creation of architecture include structural considerations, materiality and the associated dimensions of building elements and the constructive assembly of sheltering envelope components, as well as placement of façade penetrations. Architecture is intricately linked to time, place and the topography of locations, while also providing agency to embody and convey meaning.

This essay traces the development of tectonic principles from their ancient origins to contemporary applications, highlighting the significant impact of technological advancements and programmatic integration. Additionally, the rise of digital technologies has shifted traditional tectonic strategies, allowing for more complex shapes, innovative structural solutions and the ability to challenge traditional, authentic material uses. This progression enables new architectural expressions and functionalities, while also allowing designs to become more responsive to environmental requirements and the pressures of affordability.

This paper reflects on future challenges and opportunities for tectonic architecture, including the ethical implications of material choices, the pursuit of sustainability and the role of tectonics in architectural discourse. It advocates for a forward-looking approach that respects tectonic heritage while embracing innovation, urging the ongoing exploration and advancement of tectonic principles to address global architectural demands. In other words, it reaffirms the lasting importance of tectonics in shaping the future of architectural design.

PAST

The concept of tectonics in architecture goes well beyond the assembly of structural elements; it is an expressive art form that incorporates technology, form and programme. The foundational principles of architectural tectonics – characterised by the integration of structure, materiality and technique – have deep historical roots tracing back to ancient civilisations.[1] Originating from the Greek word *tektōn,* meaning builder or carpenter, tectonics embodies a construction philosophy that highlights the expressive potential of architectural elements.[2] These principles have consistently influenced architecture, shaping its form, function and aesthetics from ancient times to the present.

In ancient Egypt, the monumental pyramids and temples showcased early tectonic principles through their massive scale and precise masonry, symbolising concepts of the divine and the eternal.[3] In classical Greece and Rome, tectonics was evident in the proportionality and harmony of the orders, where structural elements like columns and pediments also held deep cultural significance, blending engineering with aesthetic ideals. The Middle Ages saw a shift through Gothic architecture's flying buttresses and pointed arches, enhancing structural support and spiritual luminosity through architectural form.[4] The Renaissance revisited classical tectonics with a focus on symmetry and human-scale integration, reflecting a return to rational architectural form aligned with humanistic values.

The modern era introduced industrial materials like iron, steel and reinforced concrete, profoundly impacting tectonic design. Architects like Le Corbusier utilised these materials to meet new functional demands and achieve greater spatial freedom, significantly altering architectural spaces.[5] At the same time, a new demand for honesty of materials tasked designers to expose and arrange building elements in accordance with material properties. This architectural trend faced challenges as the belief grew that technology could provide solutions to our earthly problems.

Structural integrity involves engineering buildings to withstand gravitational forces and environmental stresses, requiring a deep understanding of material properties and structural behaviour.[6] Historically, this is visible in the enduring domes of Roman architecture like the Pantheon, a testament to ancient engineering prowess. In modern architecture, structural integrity includes advanced engineering and dynamic modelling to achieve complex forms.[7]

Material manifestation carries the potential to enhance the sensory experience of spaces by using materials that not only express architectural ideas but also demonstrate their inherent qualities, as expressed by Louis Sullivan's adage that "form ever follows function."[8] This principle has evolved in recent decades to not only emphasise aesthetics but also sustainability, as seen in the use of timber and engineered timber that also aim to address environmental consciousness.[9]

Throughout these historical periods, tectonic principles have adapted to new cultural contexts, technologies and materials, continuously engaging with the changing human condition. This ongoing evolution highlights tectonics' enduring relevance in architecture, bridging past and present while laying foundational philosophies for future explorations in architectural design.[10]

PRESENT

Today's discourse on architectural tectonics focuses on core principles such as structural integrity, material manifestation and constructional modularity, forming a conceptual framework for designing buildings that are structurally sound, aesthetically coherent and contextually relevant.[11]

Constructional modularity leverages systematic module use for efficient and economical construction, a practice dating back to ancient structures like the Parthenon and extending forward to modern prefabricated houses designed to address urban housing needs efficiently.

Both historically and in the present day, these tectonic principles have pushed architectural boundaries, influencing how structures address functional needs and environmental challenges while appealing to human aesthetics. The ongoing application of these principles not only honours the legacy of past innovations, but also drives future advancements in building technology and design theory, making tectonics a central element of architectural education and practice.[12] This dynamic interplay between tradition and innovation continues to profoundly shape the built environment. In contrast, the "leaky building syndrome" that plagued the New Zealand building industry in the 1990s demonstrates that if tectonic principles are not well understood, or executed, serious problems will result.

The interplay between technology and tectonic design forms a dynamic and reciprocal relationship that significantly influences contemporary architectural practices. Technological advancements facilitate new architectural expressions and redefine tectonic principles such as structural integrity, material manifestation and constructional modularity.[13]

Technological innovation in materials science has introduced a spectrum of new materials, broadening both the creative and functional possibilities of architecture. For instance, the development of high-performance concrete allows for thinner, more durable structures with enhanced load-bearing capacities. Additionally, the introduction of tensile materials and technologies has encouraged the exploration of lightweight structures over vast spans.

Frei Otto's work, for example, exemplifies how tensile fabric membranes supported by minimal steel frameworks can create new tectonic forms that merge aesthetic appeal with functional effectiveness.[14]

Further revolutionising tectonic architecture are digital fabrication technologies such as 3D printing and CNC milling. These technologies have enabled the precise and efficient realisation of complex digital designs into tangible structures. Today's digital tools can generate intricate forms previously deemed unfeasible or cost-prohibitive, enabling the promotion of sustainable building practices through the use of biodegradable materials.[15] For example, the use of 3D-printed components in constructing the GAIA Pavilion by WASP demonstrates how digital tools can generate intricate forms previously rejected as unworkable, promoting sustainable building practices through the use of biodegradable materials. The integration of Building Information Modelling (BIM) and parametric design tools has also transformed the tectonic design process, making it more integrated and responsive. These tools allow for a holistic design approach that can simulate the real-world behaviours of buildings, enhancing both design quality and construction efficiency.

As most contemporary architects strive to embrace new tools and materials, the principles of tectonic design are continually reinterpreted and expanded, accommodating new challenges and opportunities. This symbiosis of technology and tectonics enriches the architectural lexicon and contributes to the evolution of building practices that are sustainable, efficient and attuned to both contemporary needs and future possibilities.[16]

CONTEMPORARY CHALLENGES AND OPPORTUNITIES IN TECTONIC ARCHITECTURE

In the evolving landscape of architecture, tectonic principles confront a spectrum of contemporary challenges that reflect broader societal and environmental concerns.[17] Yet, these challenges also present significant opportunities for innovation and advancement, particularly through interdisciplinary collaboration and research.

One of the principal challenges facing tectonic architecture today is sustainability.[18] As environmental crises escalate, architects are increasingly tasked with designing buildings that minimise energy consumption, reduce carbon footprints and promote ecological balance. This involves navigating the complexities of material sourcing, energy efficiency and long-term building performance, requiring not only the adoption of green technologies but also a fundamental rethinking of design philosophies to embrace ecologically sound practices.[19] Adaptive façade systems that respond to sunlight and temperature – such as those in the Al Bahar Towers in Abu Dhabi, designed by Aedas Architects – showcase how tectonic principles can enhance energy efficiency and indoor environmental quality through dynamic façades inspired by traditional Islamic *mashrabiya* designs.

Affordability remains a major hurdle to the widespread adoption of innovative tectonic solutions. Advanced materials and construction techniques often come with higher initial costs, making them inaccessible for lower-budget projects or in regions with economic constraints. Furthermore, the complexity of some tectonic designs can lead to increased labour and maintenance costs, posing long-term financial challenges for clients and users.[20]

The field of architecture has increasingly embraced interdisciplinary approaches to tackle complex design challenges. Collaboration between architects, engineers, environmental scientists and technologists can lead to innovative tectonic solutions that address the multifaceted demands of modern buildings, such as integrating smart technologies and bioclimatic design principles to create structures that are both environmentally responsive and aesthetically compelling. This collaborative approach extends beyond the design phase to include construction professionals, ensuring that tectonic innovations are practically and sustainably executed.[21] The Edith Green-Wendell Wyatt Federal Building in Portland, Oregon, demonstrates these principles through its retrofit with a vertical garden façade that regulates temperature and promotes urban biodiversity.

Furthermore, research plays a crucial role in advancing tectonic architecture, particularly through the integration of new materials and digital fabrication technologies. Ongoing research into sustainable materials, such as mycelium-based composites or recycled construction waste, promises to lower the environmental impact of buildings while maintaining architectural integrity. Additionally, advancements in digital fabrication, including 3D printing and robotic assembly, offer the potential to streamline construction processes, reduce waste and create more complex geometrical structures cost-effectively.[22] A prime illustration of this transformative potential is the Elytra Filament Pavilion at the University of Stuttgart, a collaborative endeavour by architects Achim Menges and Jan Knippers, with engineering expertise supplied by the university. Exhibited at London's Victoria and Albert Museum, the pavilion embodies biomimetic design principles and robotic fabrication techniques, drawing inspiration from the intricate fibrous structures of beetle wings. The pavilion's design was optimised through advanced computational algorithms, while robotic fabrication enabled the on-site assembly of its complex, lightweight structure. This paradigmatic example underscores the profound impact of digital technologies on tectonic exploration and the enduring interplay between artisanal legacy and technological innovation in architecture.

Enhancing educational programmes to focus more intensely on sustainable tectonic design can prepare future architects to meet the challenges of our time. Meanwhile, engaging with policymakers to advocate for regulations that support innovative and sustainable construction practices can facilitate the broader adoption of advanced tectonic solutions. This includes lobbying for building codes that recognise and encourage sustainable design principles and advanced construction methodologies.[23]

While tectonic architecture faces significant challenges in terms of sustainability and affordability, these challenges also present unique opportunities for growth and innovation. By fostering interdisciplinary collaboration and investing in research, the architectural field can expand the capabilities of tectonic design to meet contemporary needs. Through these efforts, tectonic architecture can continue to evolve, not just in the service of aesthetic and structural goals, but as a pivotal contributor to a more sustainable and equitable built environment. In the realm of tectonic architecture, ethical considerations are central to creating practices that are environmentally sustainable and socially equitable. Sandra Barclay and Jean Pierre Crousse's projects in Peru exemplify how the selection of materials, availability of craftsmanship and the overall design process carry profound ethical implications that can positively affect communities.[24] Furthermore, the utilisation of locally sourced materials can also decrease transportation emissions and support local economies.[25]

Ethical tectonic design also prioritises high-quality craftsmanship, which enhances the durability and functionality of buildings while respecting the labour involved in their construction.[26] High standards of craftsmanship ensure that buildings are safe and maintainable, extending their useful life and minimising the need for alterations and maintenance.[27] Ethical practices require that architects and builders uphold fair labour practices and safe working conditions throughout the construction process.[28]

Tectonic design has a significant capacity to influence social structures, making social equity an essential ethical consideration. Architectural decisions must ensure inclusivity, making buildings and public spaces accessible to everyone, regardless of physical ability, economic status or social background.[29] This approach includes designing adaptable spaces that can accommodate diverse user needs. Moreover, engaging with local communities during the design process, or using co-design strategies, helps ensure that projects reflect their needs and aspirations, fostering community ownership and place-based identity.[30] Architects and planners are uniquely positioned to advocate for ethical practices in tectonics. This advocacy can include pushing for stricter material sourcing regulations, promoting sustainable construction practices and supporting community-led planning processes. By participating in these discussions, professionals can help shape a built environment that adheres to high ethical standards, promoting sustainable and inclusive development.[31] The various building certifications available – for example, LEED, BREAM, Green Star, HomeStar, Passive Haus – are prime examples of how industry can actively promote improvements and regulatory changes.

As tectonic design intersects with advanced technologies and methodologies, it is crucial to maintain a focus on ethical implications to ensure that advancements in architectural practice contribute positively to contextual and environmental outcomes.[32] Ethical considerations in tectonics necessitate a commitment to continuous evaluation and adaptation, ensuring that the discipline not only meets aesthetic and functional demands, but also upholds principles of justice, sustainability and inclusivity.[33]

THE FUTURE OF TECTONIC ARCHITECTURE

The trajectory of tectonic architecture is set to be profoundly influenced by advancements in materials science and digital technologies and a robust commitment to sustainable practices, which promise to enhance both the functional capabilities and aesthetic possibilities of buildings, while redefining the principles of construction.[34]

Future developments in tectonic architecture are expected to leverage advanced materials like self-healing concrete, translucent wood and aerogels, which offer enhanced durability and energy efficiency, thereby reducing the environmental impact of buildings.[35] These materials enable buildings to adapt more dynamically to their environments, responding to changes in temperature, humidity and light, and are crucial in reducing the ecological footprint of construction projects.[36]

Digital technologies such as parametric modelling, artificial intelligence (AI) and virtual reality (VR) are transforming tectonic architecture, enabling more precise simulations and modelling and allowing architects to explore complex forms and structures which were previously unachievable.[37] The integration of AI and machine learning has the potential to optimise material usage and structural configurations, enhancing the efficiency of buildings throughout their construction and operational phases. Robotic fabrication and 3D printing exemplify how construction processes can become faster, more accurate and less wasteful.[38]

As challenges like climate change and resource scarcity intensify, ecologically sound practices will become increasingly crucial in tectonic architecture.[39] Future designs will need to prioritise energy efficiency and occupant well-being, incorporating elements of biophilic design to enhance indoor environmental quality.[40] A focus on the lifecycle of buildings will promote sustainable construction and demolition practices, encouraging the use of materials that can be reused or safely decomposed.[41]

While embracing innovation, it is also important that tectonic architecture respects historical contexts and architectural heritage. Future designs should harmonise new technologies with traditional aesthetics, creating buildings that reflect a profound understanding of place and history. This respect for heritage, combined with contemporary technologies and materials, can foster a rich, multi-layered architectural agency that allows the expression of place signifiers and identity.

The future of tectonic architecture demands a forward-looking approach that embraces innovation and adapts to new challenges and opportunities. Architects, engineers and designers are encouraged to push the boundaries of what is possible, exploring how new materials and technologies can redefine the relationship between human spaces and the natural environment.[42] Guided by ethical considerations and a commitment to sustainability, these advancements carry the potential to positively contribute to societal needs and environmental health.[43]

Tectonic architecture holds immense potential for the future, promising innovative expressions and heightened responsiveness to human and environmental needs. As the field continues to evolve, it will bring forward solutions that are as innovative as they are necessary, marking a new chapter in the enduring narrative of architectural progress.

CONCLUSION

In this paper, I have explored the multifaceted nature of tectonic architecture, tracing its historical roots and analysing its foundational principles. Each facet of the discussion has highlighted the profound influence of tectonic principles on the evolution of architectural design, underscoring their role in meeting both aesthetic and functional demands across eras and cultures.

The historical exploration of tectonics reveals a continuous transformation, shaped by technological, contextual and environmental changes. From ancient structures that emphasise materiality and structural integrity to modern constructions leveraging advanced materials and digital fabrication techniques, tectonics have consistently served as a foundation for innovation in architecture. This progression not only reflects an adaptation to new challenges, but also a deep respect for architectural heritage and context.

The ethical considerations inherent in material choice, craftsmanship and social equity further highlight the role of tectonics in promoting sustainable and inclusive development. As we face global challenges including climate change, resource scarcity and increasing urbanisation, the principles of tectonic design offer pathways toward more resilient and environmentally responsive architectural solutions.

Looking forward, the potential of tectonic architecture is boundless, with advances in material science and digital technologies opening new avenues for exploration.[44] These innovations present opportunities to further push the boundaries of what is possible in architecture, from achieving greater sustainability and efficiency to enhancing the human experience within built environments. However, as we embrace these possibilities, there is a compelling need to balance innovation with the preservation of local contexts, ensuring that new developments respect and enrich a sense of place.

In conclusion, the call to action for the architectural community is clear. The profession must continue to explore and advance tectonic principles, embracing interdisciplinary collaboration and cutting-edge research to address the pressing demands of our times. By doing so, we can ensure that tectonic architecture remains a vital and progressive force in shaping not only the physical environment, but also the social and environmental fabric of future generations. In this endeavour, forms, programmes and technologies are, and will remain, the key drivers for the innovation of architecture.

Associate Professor **Tobias Danielmeier** (ORCID ID: https://orcid.org/0000-0002-8611-4564) is Head of Architecture at the Dunedin School of Architecture. His work investigates the interface between industrial architecture and spaces of consumption. His research focuses on the interplay of performance and performativity in relation to place and identity of our built environment. His architectural designs have gained awards in the disciplines of architecture, design and engineering.

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