Intrinsically Linked: Conceptual Design and the Materiality of Structure

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INTRODUCING STRUCTURAL TECHNOLOGY

The foundation for the introduction of Structural Design and Construction Concepts to students of Design is of paramount importance as it sets the tone for all subsequent teaching in the field of technology. Traditional numerical approaches to teach "Structures" have been unsuccessful in instilling students with the interest or confidence necessary to transfer formulas to architectural design, and have customarily dealt with the calculations of a kit of parts, a methodology never conceived of as a conceptual system capable of architectural drama or spatial characteristics.[1] The initial exposure to structure and technology, rather, needs to be conceptually holistic and visual, not numeric or diagrammatic, in order to create lasting visual associations between actual architecture, spatial and design quality, and significant structural systems and materials. The study of structures and materiality must spring from a general conceptual theory that conceptual design and the materiality of structure are intrinsically linked.[2]

THE STRUCTURAL MATERIALITY OF MODERNITY

An examination of historical developments in the conceptual base of architectural design over the past 300 years reveals an intrinsic link between the development of new structural materials, the technological advancement of new or existing materials, and resultant architectural form and theory.[3] Little change has taken place that cannot be directly traced to the existence of new technologies. A study of the History of Architecture that does not highlight the significance of technology is incomplete; one that exploits technological issues can successfully operate as the vital link between Design and Technology streams of study, towards an integrative and inclusive architectural education that positively influences its conceptual foundations and outcome.

It is appropriate to focus on the influence of the rapid technological advances subsequent to the early 1700's. Here we can cite the scientific divide between those structural and material inventions that were the children of "technology" versus "technique" which must be differentiated to understand their implications. Technology deals with the *scientific* study of a subject which has only largely come about since the onset of the Industrial Revolution with the advent of advanced mathematical, scientific and engineering studies. Science is then able to be used as a testing ground for increasingly reliable predictions. Technology allowed for increased confidence in the design of tight building structures, and an accelerated speed of documentation and construction. Technique provides us with knowledge based on trial and error methodology, through information gathered through unscientific experimentation. Technology is, however, indebted to the experience of technique as an initiative for study.[4]

The design of architecture is closely linked to the materiality of the structure and system chosen to frame the building and the inherent strength and performance characteristics of that material. Each structural material behaves in a unique manner — and the technological development of architecture has been reliant on discoveries surrounding the best capabilities of each material.[5] Problems have ensued where a new material with unknown qualities has been used in a manner connected with known materials exhibiting unlike qualities. One material cannot be randomly switched for another except for the detriment of the design.

A course of study highlighting the intrinsic connection between structural materiality and modern architectural form and theory requires that several key topics be addressed. The issue of structural materials ought to include from a primary viewpoint, stone, iron and steel, and reinforced concrete; secondarily, masonry and timber; and thirdly, it needs to elucidate the critical co-dependence of structural materiality and construction processes, and architectural design theory in the industrialization of the assemblage building process. Technological issues must be simultaneously interwoven with a discussion of the impact of significant issues of Design and Theory which will serve to raise the level of intellectual debate and fortify the relevancy of the presentation. Presentation must clearly demonstrate the conceptual interdependency of Design and Structural

Materiality. Discussion naturally extends to include the cultural, economic and environmental impact of technological choice.[6] Historically, material choices were made based on regional availability.[7,8] Contemporarily, the structural material selection process must account for environmental considerations which not only include availability, but Sustainability.[9] Such study if addressed topically rather than historically[10] can more easily trace time-line developments and design theory ramifications on a material by material basis.[11]

Stone: Stereometry, The Rustic Hut and Gothic Revival

Stone provides an excellent starting point for discussions of the intrinsic interconnectedness of the innate technical performance qualities of a material and the resulting development of architectural expression. Exposed Stone construction has been party to a wealth of architectural stylistic expressions, substantiated by both theoretical and technological change.

By its ancient nature, revelations concerning the structural characteristics of stone are founded upon the type of experimentation that was based on techniques developed by the Greeks and Romans for their civic architecture. Even the majestic cathedrals constructed during the Gothic period relied on experimentation and often failure in the determination of the techniques which best utilized the compressive aspects of stone.12 Such structures lacked accuracy and reliability. It was not until the 1600's and 1700's that the mathematical and scientific fields which were to have a profound effect on the architectural design of stone buildings had advanced to such a point to be of value. It was knowledge in the fields of *'mensuration'* and *'stereometry'* which resulted in significant technological advances in stone construction.[13] Stereometry relies on the use of horizontal and vertical projections in determining in two dimensions the precise configuration of the complex parts of a building. Such accuracy was not possible in early times, even up to the Gothic or Renaissance periods.

A study of the Church of Ste. Genevieve by Jacques Germain Soufflot (c.1776) clearly identifies the precise technological application of stone stereometry, as well as the potentials and problems associated with the application of early principles of statics and material strengths.[14] It is important that Soufflot's architecture served as a clear theoretical statement of French Neoclassicism which took his technological applications beyond the realm of applied engineering principles.

The structural definition and often inappropriate use of stone material in "the primitive hut", as described by Rykwert in "On Adam's House in Paradise", provides an excellent point of departure for a discussion of the material attributes of wood versus stone, or tension versus compression. A review of the developmental changes in stone construction can ensue, from the tensile aspects of the failed lintel, through the corbelled arch, to the Roman arch and vault, and finally to the fine tuning of compressive forces in the Gothic arch which are more correctly disposed to encourage compression.[15]

Eighteenth century thought also gave rise to speculations regarding the origins of Gothic stone structures. Sir James Hall believed that the principle of imitation was essential to architecture, and that stone as a material was problematic in that it possessed no ornamental forms proper to its nature. Hall speculated that Gothic structural language was derived from tree forms through re-enactment.[16] An exposition of work by Antonio Gaudi, particularly the church of Sagrada Familia, provides an illuminating look at the intermarriage of aspects of Gothic structure with some innovative modern engineering principles.[17] The Gothic use of exposed stone structure provided a historical point of reference and justification for the use of exposed structure during the High Tech Movement.

Iron and Steel

Production iron during the late eighteenth century constituted the first truly modern structural material. The advent of iron construction in France and England coincided with the growing separation between the definition of Architect versus Engineer[18], and gave rise to divisiveness in Architectural Theory and Education regarding the adoption and suitability for use of the material. Where formerly the material division between grand versus vernacular architecture rested between cut stone and timber or rough masonry, iron and its surrounding controversy was delegated as an industrial material. It found its best early structural uses, in overcoming its borrowed timber language, in the construction of bridges, mill buildings and arcade roofs — which were seldom designed by Architects. Even J.N.L. Durand of the Ecole Polytechnique whose "Precis des Lecons" and its establishment of the "mecanisme de la composition" was paramount in setting forth a rationalized grid which in future allowed for the industrialization and regularization of architecture[19], rejected iron as a suitable building material.[20]

The varied structural and production characteristics of cast iron, wrought iron and steel demanded differentiated architectural treatment and can be used to further the discussion of the archi-structural ramifications of tension versus compression. The mass produceability of cast iron, combined with its brittleness contrasted the crude shapes of the more elastic nature of wrought iron. The architectural detailing of the two types of members was suitably differentiated in sympathy with the necessary construction processes. The Napoleanic preference of cast versus wrought hailed not only from its capability for detailed moulding[21], but also its production energy source. Whereas wrought iron used lumber to fuel its fires, a natural resource Napoleon considered in danger of depletion, cast iron required the higher heat provided by coke. (Early evidence of sustainability?)

The architectural work of Henri Labrouste as realized in his iron designs for the Biblioteque Ste. Genevieve (1838) and the addition to the Biblioteque Nationale (1857), raised awareness and acceptance of iron in public architecture.[22] His daring use of exposed cast and wrought iron structure, which applied amplified detailing through the exploitation of necessary connection methodology, formed the basis for a new architectural style which came to be known as Structural Rationalism which supported Gothicism in creating the historical foundations for Modern High Tech Architecture.

International Industrial Exhibitions held in England and France during the latter half of the nineteenth century provided an excellent opportunity for experimentation and exploitation of iron and steel, as well as the impetus to challenge traditional methods and materials for permanent construction, with new systems suitable for fast erection and disassembly of these temporary structures. Many significant and influential architectural icons adopted iron or steel for their primary structure because of its marked strength capabilities. The Crystal Palace, designed by Joseph Paxton for the first International Industrial Exhibition of 1851, was possible only by the simultaneous rejection of traditional masonry and the appropriate adoption and applications of the principles of both cast and wrought iron construction, industrialized assembly and glass technology.[23] The high profile use of this new greenhouse architecture raised public consciousness about the new material and helped to develop a level of confidence about its structural safety in spite of the visual lightness of construction.

The large space requirements of this new type of venue provided a platform for structural experimentation which allowed for fantastical exploitations of iron and steel structural systems.[24] The Galerie des Machines by Victor Contamin and the Eiffel Tower marked the pinnacle of nineteenth century structural steel design. The Galerie contained the largest clear space in history, with a span of 114.4 meters, achieved via application of the new three hinged arch. The Tower brings to the table the architectural implications of the invention by Otis of the elevator, in terms of the verticality of architecture and the densification of urban settlement. Multi storey steel framing, the invention of the skyscraper, and curtain wall construction had an influence on architectural design and theory, the magnitude of which was unsurpassed. The American construction of the Brooklyn Bridge, highlighted the newfound innovative potential for pure tensile construction using steel and the accompanying clarity of architectural expression for tension. Each of the aforementioned pieces were reliant on the material and structural characteristics of iron or steel to form the basis for their existence, conceptualization, spatial configuration and architectural detailing.

In spite of the disastrous setbacks that high rise steel construction faced due to unexpected fire damage during the early part of the twentieth century[25], the material was finally accepted and embraced by the architects of the Modern Movement. The AEG Turbine Factory by Peter Behrens (1908) and Fagus Werks by Mies Van der Rohe (1911) keynoted the material's inclusion into the language of Modern Architecture.[26] The controversial corner staircase detail of the Shoe Factory, exploiting the skeletal nature of the steel frame and the tensile ability of the material to cantilever, became an icon of Modern Style.[27] The material transcended its Industrial roots in Pierre Chareau's Glass House (1928), the iconographic continuum realized again in Mies Glass House in Plano, Illinois.

Steel, as a structural material, became a cultural icon for technology and modernity in the 20th century. The material of tension allowed for the creation of an architecture conceived in lightness and suspension, one requiring ballasting and mass to prevent it from taking flight. To speculate on the archi-technological ramifications of the non-existence of steel would realize the continuation of an earthbound compressive design language.

Reinforced Concrete

Reinforced concrete represents the first truly synthetic structural material, and a deeper realization of the uniqueness of strength characteristics of its components. The study of the architectural ramifications of the introduction of reinforced concrete construction, necessarily draws upon originating advances made in both stone and iron (steel) construction. The groundwork for composite material construction was prepared in the type of reinforced stone construction used in Soufflot's Ste. Genevieve, among others. This type of composite construction was significant in its exploitation of the contrasting compressive strength characteristics of stone versus the tensile capabilities of wrought iron connecting pieces.[28] In spite of the application of stereometric and engineering advancements, Ste. Genevieve would not have been possible without wrought iron reinforcement.[29]

Although the materiality of reinforced concrete did not have a significant impact on Architectural Design until the twentieth century[30], cultural and theoretical preparedness for its materialistic inclusion emanated from the Visionary Architecture of the eighteenth century.[31] The work of Etienne-Louis Boullee clearly evoked the future plasticity of reinforced concrete forms. Had Boullee lived perhaps a century later, his work was virtually realizable through the material invention of reinforced concrete shell construction. Boullee's theoretical architecture provides a referential springpoint for reinforced concrete applications in the Modern Movement as exemplified by the work of LeCorbusier and Eero Saarinen.

The intrinsic connection between Reinforced Concrete materiality and Modern Architectural Design Theory can be examined via its classifications of "Structural Typology" as well as by its unique "Stylistic" links. Four aspects of Structural Typology associated with reinforced concrete can be clearly identified. Firstly, monolithic framing, identifies the most straightforward applications of its earliest technology. Here we can cite architectural examples such as the

Theatre of the Champs Elysees by Auguste Perret (1911)[32]. The Villa Savoye by LeCorbusier (1928) illustrates the adoption of the concrete structural system and its allowance for the development of his "Five Points Towards a New Architecture".[33] No other material at the time would have permitted for a free plan or roof terrace. The extension of these principles into the magnitude of application of the Unite Projects and mass housing acts as a catalyst for an urban design and cultural discussion where many cite materiality as a causal factor in the subsequent development of misdirected settlement patterns.[34]

Secondly, the excitement of plasticity and cantilevers, presents vital architectural forms which, likened to the work of Boullee, represent the reality of wild architectural vision. Without the technological developments of reinforced concrete, the work of Eero Saarinen, Pier Luigi Nervi and Frank Lloyd Wright would form an appendix to a text on Eighteenth Century French Visionary Architecture as they highlight a type of architectural fantasy realizable only through reinforced concrete.[35]

The third type of Structural Typology is Long Span construction. This use of reinforced concrete includes the invention of prestressing by Eugene Freyssinnet as can be seen in his design for the Airship Hangers at Orly (1916) which enabled reinforced concrete to compete with pure tensile steel systems. Long Span construction not only influenced the course of modern architectural design, but moreover, enabled significant change in urban morphology. It provided advanced technology to support the construction of bridges and general urban highway and road system networks which facilitated the decentralization of urban residential neighborhoods and industry.

The fourth category of Structural Typology refers to the industrialization of the design and construction process through the application of Precast Concrete systems. Precast concrete, as an applied modular system, has immense ramifications on modern architectural design principles. Akin to discussions about the use of mass produced cast iron systems, precast concrete requires an examination of the impact of the desired repetition of fabricated elements and connections on both the layout and spatial qualities of the building. There are perhaps more notable unsuccessful case study applications to explore, including Moshe Safdie's design for "Habitat" at Expo 67 in Montreal, and Arthur Erikson's "Anthropology Museum" at the University of British Columbia (1975). Both projects boast unique problems peculiar to their specific structural and spatial configuration which provide an excellent basis for discussion and a workup of suggested alternate solutions, either using or avoiding precasting systems.

During the 20th century, reinforced concrete made specific material ties to the "stylistic" architectural movements of Futurism, Italian Rationalism and Brutalism. The Futurist Messagio of Antonio Sant'Elia (1914) makes a clear link between the technology of materials and the vision of a new modern architecture.[36] The North American image of the reinforced concrete grain elevator[37], an icon of industrial technology, and the fluid vision of plastic concrete forms, pervade the images of the Futurist Citta Nuova. Both monument and apartment block share the fluidity of the concrete image, a vision that can be seen to have influenced the form of housing designed under the premise of the Brutalist Movement in England and France. It is the material roughness and coldness of concrete and the associated applications of crude masonry, which when combined with urban form theories advocating high rise housing developments, eventually led to the social damning of the form with its material implications.[38]

The permanence and solidity of reinforced concrete were successful in aiding the formation of a formalist architectural typology which resulted in a close link between materiality and High Modern Architecture. Interestingly, when Modern Architecture fell into disfavor due to the pressures of Post Modernism, the material aspects of Modernism were replaced by less enduring architectural fabrics. Many edifices of the Modern Movement will endure due to their materiality, well beyond the current decay of many Post Modernist constructions.

The Architecture of Assembly: The Ramifications of Industrialization on Architectural Design

The emergence of an industrialized society during the early part of the nineteenth century began to have a significant impact not only on the technology and materials which were rapidly becoming available to architects, but more importantly, industrialization necessitated a change in the way buildings were designed and planned for construction and assembly.[39] The theory of design developed and practiced by several architectural schools of the early 1800's, was successful in preparing for a changeover towards rationalized planning to facilitate modular assembly.[40] Although the economic rationale behind J.N.L. Durand's grid mecanisme de la composition at the Ecole Polytechnique was in conflict with some of the classical design principles at the Ecole des Beaux Arts[41], the shared aspects of symmetry and regularity in their planning provided a platform from which industrialized modular design in iron could easily proceed. The works of Labrouste and Paxton are testimony to the successful transfer of ideology from classical arrangement to prefabricated modular cast iron design. It is significant that the success of early industrialized applications hinged on the material qualities and limitations of iron. Needless to say, such highly organized prefabricated works would not have been possible using traditional classical materials and methods.[42]

The essential theories that formed the basis of Structural Classicist and Structural Rationalist thought, combined with a Gothic affinity for exposed structural systems, were transported into Modern Architectural Theory as the roots for the British High Tech Movement. Reyner Banham's characterization of the "serviced shed"[43] illustrates reliance on Durand's modular grid planning, Gothic exposed structure (although now characteristically, steel), and an exposure of construction processes and detailing as the textural expression of architectural "finish". The serviced shed aesthetic recalls the structural systems and materiality of the industrial motif. Representationally, in publications, buildings such as Rogers' factory building at Inmos include exploded axonometrics of the structural assembly of the building, alongside sequence photographs illustrating the construction process. Such representation recognizes a distinct change in the perception of the architectural design and construction process, from wet to dry, from site intensive to factory controlled.[44]

The materiality of "Assemblage Architecture" draws heavily on the properties and potentials of steel "systems", making full use of the iconographic language of tensility. From the early intuitive use of tensile cross bracing in Paxton's Crystal Palace, to the purposeful lacelike appliqué on the Pompidou Centre by Piano and Rogers, the intrinsic co-conception of structural and architectural aesthetic in recognition of the material potential of structural systems peaks in the creative act of realizing "Assemblage Architecture". Of significance, as well, is the intrinsic inclusion of modularity in the two and three dimensional spatial organization of the building. Whether an linearly extended repeated module, as in Fosters' Sainsbury Centre (1977) or the multi directional Cartesian grid extension of their Renault Factory, the notion of repetition, of both structural bay and connection detail become centrally paramount to the conceptual realization of the architectural design philosophy. There has been, in fact, a re-establishment of the craft mentality in the design and construction associated with exposed structural detailing and a close and co-operative relationship between the Architect and Engineer.[45]

CONCLUSION

It is fitting that the co-dependent evolution of structural materiality and Modern architectural design should culminate in a discussion of "Assemblage Architecture". This Modern edification of the early thoughts of Structural Rationalism requires the ultimate understanding by the Architect of the potentials of materiality and structural systems in order to effect the successful detailed design of exposure. The Architecture of Assembly requires that the Architect not only have a thorough understanding of the appropriate application of structural systems and materials, but skilled hands that are capable of treating each detail with sensitivity towards its visual and constructional realization.[46] Traditional contemporary architecture, in its use of suspended ceiling systems and gypsum wall board, effectively camouflages the essential structure of the building, whose detailing may well be left to a visually unconcerned consultant, and effectively detaches the architect from the potential vitality of the Gothic vitality of structure.

The process of building on a rich Architecturally Design oriented conceptual base ensures that the student will eventually become the master of structure rather than the servant of the engineer, through understanding the intrinsic interdependence of Conceptual Design and Structural Materiality. The architectural examples that I have included in the paper are intended only to suggest a limited point of departure. Enrichment via the inclusion of additional significant architectural pieces, serves to expand and intensify the conceptual base to support specific archi-regional references.

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