Computer aided curvilinear architectural design

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Background- Curvilinear Form in Architecture.

Architectural curvilinear form has been around since the dawn of building shelter. Vernacular architecture, generally of earth construction, is by the nature of the materials and the construction techniques, curvilinear in form. The practical aspect of the structural curved arch was discovered by early builders, and 3200 year old mud brick storage rooms built with arches survive intact in Egypt. As civilizations developed, preference was given to linear forms, yet curved form continue to develop over the centuries, initially as structural enhancements, then later as an aesthetic. The 43.2 meter dome of the Roman Pantheon (c. 118-128), was one of the first uses of concrete (and one of the last, until 1796, when the technique for making concrete was rediscovered). Sixth century Byzantine architecture made extensive use of the dome, as is exemplified by the magnificent Hagia Sophia in Istanbul. In the East, simplicity and form combined to create functional curvilinear structures. The modular roof design of the Japanese Pagoda, for example, is highly advanced in its use of materials and resistance to earthquakes. Incredible advancements in structural engineering and other civil engineering forms were achieved in the Far East, yet the lack of communication between the East and the West prevented much of the technology from making its way into the Western architectural form. Most of the curved form developments in the West of for the next thousand years were refinements on the arch and the dome, reaching an apex for one of the most ambitious domes of the Renaissance, the Florence Cathedral, designed and built by Brunelleschi using innovative stonework techniques from 1420 to 1436. The construction of the Taj Mahal between 1630 and 1653 could be said to represent the perfection of the dome form, while perhaps also sealing the use of the dome as an aesthetic, rather than a practical, building style. Yet the graceful form of the Gothic flying buttresses, developed by the engineers of the 12th century to support the lofty churches with expansive glazed windows, must have inspired the post-Renaissance explorations into curvilinear form for the sake of aesthetics. The Baroque period of the 17th century, lavish with curvilinear representing the spirit of the age, as did the later Rococo style.

Yet these forms were likely considered too extravagant even at the time, and styles generally reverted back to linear forms.

In the 19th century, new metallurgical materials sparked new forms: the wrought iron Eiffel Tower (1887-1889), and Bibliotheque Nationale (1859-1867), by Henri Labrouste, with a wrought iron domed skeleton which allowed for an glazed center apex, both emphasize the natural and graceful lines of force which were facilitated by the strong, lightweight materials (lightweight, that is, relative to stone or concrete). The later part of the century brought the short lived Art Nouveau movement, with its fluid, curvilinear lines, and the great Spanish architect, Antonio Gaudi, who wrote,"The straight line belongs to man, the curve to God". His buildings in Barcelona, then considered by many as freakish forms, are now regarded as masterpieces of the era. In the 20th century, with the advent of pre-stressed concrete (1927), architects such as Alvar Aalto and La Corbusier made use of the latest structural developments and designed magnificent curvilinear buildings, while Eduardo Torroja, Felix Candela, and Erin Saarinen explored the limits of minimalist curved forms based on the mathematically precise, optimal load-bearing hyperbolic paraboloid shapes. The Guggenheim Museum (1956-1959) in New York City with its circular exhibition space, which Wright refers to as "quiet, unbroken wave", is one of Wright's greatest works. The latter part of the 20th century brought examples of what could be called modern curvilinear form, with the Sydney Opera House(1957-1973) perhaps being one of the finest examples, as well as being an excellent study of the interaction (and difficulties) between architects and engineers when it comes to pioneering new ways to create form on the public building scale. Yet the predominant architectural form in the 20th century remained linear. Why? The limitations of hand drawn architectural drawings leads to linear buildings that are easily rendered in 2D form, whereas three dimensional curvilinear form is facilitated by three dimensional rendering tools, not available until recently.

Computer as Design Tool

Fabric architects were the first to use computers to optimize form and design in architectural structures. Based on soap bubble research pioneered by Frei Otto in the late 1950's and resulting in the development of the tension fabric structures, Otto's funicular

1972 Olympic roofs in Munich were designed with computer program developed by Klaus Linkwitz at the University of Stuttgart. Later fabric pioneers such as Horst Berger worked with large engineering firms which developed proprietary (and closely guarded) computer software to design some of the largest fabric structures in the world, such as the Haj Terminal in Saudi Arabia (1981).

Of course, in the realm of engineering since the dawn of the space age, engineers have been pushing the boundaries of computers for analysis, and were used on larger building projects by the building engineers in the early days of computing, but generally only after the architect had completed the design. Finite element programs, originally developed for the aerospace industry (NASA), have recently become available to smaller design firms, narrowing the traditional expansive gap between architects and engineers. In a sense, the practice of building structures is coming full circle, with the concept of the Renaissance Master Builder, who oversaw all the (inseparable) aspects of design and construction, becoming once more a plausible role for designers, as computers become more accessible.

In the past few years, computers have gained status as a standard tool for architectural design. As history has shown, as new materials and tools become available, their use is eventually fully incorporated to the absolute limit resulting in entirely new genres. The nature of architectural design itself is currently in an evolutionary phase. Yet the transition is still in its infancy, and could potentially lead to realms only hinted at by the most recent computer aided architecture. In the early days of CAD, in the 1980's, the computer was primarily used for drafting. Yet many architects and institutions continued to rely on traditional hand drawn architectural drawings, and some universities even prohibited the use of computer aided drawings for final submissions, in the thought that it limited the creative process (which perhaps the early computer tools did). By the 1990's, the computer in architecture became mainstream, and soon thereafter, the limits of the existing technology were pushed. The concept of the architectural "blob", for example, of 3D curvilinear form, became popular in architectural literature in the early and mid 1990's, and many firms specialized in the application of the blob in practice. Blob design was generally based on the use of the newly available B-spline technology, and allowed previously unworkable designs (in terms of construction drawings and artifact production) become fashionable during this period. As the use of the computer has matured, the prevalence of the random blob has (thankfully) decreased, as the novelty wore off and the technology to create blob designs became commonplace.

Current state of the art of computer aided architecture could perhaps be represented by Frank Gehry's Guggenheim Museum in Bilbao (1993-1997), digitally rendered and refined, after the shape was physically formed sculpturally using massing foam blocks, with the use of Catia, a popular aerospace CAD tool, although it must be noted that the Bilbao Guggenheim, often touted as the coming of age of computer aided architecture, uses a very linear interior structure, and the curved outer façade (and inner skin) are bolted onto the interior structure, similar to the methodology the French architect and engineer team Frederic Bartholdi and Gustave Eiffel used to design and construct the Statue of Liberty in 1884. In other fronts, Renzo Piano's Tjibaou Cultural centre in New Caledonia (1991-1998) was designed from bottom to top with computers, as well as his Kanzai airport (1988), which was pioneering in its attempt to use computational fluid dynamics software to optimize the shape with the thermal performance of the building.

Current Development Overview

Developments in the methodology of applying computational resources to the creative process of architectural design have been accelerating in the past years. The advanced state of digital visualization tools, for example, allow for ultra-realistic portrayal of a given design. Such programs, however, generally are only useful after the concept (and details) have been decided prior to the use of the computer as an aid. The nature of the creative process itself has been explored and advancements been made to recreate the traditional conceptual creative venues of architecture, such as digital sketching and massing tools, with the use of the computer. Shape grammars can be programmed to fit a certain ideal set of shape requirements. Digitally stored libraries of information, accessible by systems such as case base reasoning, as well as knowledge based systems, offer the potential to help guide the design process in a more efficient manner. Computer collaboration tools, which accelerate the transfer of information between parties, offer the promise of synchronizing and converging the often diverse intent of a building project.

Other programs, such as genetic algorithms and intelligent agents, can aid in the optimization process. All of these tools have potential to be of great use to the architect, but none in and of themselves offer the promise of the recreating the concept of the master builder, the designer or single design team, that can combine and optimize the architectural design and engineering requirements that a modern building demands.

Combining form and structure

Structural optimization codes which can both analyze and optimize a design based on parameters set by the designer have been accessible for quite some time, yet these tools are generally not employed by the architectural profession. The form and structure of a building project have been treated as separate processes. The elegance of combining these two facets of design is often lost. Although several noted architect/engineers, such as Santiago Calatrava, have been successful at unveiling the beauty possible with structural form, it is only through their sheer genius that their works of art and engineering have come to pass. Is it possible to create a computing tool that will allow the more typical creative designer to extend the realm of the design that combines form and structure? Two paths of the puzzle are presented here, first by their engineering definition, then by their application to the building trade, and finally with some thoughts as to how these can be integrated into the creative design process in the future.

Optimization in Engineering

Structural optimization is a numerical technique for the determination of an optimum material distribution in a given design space. The numerical technique in its current common form involves formulating a design with a given set of parameters, specifying which parameters can be adjusted, setting the constraint conditions, and running the program to find the optimal solution based on the input. The process is analogous to being on a hilly surface with the goal of finding the maxima or minima. The contours of the hill represent the parameters, and the constraints can be considered fences which cannot be crossed. Because the computer is essentially blind as it searches for the maxima/minima, it will initially determine its path by discovering the local gradient around the starting point (by a design sensitivity analysis), proceed until it hits a fence (a constraint), the follow the fence until it finds a maxima/minima, which will generally be a junction of two or more constraints. Approximation concepts are used along the path to the maxima/minima, which couples parameters and constraints into sub-sets of variables in a process known as design variable linking. The process distinguishes the design variables from the analysis variables and utilizes the linking to determine the path to the optima. Approximation allows for speedier path to the optima, as performing a full analysis at each step along the way would be highly computationally expensive. Modern programs generally use the Kuhn-Tucker conditions to determine the maxima/minima, which involves calculating the sum of the gradient vectors of the objective and constraint functions, which will be zero at the optimum. A popular finite element program set Patran/Nastran (the pre- and post-processor) allows for hundreds of design variables and hundred of constraints to be simultaneously solved. A common baseline is the study of a basic beam/truss structure, such as the Michell truss, which also has an analytical solution.

Topological optimization, which allow topological changes to the general shape for a given load, are considered here, as these are most applicable to the combination of engineering and architecture that we seek to incorporate into the design of a structure. The default methodology seeks the smallest volume of material for a given load, by seeking maximum stiffness for a minimum of stored elastic energy. Generally, a starting solution is given, and the computer removes material in its search for the optima. Genetic and other evolutionary methods have been used with some success. Querin et. al. (1999 and 2000) outline an additive method in several papers using evolutionary algorithm which allows for the thickness of the design to vary as well. Steven et. al. (2002), have worked on methods that optimizes maximum stiffness and minimum stress simultaneously using both additive and subtractive methods. Extending the process to laminate structures (but only in 2D), Hansel et.al (2002) have combined a heuristic algorithm which removes single layers of material at locations where it is not needed, with a genetic algorithm which adds local reinforcement to areas to meet the specified structural needs. In this manner, complex patterning of laminate layup can be determined by the computer. Such developments could be applied to the “Gehry problem” of engineering a structure of a given shape to optimal dimensions, eg. a structure that is single layer of varying thickness material that complies with an architect’s design, avoiding the current problem in such buildings as the Bilbao Guggenheim, where the dead space in between the outer and inner structure can be as much as 5 meters.

The normal optimization methods generally have fixed given loads. In a paper by Chen and Kikuchi (2001), a system for creating a topologically optimized linear elastic structure to design dependent loads is outlined. This points a way for the creation of a system which can take in more general parameters in order to determine a given optimal shape. In Chen and Kikuchi's paper, problems with hydrostatic pressure loading are used as a means to study the creation of structures which can resist loads optimally. Nature seems to work in a similar manner, for example, a tree will grow differently in regions of high wind compared to a sheltered tree of the same species.

There are still considerable hurdles to overcome before the realization of creating 3D structural volumes based on optimal material usage, yet strides are progressing rapidly. Golay and Seppecher (2001) have proposed a system based on a fictitious material (i.e. with a theoretical stress strain curve) in order to work out the mathematics of finding a optimal topology with only the forces and material characteristics as parameters. Their work points to possibilities of discovering entirely new shapes, much as nature continually surprises us with intricate shapes, because, as Leonardo pointed out in the 15^{th} century, "Every action in nature takes place in the shortest possible way". As the growing body of research shows, optimizing architectural structures in which the topology is determined by the load and spatial characteristics required, is becoming a more realistic proposition every day.

Computational Fluid Dynamics

The currently separate research into applying computational fluid dynamics to buildings in order to predict thermal performance and comfort is also developing by leaps and bounds in the past years. Current limitations generally derive from the lack of computing power, rather than the application of theory, which is fairly developed and based on basic theories of physics: mass conservation (equations of continuity), momentum in the x,y, z directions (Navier Stokes equations), and the principle that energy is conserved (energy equation). These five equations are not possible to solve analytically, so the partial differential equations are discretized and calculated by the finite volume method. The complicating factor of modeling turbulence creation and dissipation requires simplifications to be made in the modeling of fluid motion, resulting in results that generally must be verified empirically to be useful. Furthermore, limitations in computational resources (i.e. solutions that can solve by modern computers in less than a few days), requires analyst to generally consider only a two-dimensional model. As the technology of computing power increases, "purer" equations to model turbulence will become reasonable to use, and the process of analyzing thermal characteristics of a general given three dimensional volume will be a more likely proposition.

There are two methods currently utilized to measure the thermal performance of a building: the simpler, more assumptive method used is the Energy Simulation method (ES) which is a networked nodal based system which breaks up the regions according to the room layout of a building, and averages room and wall temperatures and balances mass and thermal transfers throughout the entire building. Although utilized for well-validated computer models such as TRNSYS, BLAST, ESP-r, Energy Plus, and DOE-2, the nodal approach is limited as it assumes room air is completely mixed and uses empirical models (based on standard rectangular dimensional layouts) to model convective heat transfer (some using a pressure based method) between each room. Thermal comfort within each room is not predicted, as well as indoor air quality (air changes) is not considered with the ES model. To implement a method which includes intra-room air movement, a CFD approach, which includes momentum effects, must be used. Furthermore, the nodal approach because of its empirical inclusions cannot be adapted to new topologies that have not been previously experimentally measured.. Beginning with Negrao (1998), several papers outline methods for coupling ES with CFD (Bartak et. al, 2002, Zhai et. al, 2002, and Zhai and Chen, 2003). Because wall temperatures only need to be updated on a hourly scale, whereas air movement and temperatures require updating on a micro-second time scale, the advantage of combining the two methods allow for each method to perform the calculations which are most appropriate to the method. For example, CFD performs poorly (because of round off errors) in modes where changes occur slowly over time, such as thermal transfer through walls, and is more suited for rapidly changing turbulent air flow as is found in buildings.

In such models, CFD algorithms use the surface temperatures calculated by the ES data, and ES algorithms use the CFD data to calculate the convective heat transfer coefficients and air transfer between each room. This combinational approach offers great potential to thermally model a given three-dimensional volume. CFD applications are also required to study innovative technologies such as passive downdraught cooling (Bowman, 1996), solar chimneys (Gan, 1998) which can be integrated into the building envelope to decrease heating and cooling requirements.

A review of the available research reveals only a few studies of shape and its influences thermal and ventilation characteristics of the volume inside. A paper by Kindagen et. al (1996) studied the effect of roof shapes on airflow in buildings. Using CFD, the authors discovered that the exterior shape had significant effect on the ventilation inside, yet the paper only researched a few simple shapes and concludes by recommending further research with more varied parameters. Another paper by Landon and Campo (1999) looked at the process of optimizing shape to improve natural convection. Although the authors only looked at laminar 2D flow for a small object, the research gives an idea of the challenges that will be faced to combine structural and thermal optimization simultaneously.

Conclusion

As nature demonstrates, a structure which is optimal both structurally and thermally will be curvilinear in form. The idea of creating an architectural volume based on structural and thermal optimization is within grasp of reality using computers, yet it is clear that a great deal of research of the specific components of the system still needs to be developed prior to the deployment of full-scale, three dimensional integrative approach. The material and energy requirements could offer advantages for our resourceful consumptive methods currently employed. The aesthetics of such optimal structures will likely have a beauty of their own, yet retaining the flexibility of modifications based on external parameters, including the desired aesthetic, will be paramount to the acceptance of an integrated solutions approach.

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