Geometric Conceptualization
In the Architectural Engineering Curriculum

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Abstract

Geometric conceptualization has always been among the essential mental tools required for the invention and modeling of spatial structures, as well as for the structural, spatial and dimensional coordination in buildings. The downplayed role of geometry in most architectural engineering curricula may be responsible for engineering students' low performance in geometric conceptualization and visualization. This paper presents a number of geometric topics, which are inherently related to the architectural engineering education, and which I have integrated into my instruction of the Architectural Engineering courses at the University of Texas at Austin.

Introduction

Geometry plays a central role in the design of buildings in the broad sense (Motro, 1992). The abstractions, definitions, and symbols of the world of solid geometry have always been among the essential mental tools required for the invention, discovery and modeling of buildings and spatial structures in general.(Ristine,1997). Complex and sophisticated knowledge and use of geometry underlies the conception, design and construction of the most significant achievements in the history of buildings: Japanese joinery, intricate stereometric developments of Medieval Architecture and Gothic traceries are just a few historical examples. 2Oth century developments in building construction, such as paraboloidal concrete shells and geodesic domes, display an incredibly sophisticated spatial and structural conceptioning. New material technologies allude to new structural and architectural conceptions and configurations that, as Emmerich notes: "contain a whole range of forms: antiprisms, polyhedra, torus, space packings, and all kinds of hypar-spatial arrangements, creating a completely new architectural vocabulary (Emmerich, 1996). The new evolving trends in structural conceptioning and the exploration of various aspects of the relationship of geometry to the unity of structural and architectural conception and expression has been the subject of the First International Conference on Structural Morphology that took place in 1992 in Montpellier, France. (Motro, 1992)

From a different viewpoint, the design and construction of a building requires the coordination between distinct systems of organization, from functional hierarchies and circulation networks to configurations that derive from environmental considerations and configuration that are determined by the strength of materials, safety and security requirements. All distinct systems of organization need to be translated into spatial configurations. The world of geometry provides the tools to design systems and subsystems of order, hierarchies, and patterns and ultimately to describe the building as a complex network. Obviously, dimensional coordination in the design process is essential in the fabrication and construction processes as well.

The role of geometry in the education of the architectural engineer is an old one. Yet, with the advent of computers, which replaced many of the manual graphical processes traditionally taught to engineers, and the increased need for specialized courses, the in depth study of geometry has been downplayed in the curricula of most architectural engineering programs. As a result, low performance in geometric conceptualization and visualization has been often identified as a weakness of architectural engineering graduates. A departmental knowledge-skill survey, conducted by the Architectural and Civil Engineering curriculum committee at the University of Texas at Austin, has clearly indicated that Architectural Engineering and in particular Civil Engineering students' skills in 3D perception and visualization are not at the expected level. Undoubtedly, lack in 3D visualization is directly related to poor 3D geometric perception.

For the last few years I have consciously aimed at strengthening students' skills in geometric conceptioning and visualization by including in the curriculum of the Architectural Engineering program of the University of Texas at Austin a more systematic study of geometry.

The primary objective in this effort has been to identify relevant areas of geometry and topics and to group them in knowledge units. A second objective has been to integrate the instruction of geometry in existing courses early in the curriculum of the Architectural Engineering program at the University of Texas at Austin, without a significant change in course syllabi, and without discouraging young students who enter the program with a very limited knowledge of geometry.

The geometric concepts, which I have integrated in the Architectural Engineering education, are presented together with examples of relevant student projects.

Geometrical concepts included in the revised curriculum

Euclidean geometry, which dates back to the school of Alexandria, remains the primary source of geometric concepts that address the 3D nature of buildings. The study of the properties of polygons and polyhedra, which in fact is the subject matter of the thirteenth book of Euclides, sets the rules for the assemblage of regular shapes that fill up the space exactly around a point. The rules and principles of combinatorial geometry, as was called the geometry that discusses plane and space assemblages of polygons and polyhedra, have not changed in time. They still provide fundamental concepts for the development of planar and spatial network and set the abstract basis for structural geometry (Emmerich, 1996). The conditions of rigidity of Euclidean solids, studied by Cauchy (Cauchy, 1812) link geometry with structural behavior and are also of primary importance to the education of architectural engineers.

The most recent developments in architectural and structural technologies allude to a wide array of thin surfaces, stretched membranes, self-tensioned structures composed of struts and cables, etc. These new structures, according to L.Valvani, require the understanding of more recent and less familiar morphologies such as: “the periodic anticlastic surfaces, the rhombo and zonohedra, the infinite polyhedra, space labyrinths and many hyperspatial surfaces”(Vavlani, 1991). In fact there is a body of more recent geometries, that address different configurations than the Euclidean, or focuses on different non-dimensional aspects of the architectural or structural morphology. The knowledge of parabolic geometry, for instance, is the *sine qua non* for the design and visualization of tensile membranes. Concepts in topology can be of critical importance in the study of special types of structures such as the re-configurable or deployable structures. New developments in fractal geometry, can also provide a useful tool for the visualization of tree-like structures and a method for the analysis of self similar systems in general. An effort has thus been made to selectively include in the curriculum concepts from other than Euclidean geometries, the knowledge of which, I believe, can offer to the architectural engineer tools for the study and visualization of architectural and structural systems. These concepts have been grouped in three distinct units. The topics covered in each unit are briefly introduced:

UNIT I: ***Geometry of Planar Networks***

This unit includes geometric concepts, principles and constructions that address the organization of 2D systems of elements in planar networks as related to building design and construction. Two distinct subunits are addressed: self-similar systems, such as grids, lattices tiles and nets, and growing systems such as spirals and fractals. More specifically, Unit I introduces students to the following concepts:

SELF-SIMILARITY AND SURFACE TILLING

1. Tilling with polygon
   - Tillings with regular polygons
   - Tillings with semi-regular polygons
   - Transformations of regular tillings
2. Proportioning Systems and Tilling
   - Based on rational numbers ratios
   - Systems of proportion based on
     1. Golden means and the Fibonacci growth
     2. Harmonic decomposition of squares and rectangles
3. Hierarchy and Similarity in Tilling

GROWTH AND SIMILARITY IN PLANE

1. Spirals
   - Archimedes spiral
   - Fibonacci spiral
   - Logarithmic spiral
2. Fractal shape development

UNIT II: ***Geometry of Polyhedra and Spatial Networks***

This unit includes geometric concepts, principles and constructions that address the geometry of polyhedra and the organization of systems of polyhedra in spatial networks. This unit is further subdivided into 3 sub-units which address: a) the geometry of polyhedra (regular and irregular), b) the space packing of polyhedra in linear and grid organizations, and c) topological aspects of polyhedra. The design and visualization of buildings of complex 3D morphology, flat and curved space trusses, and modular buildings are few of the applications of the polyhedral geometry.

Proportions and proportioning systems is a common subject in both Units I and II. Proportioning systems have always been among the most essential elements of visual order and an important consideration of aesthetics. At the same time they become the basis for dimensional coordination in building design fabrication and construction. The “golden ratio,” which is not merely a human invention, but the most common ratio in the geometry of natural forms as well, is included in both units since it alludes to planar and spatial tilling and tessellations that have been encountered often in architectural history.

More specifically Unit II introduces students to the following concepts:

POLYHEDRA

Platonic & Archimedean Polyhedra

- Golden means and the mathematical basis of the Platonic solids
- Rigidity of polyhedra (Maxwell’s law)
- Truncation of regular polyhedra

Symmetry in Polyhedra

- Rotational symmetry
- Reflection symmetry

Duality and Enantiomorphy in Polyhedra

- Duality in regular polyhedra
- Antiprisms

JOINING POLYHEDRA/ SPACE FILLING PROPERTIES OF THE POLYHEDRA

- Space frames from: Platonic and Archimedean polyhedra
- Plane tessellations
- Linear developments of polyhedra

- Helical combination of polyhedra: Octamast, Tetra-helix etc
- Geodesic domes and geodesic math
- Tensegrities: linear and grid organizations

TOPOLOGICAL RELATIONS IN POLYHEDRA

- Transformation
- Juxtaposition
- Proximity

UNIT III: Surface Generation Geometry

This unit includes geometric concepts which are of critical importance for the morphological exploration and design of shell, skeletal, tensile structures, etc. More specifically Unit III introduces students to the following concepts:

CURVE GENERATION

- Conic Curves: Ellipse, Parabolas, Hyperbolas
- B-splines
- Bezier curves
- Surfaces from curves

DOUBLE CURVATURE SURFACES

- Synclastic
- Anticlastic
- Proximity

RULED SURFACES

- Hyperbolic Parabolas (Hypar surfaces)
- Classification of Hypar surfaces

TOPOLOGICAL SURFACES

- Torus
- Moebius strip

Integration of Units in the curriculum: Revised courses' conduct

The content of the two knowledge Units, I and II, has been integrated in the instruction of the "Introduction to Design I" course that I have been teaching in the Architectural Engineering program since 1996. This course is taught at the junior level and introduces students to aesthetic design principles and concepts and the study of 2D and 3D abstract form.

More specifically the course covers the following areas:

- Introduction to the creative application of design and ordering principles in abstract 2D problems.
- Introduction to the creative application of space/form relationships in abstract 3D problems.
- Introduction to space organization concepts and principles.
- Proportioning systems and their application in 2D and 3D design problems.

Since the study of 2D and 3D abstract forms has always been the primary objective of this course, the integration of Units I and II has in essence expanded the knowledge content of the course and has introduced a more systematic approach to the study of form by offering the students the tools to explore it.

Architectural Engineering students are trained in aesthetic design through the development of 2D and 3D projects and assignments (the construction of 2D and 3D physical models is always part of the assignment requirement.) The "Introduction to Design I" course is structured around a series of design assignments. In their design assignments, students are given a chance to develop their creative and artistic skills; as a result they are almost always enthusiastically engaged in them.

Design assignments are usually introduced after a general presentation of the aesthetic concepts and principles, which need to be taken into account during the assignment development. Examples of actual applications in the design of buildings are always included in the presentation. Geometric concepts and principles addressed by the assignment are presented at the same time. In most cases in the introduction of the design assignment, students are first presented with an achievement in the history of architecture, or building design in general, and subsequently the underlying aesthetic and geometric principles are analyzed. Usually the topics of each Unit are presented and explored in the course of two consecutive design assignments.

The presentation of the geometric concepts of the Units is not always a thorough one. In most instances it only covers an introduction to the concept and its relationship to architectural engineering applications. Students are expected to further explore the geometric concept at hand during the development of their class assignments. In general, students are expected to acquire a good grasp of only a few basic Euclidean geometry concepts related to polygons and polyhedra. In other fields of geometry, such as parabolic geometry, fractal geometry and topology, the objective is simply to expose students to the concept.

The 3D design assignments, in addition to aesthetic and compositional requirements, always involve the exploration of a fundamental structural concept that is directly related to the geometric basis of the assignment. As an example, I will refer to a design assignment, where students are expected to design and build the scale model of a spatial structure composed of anti-prismatic tensegrity units. The geometric configuration of a tensegrity anti-prism is a very challenging engineering problem since stability in tensegrity units occurs only at two symmetrical positions. This assignment is in general very difficult in both conceptioning and construction. However, the students' response has been simply amazing. Curiously enough, students enjoy this assignment a lot, and have invented many imaginative ways for combining the units together. (Figure 3)

Although most of the geometric topics are presented at the beginning of each assignment, the class format during the project development is very flexible. For instance additional class discussions may be held on theoretical or geometric issues when an interesting question is raised by a student. Student design assignments are presented and explained by the author-student and a class discussion always follows. Since each student explores a different aspect of a geometric concept, the entire class benefits from the presentation and discussion of the student assignments. Assignment presentations contribute greatly to the learning process.

Students have been shown to respond very positively to this course structure. They usually ask for further references and explore geometric concepts in depth on their own. The majority of the student assignments display a sophistication in the handling of geometry and creativity in the design. (Figures 1- 5). The "Introduction to Design I" course evaluation by the students has been excellent (4.7/5)

Unit III is entirely integrated in the instruction of the "Advanced CAD Systems and Methods" course. This is an upper division / graduate course, that I teach, and in which I have combined the instruction of innovative digital media with the instruction of advanced geometric concepts and principles. The structure of this course and the way Unit III contents have been integrated into it will be thoroughly discussed in a future paper.

Conclusions

The instruction of geometry has been successfully combined with abstract design and structural concepts and has been integrated in the Architectural Engineering curriculum at the University of Texas at Austin. Geometric concepts are introduced early in the curriculum and in the context of class design projects. More specifically in the revised "Introduction to Design I" course, that I teach at the Architectural Engineering program at the University of Texas at Austin, geometry has been integrated as a creative tool for:

- The development of 2D design problems
- The study of 3D abstract form
- The proportional and dimensional organization of systems of 2D and 3D forms
- The exploration of the structural efficiency of abstract 3D forms

Finally geometry is introduced as a way to develop an appreciation of the architectural engineering processes of the past.

It is hoped that this course has succeeded in inspiring young Architectural Engineering students to further explore the role of geometry as an essential mental tool required for the invention and modeling of spatial structures and for the spatial, structural, and dimensional coordination in building design.

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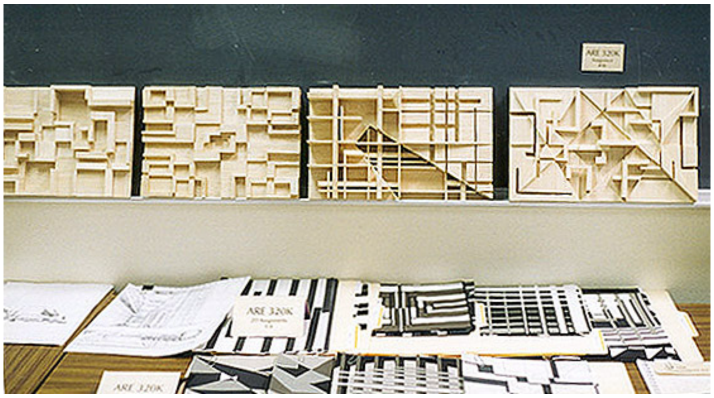
FIGURES



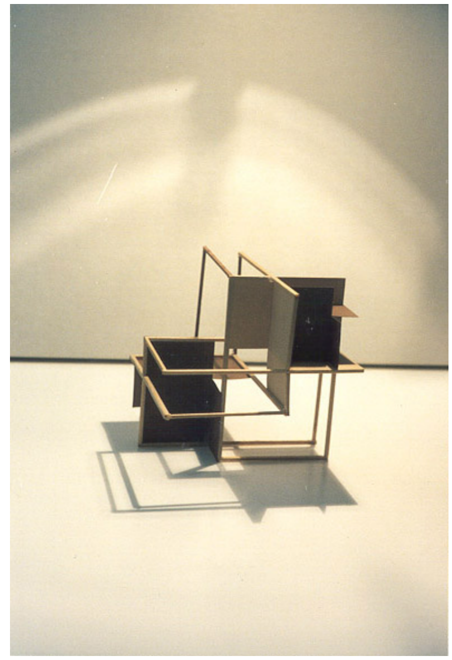


Figure 1: 3D development from a plane tesselation of
the ϕ or θ theme
Figure 2: Golden ratio planar proportions in a 3D structure

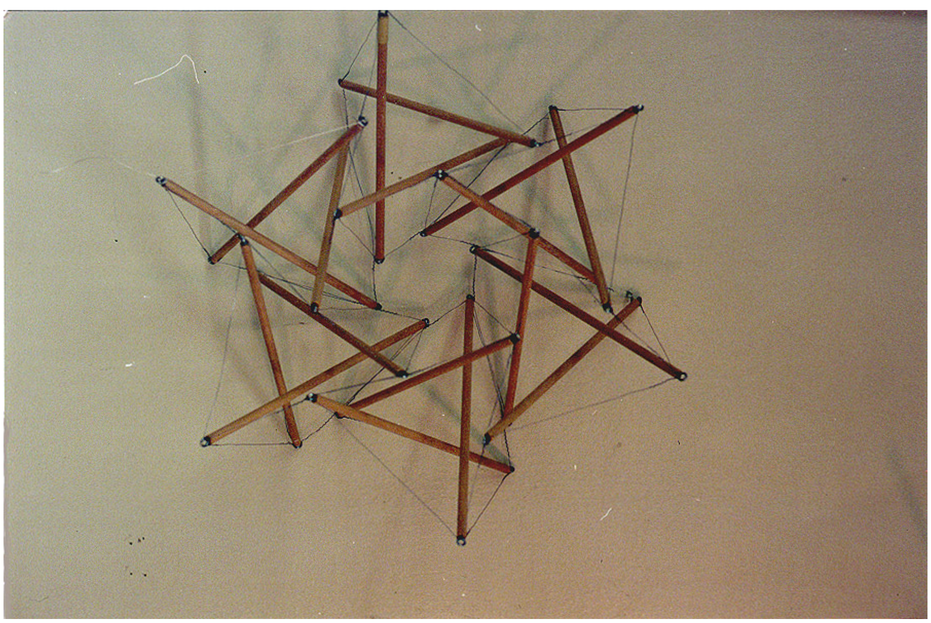
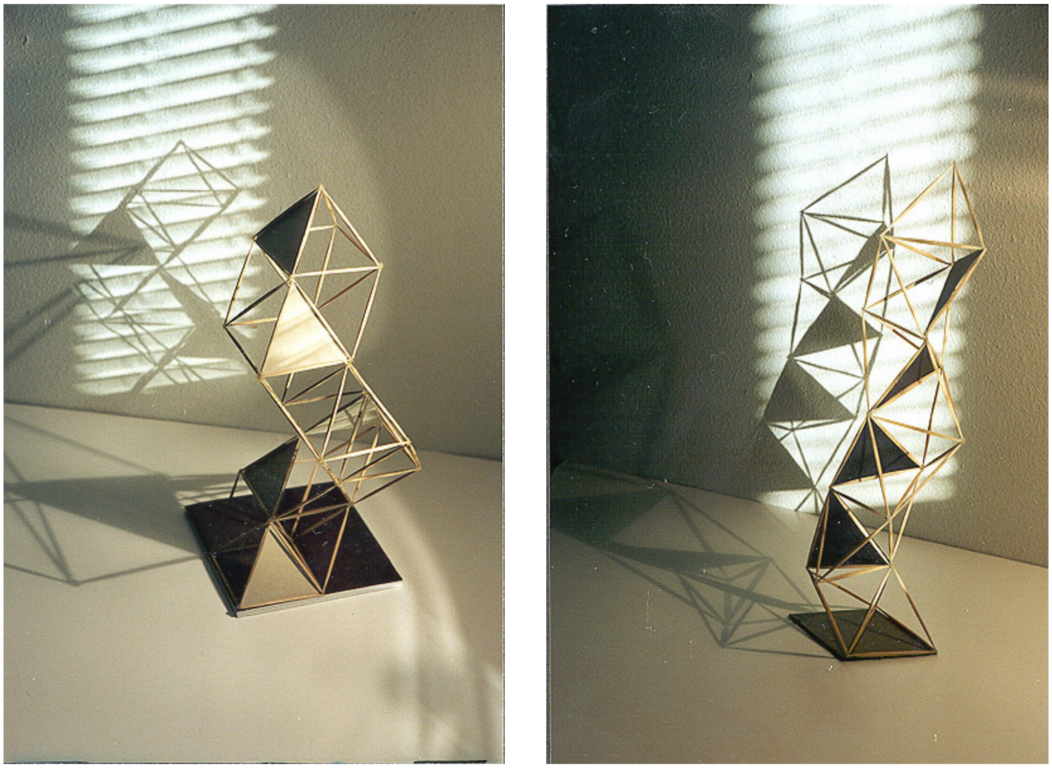


Figure 3: Tensegrity structure composed of tensegrity anti-prisms



Figures 4 : Spiral developments of tetrahedral and pyramidal forms

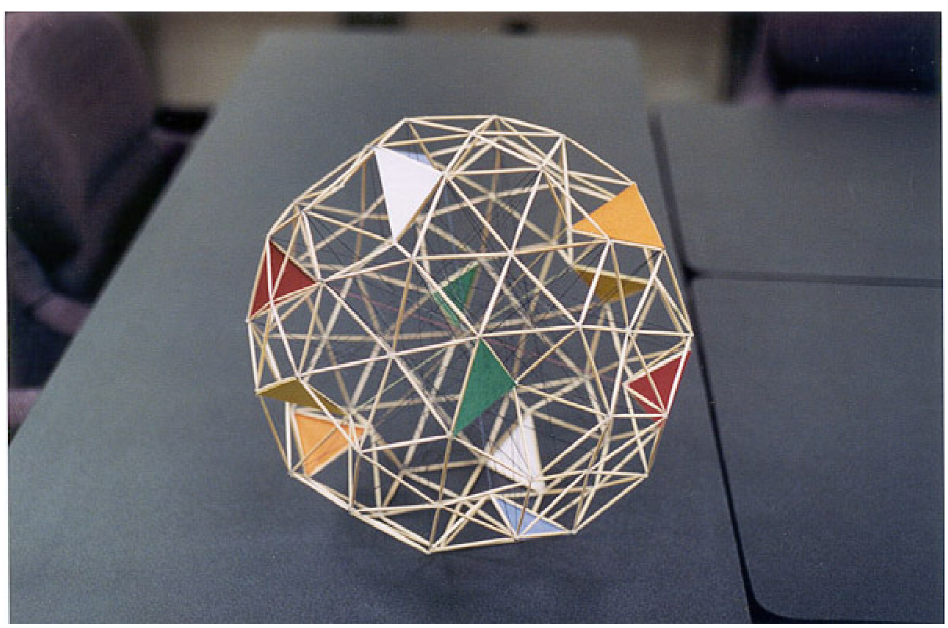


Figure 6: Geodesic subdivision and topological relationships in a sphere