COLUMBIA UNIVERSITY — ARCH A4118

Graduate School of Architecture Planning and Preservation — Fall 2013

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SYLLABUS

OVERVIEW

This class is not just about cathedrals. But in cathedrals we often find pure harmony between structure and aesthetic, where the structure itself is expressed to add spatial tension and heighten the experience of its occupants. We see this in the thin concrete shells of Felix Candela, the cast iron bridges of Thomas Telford, the sweeping fabric roofs of Jörg Schlaich, and the hyperboloid towers of Vladimir Suchov.

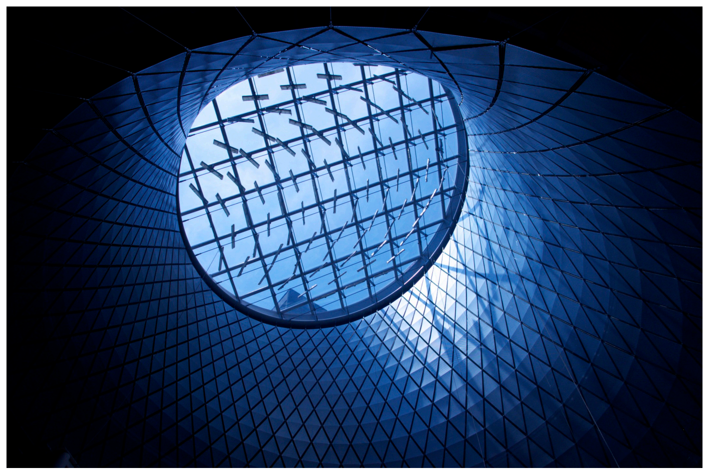

Figure 1. Fulton Center Cable Net

The implementation of such structure requires intimate knowledge of the principles and precedents of the assembly, as well as unique construction considerations and the analytical techniques used to validate its performance. An analysis of these aspects will confirm that these assemblies exist not only because of their compelling form, but likewise as a result of the ability of early designers to prove that they can be built using conventional construction techniques at reasonable cost, and perform adequately throughout their useful lifetimes despite their unique and unusual configuration.

Students will gain a holistic understanding of these essential characteristics through group-based research and design projects. Groups will select an existing assembly, which they will explore through four class modules: principles and precedents, analysis, construction, and innovation. Each group will prepare and deliver a presentation for the class at the end of each module.

Lectures will be given for a portion of each class and will focus on notable case studies related to the current module. Students are expected to walk away from this class with a fundamental understanding of structural stability, a taxonomic approach to selecting structural solutions, and familiarity with some of the most historically significant successes and failures within this realm. As a consequence of the class format, students will also gain familiarity with the works of great engineers throughout history.

HISTORICAL CONTEXT

Primitive

For millennia, the building systems that pushed the development of informed structure were built for the primary purpose of worship or celebration of divinity. Throughout the course of human development leading to the early 18th Century, our understanding of structure and its underlying principles was gained principally through experimentation, "trial and error".

These buildings are likewise notable for their expression of structure. In many cases, the architectural approach to such buildings hinges on the ornamentation and treatment of primary structural members.

A notable fact about early structures (before the 18th century) is that their forms are characterized by limitations in the types of internal forces that could be developed. It is this fact that led to the widespread implementation of classic structural forms.

Available building materials were largely limited to timber and stone. The Greeks took full advantage of the possibilities posed by their superior stock of available building materials. One such example is the ashlar masonry composed from Pentelic marble – a stone which allowed the joints between bearing elements to be ground together as finely as desired.

Columns of the Temple of Jupiter at Baalbek reached a height of 20m with a diameter of just 2m – an aspect ratio of 10:1, equivalent to that of some of our tallest and most slender structures to date. Yet there is no mortar between these stones – they are merely stacked. This form can carry no significant tension, bending or shear – only compression. Yet the structure is clearly stable. These columns have stood for 2,000 years.

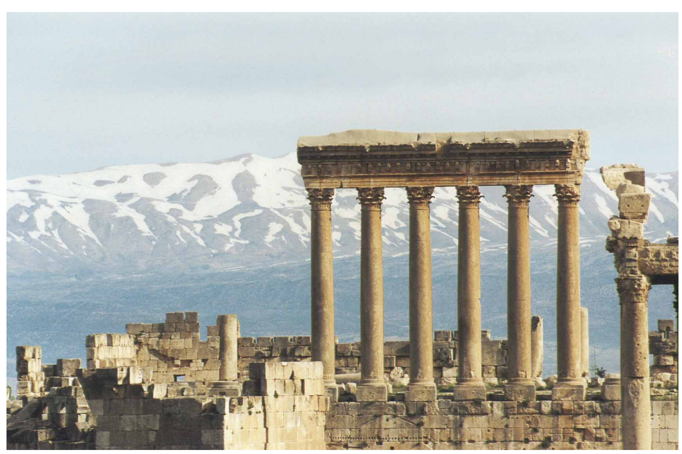

Figure 2. Temple of Jupiter, Baalbek.

Architecture of the time is characterized by these slender and closely spaced columns. Spans within these buildings were often limited, and built from high quality timber, which has not survived the centuries since its construction. Stone elements, such as the lintel above the columns at the Temple of Jupiter, could be called beams however their structural behavior relies as much on arching as it does in bending.

Romanesque

Increasing interest in religion between the 9th and 12th centuries led to a departure in the typical basilica-style church for structures that could hold many more people. It was not long before conventional cathedral design settled on a plan shaped like the Latin cross. Pilgrims' portals to the west, altar to the East. Just beyond the portal was the nave, or main seating area. A dramatic increase in catholic worshippers during these centuries put pressure on designers of cathedrals to make the nave as big as possible. Of course, this is not without its challenges.

It is arguable that the most fundamental decision in the design of a building has throughout history lied at its top: the roof. The mechanisms for supporting the roof inevitably dictate virtually every aspect of a building's form, from the ceiling and soffits to the walls and windows – if there can even be any windows – to the layout of the floor and the foundations beneath.

For the influential designers guiding the evolution of cathedrals through these centuries, the answer to this question lied in the arch. They had learned early on that the virtues of the beam could only be stretched so far. As stone and wood were the only realistic materials they had at hand, even a modest beam could become prohibitively expensive and virtually immovable. It was noted as well that a building with a beam-supported roof had poor acoustic properties – a quality that was becoming increasingly more important in cathedrals.

Figure 3. Hagia Sophia, internal perspective showing domed roof.

Builders began to use arches, vaults and domes to create impressive spans within their structures. Central columns vanished and the roof itself shot up to previously inconceivable heights. The reinvented structures marked a new architectural age, though this age would not get its title until the 19th century, when it would be called "Romanesque" due to the similarities between the shape of the roof and the Roman arch.

With the problem of the roof solved, the remnants of the building – walls, columns, supports and foundations – merely become a mechanism for guiding the weight of the roof to the ground. This weight, which builders call “load”, flows through the building like an elaborate network of rivers and tributaries. It is the job of the builder to channel the flow of load to the ground safely, while preserving – and perhaps enhancing – the aesthetic and functional properties of the building.

The medium available to builders of this era was of course stone. The fact that cathedrals wound up in the form of stacked stone blocks may not surprise anyone, however the story becomes much more interesting when one examines how this type of material and form of construction were well adapted to the limitations of the pre-scientific mind.

When a structure collapses, our first reaction is to question its pre-catastrophic strength. In many modern cases, this approach is natural and correct.

But consider this. The simplicity of a stacked structure is easily seen in its one critical objective: design every part of the stack to bear the weight of the structure above. The limit to the height of a tower would naturally be that at which its own weight would crush the very lowest part.

A standard brick weighs 120 pounds per cubic foot. In order to crush that brick, one must apply a pressure of somewhere around 6000 pounds per square inch. According to our theory, a tower with parallel walls could be built to a height of 7,000 feet – more than 7 Eiffel Towers, or 100 columns from the Temple of Jupiter stacked on top of each other.

Obviously, strength is not an issue. It is in fact stability that makes all the difference.

When builders introduced the arched roof to the cathedral, they invariably made the network of tributaries and rivers even more complex. Arches, by their design, want to kick out at their supports. The roof of the cathedral, therefore, was working very hard to push the walls over.

This wasn’t a very big deal with small churches, but in large cathedrals, this lateral thrust against the walls became massive. And walls had to be made strong enough to withstand this thrust. This means thicker walls and smaller windows, which by no coincidence are two defining characteristics of Romanesque architecture.

Figure 4. Hagia Sophia, external perspective showing massive buttress system.

Gothic

By the 12th century, builders were pushing the limits of what they could accomplish with this type of architecture. The windowless spaces resulted in such darkness that religious art itself was devalued within the cathedral, as there was no light with which to view. A lack of openings led to sweltering and uncomfortable conditions for everyone inside. Another revolution in cathedral design was needed.

The site of this revolution was in what is now a northern suburb of Paris. In 1125, plans were announced for Saint Denis Basilica by the Abbott Suger. The cathedral Suger realized is today referred to as the prototype for a new type of architecture: Gothic.

Saint Denis would take many years to build, and Suger was faced with one perennial problem: the original church had to remain in use while the new cathedral was built atop the same sanctified site. When the original church was finally demolished, worship had to commence in the new cathedral immediately, even though it was not yet finished.

This transition occurred on June 11th, 1144, with the completion of the choir. The partially-completed cathedral was completely encased in golden panels for a ceremony that drew royal and religious figures from great distances. The first mass in the new choir was more of an immaculately-choreographed extravaganza. Attendants were stunned not only by the performance put on that day, but perhaps even more so by the cathedral itself.

Figure 5. Wall construction of Hagia Sophia (left), and Saint Denis Basilica (right).

Despite the impressively high ceiling, Suger's creation bore remarkably thin walls, pierced by windows so large that he had managed to turn them into art pieces in their own right, by filling them – for the first time – with stained glass.

Visitors to the cathedral that day took their experiences and observations with them. The response by King Louis VII clearly indicated his intention to push greater French churchmaking in the direction of Suger's philosophies. In addition to size, builders were to maximize light. Anyone unclear about how to do both would have to get in touch with Abbott Suger.

The response to the shift in design was staggering. In less than 300 years, 80 gothic cathedrals were erected in France. Millions of tons of stone were quarried in the Ile de France during these centuries – more, it has been said, than in any equivalent length of time in ancient Egypt.

The ferocity with which builders approached the new technique spread to such distant towns as Sens, Senlis, Noyon, and Laon, as well, of course, to Saint Denis' southern Neighbor, Paris.

The virtues of the gothic cathedral centered stemmed from its structural system, which remained stable with slender members and many penetrations in its fortified walls. A key player in this system was the flying buttress which, like the massive piers that came before it, resisted the lateral thrust of the vaulted roof.

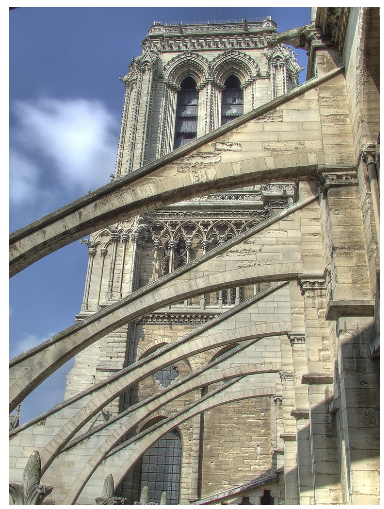

Figure 6. Flying buttresses of Notre Dame de Paris.

Unlike the earlier piers however, the flying buttress was informed by the specific types of loading it would see, and adopted a unique form that addressed these loads while remaining stable. It illustrates that the stability of the stone, and not its strength, was the guiding constraint.

There are two primary loading cases for the flying buttress. The first is of course the horizontal thrust of the vaulted cathedral roof. The element carries this load in pure compression.

The member must also be stable under its own self weight. Under this gravity load, it must span between the buttress on one side and the cathedral wall on the other. Comprised of stacked stone, it cannot do this in bending. In response, the buttress has adopted an arched underside, which allows it to span this weight to the adjacent members.

Given this stability, the buttress can be light, as it carries both load types in compression (and as we have seen, stone is very strong in compression). Stripped of bending, tension and shear forces, the supporting members of our structural system return to an impressive degree of slenderness, like that seen in the columns at the Temple of Jupiter.

The stability of the flying buttress is affirmed by its geometric shape, which remains true to its *funicular form*. The funicular form of an element can be defined loosely as that which mimics the natural path of principal forces within it. Builders established a form that, while slender, encapsulated the funicular form resulting from the varied loading conditions experienced by the member throughout its lifetime.

An understanding of the importance of stability over strength in masonry structures allowed builders to create some amazing forms. The signature rose windows of French cathedrals such as Notre Dame de Paris are framed entirely in unreinforced masonry. The stone's slenderness makes it look truly lacy, once again underscoring that if properly restrained, such structures can be extremely elegant.

And it was clear to designers that, in order to take advantage of the stability of masonry under pure compression, particular shapes were necessary.

Modern

While it was known by builders in the Gothic period, the true shape of the line of thrust within an arch or vault was more concisely demonstrated by Antoni Gaudi in the 19th Century. In contrast to the circular arches of the Romanesque and parabolic shapes of the Gothic, designers such as Gaudi followed the *catenary* curve. Such members, subject to uniform loading, saw only pure compression, and– like flying buttresses – could be exceedingly slender and efficient.

Figure 7. Sagrada Familia, Barcelona.

The catenary curve is defined by an object with only tensile capacity – such as a cable – suspended between two points, and loaded only by its own self-weight. The cable assumes a static form in which only pure tension results. When flipped over, this curve similarly reflects one of pure compression.

Such daring forms were unsusal at the time, as it was difficult to establish the geometry required for a complex series of arches. Stacked arches, which were common in cathedrals like Sagrada Familia, took on a *compound catenary* form, with a sharp point at the support of an arch above. Each arch was therefore unique in its form, which was a product of its own weight and span, as well as the weight and location of arches and other elements it supported from above.

To determine the shape of each arch, Gaudi brilliantly implemented the catenary equivalent of his cathedrals through early physical, analytical models. His "catenary studies" were in effect upside down cathedrals. Each chain represented the position of an arch, and the weights represented roughly the weight of the cladding and ornamentation delivered to the system at specific locations.

Figure 8. Gaudi's catenary study for Sagrada Familia.

This upside down model became the blue print for the final structure.

Gaudi's Sagrada Familia, which was begun late in the 19th Century, marked in many ways the end of an era of building design that had existed since the dawn of manmade structures. The limitations in the array of available building materials was already beginning to fade. The steady march toward ideal compressive masonry structures culminated with their obsolescence, as iron, steel and ultimately reinforced concrete led to ordinary structures that could remain stable under sustained tension and bending forces.

Simlarly, there had been a sea change in the way in which buildings were designed.

The work of individuals such as Robert Hooke, Leonhard Euler, and Thomas Young in the 17th and 18th centuries led to an understanding of the behavior of structural materials. From this understanding came modern structural analysis and design, and a shift from the empirical approach to one informed by physical principles and mathematical guidelines.

In the 19th and early 20th Century, structural forms grew increasingly divorced from the narrow band of catenary-driven shapes, and embraced bending and tension through new materials and the design methods used to predict their behavior.

The thin shells of 20th Century designers such as Felix Candela still characterize the efficiency that comes from an overwhelmingly compressive form. However deviations from pure compression are welcome in his approach, and are dealt with through the use of reinforced concrete, with the capacity to resist the bending that results.

Rather than using a form based purely on the thrust line of his structures, Candela's work reflects a harmony between structural efficiency, ease of basic analysis, and ingenious construction technique. It is the coalescence of such numerous characteristics that informs the contemporary designer of an ideal structural system, given its intended use, the site environment, and the technical and financial limitations that surround the project.

CLASS OBJECTIVE

In this class we will focus on the contemporary building environment, with modern materials, analytical methods and construction techniques at our disposal. We will seek out and study examples of building systems from the 20th and 21st Century where the building form and aesthetic involves, and is many cases, driven by the chosen structural form.

Throughout the four modules, we will critically assess structural forms ranging from fundamental to novel. We will seek to determine the drivers for the selected form, and explore how these forms reflect our collective definition of *structural efficiency*. Through individual and group work, we will establish the behavior of structural forms analytically through first principles and computational analysis.

BREAKDOWN OF MODULES

I. **Principles and Precedents.** Student groups will survey existing structural assemblies and select one for extensive study throughout the semester. Each group will prepare a presentation introducing that assembly, highlighting in detail its fundamental physical principles and notable precedents in history.

II. **Analysis.** Each group will prepare and carry out a procedure for analyzing and validating the assembly using an existing case study as the analytical context. Students will prepare a presentation on their strategy, the techniques and technologies used, and the results of their analysis.

III. **Construction.** Each group will explore the art of constructing their assembly in the field, noting common virtues and challenges faced. Students will prepare a presentation on these characteristics, noting also issues related to environmental sustainability and physical longevity of the structure over its lifetime.

IV. **Innovation.** Student groups will use the final module to prepare a conceptual design for a system that implements their chosen assembly, which acknowledges the considerations explored throughout the class. Extra credit is awarded to designs that successfully iterate on prior implementation.

GRADING

Students will receive grades based on the quality of their presentations and supplemental deliverables as assigned at the beginning of each module. Presentation and deliverables for each module will carry a 25% weight toward the final grade in the class.

SCHEDULE

Students are advised that this schedule will change, and attendance at class is critical to awareness of shifts in deadlines and milestones.

Class	Date	Module	Activity
1	9/3/2013	Introduction	Lecture
2	9/10/2011	Principles & Precedents	Lecture/Group Consultation
3	9/17/2011	Principles & Precedents	Lecture/Group Consultation
4	9/24/2011	Principles & Precedents	Lecture/Group Consultation
5	10/1/2011	Principles & Precedents	Student Presentations
6	10/8/2011	Analysis/Construction	Lecture/Group Consultation
7	10/15/2011	Analysis/Construction	Lecture/Group Consultation
8	10/22/2011	Analysis/Construction	Student Presentations
9	10/29/2011	Construction	Lecture/Group Consultation
10	11/12/2011	Construction	Lecture/Group Consultation
11	11/19/2011	Construction	Student Presentations
12	11/26/2011	Innovation	Lecture/Group Consultation
13	12/3/2011	Innovation	Lecture/Group Consultation
14	12/10/2011		Student Presentations

RESOURCES

TEXT

WEBSITES
Structurae: http://www.structurae.com

Textbooks – Purchasing is optional, most readings will be made available via course website.

Developments in Structural Form | Rowland Mainstone (Columbia Univ. Library) $100.00
Structure & Architecture | Angus J. Macdonald (Columbia Univ. Library) $29.95
Structural Design for Architecture | Angus J. Macdonald (Columbia Univ. Library) $48.95
Structure as Architecture | Andrew Charleson (Columbia Univ. Library) $60.95