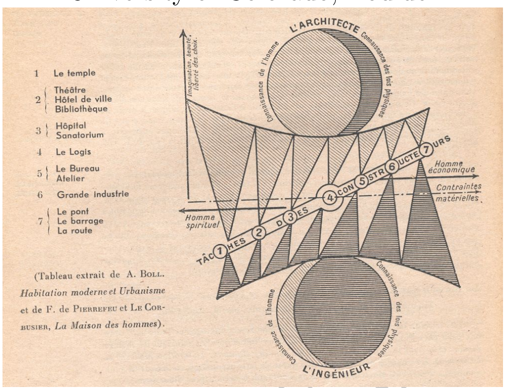
CVEN 4835/5835

Structural Analysis of Iconic Structures

Sense and Simplicity

October 8, 2018

Prof. Victor E. Saouma
saouma@colorado.edu
http://civil.colorado.edu/~saouma
Dept. of Civil Engineering
University of Colorado, Boulder



Le Corbusier illustation of the inter-relationship between architecture and structural analysis.

Background

The structural engineering component of a typical civil engineering curriculum entails: Statics, Mechanics of Materials, Structural Analysis, and Design courses. Those with a strong interest in Structures may take in addition: Advanced Mechanics of Materials, Matrix Structural Analysis. Those courses tend to be dry, uninspiring, challenging to relate to, and limited to rectilinear structural components. Some find them "boring".

This course will seek to motivate students by examining the intersection of Structural Analysis/Design with Architecture, combining rigor with beauty.

This is best examined through *iconic* structures of a type seldom taught in undergraduate curriculum (arches, cables, shells), three-dimensional frames. Those may be bridges, towers, stadiums, cathedrals, museums, or large civic structures.

Whereas in modern days, many will immediately attempt to use complex finite element models, this course will place heavy emphasis on hand calculations rooted in the fundamentals of mechanics.

Description

This course will thus take us beyond the rectilinear realm of classical structural analysis, and lead us to explore the beauty of curvilinear or more complex iconic shapes. Emphasis will be placed on a rigorous, mechanics based, development of theory. Then, simplified analysis methods will be developed and applied. As a vehicle for this development, we will focus on iconic structures. Students will be using exclusively analytical solutions (i.e. no finite element analysis).

What this course is not about: philosophical, societal, historical considerations governing design and architecture. It is not either a "light course" to visit Paris.

This will be a demanding and high level short course on structural analysis (about xx hours of lectures) for highly motivated students.

Format

We will start with a one day long meeting in Boulder to discuss coverage, expectations, format and pre-departure reading assignment. We will have a brief review of Matlab, and Mathematica. The "Art & Science" of structural engineering will be discussed, followed by a brief discussion of the Morandi bridge collapse in Genova.

On most days, there will be 4 or 6 hours lectures in a classroom setting, followed by afternoon site visits. On some occasions, lectures or site visits will be all day. There will be in class supervised exercises focusing on the topic covered. Students should be able to complete them in class, if not later that night. There will be no "homeworks" per se.

Students will be expected to maintain a day by day journal (OneNote format) that includes technical notes (from lectures), worked in class exercises, and report on site visits.

The reading list is long and exhaustive. Students will be expected to summarize 2-3 papers of each topic in about 10 slides.

Each student will be working on a project related to an *iconic* structure (structural analysis), and will make a presentation on the last day.

Students should come to class with their laptop preloaded with the required software. At least two weeks before, student shall receive detailed instructions on how to install software and related tutorials.

When and Where

This course is likely to be offered during the Maymester of 2018 (3 weeks in May) in Paris with the collaboration with the at the *Ecole Spéciale des Travaux Pratiques* (ESTP) in Cachan & Paris.

Prerequisites

- Statics (CVEN 2121) and Structural Analysis (CVEN 3525), B and above.
- Mathematica* (most of the calculation will entail lengthy algebraic operations).
- One Note*
- Matlab*
- Familiarity with a "good" drafting (vector based) program such as Visio, AutoCad, SolidWork, Adobe Illustrator.
- VPN to CU.
- Ability to draw clear free body diagrams, and to sketch structures to highlight load paths.

* Students are expected to bring their laptop with this software preloaded. The University has a site license for students.

Site Visits (tentative)

- Alexandre III Bridge
- Eiffel Tower
- Passerelle Simone de Beauvoir
- CNIT (SETEC)
- Pont de Normandie (Eiffage)
- Notre Dame
- La Grande Arche
- Sainte Chapelle
- Centre Pompidou
- Passerelle Leopold Senghor
- ESTP; (bouygues) Louvre Entrance
- Forum des Halles
- Bouygues

Invited Speakers (tentative)

- Bernard Vaudeville
- Michel Virlogeux
- Marc Miram
- Bruno Godart
- Pre; STETC

Cultural sites close to technical visits

Not exhaustive.

- Louvre Museum
- Pompidou Museum
- Museee d'Orsay
- Musee Quai Branly
- Omaha Beach;
- Mont St Michel
- Versailles

Coverage

Most or required reading documents are available from the instructor in pdf format.

This is a preliminary draft, coverage, references need to be finalysed.

W1-D1: Getting Started; Working tools (Boulder)

Coverage: a) Introduction, expectations, grading, logistic. b) A brief history of structural analysis. c) The art of structural engineering, how "form follows functions", architectural value of iconic structures designed by structural engineers (and not architects); b) Review of Mathematica and Matlab; b) Morandi bridge collapse (Genova 2018); c) Art and Science of structural Engineering.

Exercise In about 15 slides, discuss content of at least 5 of the papers listed below.

Reading: Morandi (1962), Beghini et al. (2014), Hines (2012), Bradshaw et al. (2002)

Additional Reading: Muttoni (2004), Alen and Zalewski, 2010, Kurrer (2008), Becchi (2002), Salvadori and M. (1981), Salvadori (1986), Malerba (2014), Morandi (1969), Nervi (1956),Allen (2014)

W-1-D2; Straight Lines: Trusses

Coverage: Review of Truss analysis; Optimal Design.

Examples: Alexandre III bridge, Eiffel tower.

Exercise: Complete approximate analysis of Eiffel tower. Iterate toward an optimal design for a cantilevered structure.

Reading: Alexandre III: Stephenson1 (2009); Eiffel Tower: Payá-Zaforteza et al. (2009), Billington and Mark (1983, pp. 37-65:), Weidman (2009). Topology Optimization: Baker et al. (2015), Baker et al. (2013)

Additional Reading: Sandaker and Eggen (1992, pp. 66-76:), Stromberg et al. (2012)

W-1-D3: Shape and Form: Cable Structures

Coverage: Advantages and disadvantages of cable structures, how load dictates shape of cables, funicular, derivation of governing differential equation for both parabolic and catenary shapes.

Examples Dulles Airport (Saarinen), Alitalia Hangar (Morandi), Sagrada Familia (Gaudi)

Exercise Matlab code for the approximate analysis of Nervi's Burgo paper mill in Mantua

Reading: a) Burgo's paper mill: Nervi (1963, pp. 164-167:), Lori (2009, pp. 66-69:).

Additional Reading: b) Dulles airport: Sandaker and Eggen (1992, pp. 180-185:).

W-1-D4: Cable structures: Bridges

Coverage: Suspension versus cable stayed bridges; Derivation of governing equations, Introduction to the concept of geometric nonlinearity,

Examples Dulles Airport (Saarinen), Alitalia Hangar (Morandi), Sagrada Familia (Gaudi)

Reading: a) on bridges: Virlogeux (1999); b) Cable stayed bridges: Bimson (2007), Davalos (2000)

Additional Reading Pollalis (1999), Hines and Billington (1998), Honigmann and Billington (2003).

W-1-D5; Pont de Normandy

Day trip

W-2-D1; Frames Revisited

Coverage: Shear, Moment, Torsion diagrams of 3D frames; Approximate analysis of frames.

Examples: la Grande Arche; and *Magazzini Generali*

Exercise Complete spreadsheet program for approximate analysis of frames.

Reading: a) La grande arche: Chaslin and Picon-Lefebvre (1985), Viets ("La Grande Arche De La Defense"); b) Magazzini Generali: Billington and Mark (1983, pp. 111-134:).

Additional Reading: Chaslin and Lefebvre (1989)

W-2-D2: Soaring Structures: Gothic Cathedrals

Coverage: a) Stability of Gothic cathedrals, challenge in the transfer of the horizontal thrust caused by the vaults, roles of flying buttresses, b) Graphical method, thrust lines, load transfer; Impact of low tensile strength of masonry structures.

Examples: Notre Dame

Exercise: Matlab code to determine and plot lines of thrusts.

Reading: a) Heyman (2006, chapter 3) , Heyman (1997). b)Heyman (2003) chapter 5. c) Billington and Mark (1983, pp. 211-251:).

W-2-D3; The Mechanics of Arches

Coverage: Advantages of arches, three hinge arch, optimal shape of an arch, semi-circular vs parabolic.

Example generic

Exercise Analyis of 3 centered arch (Matlab), plot internal forces.

Reading: Sonavane (2014), Duflot and Taylor (2008)

W-2-D4; Arches for Bridges

Coverage: Two hinged statically indeterminate arch.

Example Salginatobel Bridge (Maillart), detailed analysis.

Exercise Complete Matlab code for the analysis of a two hinged arch.

Reading Assignment: Salginatobel bridge: Drake (2010), Billington (1979, pp. 77-89:), Billington and Mark (1983, pp. 161-184:)

Additional reading: Hauck (1986)

W-2-D5; Laboratory visits

W-3-D1; As Complex as Can be: Helicoidal Arch

Coverage: Review of three dimensional vector mechanics, 6 internal forces in a curved structure.

Example: Generic

Exercise: Complete class exercise.

Reading: Lecture Notes

W-3-D2; Domes

Coverage: Approximate analysis of domes.
Example: St Peter, Florence (Bruneleschi).
Exercise: Complete class exercises.
Reading: Lecture Notes; Lopez (2006)

W-3-D3; Perfect Shapes: Shell*

Coverage: a) Theory; free body diagram; highlight of the derivation of the eighth order PDE for shell. b) Simplifications; Membrane theory. c) Statically indeterminate dome/cylinder. full day lecture
Example Palazetto dello Sport by Nervi
Exercise Matlab assignment.
Reading: a) Theory: Georg and Saouma (2014); Saouma's Lecture notes, Peerdeman (2008); b) Palazetto dello sport: Howard (1966). Bucur-Horváth and Săplăcan (2013);
Additional Reading: Billington (1965)
Homework:

W-3-D4; Experimental Methods

Coverage: Derivation of shapes from experimental techniques.
Examples Gaudi, Nusmeci, Isler.
Exercise Write a brief report.
Reading a) Gaudi: Collins (1963) Huerta (2006), Grima, Gomez Serrano, and Aguado (2007); b) Nusmecci: Capomolla (2006); c) Isler: Isler (1994).

W-3-D5; Presentations; Final Exam

Presentation of each student project (AM); FInal Exam (2 hrs) PM

Other references

Huxtable (xxx), Olmo and Chiorino (2010), Nervi (1965), Tzonis (2004), Collins (1963), Huerta (2006), Grima, Gomez Serrano, and Aguado (2007) A three hour comprehensive exam.

Grades; Examinations

Grades will be based on: 30% Project and Presentation; 30% Field book; 40% Final Exam. The final grade will depend on the average of the two highest individual point totals (h) for the course. The final letter grade that you get is determined by taking your point total and putting it in one of these

Letter Grade	A	A-	B+	B	B-	C+	C	C-	F
Range of Point	h*1.00	h*.939	h*.919	h*.899	h*.819	h*.799	h*.779	h*.719	¡h*.699
Total	h*.940	h*.920	h*.900	h*.820	h*.800	h*.780	h*.720	h*.700	

References

Alen, E. and W. Zalewski (2010). *Form and Forces, Designing Efficient Expressive Structures*. Wiley.

Allen, David H (2014). "Continuum Mechanics, Art and Structures". In: *How Mechanics Shaped the Modern World*. Springer, pp. 207–242.

Baker, William F et al. (2013). "Maxwells reciprocal diagrams and discrete Michell frames". In: *Structural and multidisciplinary optimization* 48.2, pp. 267–277.

— (2015). "Structural Innovation: Combining Classic Theories with New Technologies". In: *Engineering Journal; American Institute of Steel Construction* 52.3, pp. 203–217.

Becchi, A. et al. (2002). *Towards a History of Construction; Dedicated to Edoardo Benvenuto*. Birkhauser Verlag.

Beghini, Lauren L et al. (2014). "Connecting architecture and engineering through structural topology optimization". In: *Engineering Structures* 59, pp. 716–726.

Billington, D. (1965). *Thin Shell Concrete Structures*. McGraw Hill.

Billington, D.P. (1979). *Robert Maillart's Bridges; The art of Engineering*. Princeton University Press.

Billington, D.P. and R. Mark (1983). *Structures abd the Urban Environment*. Tech. rep. Department of Civil Engineering, Princeton University.

Bimson, D.T.O. (2007). "A Critical Analysis of the Pont de Normandie Cable-Stayed Bridge". In: *Proceedings of Bridge Engineering 2 Conference*.

Bradshaw, Richard et al. (2002). "Special structures: past, present, and future". In: *Journal of structural engineering* 128.6, pp. 691–709.

Bucur-Horváth, Ildikó and Radu V Săplăcan (2013). "Force Lines Embodied in the Building: Palazzetto dello Sport". In: *Journal of the International Association for Shell and Spatial Structures* 54.2-3, pp. 179–187.

Capomolla, RINALDO (2006). "Il ponte sul basento di sergio musmeci. il progetto della forma strutturale prima dellavvento del calcolo automatico". In: *Atti del Primo Convegno Nazionale di Storia dellIngegneria*.

Chaslin, F. and V. Picon-Lefebvre (1985). *La Grande Arche de la Defense*. Electa Moniteur.

Chaslin, François and Virginie Picon Lefebvre (1989). *La grande Arche de la Défense*. Electra Moniteur.

Collins, G.R. (1963). "Antonio Gaudi: Structure and form". In: *Perspecta* 8, pp. 53–90.

Davalos, E. (2000). *Structural Behaviour of Cable-Stayed Bridges*. Tech. rep. M.S. Thesis of E. Davalos Supervised by J. Connor. Cambridge: Massachusetts Institute of Technology.

Drake, RS (2010). "A critical Analysis of the Salgintobel Bridge". In: *Proceedings of Bridge Engineering Conference*. University of Bath, Bath, UK.

Duflot, Philippe and Doug Taylor (2008). "Fluid Viscous Dampers: An Effective Way to Suppress Pedestrian-Induced Motions in Footbridges". In: *Third International Conference: Footbridge*.

Georg, R. and V. Saouma (2014). *Historical Analysis of Arches and Modern Shells*. Tech. rep. M.S. Thesis of Ryan Georg supervised by V. Saouma. Boulder: University of Colorado.

Grima, R., J. Gomez Serrano, and A. Aguado (2007). "The Use of Concrete in Gaudi's Sagrada Familia". In: *International Journal of Architectural Heritage*, pp. 366–379.

Hauck, G.F. (1986). "Structural Design of the Pont du Gard". In: *Journal of Structural Engineering* 112.1, pp. 105–120.

Heyman, J. (2003). *Structural Analysis; A Historical Approach*. Cambridge University Press.

— (2006). *The Science of Structural Analysis*. Imperial College Press.

Heyman, Jacques (1997). *The stone skeleton: structural engineering of masonry architecture*. Cambridge University Press.

Hines, E.M. and D. Billington (1998). "Case Study of Bridge Design Competition". In: *ASCE J. of Bridge Engineering* 3.3, pp. 93–102.

Hines, Eric M (2012). *Understanding Creativity*. Tech. rep. Festschrift.

Honigmann, C. and D. Billington (2003). "Conceptual Design for the Sunniberg Bridge". In: *ASCE J. of Bridge Engineering* 8.3, pp. 122–130.

Howard, H.S. (1966). *Il Palazetto dello Sport: An Architect's Approach*. TH845.h6. Mc Graw Hill.

Huerta, S. (2006). "Structural Design in the Work of Gaudi". In: *Arcitecture Science Review* 49.4, pp. 324–339.

Huxtable, A.L. (xxx). *Pier Luigi Nervi Engineer*. George Braziller, Inc.

Isler, Heinz (1994). "Concrete shells derived from experimental shapes". In: *Structural engineering international* 4.3, pp. 142–147.

Kurrer, K.E. (2008). *The History of the Theory of Structures*. Ernst & Sohn.

Lopez, GM (2006). "Poleni's manuscripts about the dome of Saint Peter's". In: *Proceedings of the Second International Congress on Construction History, Cambridge: CHS*. Vol. 2, pp. 1957–1979.

Lori, T. (2009). *Pier Luigi Nervi*. (NA1123.N4 A4 2009). Motta Architectura.

Malerba, Pier Giorgio (2014). "Inspecting and repairing old bridges: experiences and lessons". In: *Structure and Infrastructure Engineering* 10.4, pp. 443–470.

Morandi, Riccardo (1962). “Engineering and architecture”. In: *Journal of the Royal Society of Arts* 110.5066, pp. 75–92.
— (1969). “Some Types of Tied Bridges in Prestressed Concrete”. In: *Special Publication* 23, pp. 447–466.
Muttoni, A. (2004). *L'art des Structures*. Presses Polytechniques et Universitaires Romandes.
Nervi, P.L. (1956). *Structures*. (TA683 .N42 c.2). F.W. Dodge Corp.
— (1963). *Buildings, Projects, Structures (1953-1963)*. (NA1123N4A433). Praeger.
— (1965). *Aesthetics and Technology in Building*. Charles Eliot Norton Lectures; (NA4125 .N413 c.3). Harvard University Press.
Olmo, C. and C. Chiorino (2010). *Pier Luigi Nervi, l'Architecture comme Défi*. Silvana Editoriale.
Payá-Zaforteza, Ignacio et al. (2009). “Use of ConcepTest in a Course on Building Structural Analysis for Teaching Construction History”. In: *Proc. Third International Congress on Construction History*, pp. 1147–1154.
Peerdeman, Bart (2008). “Analysis of thin concrete shells revisited: Opportunities due to innovations in materials and analysis methods”. In: *Master's thesis the Netherlands: Delft University of Technology*, pp. 30–50.
Pollalis, S.N. (1999). *The Making of Calatrava's Bridge*. MIT Press.
Salvadori, M. (1986). *Structure in Architecture; The Building of Buildings*. Prentice-Hall.
Salvadori, M. and Levy M. (1981). *Structural Design in Architecture*. Prentice Hall.
Sandaker, B.N. and A.P. Eggen (1992). *The Structural Basis of Architecture*. Whitney Library of Design.
Sonavane, T. (2014). *Analysis of Arches*. Tech. rep. M.S. Thesis of T. Sonavane Supervised by V. Saouma. Boulder: University of Colorado.
Stephenson1, V.J. (2009). *A Critical Assessment of the Pont Alexandre III Bridge*. Undergraduate Report, University of Bath.
Stromberg, Lauren L et al. (2012). “Topology optimization for braced frames: combining continuum and beam/column elements”. In: *Engineering Structures* 37, pp. 106–124.
Tzonis, A. (2004). *Santiago Calatrava; The Complete Work*. Rizzoli, New-York.
Viets, Bradley Angell-Trenton Jacobs-Elizabeth. “La Grande Arche De La Defense”. In:
Virlogeux, Michel (1999). “Recent evolution of cable-stayed bridges”. In: *Engineering structures* 21.8, pp. 737–755.
Weidman, PD (2009). “Modified shape of the Eiffel Tower determined for an atmospheric boundary-layer wind profile”. In: *Physics of Fluids* 21.6, p. 067102.