Course Title:

Geometric Structural Design
The principles of 3D graphic statics and structural modeling

Fall 2018,
ARCH 732-003
Thursdays 2-5 pm; Room 324
Course outline

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PSL

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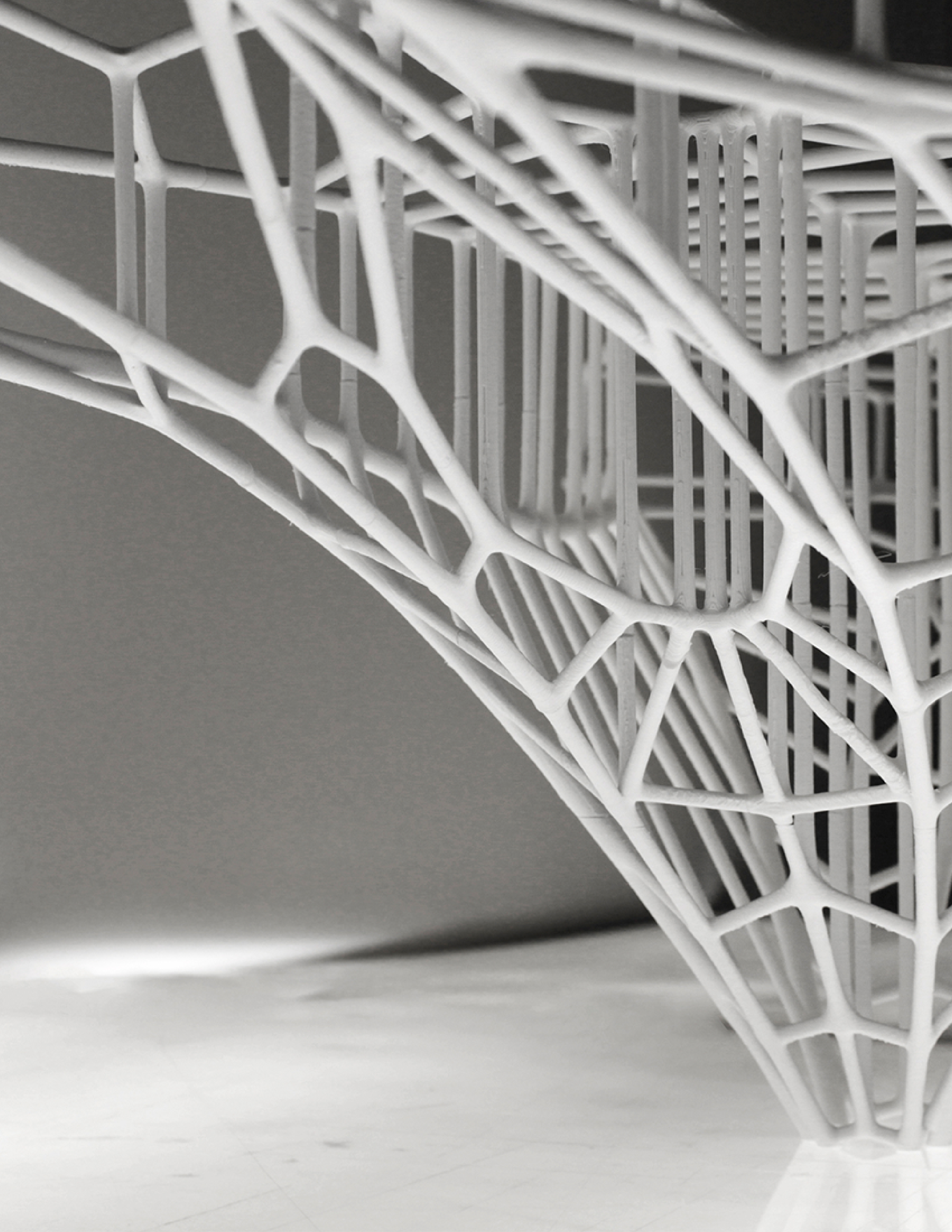


1 Course description

Geometric Structural Design provides a comprehensive introduction to novel geometric methods of structural design based on 2D and 3D graphical statics (Rankine, 1864; Maxwell, 1870; Wolfe, 1921; Akbarzadeh, 2016). The primary emphasis of the course will be on developing a general understanding of the relationship between structural forms in equilibrium and the geometric representation of their internal and external forces. This link is the main apparatus for designing provocative structural forms using only geometric techniques rather than complicated algebraic/numerical methods. Moreover, special consideration will be given to materialization of the structural geometry and the proper fabrication techniques to construct the complex geometry of the structure.

Note that this course is based on ongoing research in the field of 3D graphical statics, and therefore provides students with the opportunity to directly contribute to the current research in geometric methods of structural design. Familiarity with a parametric software is required, and code-writing ability is an asset. Particular attention will be given to structural model making and careful structural drawings. The outcomes of the course will become a primary collection of Polyhedral Structures Laboratory. Also, a unique summer research fellowship will be available for highly motivated students to build a one-to-one scale structural prototype based on the forms developed in the class.

2 Methodology

The course is divided into five consecutive parts with specific intentions; *Part I* will introduce the geometric principles of equilibrium of structural forms (Wolfe, 1921; Akbarzadeh et al., 2015a); *Part II* will focus on structural form finding using geometric techniques (Akbarzadeh et al., 2015c; Lee et al., 2016); *Part III* will concentrate in manipulating the geometry of the structural form and its force diagram to explore various architectural schemes (Akbarzadeh et al., 2015b; Akbarzadeh, 2016); and *Part VI* will specifically emphasize the choice of material and the fabrication techniques to construct complex spatial forms. Table 1 provides a brief overview for each part and its relevant aims and objectives.

2.1 Aims

Therefore the course has the following particular intentions:

- to introduce the concept of equilibrium using geometric techniques, expanding the reciprocal relationship between the elements of an equilibrated structural form and its force diagram;
- to emphasize the use of geometry in designing complex yet efficient structural forms and deriving the internal and external forces using geometric diagrams;

Course sections	*Aims*	*Objectives*
Part I: the principles of equilibrium	• introducing geometric equilibrium of forces in 2D and 3D; • hinting on the properties of form and force diagrams; • defining global and nodal equilibrium;	• to construct parametric form and force diagrams; • to represent different states of equilibrium geometrically;
Part II: form finding explorations	• introducing the technique aggregation in the force diagram; • describing the force subdivision technique; • providing the computational framework for form finding;	• to construct complex structural forms by designing their force diagram; • to produce various structural forms by redistributing the internal forces;
Part III: manipulating/articulating the design	• introducing geometric degrees of freedom of the form and force diagrams;	• iterative design process to fulfill specific architectural needs;
Part VI: materializing the structural geometry	• introducing various materials translating structural geometry into building components; • reviewing multiple fabrication techniques for constructing spatial structural geometry;	• to choose a specific material and translate the structural geometry into a volumetric object based on the properties of the chosen material; • to devise a proper fabrication technique for constructing the structural geometry;

Table 1: Various parts of the course and their aims and objectives.

- to simplify the understanding of complex structural concepts using geometric language instead of numerical methods; and,
- to investigate different materials and fabrication techniques to realize spatial structural forms.

2.2 Objectives

On completion of this course, students should be able to:

- describe the equilibrium of structural concepts using geometric methods of graphical statics in 2D and 3D;

- construct structurally informed, novel architectural concepts and derive the internal and external forces in the system geometrically; and,
- understand the challenges in materializing spatial structural forms and develop appropriate fabrication techniques to construct their complex components.

3 Grading

Table 2 provides the grading criteria of the course:

Assignment	*% of grade*	*Due date*
Session attendance	10	
Exercises	30	Sep 13;27, Oct 18, Nov 1; 15, 29
Structural model	40	Nov 30 – Dec 6
Final structural model	19	Dec 19
Force model	10*	

Table 2: Grading criteria;
∗ Additional points for the groups who build their force model for their final projects.

4 Lecture schedule

Table 3 represents the schedule as well as the tiles of the lectures of the course and their related exercises.

Course Sessions		*Titles*
Part I: Intro		
Aug 30	w1	Introduction to geometric methods of structural design
Part II: Form finding techniques		
Sep 6	w2	2D structural form finding; Exercise 1: aggregation/subdivision
Sep 13	w3	Review Exercise 1
Sep 20	w4	3D graphic statics; Exercise 2: aggregation
Sep 27	w5	Review Exercise 2
Part III: Articulating the design		
Oct 11	w6	3D Graphic Statics; Exercise 3: subdivision
Oct 18	w7	Review Exercise 3
Oct 25	w8	physical form finding; Exercise 4: sectional model of the structure
Nov 1	w9	Midterm review
Part IV: Materializing the design		
Nov 8	w10	Exercise 5: fabrication technique
Nov 15	w11	Review Exercise 5
Nov 20	w12	Exercise 6: assembling parts
Nov 29	w13	Review Exercise 6
Dec 19	w14	Final Review: a complete conceptual model and one-to-one scale prototype

Table 3: Lecture schedule with specific dates for exercises, midterm, and final review dates.

5 Exercise I

Design a compression or tension only structure to support a foot bridge/Hyperloop bridge over Schuylkill. Use 2DGS plugin for Rhino to test your aggregation and subdivision techniques (Please follow the instructions on the course folder to install the plugin).

- aggregate polygons to find a compression-only structural forms; the exterior polygon represents the global equilibrium and defines how many supports you will have for your bridge and how many components will transfer the loads from the deck of the bridge to the supports;
- develop three different subdivision rule that can be applied to the aggregated polygons and generate a more intricate structural solution. The subdivision rules should clearly explain the process involving subdividing edges and cells to create particular features in the structure;
- it is required that the designer develop his/her subdivision techniques and explain the process of the subdivision with simple diagrams.
- the best design will be judged based on how the developed subdivision technique can turn the force diagram into an unexpected structural solution;

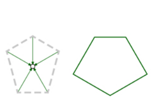
5.1 Deliverable

The structural concept should be delivered in **all** following formats:

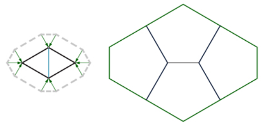
- *drawing* (due Sep 13): the drawings of the form and force diagrams should be presented on (16″width x 9″ height) documents. The precision of the drawings will affect your score.

  The drawings should be polished in Adobe illustrator with the same document size as the paper. Special attention should be given to the line weights of the drawing; thicker line weight presents a member with larger force magnitude and vice versa. The color convention of the reaction/applied forces should be similar to the given examples in the paper by Akbarzadeh et al. (2014).

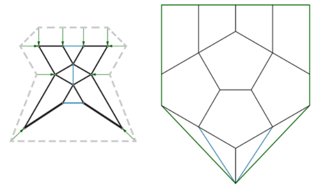
  The drawings should very well explain the design process as well as the subdivision logic. The rendering should be presented in the same format (16 x 9), but the digital model should be placed in the provided background (Figure 1). The rendering should suggest some volumetric aspects of the 2D concept of the bridge including your choice of construction material.



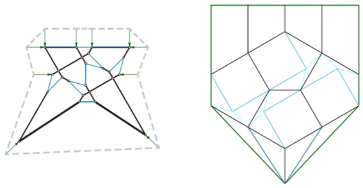
Pentagon



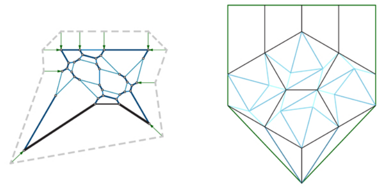
“Cairo Grid”



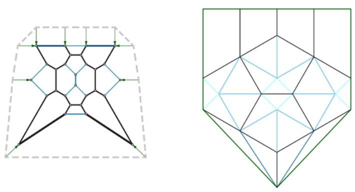
2-leg Support



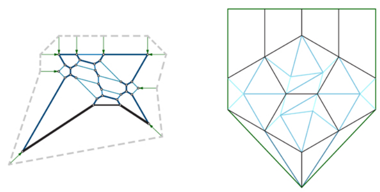
Subdivision
Type A



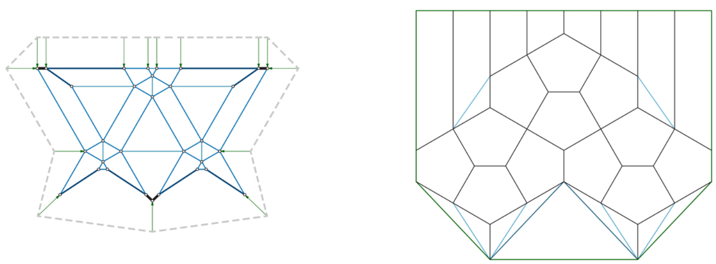
Subdivision
Type A+B



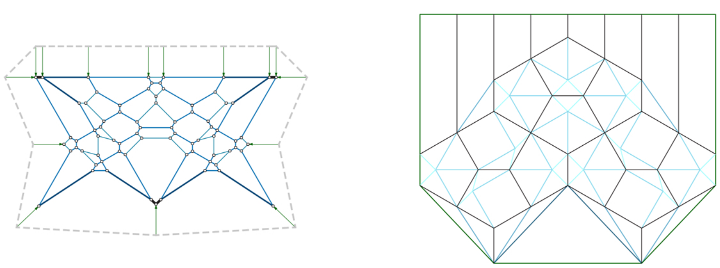
Subdivision
Type C



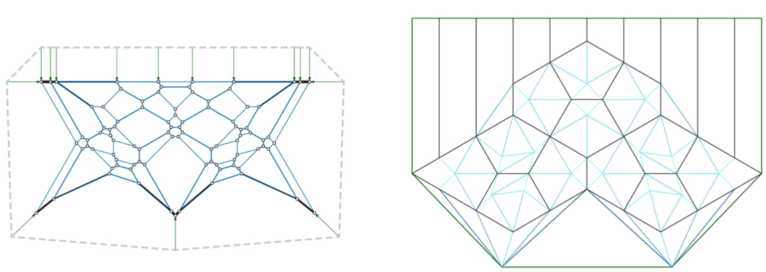
Subdivision
Type A+B+C



3-leg Support



Subdivision
Type A+B



Subdivision
Type A+B+C with 3-leg optimization

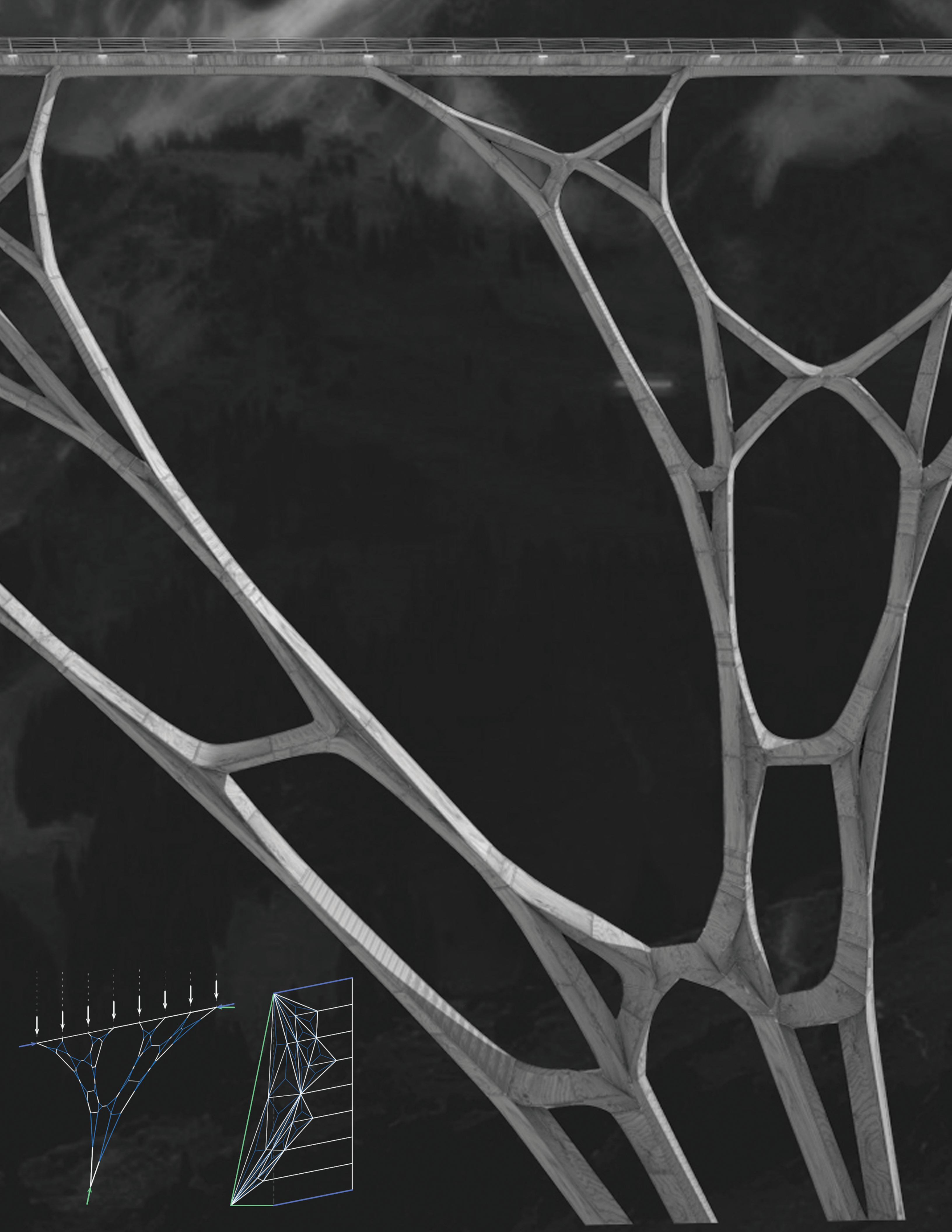


Figure 1: Replace the background scene (16x9) with a picture of Schuylkill river for the rendering of your bridge.

6 Exercise II

The main objective of this exercise is to develop an understanding on how to design constrained funicular solutions for specific boundary conditions. Each student should design a bridge spanning from point A to point B with different heights. Use the techniques you developed for your aggregation/subdivision exercise.

6.1 Deliverable

The following items should be delivered on Sept 27th:

- the complete form and force diagrams for the constrained model of your design. The file should be very clean and precise. Try to control your parameters so that changing one parameter does not result in representational failures.
- the preferable format for your drawings would be .ggb files.
- consider specific material for your bridge such as stone, concrete, brick, steel and design the volume of your bridge accordingly.
- present a rendering of your bridge merged with the landscape around it.

7 Exercise III

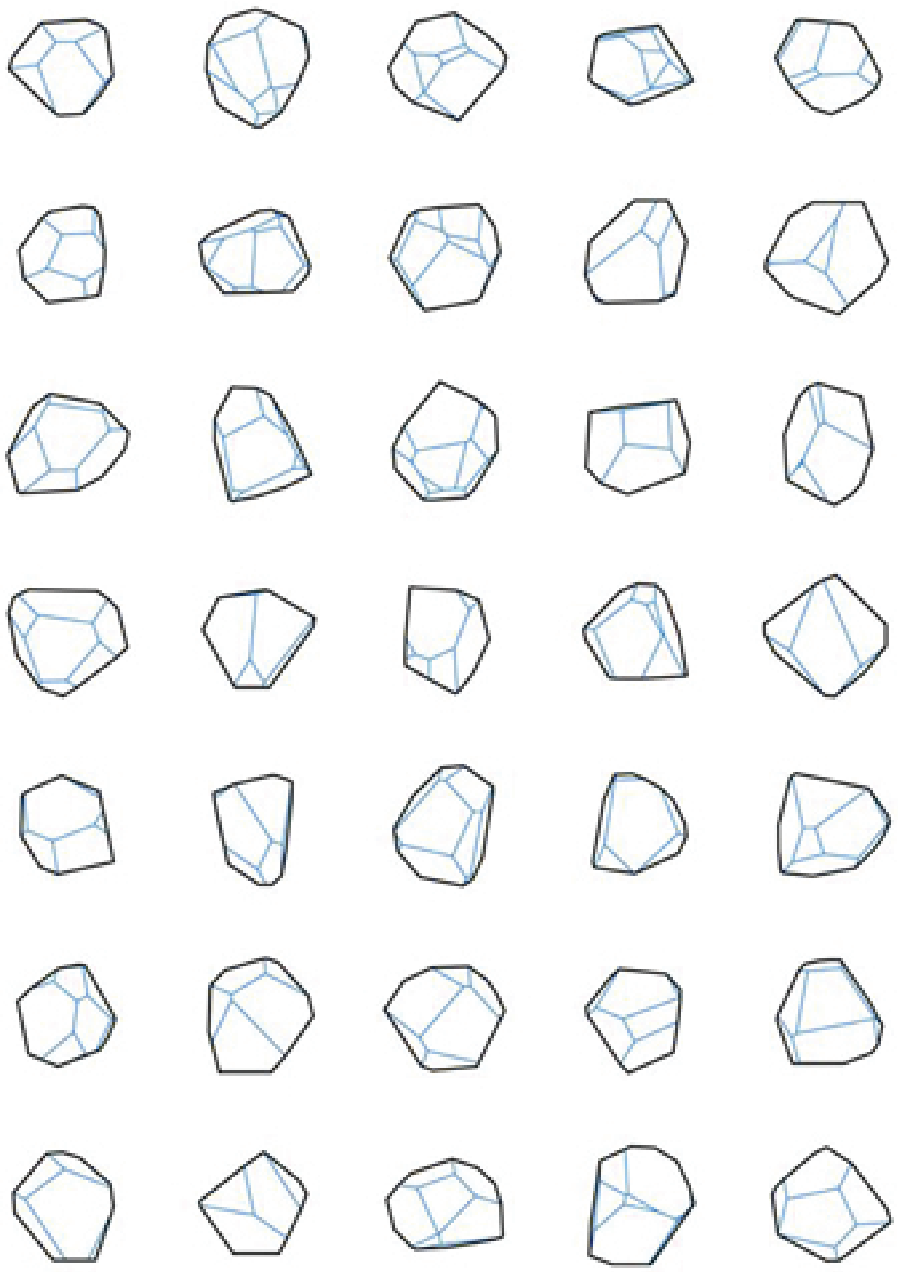
The following exercise will prepare you to design non-conventional spatial structural forms by controlling their force diagrams in 3D using *PolyFrame* tool. The main of objective of this section to explore a variety of compression-only forms by deliberately designing their force diagram and its aggregation logic.

- start by modeling various simple polyhedrons with no more than six sides;
- explain how these polyhedrons can be aggregated to make a larger group of polyhedrons;
- you can start with your 2D explorations and try to generate similar structures in 3D.
- pay attention how you can control the geometry of the form diagram by changing the geometry of your force aggregation; for instance, how could you make curves, straight lines, branches, etc.
- This exercise should be pursued by groups two, and each team is responsible for the generation of various force diagrams by aggregating polyhedral cells;
- Each team should explore *6 different configurations* of aggregated polyhedral cells and extract their reciprocal form diagram using *PolyFrame* Plugin;
- The investigation of the effects of the type of aggregation on the resulting form is quite valuable and necessary.

Note : Please do not use Voronoi command in Rhino/Grasshopper; the Voronoi command will only generate tetrahedral structural forms that have a very restrained topology which makes it difficult to manipulate for design purposes.

7.1 Deliverable

- *Digital models* (Due October 18th): present your force aggregation studies in a format of $.3dm$ drawings in the class.



8 Exercise IV

This exercise will help you discover more interesting features in funicular structural forms revealing specific design techniques in the force diagram. Each group has been assigned a particular force diagram and for the session on Thursday (Oct 25t):

- each group should analyze the assigned force diagram copied in the folder of the group; by analysis means, you need to identify certain design configurations in the geometry of the force diagram that results in specific design features in the form;
- show and present those design features in exploded axon in the class;
- apply some similar ideas from the assigned model into your design and explain how this idea can be explored and advanced further;
- each group should also visit other force diagrams in the public folder and get some inspiration for their design.

8.1 Deliverable

Each group should:

- present their studies and analysis of the assigned model in a form of exploded axon drawings which will be a n excellent exercise to prepare for the mid-term presentation;
- show some advances in their force diagram and its derived form; and,
- submit the digital format of their studies (3dm).

9 Exercise V

The objective of this exercise is to test the structural modules you have developed since the beginning of the semester. For this exercise each team should:

- build a physical tensile structural model of their proposed module;
- the structure should be bounded to an acrylic box with the dimensions 16″w x 22″ l x 16″ h. The faces of the acrylic box should be made out of 1/4″ acrylic sheets. Please coordinate among your self to use the exact same model for the construction of your structures;
- You should develop a robust connections for your structural models; note that the imprecision in your connections might change the lengths of your members which will result in hanging members in the structure;
- pay attention to the details of your end connections as they transfer loads to the plates and they should be fixed well.

9.1 Deliverable

The following items are necessary for the mid-term review of your project (Due November 8th):

- the complete structural model representing a spatial tensile structure in equilibrium;
- relevant drawings of the form and force diagrams including exploded axon of the force diagram and its corresponding features on the form;
- the digital model of your setup as well as your final form and force models.

10 Exercise 6

The objective of this exercise is to materialize the bar-node configuration of 3DGS methods. The goal of this study is to materialize a concept designed through the semester in the form of an installation for the outcome of the course. All teams will work together in the design, materialization, fabrication, and assembly of the project.

For this exercise each team should:

- research various methods and techniques that can be used to materialize the structure;
- consider a variety of materials including timber, polycarbonate, polyurethane (foam), aluminum sheets, PLA, fabric, plywood veneer, etc.;
- consider a variety of fabrication methods, including milling, vacuum forming, robotic wire-cutting (if accessible), etc.;
- note that we are not interested in making a cumbersome structure, thus avoid masonry and concrete members!;
- present your research and precedent study in the form of a presentation;
- show multiple schematic studies on the geometry of the parts and your proposed method of fabrication;
- your proposals should consider the lack of a significant budget, and the fabrication proposals should use simple, but smart construction techniques.

10.1 Deliverable

The following items are necessary for the mid-term review of your project (Due November 20th):

- presentation including the research and your proposals for materialization of your form;
- drawings describing the procedural geometric techniques used to design the parts, and the methods of construction;
- a mock-up of the part as a proof of concept.

References

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