Course Title:

Geometric Structural Design
3D graphic statics to fabrication

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ARCH 632-002 Course outline

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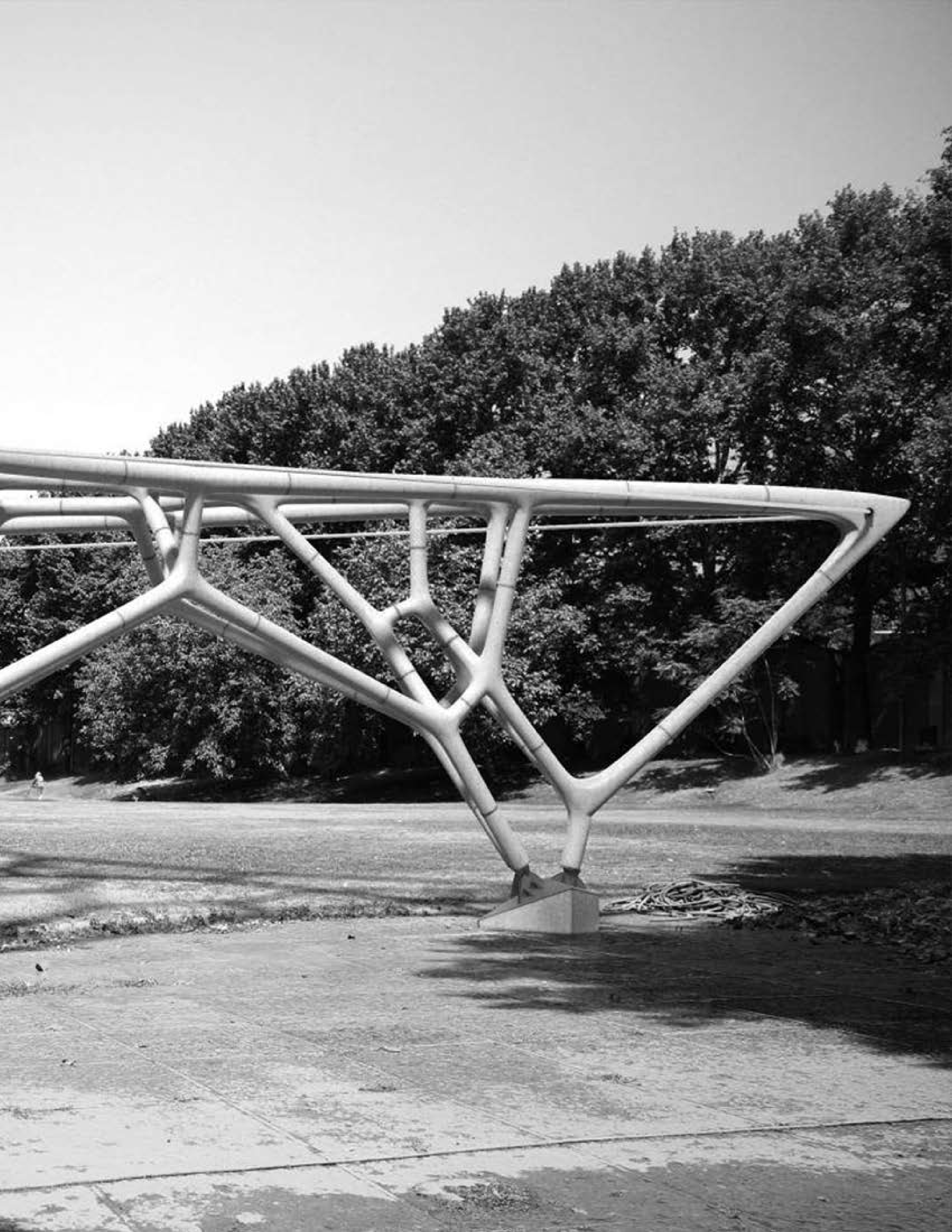

1 Course description

Geometric structural design I 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 main 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 relationship will be used as the main apparatus in 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 an on-going 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. Special attention will be given to structural model making and careful structural drawings. The outcomes of the course will be exhibited for a period of time after the final review at the end of the semester. In addition, a spacial 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); *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); *Part IV* will provide the necessary procedures to constrain the form and force diagrams to specific locations and control the boundary conditions (Akbarzadeh et al., 2016); and *Part V* 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;

Course sections	*Aims*	*Objectives*
Part I: principles of equilibrium	• to introduce geometric equilibrium of forces in 2D and 3D; • to hint on the properties of form and force diagrams; • to define global and nodal equilibrium;	• to construct parametric form and force diagrams; • to represent different states of equilibrium geometrically;
Part II: form finding explorations	• to introduce the technique of force aggregation; • to describe the force subdivision technique; • to provide 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 the design	• to introduce the geometric degrees of freedom of the form and force diagrams;	• iterative design process to fulfill specific architectural needs;
Part IV: constrained form finding	• to introduce the procedures to construct the form and force diagrams constrained to specific boundary conditions;	• to reproduce the form and force diagrams for predefined support locations and applied loads;
Part V: materializing the structural geometry	• to introduce various materials translating structural geometry into building components; • to review 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 emphasize the use of geometry in designing complex yet efficient structural forms and deriving the internal and external forces using geometric diagrams;
- 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	Jan 23 – Apr 30
Structural model	30	Mar 20 – Apr 24
Fabricated prototype	30	Apr 17
Force model	10*	

Table 2: Various parts of the course and their aims and objectives;
∗ 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			
	Jan 11	w1	Introduction to geometric methods of structural design
	Jan 23	w2	Constructing 2D funicular forms and their force diagram; Exercise 1
	Jan 30	w3	Review Exercise 1
Part II:			
	Feb 6	w4	Aggregating/Subdividing the force diagram as a design technique; Exercise 2
	Feb 13	w5	Review Exercise 2
	Feb 20	w6	3D Graphic Statics; Computational form finding session; Exercise 3
	Feb 27	w7	Review Exercise 3
Part III:			
	Mar 13	w8	Programming the design; producing architectural spaces; Exercise 4
	Mar 20	w9	Midterm review
Part IV:			
	Mar 27	w10	Introduction to constrained form finding techniques in 3D; Exercise 5
	Apr 3	w11	Review Exercise 5
Part V:			
	Apr 10	w12	Materializing the structural geometry; Exercise 6
	Apr 17	w13	Review Exercise 6
	Apr 24	w14	Final Review

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

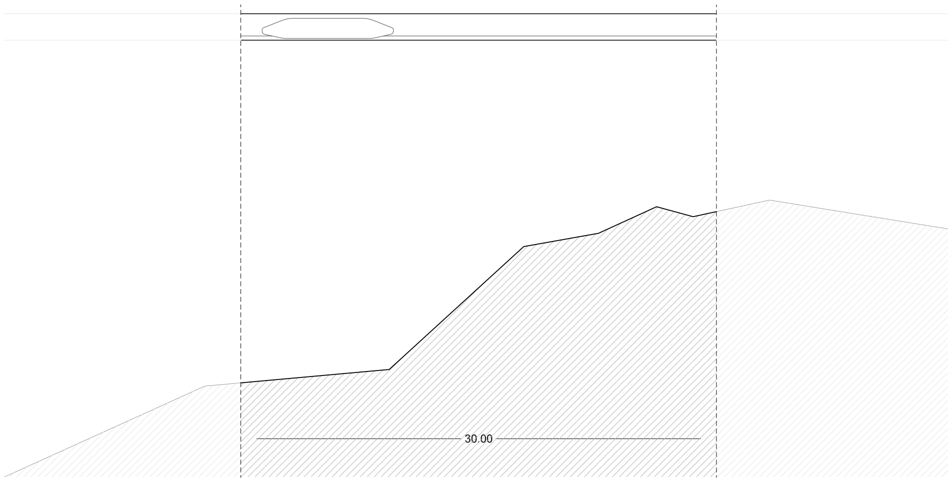

Figure 1: The suggested boundary condition to design a supporting structure for a 30 meter module of Hyperloop track.

5 Exercise I

Design a compression/tension only structure to support a modular Hyperloop track spanning 30 meters (Figure 1) The structural must fulfil the following criteria:

- The concept should be constructed in a parametric software and be constrained to specific support locations. It should be shown that a change in the location of the supports results in a new form geometry in equilibrium;
- the final structural concept should be the result of the application of subdivision techniques on the initial funicular form; the various subdivision techniques and their relevant steps should be explained in detail;
- it is recommended that the designer devise his/her own subdivision techniques and the process of using them to reach the final concept. In fact, the same reproduction of the examples of the class is not allowed;
- the concept should convey the possibility of its use as a modular system; therefore, the connection configuration of the adjacent modules might be considered as a design criterion;
- the maximum length for the compressive members, which are not connected to the supports, should not exceed 2 meter.

5.1 deliverables

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

- *drawing* (due Jan 30): the drawings of the form and force diagrams should be printed on carefully-cut sheet of papers (16"width x 9" height) attached

Figure 2: A suggested background scene for the rendering of multiple spans of the structural concept.

to a piece of white foam board with the same dimensions.

The digital format should also be constructed in Adobe illustrator with the same document size as the paper. special attention should be given to the line weights of the drawing; the members with greater force magnitude should be presented by thicker line weights than those with lesser magnitude of the internal force. The color convention of the reaction/applied forces should be similar to the given examples.

The drawings should very well explain the design process as well as the subdivision logic.

The rendering should be presented in the same format, but the digital model should be placed in the provided background (Figure 2). The rendering should represent the concept in multiple modules side by side or a single module (optional) suggesting the volumetric concept of the bridge.

- *Parametric model*(due Feb 6th): The parametric model ($.gh/.ggb$ format) should be presented parallel with the drawings; it should demonstrate the constraint of the form and force diagram and the level of control in the design by changing the location of the supports.
- *physical model* (due Feb 13th): the physical model should be constructed as a working tension-only structural form constructed from (possibly metal) strands subjected to the applied loads. The model should be constructed on a piece of plywood (1/4″ thickness, 16″h x 16″w) veneered by back/white paper.

6 Exercise II

The following exercise will prepare you to design non-conventional compression–only spatial structural forms by controlling their force diagrams in 3D using *Form and Force Polyhedron* tool (Section 6.2). The main of objective of this section to explore variety of compression-only forms by deliberately designing their force diagram and its aggregation logic.

- This exercise should be pursued by groups two, and each group is responsible for the generation of various force diagrams by aggregating polyhedral cells;
- Each team should explore *four different configurations* of aggregated polyhedral cells and extract their reciprocal form diagram using *Form and Force Polyhedrons* 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/Grasshoper; the Voronoi command will only generate tetrahedral structural forms that have a very restrained topology which makes it difficult to manipulate for design purposes.

6.1 Deliverables

- *Digital models* (Due Feb 13th): present your force aggregation studies in a format of $.3dm$ drawings in the class.

6.2 Installation of Form and Force Polyhedron Plugin

To install the tool:

- Please copy the $''Form\_and\_Force\_Polyhedrons''$ folder in your root drive $(C:)$;
- drag and drop the $''Form\_and\_Force\_Polyhedrons.rui''$ into your Rhinoceros window;
- enjoy form finding in 3D!

References

M. Akbarzadeh. *3D Graphic Statics*. PhD thesis, ETH Zürich, Zürich, Switzerland, 2016.

M. Akbarzadeh, T. Van Mele, and P. Block. On the equilibrium of funicular polyhedral frames and convex polyhedral force diagrams. *Computer-Aided Design*, 63:118–128, 2015a.

M. Akbarzadeh, T. Van Mele, and P. Block. 3d graphic statics: Geometric construction of global equilibrium. In *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium*, Amsterdam, The Netherlands, 2015b.

M. Akbarzadeh, T. Van Mele, and P. Block. Three-dimensional compression form finding through subdivision. In *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium*, Amsterdam, The Netherlands, 2015c.

M. Akbarzadeh, T. Van Mele, and P. Block. Three-dimensional graphic statics: Initial explorations with polyhedral form and force diagrams. *International Journal of Space Structures*, 31(2):217–226, June - September 2016. doi: 10.1177/0266351116660802.

J. C. Maxwell. On reciprocal figures, frames and diagrams of forces. *Transactions of the Royal Society of Edinburgh*, 26(1):1–40, 1870.

W. J. M. Rankine. Principle of the equilibrium of polyhedral frames. *Philosophical Magazine Series 4*, 27(180):92, 1864.

W. S. Wolfe. *Graphical Analysis: A Text Book on Graphic Statics*. McGraw-Hill Book Co. Inc., New York, 1921.