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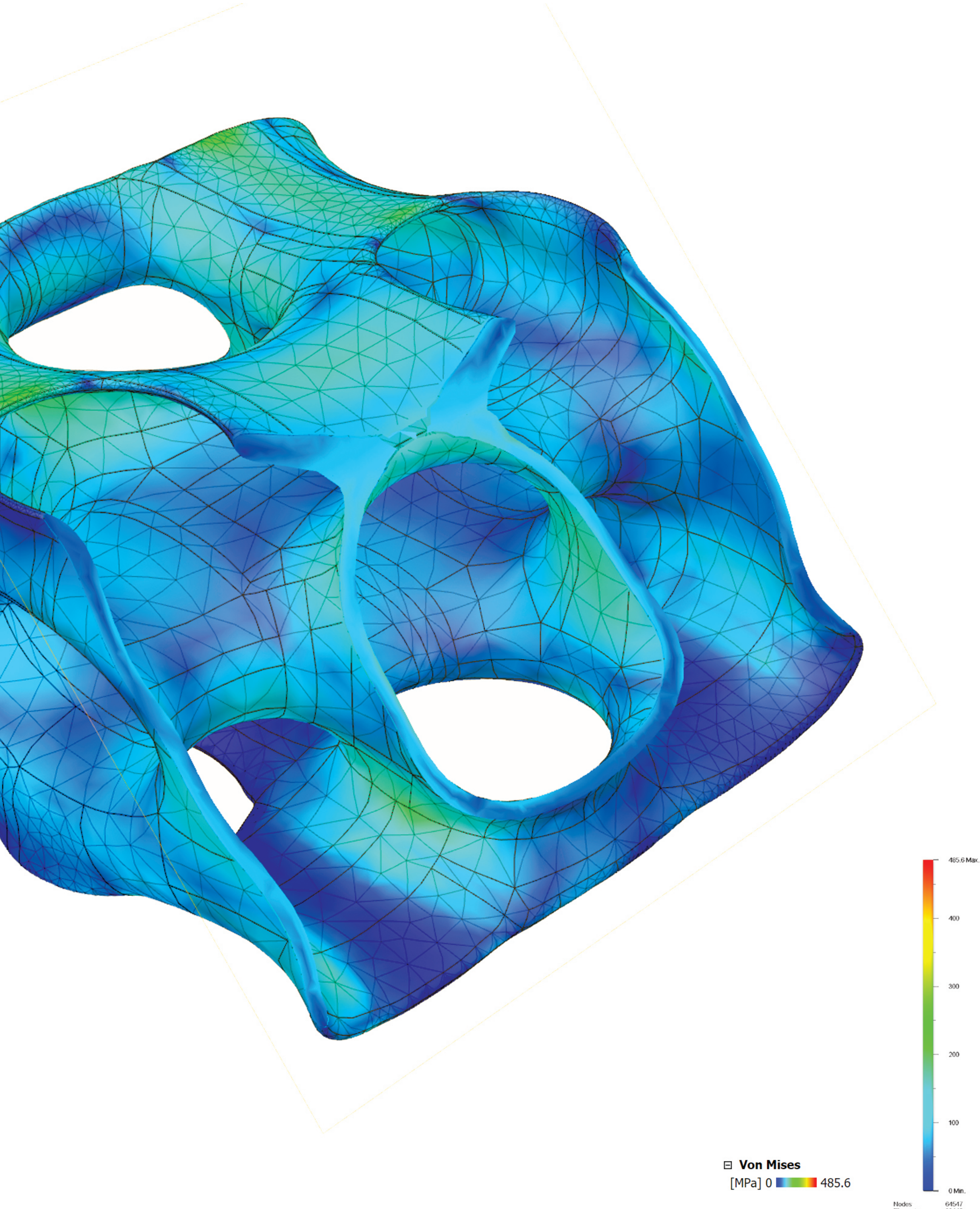
**Innovative, Prefab Structural Concrete**

Research seminar on the structural design and robotic fabrication of P2P Site–less House

**Spring 2019,**
**ARCH 732-002**
**Mondays 9-12 am**

Polyhedral Structures Laboratory
Advanced Research and Innovation Lab
School of Design
University of Pennsylvania Innovative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# 1 Course description

This course intends to push the boundaries of design and fabrication of complex yet efficient structural concrete by using robotic fabrication methods. This research seminar will investigate structural design methods and robotic fabrication techniques that allow the construction of lightweight, high-performance, precast concrete (LHPC) modules for applications in residential/infrastructural projects (Figure 1). We propose to design concrete modules with variable external and internal structural and cavity configurations. The proposed modules will consist of a continuous external structural shell and a spatial structural geometry on the interior such that the internal forces are efficiently transferred to the outer surfaces while reducing the volume of concrete in the interior of the component similar to the structure of a bone (Figure 3).


Figure 1: (a) Robot Arm used for Hot-wire cutting; (b) high density EPS foam cut with hot wire robotic arm; (c) modular mold; (d) constructed prefab concrete parts.

The course intends to develop innovative structural solution applicable to the design development process and fabrication of the *P2P Site-less House* concept developed in the Fall 2017 studio taught by Prof. Robert Stuart Smith.

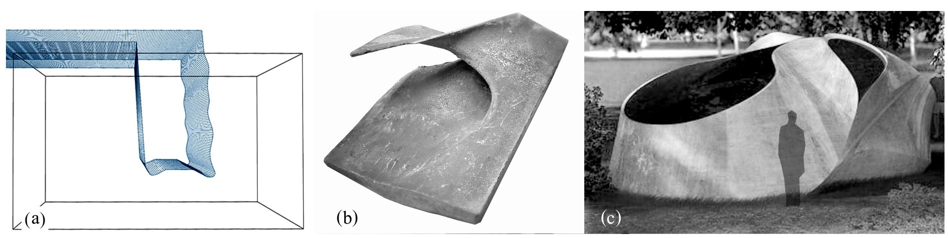


Figure 2: (a) The path of the cutting wire in the foam; (b) a prefab prototype with a complex, ruled surface geometry; and (c) a conceptual design of a site-less concrete prefab structure.

To achieve these goals, the students will work in teams, and each team will be responsible for the detail design and construction development of specific parts of the house to complete the project. The students will also design the assembly mechanisms for the prefabricated system and they will investigate the material transition from exterior to the interior and will provide solutions to include furniture, equipment, and embedded lighting within the prefabricated parts. The outcome of the course will include a book of the construction document for the entire house and one-to-one scale prototype of minimum three modules assembled to reflect the strategies to deal with various fabrication challenges of the house.

## 1.1 Aims and objectives

The primary objective of the course is to address the fabrication challenges of the Tiny House project. The structure of the course is twofold: first to research the fabrication challenges and find solutions to rationalize and improve the existing design of the house; and secondly, to fabricate a part of the house assembled in the form of a mock up to manifest the solutions to construct the entire project.

# 2 Course methodology

This course will include multiple teaching and research modules with the overall objective of developing high-performance structural units. These modules are designed to initially introduce graduate students with various design parameters and engineering concepts in the design of such components and motivate students to develop this research further during this course. These modules will include **an introduction to design and rationalization of complex ruled surface geometry**, **robotic wire-cutting**, **structural analysis of solid components**, **cast-in-place concrete construction**, **topology optimization of a structure**, and **assembly of prefabricated parts** into an efficient self-supporting structure. The following sections will briefly expand on each module and its intentions to accomplish the overall objective of the research.

## 2.1 Module 1: Introduction to ruled-surface geometry

This module will introduce the mathematical properties of ruled surface geometries and will ask students to develop aggregation of such geometries to represent spatial structural system. This research is highly inspired by minimal surface geometry of spatial structures in nature as shown in Figure 3. The student will research various structural patterns in nature and geometrically reconstruct/rationalize such patterns using ruled surface geometry.

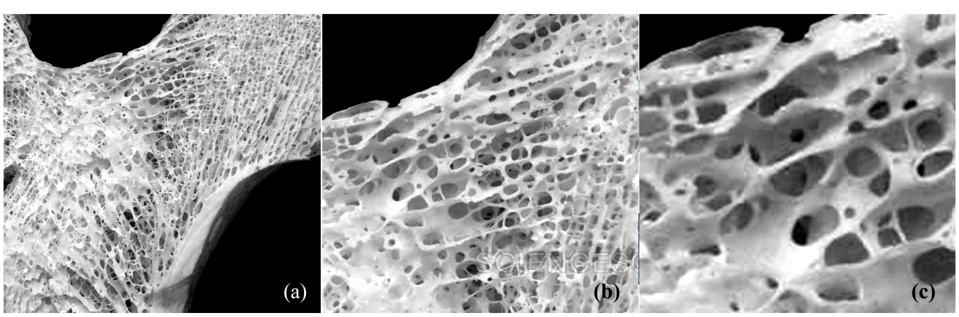


Figure 3: (a) A section of a femur revealing the interior spatial structure and its exterior shell; (b) a close up view of the internal structure; and (c) another magnified view of the internal minimal surface geometry of the spatial network (Image courtesy: Fine Art America).

## 2.2 Module 2: Introduction to robotic wire-cutting

The primary reason for choosing ruled surface geometry as a mean and constraint for the purposes of this research is the ease in the construction process of such surfaces. In this module students will be introduced to robotic wire-cutting techniques to generate such surfaces. in this research, the main challenge is control the robot's motion and the design parameters to fabricate both small and large ruled surface geometries for the internal spatial structure and the external finished surfaces of the parts.

## 2.3 Module 3: Workshop in Finite Element Analysis

The main intention of this research is to develop lightweight, high-performance structural concrete. Thus, this module will teach students to structurally analyze their designs and observe and the effects of scale, direction, and porosity of their ruled spatial structure in the structural performance of their design (Figure 4).

## 2.4 Module 4: Casting spatial concrete

This module will concentrate on the construction of the structural parts. The main challenge is to develop an integrated formwork connecting the exterior shell to the interior spatial geometry. This module will also introduce concrete mixture technology that provides a particular slump allowing the mix to reach and fill complex and narrow channels of the formwork.

## 2.5 Module 5: Workshop in topology optimization

This module will introduce the use of topology optimization in the design of efficient structural components. In this section, students will learn how to remove excessive materials in their parts to reduce the weight of the system and thus design more efficient structural components (Figure 4). The objective of this module is to use the result of topology optimization to identify the regions in the section of the parts where the internal spatial structure should be denser than other areas. Reducing the density of the internal spatial structure where the internal stress is low results in the design of a lightweight, high-performance structural component.

## 2.6 Module 6: Assembling the parts to construct the whole

The final stage of the course will concentrate on the design of the interface between the parts for assembly purposes. As mentioned earlier, one of the main goals of the course is to use the outcome of this research in the construction of prefab site-less house. The structural parts designed in previous modules should establish a self-supporting wall/section of the house as shown in Figure 2.

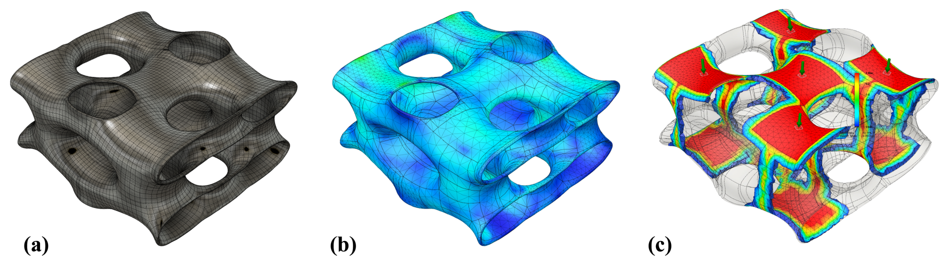


Figure 4: (a) A volumteric mesh model of a spatial surface structure; (b) the stress results of the finite element analysis of the shell; and (c) the topology optimization results under the same loading conditions.

# 3 Course Outcome

The outcome of the course will include the collection of multiple individual reports for each exercise as well as a built structure. The structure will have an external ruled surface geometry made of prefabricated parts with internal cavities each of which has been structurally optimized to work efficiently in the system.

### Format of the report

The reports will be written in LaTeX Editor and the necessary instructions will be given to the students in the first session of the course.

### About the research

This research will become a part of an ongoing investigation funded by the American Concrete Institute (ACI) at the Polyhedral Structures Laboratory, School of Design, University of Pennsylvania.

# 4 Lecture schedule

Table 1 represents the schedule including the titles of the lectures and their related exercises.

| *Course Sessions* | *Dates* | *Titles* |
|---|---|---|
| week 1 | Jan 16 | Ruled surface geometry for spatial structures |
| week 2 | Jan 21 | ~~No class~~ |
| week 3 | Jan 28 | Review exercise 1 |
| week 4 | Feb 4 | Robotic wire cutting workshop |
| week 5 | Feb 11 | Review exercise 2 |
| week 6 | Feb 18 | Introduction to finite element analysis |
| week 7 | Feb 25 | Review exercise 3 |
| week 8 | Mar 4 | ~~No class~~ (Spring break) |
| week 9 | Mar 11 | Casting spatial concrete |
| week 10 | Mar 18 | Introduction to topology optimization |
| week 11 | Mar 25 | Midterm review (exercise 4) |
| week 12 | Apr 1 | Controlling the structural density |
| week 13 | Apr 8 | Review exercise 5 |
| week 14 | Apr 15 | Part to whole: assembly of the parts to construct the structure |
| week 15 | Apr 22 | Final production |
| week 16 | Apr 29 | Final Review: exhibiting the assembled parts as a self-supporting structure |

Table 1: Lecture schedule with specific dates for assignments and reviews.

*Image credits:* Coronal Section of the skull of Nine-banded Armadillo, Digital Morphology; National Science Foundation Digital Library at the University of Texas at Austin.