CEE546 – FORM FINDING OF STRUCTURAL SURFACES

GROUP ASSIGNMENT 2 (20%): FORM FINDING OF PRESTRESSED MEMBRANES

Objective:

In this assignment, you will code a form finding and analysis procedure for a pre-stressed system and design a pre-stressed membrane structure that is structurally and environmentally efficient. You will

- collaborate in a team of 2 (preferably one engineering and two architecture student) to accomplish this assignment,
- understand and apply the basic concepts of the force-density method by developing your own MatLab code to analyse a pre-stressed cable dome; (assignment 2A)
- interpret the design brief for a pre-stressed membrane rain water harvester/community center mounted on a shipping container; (assignment 2B)
- make a preliminary physical model to inform your numerical model;
- carry out the numerical form finding using the commercial software Form Finder so that the pre-stressing, sag/radius and curvature ratios are appropriate, the design shades properly and does not facilitate ponding;
- develop a construction process and at least two crucial connection details;
- effectively communicate your design development on one poster.

Keydates:

- Your Assignment 2A report (1 ½ page) (5%) and calculations (5%) (hardcopy) are due on **Wednesday March 25th in class**.
- Your physical model (5%) and one portrait size poster (5%) explaining your design development of the Water Harvester are also due on **Wednesday March 25th in class.**

GROUP ASSIGNMENT 2A Analysis of the Geiger dome using force density

Reading: *Form-finding of cable domes by simplified force density method*

The goal of the assignment is to use the force-density method to evaluate the internal forces in the Geiger dome, illustrated in Figure 1a. Although the Geiger dome is the object of this assignment, the method is applicable to other types of cable domes, such as the sunflower dome and the bird's nest dome (see Figure 2).

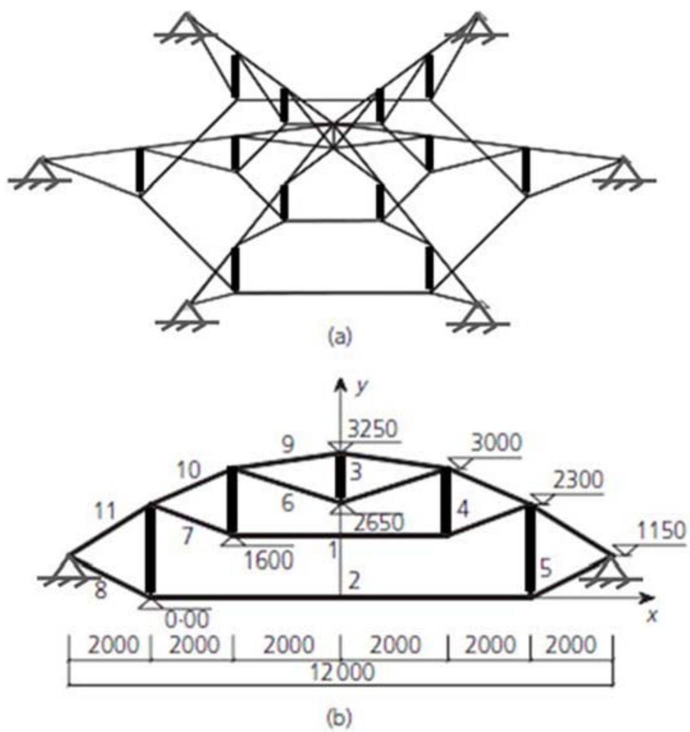

Figure 1: Illustration of the Geiger dome: (a) perspective and (b) geometry of the representative section

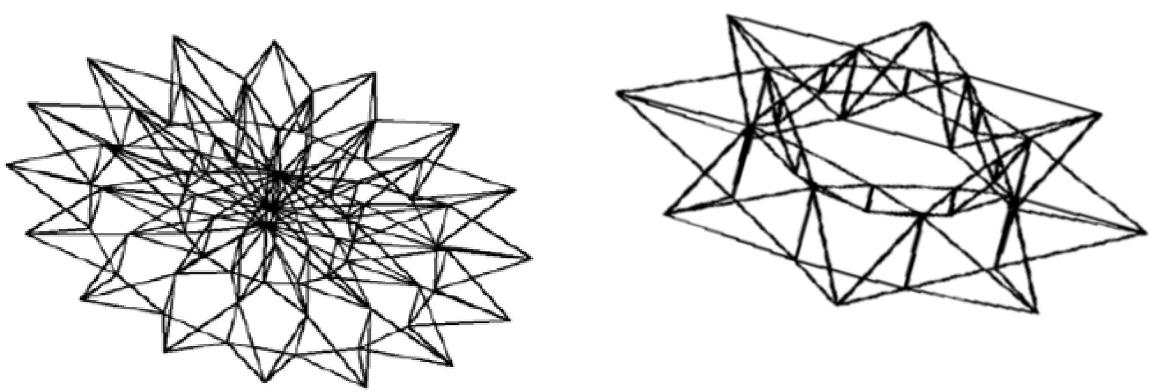

Figure 2: Illustration of the sunflower dome (left) and the bird's nest dome (right)

To evaluate the internal forces in the Geiger dome (or any other cable dome), follow the steps given below:

1. **Take out a representative element group (for the Geiger dome, see Figures 1b and3):**

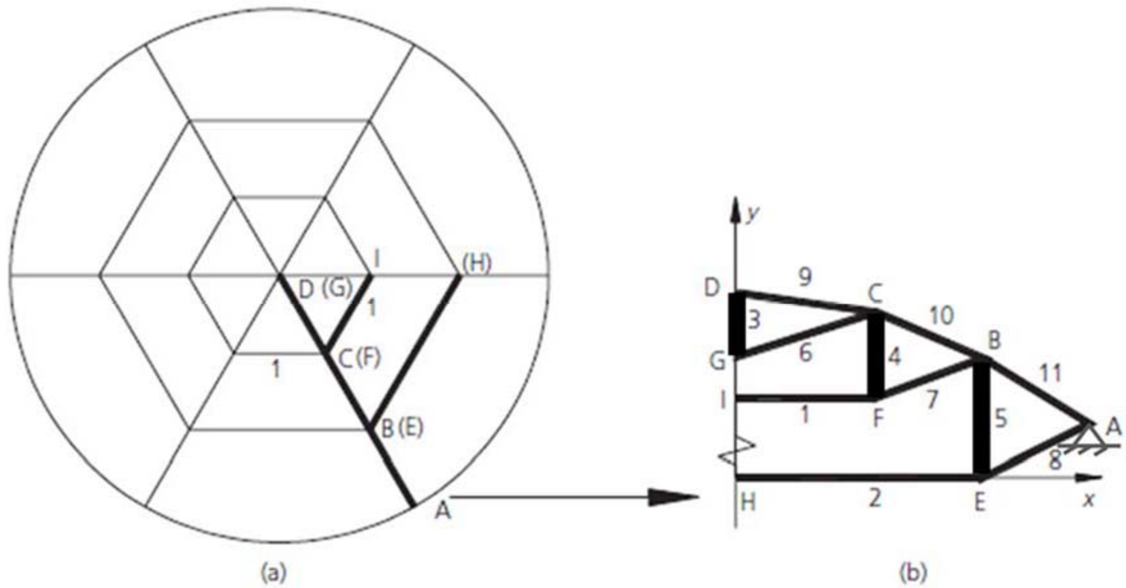

Figure 3: Illustration of a representative element group for the Geiger dome: (a) plan view, (b) representative section

Symmetry is explored to simplify the analysis. However, to correctly estimate the internal forces in all elements of the dome, we have to transfer the representative section back to the original spatial system at the end of this procedure (see step 7).

2. Construct the connectivity matrix C and the coordinate matrix B of the system

The connectivity matrix C has *m* rows corresponding to the number of elements and *n* columns corresponding to the number of nodes. Each element of the matrix is determined as follows:

$$C_{ij} = \begin{cases} 1 \text{ if the element } i \text{ begins at node } j \\ -1 \text{ if the element } i \text{ ends at node } j \\ 0 \text{ for all other cases} \end{cases}$$

The coordinate matrix B has *n* rows corresponding to the number of nodes and 3 columns corresponding to x, y and z directions, respectively.

3. Estimate the diagonal coordinate difference matrices U_{diag}, V_{diag}, W_{diag} and the diagonal element-length matrix L_{diag}

To estimate the coordinate difference matrix [UVW], multiply the connectivity matrix C with the coordinate matrix B:

$$[UVW] = C*B$$

To estimate the coordinate difference vectors U, V and W, take out columns 1, 2 and 3 of the [UVW] matrix, respectively. Now, to construct the diagonal coordinate difference matrices U_{diag}, V_{diag} and W_{diag}, each element of the vectors U, V and W becomes an element in the diagonal of the corresponding matrix U_{diag}, V_{diag} and W_{diag} with all other elements in the matrix equal to zero.

Based on the nodal coordinates (x, y and z) of the elements, estimate the element lengths. Construct the element-length vector L by attributing the length of element *i* in row *i*. To construct the diagonal element-length matrix L_{diag}, each element of the vector L becomes an element in the diagonal of the matrix L_{diag} with all other elements in the matrix equal to zero.

4. Estimate the equilibrium matrix A

The equilibrium matrix A is composed of the following matrices:

$$A = [E1\ E2\ E3]$$

where $E_1 = C^T * U$, $E_2 = C^T * V$, $E_3 = C^T * W$

Important note:

Since we are analyzing only a section of the dome (along the x and y directions), we have to delete the columns related to the z axis. Consequently, the equilibrium matrix A reduces to

$$A = [E1\ E2]^T$$

Additionally, we have to delete all rows related to boundary conditions and symmetry.

5. Estimate the force densities q

To estimate the force densities q, the following homogeneous linear system has to be solved:

$$A*q = 0$$

6. Estimate the internal forces S

To estimate the internal forces S in the elements use the definition of force density:

$$q = S / L$$

7. Estimate the internal forces in the dome

To estimate the internal forces in all elements of the dome employ symmetry (see Figure 3).

GROUP ASSIGNMENT 2B: Form Finding of a
Community Centre – Rain Water Harvester for the Puerto Rico

Additional Info: Form Finder tutorials

The goal of this assignment is to design and develop a pre-stressed membrane structure for a Community Centre – Rain Water Harvester for the villages in Puerto Rico recovering from the devastating 2019-2020 earthquake (https://en.wikipedia.org/wiki/2019%E2%80%932020_Puerto_Rico_earthquakes).
The design should be modular and count on at least 2 ground 'lined' shipping containers as storage tanks and primary support structure for the structural surface (catchment area). The entire design should preferably be demountable and fit within the container (to be transported and deployed elsewhere). The structural surface will also hold a community center.

Physical Model
You are expected to develop and present a **physical model** scale 1:20 or 1:50 of one design. Pay attention to details (correct sag/span ratio, no flat areas, no piercing of the membrane, small radii of curavtures, no ponding, designated areas for rain-water run off etc.)

Numerical Model
Based on you physical model, you are now expected to carry out the initial numerical form finding of your design using Form Finder. The numerical form finding will demonstrate that your surface is structurally efficient and will shade and shelter. The following matters are expected to be addressed in in a parametric study of your design (ie vary certain parameters and investigate its effect on) :

1. *STRUCTURAL EFFICIENCY: PROPERTIES and PROPORTIONS***:** for all elements, net, lines, points (show all sag/span rations, pre-stress values etc are acceptable) (FormFinder)
2. *SHADING and SHELTER: RAIN/SUN ANALYSIS:* for a specific geographic location in Puerto Rico demonstrate how your design will efficiently shelter shade/ shelter for the 3 worse scenarios (FormFinder).

Your numerical studies in FormFinder will form the basis for **one hardcopy portrait poster** that will convince an NGO to invest in your project. The poster needs to contain appealing drawings (renderings) of your design in context, results of your parametric study (structural efficiency and rain/sun analysis), a construction process and at least two relevant connection details.

Grading Rubric:
EXEMPLARY (A+):

- *Physical model*
  - o The typology is very innovative and well-suited for the context,
  - o The presented design successfully goes beyond what was expected in the brief (eg.considers circulation patterns of people),
  - o The model clearly shows that the design criteria for membrane structures are well resolved (eg. clear anticlastic curvature, correct span/sag ratios, no flat ponding areas, water run-off elegantly solved, etc)
  - o Well crafted model, details are developed with a lot of care
- *Poster*

- Accurate application of the form finding technique with a discussion of meaningful results, identified the most important project design parameters and demonstrated how they affect and altered to structural and environmental behavior of the membrane,
- Pictorial demonstration of an efficient construction process and more than 2 construction details,
- Appealing portrait poster with the right balance of images, text and formulae

ACCOMPLISHED (A—A$^-$)

- *Physical model*
  - The typology is suitable for the context,
  - The model shows that the design criteria for membrane structures are well resolved (eg. clear anticlastic curvature, correct span/sag ratios, no flat ponding areas, water run-off elegantly solved, etc)
  - Well crafted model
- *Poster*
  - Accurate application of the form finding technique with a discussion of meaningful results, identified the most important project design parameters and demonstrated how they affect and altered to structural and environmental behavior of the membrane,
  - Pictorial demonstration of an efficient construction process and two construction details,
  - Appealing portrait poster with the right balance of images, text and formulae

DEVELOPING (B-B$^+$)

- *Physical model*
  - The typology is a standard form,
  - The model shows that some of the design criteria for membrane structures are resolved
  - Working model
- *Poster*
  - Somewhat accurate application of the form finding technique with some discussion of results
  - Demonstration of a construction process and/or construction details which might not be totally efficient or realistic,
  - Good portrait poster with the right balance of images, text and formulae

BEGINNING (C-B$^-$)

- *Physical model*
  - The typology is a standard form,
  - The model shows that some of the design criteria for membrane structures are resolved but many are lacking.
  - Sloppy, working model
- *Poster*
  - Somewhat accurate application of the form finding technique with some discussion of results
  - Demonstration of a construction process and/or construction details which might not be totally efficient or realistic,
  - Poor portrait poster