Building a Load-bearing Truss for Introductory Statics Course

Ahmet Coskun, Mehdi Abedi, and Kai-tak Wan*
Mechanical & Industrial Engineering
Northeastern University, Boston, MA 02115

Abstract

The term project for Statics is to design and construct a load bearing truss. Groups with 5 members use toothpicks and wood glue to construct a 3-dimensional structure to hold a hemispherical metal shell above a circular hole in a substrate. A universal testing machine applies an external compression until the truss collapses or reaches its maximum load capacity. Each truss will be evaluated based on ultimate breakage load, failure mode analysis, cost analysis, and aesthetic appearance etc. The course curriculum comprises planar 2-D trusses and only touches on 3-D. The term project promotes design and serves as preamble to subsequent courses such as Mechanics of Materials, Finite Element Analysis, Machine Design, Vibration, Advanced Manufacturing etc.

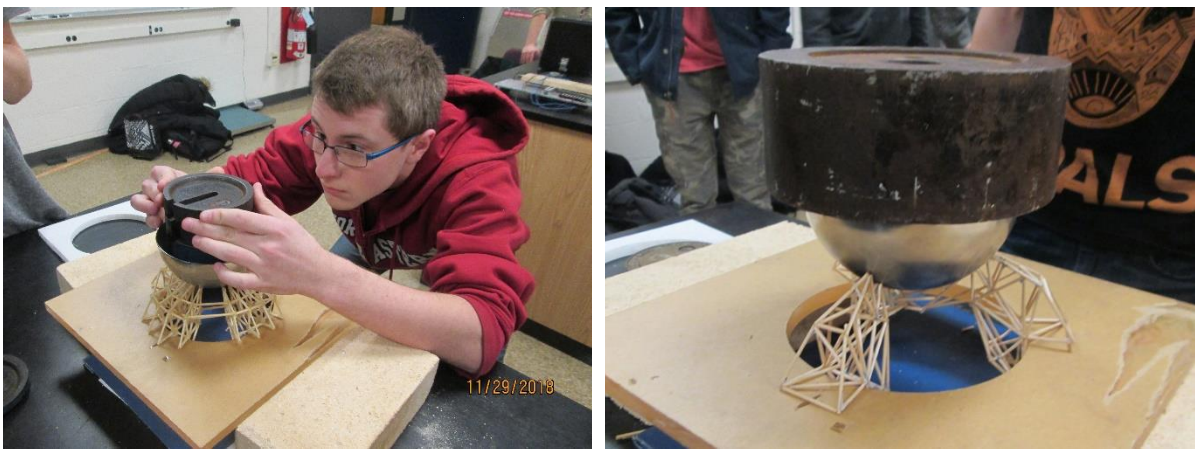

Figure 1. Sample trusses to hold a hemispherical metal shell. Additional static load can be added as shown. Instron universal testing machine is also used to find the exact ultimate failure load.

Introduction

ME 2350 Statics is an introductory course for freshman engineering students in mechanical and civil engineering. It is a mandatory core course prior to other higher-level courses. As in most US institutes, Statics has been conducted as conventional lectures and most homework involves calculation of force and moment balances. To promote experiential learning, we introduce a design component such that participants can delve deeper into the subject and prepare for subsequent courses in solid-mechanics, design, materials selection, and structural engineering.

Building load-bearing structures such as bridges across a gap are common projects in high school and freshman engineering courses, and many examples can be found in school exhibitions and internet pages. To raise the bar, we challenge the students to build a 3-dimensional truss and to perform failure analysis based on the rudimentary principles.

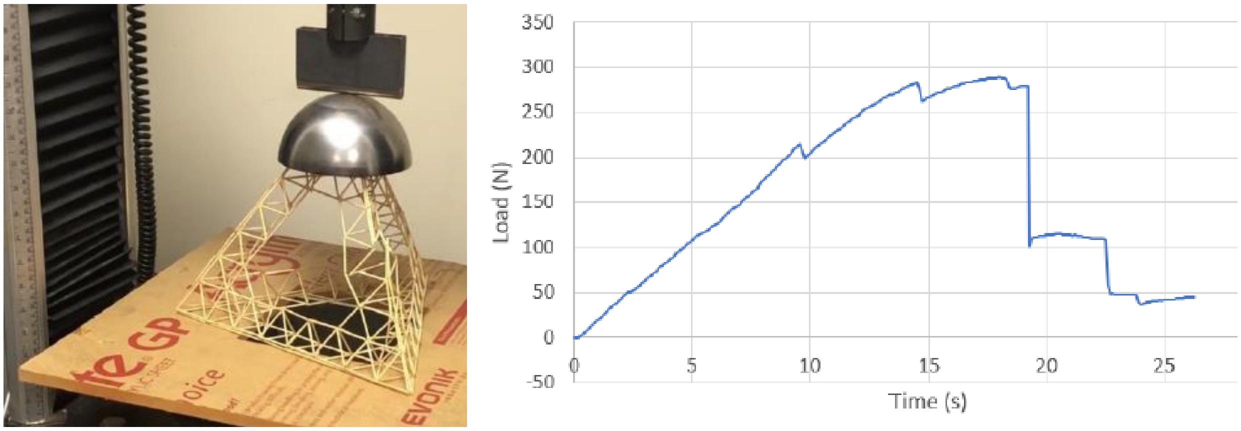

Figure 2. Testing failure load (left) and displacement versus load (right) graph indicating maximum load capacity. Sudden jerks during loading are the result of local joint breakage or individual beams.

Project

The *objective* is to design and construct an axisymmetric cantilever truss to support a hemispherical shell with radius R_s = 10cm over a hole with radius R_h = 12cm. The lowest point of the shell is at least 2cm above the substrate. The circular rim can face either up or down. *Materials* used are confined to the most 200 toothpicks as beams, and only full-length (3cm) or half-length toothpicks can be used. Wood glue with short curing time or more expensive Loctite glue with lengthy curing times is used as joints. Size of adhesive blobs at joint do not exceed 3mm in diameter. Number of junctions is unlimited but included in project cost mimicking total material and labor costs defined by the following function:

$$Cost = \$1 \times total\ length\ of\ the\ beams + \$3 \times total\ number\ of\ joints$$

Maximum load capacity of the designs are determined applying additional compression by an Instron universal testing machine until the structure collapses (Figure 2). The loading process and the consecutive failing steps are monitored in-situ and video recorded. The mechanical and cost advantages are calculated:

$$\text{Mechanical-Advantage} = \frac{\text{Maximum load capacity (N)}}{\text{Mass of the truss (kg)}}$$

$$\text{Cost-Advantage} = \frac{\text{Maximum load capacity (N)}}{\text{Cost (\$)}}$$

An independent jury ranked aesthetics of truss designs from visually most appealing to least. All designs also ranked independently based on their Mechanical-Advantage and Cost-Advantage, in addition to visual appeal.

Figure 3. Trusses collapse at maximum loads. Most failures are results of (i) excessive bending rather than axial tension or compression and (ii) weak joints, and do not conform to the materials covered in ME 2350.

Analysis

ME 2350 only covers 2-dimensional trusses under axial load, shear and bending moment of rigid beams with infinite strength. All joints are assumed free to rotate or pin joints. Rigorous failure mode analysis is not introduced in the course. When external load, either discrete or distributed, is applied to the truss, deformation deviates from the ideal. For instances,

(i) Triangular openings with 3 beam members are stable, while openings with 4 or more members are incapable to support overall shear of the truss. Beams at diagonal to the opposite vertices have be introduced to create triangular openings.

(ii) Radial and circumferential (hoop) stresses are not covered in ME 2350, but such forces play the critical role to support external load in 3-dimension. The hemispherical shell introduces a large hoop stress at the contact. Some truss comprises 3 separate parts with each contacting the shell at a point. In such designs, hoop stress is irrelevant.

(iii) Upon curing, some trusses have their bases geometrically distorted as a result of differential curing of individua joints. Initial loading causes the truss (joints and beams) to oriented with the loading axis, which is reflected by small sections of load-displacement relation.

(iv) Beams do not fail under external tensile or compressive loads (Figure 3), but bending, which will be covered in subsequent course of ME 2355 Mechanics of Materials.

Elastic modulus of the beams is therefore of secondary importance compared with the flexural rigidity.

(v) Some joints fail as the glue is not properly cured. Joint strength is enhanced by exposing the truss to sunlight or ultraviolet radiation which facilitates cross-linking of polymer materials. In case of long beam span, the pin joint approximation does not hold.

Each student group will compile a full report with full description, analysis (Figure 4), video clips showing external loading, deformation of trusses, and ultimate collapse of truss at maximum load, cost analysis. Some groups present MATLAB codes and computational results, and even sophisticated stress-strain analysis using finite element analysis software of ANSYS or ABAQUS, though large deformation cannot be accounted for. Each group will orally present their design criteria and reasoning.

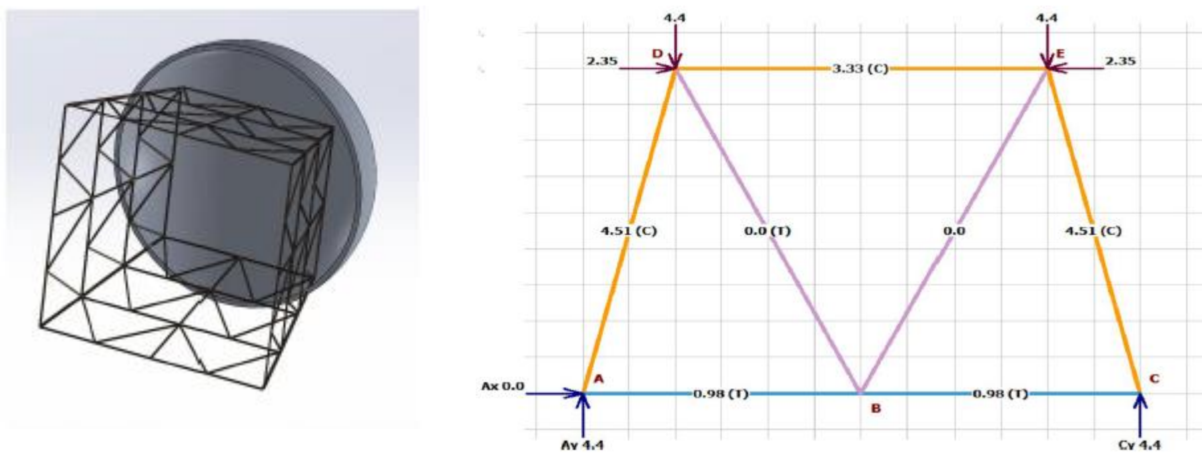

Figure 4. Preliminary design sketches (left) and member force estimations (right) from one of the projects.

Conclusion

The term project promotes experiential learning, which is part of Self-Authored Integrated Learning (SAIL) system of Northeastern University, and design according to the ABET accreditation guidelines. The project increases the level of hands-on activity and creativity of students who develop critical thinking skills to predict and visualize the failure parameters while considering artistic side of their designs before converting their idea into a product. It also serves as a preamble to subsequent higher-level courses as they are exposed to mechanical testing instrumentation, programming software, and are challenged with project management, teamwork, conflict resolution among the team members during design and construction phase of the project, and oral presentation.