Prof. R. Perucchio

# ***PROJECT 2 – Design and Test of a Cantilever Truss***

Assigned Friday Oct 20 , due Monday Nov 13

**Objectives:**

1. Design an optimized cantilever truss under geometrical and strength constraints.
2. Compute truss forces and deformations using the Dr. Frame software.
3. Practice analytical verification of statically determinate truss conditions.
4. Learn elementary operations on the Siemens NX Solid Modeling software.
5. Learn the effect of buckling through experimental testing on truss models.
6. Practice working with Excel tables.
7. Practice team report writing.

**Team Work:**

- Students will continue to work within the same design teams assigned for Project 1. All team members are expected to work in collaboration.
- Each team will design and manufacture an optimized truss and submit a single project report.

**Design Objective:**

- The goal is to design a structurally optimized model of a cantilever truss, which is light yet stiff when tested and which transmits the smallest possible axial forces in tension and compression.
- The design process consists of two iterations, resulting in a optimized truss configuration – see below Truss Design Cycle.
- The optimized truss will be manufactured and tested for displacement and buckling behavior.

The design goal is to maximize the efficiency of the truss. This requires **increasing the stiffness while reducing the weight and the internal forces, see below Equations 1 and 2**.

The score for the design efficiency (**30 points total**) is divided as follows:

- **20 points max** based on stiffness to weight ratio.
- **10 points max** based on the magnitude of the internal forces.

**Geometrical Specifications:**

1. The design envelope is the 50 cm by 50 cm grid shown in Fig 1.
2. Bridge must be a cantilever truss statically determinate, designed to fit in the design envelope. Thus, the overall dimensions must span 50 cm horizontally, with maximum vertical dimension of 50 cm.
3. Joints must be located only in correspondence of the grid points (Fig 1)
4. Bar elements must be positioned at either 45º or 90º and cannot cross each other.
5. Support constraints (one fixed hinge and one roller) must be applied at joints A-F in Fig. 1. The fixed hinge must be positioned always above the roller.
6. A vertical force P = 0.5 kN must be applied at a single joint along the line of application (joints G-L in Fig. 1). The force is applied at the top joint if more than one joints are located on the line of application.

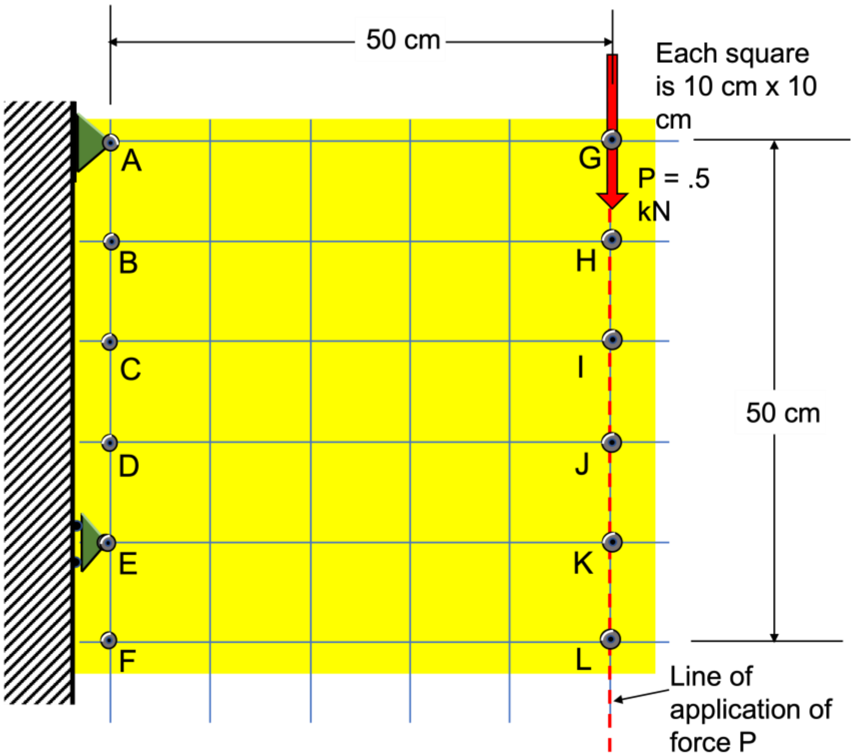


Figure 1 – Design envelope and truss grid.

**Material Properties and Factor of Safety.**
The truss to be tested in the lab will be created with high quality plywood. Truss elements will have 4 mm x 16 mm uniform rectangular cross sections. The initial iteration should have the following average mechanical properties of plywood: elastic modulus $E = 3.5GPa$, strength in tension $\sigma_{st} = 60\ MPa$, in compression $\sigma_{cr} = 35\ MPa$, density $\rho = 700\ kg/m^3$. These dimensions and material properties should also be used for designing the truss in Dr.Frame. The elastic modulus of plywood was calculated by averaging data from many samples of plywood.

A factor of safety of 1.7 must be used throughout the design process.

**Truss Design Cycle**

| |
|---|
| To illustrate the design cycle, we refer to the sample truss based on a 60 cm by 50 cm grid shown in Figures 2, 3 and Tables 1, 2. Note, however, that because its dimensions exceed the design envelope given in Fig. 1, this particular configuration cannot be used for the present assignment. |

Each team will perform two design iterations on the truss problem. In the first iteration, the team selects a truss configuration that satisfies all the requirements defined above. This implies the following steps in Dr.Frame:

1. Select the default member properties (the cross-sectional dimensions and elastic modulus – see above).
2. Select the appropriate grid spacing.
3. Generate the truss geometry by introducing the bar elements into the grid. Apply the boundary conditions on the constrained end. Follow the geometrical, support, and grid requirements given above. The element geometry is entered in the Excel spreadsheet (shown in Table 1 for the sample truss) which must be set up to automatically compute the truss weight.
4. Verify manually that the configuration is statically determinate.
5. Apply the load to the free end of the truss and display the deformed shape (sample truss, Fig. 4). Verify that the deformations are acceptable.
6. The computed internal element forces (sample truss, Fig. 5) are entered in the Excel spreadsheet. This must be set up to automatically verify that the computed internal stress is less than or equal to the allowable stress in tension or compression. Table 1 shows the results for the sample truss in Fig. 2. Notice that, in this example, the verification indicates truss failure.
7. If the truss passes the verification, copy the joint displacements from Dr.Frame's output as in Fig. 6 for the sample truss.
8. Finally, in a separate section of the same spreadsheet (sample truss, Table 2):
   a) record the weight of the truss,
   b) record the downward *displacement* as the deformation at the point of application of the load,
   c) record the maximum element forces in tension and compression,
   d) calculate the *truss stiffness* as

      *stiffness = load/displacement* (1)

   e) calculate the truss efficiency as

      *efficiency = stiffness/(weight x critical element force).* (2)

      where the *critical element force* is the magnitude of the maximum element force in tension or compression.

If the truss does not pass verification, make the appropriate changes in step (3) and repeat the process. The current design iteration is not completed until the results are verified.

In the second design iteration the truss geometry is modified in order to increase the truss efficiency. This iteration follows exactly the same step (1) – (8) used for the first iteration. The second iteration must contain the optimized truss (i.e., with the highest efficiency.)

**<u>Data Preparation for Truss Lab Testing</u>**:
The design cycle is completed. At this stage each team has produced an optimized truss design in Dr.Frame. Each team will convert the Dr.Frame model into the NX model required to drive the laser cutter taking the following steps:

- Verify with TAs that bridge is statically determinate.
- Following the video instructions posted in Blackboard (Access to Tools/Panopto Content/Dr Frame & Project 2 Videos) and the instructions given in the recitations:

a) Download & run the Python code to extract truss geometry from Dr.Frame. The code creates an output with the name XX_ME104_Project2.dxf , where XX should be replaced by the design group number written in a two digit format (e.g., not "2", but "02")
b) Use NX to change the Python output to a 3D model. Create a drawing in NX of the 3D model and save it as a dxf file with the same name.
c) Submit via Blackboard the drawing file (dxf), the Dr.Frame file, and the Excel file containing the spreadsheet with the complete results (Tables 1 and 2) for the optimized truss.

**THESE THREE FILES MUST BE SUBMITTED BY NOVEMBER 2. NO LATE SUBMISSIONS ACCEPTED**

**Truss Lab Testing (Nov 5 – Nov 8: sign up form to be circulated)**

The TAs will manufacture the trusses for lab testing under the supervision of Cadence Brunecz.

- Each team signs up for a testing time slot. All team members must be present when their design is tested.
- The optimized truss will be manufactured in the ME lab with high-quality plywood through laser cutting.
- The plywood truss will be tested as follows:
  a) apply at the free end a load of 4.905 N (.5 kg mass) and record the deflection of the structure at the load point (5 tests).
  b) apply increasing load and study the in-plane buckling behavior of the truss elements under compressive internal forces (5 tests).

**Post Processing of Testing Data:**

- The average value of the recorded deflections gives the *measured displacement* from which *the measured stiffness* is computed as

  *measured stiffness = (applied load)/(measured displacement)* (3)

- Finally, the maximum value between the measured and computed stiffness is used to update the previously calculated efficiency as

  *updated efficiency = (max stiffness)/(weight x critical element force),* (4)

  where weight and critical element force are the computed values for optimum truss.

**Project Report:**

Each team submits via Gradescope a single written report as a pdf document by **Nov 13 at 11:00 pm Project Report submission**. This must include

- **Title page**
- **Abstract** (.5 page): give a brief summary of the report including the weight, stiffness, and efficiency of the truss for your optimized design.
- **Introduction** (1 page): define the design objectives. List all design constraints (dimensions, grid, supports, load, etc..). Give the material parameters.

- **Truss design** (6-page max.): describe the approach followed to refine your truss design from the first to the second iteration. Use two subsections, one for each iteration of your design. Each subsection must include:
  a) a figure from Dr.Frame showing the truss geometry with element dimensions and joint labels (see Fig. 3),
  b) a figure from Dr.Frame showing the deformed shape of the truss (see Fig. 4),
  c) a figure from Dr.Frame showing the element forces, the support reactions and the applied load (see Fig. 5),
  d) a figure from Dr.Frame tabulating the joint displacements (see Fig. 6).
  e) an Excel table showing the weight calculation and strength verification (follow the structure of Table 1),
  f) an Excel table with the truss results as in Table 2.
- **Truss testing** (3-page max): For the optimized truss tested:
  a) Compare the results obtained from the lab experiments and the numerical model. Explain possible sources of discrepancies and error.
  b) Update truss stiffness and efficiency based on the experimental results.
  c) Describe with observations and figures (forms to be provided) the buckling behavior observed during the tests.
  d) Discuss how you would change your design to take into account the buckling.
- **References**: list all the references consulted (if any) in the course of the project.

**Formatting:**

The report must be typewritten with single line spacing.

- Your name, group number, date, course, name of instructor and an illustration (if relevant) go on the cover page.
- Each figure and table must be numbered and must have a caption. In the text, refer to a figure or table by its number (ex., Fig. 1, Tab. 3). Number the pages.

**Timetable:**

| | |
|---|---|
| Oct 20 – | **Project is assigned**. |
| Oct 24 – 26 | **Recitations** (**must watch video before the recitations**) Excel table creation for truss verification, and elementary operations in NX solid modeling. |
| Oct 22 – Nov 1 | **Office hours:** check truss static determinant status with TAs or Prof. Perucchio. |
| Nov 2 **–** | **Submit the NX truss drawing (DXF), the Dr.Frame files, and the Excel file via Blackboard.** |
| Nov 5 – Nov 8 | **Lab testing**: sign up form to be circulated. |
| **Nov 13 11:00 pm** | **Project Report submission.** |

# ***PROJECT 2 – Appendix***

## ***SAMPLE TRUSS ANALYSIS***

Figure 2 – Sample truss (notice the 60 cm x 50 cm grid.)

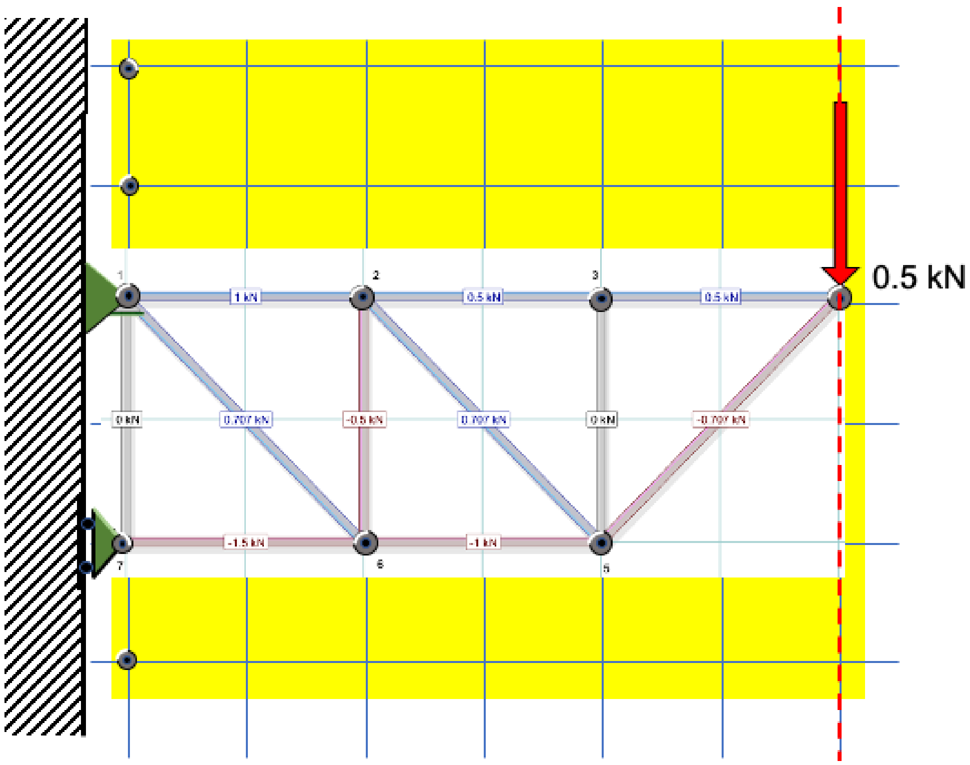

Figure 3 – Sample truss – dimensions.

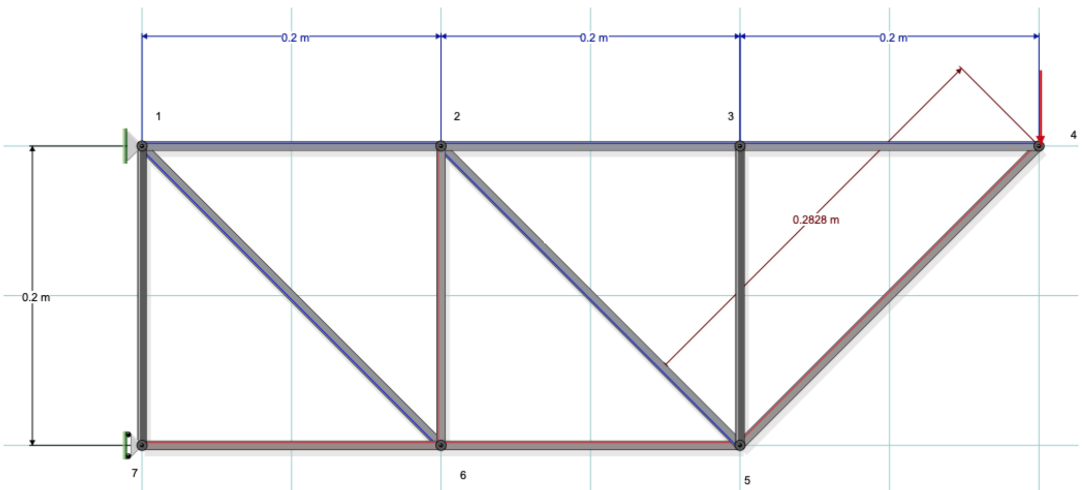


Figure 4 – Sample truss – deformed shape.

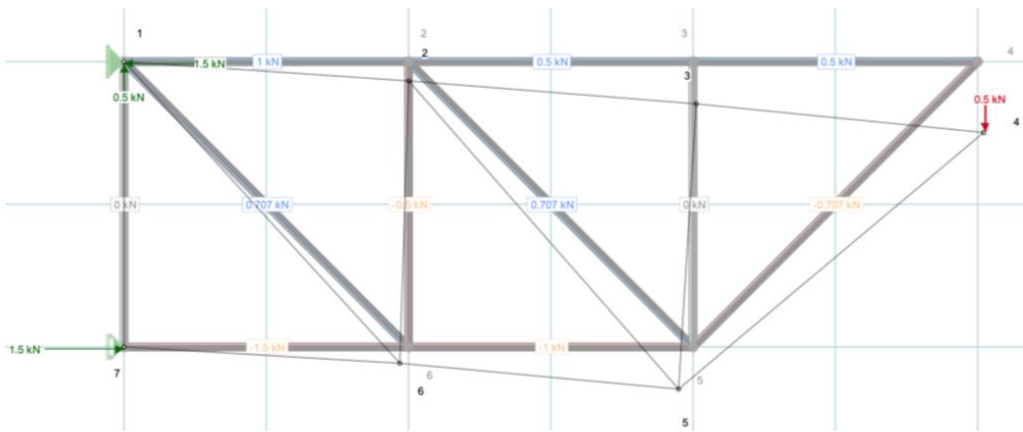


Figure 5 – Sample truss – load, internal forces, and reactions.

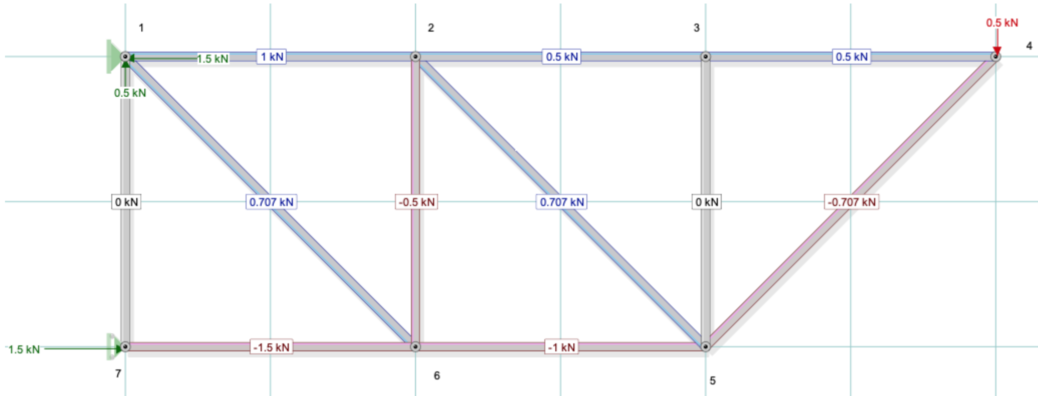

Figure 6 – Sample truss – Joint displacement data.

```
=============Joint Results============
  ID       U_x (mm)          U_y (mm)       Theta_z (rad)
   1   0.000000e+00      0.000000e+00      0.000000e+00
   2   1.953634e-02     -1.561970e+00      0.000000e+00
   6  -7.059488e-01     -1.326653e+00      0.000000e+00
   3   2.548526e-01     -3.423662e+00      0.000000e+00
   4   4.901689e-01     -5.755987e+00      0.000000e+00
   5  -1.176581e+00     -3.423662e+00      0.000000e+00
   7   0.000000e+00     -9.930168e-20      0.000000e+00
```

Table 1 – Data for sample truss in Figures 3-5.

| CROSS SECTION | | | | ELEMENT | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| elem | width [mm] | depth [mm] | area [m^2] | length [m] | weight [N] | internal force [kN] | applied stress [MPa] | allow. stress [MPa] | strength failure | crushing failure |
| 12 | 3.2 | 16 | 5.12E-05 | 0.2 | 0.0683 | 1 | 19.53 | 35.29 | no failure | |
| 23 | 3.2 | 16 | 5.12E-05 | 0.2 | 0.0683 | 0.5 | 9.77 | 35.29 | no failure | |
| 34 | 3.2 | 16 | 5.12E-05 | 0.2 | 0.0683 | 0.5 | 9.77 | 35.29 | no failure | |
| 17 | 3.2 | 16 | 5.12E-05 | 0.2 | 0.0683 | 0 | 0.00 | 35.29 | no failure | |
| 67 | 3.2 | 16 | 5.12E-05 | 0.2 | 0.0683 | -1.5 | -29.30 | -20.59 | | crushing failure |
| 56 | 3.2 | 16 | 5.12E-05 | 0.2 | 0.0683 | -1 | -19.53 | -20.59 | | no failure |
| 26 | 3.2 | 16 | 5.12E-05 | 0.2 | 0.0683 | -0.5 | -9.77 | -20.59 | | no failure |
| 35 | 3.2 | 16 | 5.12E-05 | 0.2 | 0.0683 | 0 | 0.00 | 35.29 | no failure | |
| 16 | 3.2 | 16 | 5.12E-05 | 0.283 | 0.0967 | 0.707 | 13.81 | 35.29 | no failure | |
| 25 | 3.2 | 16 | 5.12E-05 | 0.283 | 0.0967 | 0.707 | 13.81 | 35.29 | no failure | |
| 45 | 3.2 | 16 | 5.12E-05 | 0.283 | 0.0967 | -0.707 | -13.81 | -20.59 | | no failure |
| | | | Total | 2.449 | 0.8364 | | | | | |
| | | | Material | | Density [kg/m^3] | | | 680 | | |
| | | | | | Elastic Modulus [GPa] | | | 8.3 | | |
| | | | | | Strength tension [MPa] | | | 60 | | |
| | | | | | Strength compress. [MPa] | | | 35 | | |
| | | | Factor of safety | | | | | 1.7 | | |
| | | | Live Vertical Load at Joint 4 [kN] | | | | | 0.5 | | |
| ** NOTE: DESIGN IS NOT VALID SINCE TRUSS FAILS IN COMPRESSION ** | | | | | | | | | | |

Table 2 – Results for sample truss in Figures 3-5.

| | | |
|---|---|---|
| TRUSS WEIGHT | 0.836 | [N] |
| DEFORMATION AT JOIN | 5.756 | [mm] |
| MAX EL. FORCE (COM | 1.5 | [kN] |
| MAX EL. FORCE (TENS | 1 | [kN] |
| TRUSS STIFFNESS | 86.87 | [kN/m]] |
| TRUSS EFFICIENCY | 69.23 | [1/(Nm)] |