ASEN 2002: Design, Construction, and Testing of a Truss Structure - Fall 2019

ASEN 2001: Introduction to Statics, Structures and Materials

University of Colorado at Boulder

Assigned: Monday, Sept. 30th, 2019

Lab Due: Sunday Nov. 3rd, 2019, 11:00 P.M. No extensions.

I. Summary

In this lab, you will design, fabricate, integrate, and test a truss structure as part of a design-build competition with your peers. You will be applying concepts and analysis methods introduced in lectures as well as learning about a product development cycle. Learning objectives for Lab 2 include:

- Applied truss analysis (Classical and Computational)
- Applied computational tool development
- Applied uncertainty analysis and sensitivity analysis
- Balancing risk and performance in Aerospace design

II. Logistics

Group assignments will be provided by your lab section's TA at the beginning of your section. The anticipated schedule of activities is shown below. The main deliverables for this lab are (1) a MATLAB truss analysis code, (2) a Critical Design Review (CDR) presentation, and (3) a written report. Following the typical industrial design process, **each team will first split into two sub-teams of 2-3 students each.** Each sub-team will independently develop a truss design and a MATLAB truss analysis tool.

Monday	**Tuesday**	**Thursday**
September 30th Conceptual design analyses, Computational tool development	October 1st Lecture	October 3rd Lecture
October 7th Computational tool development	October 8th Lecture	October 10th Unit Exam 2

Monday	**Tuesday**	**Thursday**
October 14th Detailed Design, Sensitivity Analysis	October 15th Lecture	October 17th Lecture
October 21st **Critical Design Reviews**, Fabrication and integration	October 22nd Lecture	October 24th Lecture
October 28th Integration and test, **Design Demo, Tube Kits Returned**	October 29th Lecture	October 31st Lecture
<- Sun Nov. 3rd Lab 2 Due November 4th Lab 3 Starts	November 5th Lecture	November 7th Unit Exam 3

At CDR the team will come together and present the two designs developed by the sub-teams and provide a rationale for down-selecting the design which is then to be fabricated and tested. Only one design per team will be built and enter the design competition.

This combined experimental and design laboratory assignment will involve a number of different tasks, which should be evenly distributed among team members. Clear communication within the group as to individual responsibilities throughout the lab will be critical to a successful team effort. Make sure to use the lab periods efficiently. **Attendance in labs is required.**

Two MATLAB codes (one for each sub-team, including the input files for your truss design), the PowerPoint slides of your CDR presentation, and the written report must be uploaded to Canvas by the due date.

III. Design/Build/Test Competition Rules

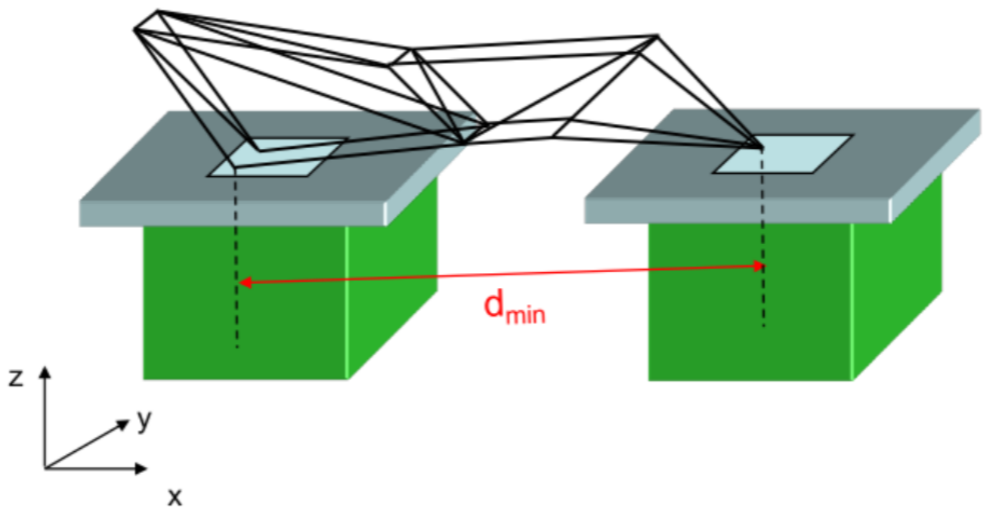

Fig. 1 Basic geometry of competition truss and performance metric

The truss rests on a set of supports mounted on two square base plates, one placed on a lab table and one on a lab cart. The objective of the truss competition is to build a structure where the minimum distance, d_{min}, between the support points on different plates is maximum. The structure will only be subjected to its own weight for the purpose of the competition. Additional joints loads may be applied for model verification and testing purposes. Detailed competition rules are as follows:

1) The only contact the structure may have with its surroundings is at distinct plates on the provided base plates as detailed in Figure 2 below. The structure must have either 3 points of contact (three joints on three rails) or 4 points of contact (two joints on two rails and two joints on two pads).

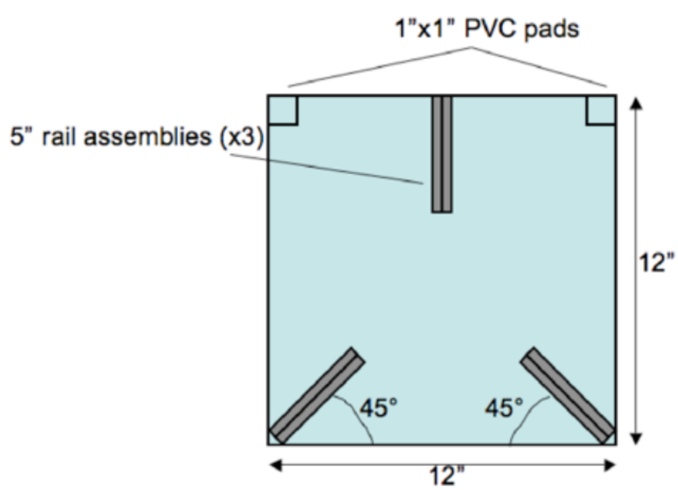

Fig. 2 Basic geometry of competition truss and performance metric

2) One of the basic plates must be placed on a standard cart on the other on a lab desk. The plate may be clamped to a support for stability, but the truss may not come in contact with any clamps. Make sure that the plates are at the same height and leveled relative to each other.

3) Teams will be provided with the following materials (note: there is no requirement to use all material provided.):

   - Truss kit members. See Appendix for size and quantity.
   - $\frac{1}{2}$" diameter steel balls with chrome plating (30).
   - 2x12"x12" PVC base plate to be used only in competition.

   Note: In the design process you should consider that the *true length* of a strut includes the fiber glass rod, the magnets and half of the two ball joints. So, the nominal length of the fiberglass rod may be significantly shorter. An example is given below.

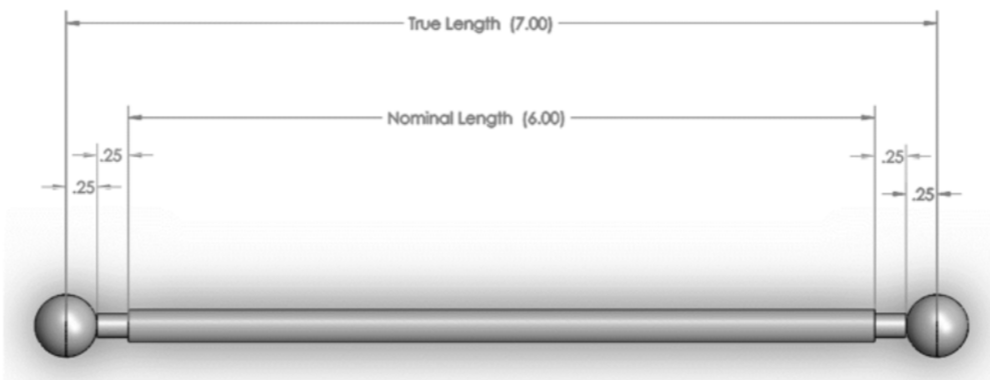

Fig. 3 Nominal versus True Length

   Read carefully and follow the guidelines and additional design rules defined in Appendix 1. Violating these guidelines and design rules will result in both a disqualification from the design competition and a score reduction for the lab grade.

4) Prior to the CDR each team will have access to a test kit with pre-assembled bars and 30 ball joints. These bars are NOT allowed to be modified and are NOT going to be available for your final design. You will be turning these bars in at your CDR. The bars and joints must be returned to their lockers at the end of each lab section as these kits are shared between lab sections.

5) All groups must complete the CDR by the assigned scheduled time. No extensions or after hours CDRs will be allowed. This is in order to receive your Tube Kit on time in lab.

6) Once you pass CDR you turn in your Test Kit with assembled struts, receive your full building Tube Kit, and exactly as many magnets and sleeves as you need for your design (you will have to know these numbers before you come up for your kit). Any magnets or sleeves requested after this point must have an acceptable explanation.

7) The truss geometry defined by the 3D node positions and member member connectivity presented at CDR may

not be altered during fabrication and integration. Magnet pole orientations may be rearranged at the team's discretion. For this reason, only the provided Elmer's glue may be used so the magnets are removable. **NO other glue products may be used to secure the magnets into the struts.** This will be a violation of the rules and result in a lab deduction.

8) Sleeves may be secured with loctite however, **students are responsible for the removal of ALL magnets and sleeves by the end of the last lab period.** Failure to do so will result in disqualification and a point deduction.
9) Teams will be required to collapse their truss structures and store their struts in the Tube Kit at the end of each lab section. You may take the Tube Kit home for access outside of lab time, since the storage room is locked outside of lab time.
10) If the as-designed truss fails to support its own weight, the team receives a distance score of zero. Note: this by itself has no negative impacts on the group grade as long as the reasons for the failure to support itself are explained in the report.
11) Integrated trusses which do support their own weight will have a distance score as measured by instructors/-TAs/LAs.
12) After final testing, teams will be **required** to remove any tape used to mark strut members, magnets, and sleeves. Failing to comply with this requirement will result in a 50% score reduction for the lab grade.
13) Any additional rules deemed necessary by the instructors will be added to this document on Canvas and announced.

IV. Joint Strength

A crucial design element is the joint composed of one ball joint and several magnets. The magnets are glued into the hollow fiber glass struts. In a typical design process, extensive testing would be performed to characterize the strength of this joint configuration. Due to time constraints you will not be able to perform such tests. Instead we provide you with the statistics of joint strength tests. The maximum force in a ball joint- magnet assembly is described by a normal (or Gaussian) distribution with a **mean value of 4.8N** and a standard deviation of **0.4N**.

V. Design Analysis

Simple structural models can be used to provide design intuition when selecting the general architecture of a structural design. More detailed models and/or computational models are then used to refine the design as necessary. In this lab, you will use the following series of design analysis steps along with any others your team chooses.

A. Concept Models

Simple concept models should be used to explore the possible truss architectures. Concept models simplify the truss to basic geometric shapes describing the outer mold line of the truss. The detailed arrangement of individual bars is omitted and gravitational loads are lumped into a few point loads. Using free body diagrams and static equilibrium identify regions of peak load and their sensitivity to the geometric design variables can be determined. This process results in a general architectural plan which is then refined in the following steps.

B. Detailed Design and Computational Analysis

Once the basic truss architecture is identified, a detailed layout of the truss is developed. The process is supported by computational analysis, which can efficiently capture the detailed geometry of a final design. An appropriate 3-D truss analysis tool should be developed using the Method of Joints. This tool should be coded in MATLAB **and the 2-D truss analysis code provided may be used a starting point**. For visualizing the geometry and the bar forces you may use a MATLAB routine *plottruss* available on Canvas.

The development of the MATLAB truss analysis tool is one of the major learning goals of this lab. **Each sub-team is required to develop a MATLAB code independently**. The codes of both sub-teams have to be uploaded through Canvas together with the input files of the two designs developed by the sub-teams.

Please note; if you use a design with a four-point base, develop a model with appropriate support conditions such that the truss can be analyzed by the computational tool.

C. Sensitivity Analysis

All engineering systems are subject to uncertainty, either because material of geometric parameters randomly vary (see Joint Strength above), the loading and support conditions are uncertain, or one does not know exactly how to model and predict particular physical phenomena. Among these sources of uncertainty, the main sources for the truss design are assumed to be due to stochastic variations in the joint strength and imprecise locations of the joints. To account for the variation in joint strength one typically introduces a **safety factor** which decreases the joint strength value used in the design process. For example, if the nominal joint strength is 4.5N and a safety factor of 2 is used, the joint strength used in the design process is 2.25N. Considering that the variation of the joint strength is described by a Gaussian distribution, select a safety factor and provide a rationale for your choice. Use your MATLAB code to study how the different choices of safety factors influence your design.

To estimate the influence of the variation of joint locations study the sensitivity of the bar forces with respect to the joint locations. Assuming that the variations of the joint locations can be described via a normal distribution, one can analyze the truss for randomly varying joint locations and derived from these analyses a statistic on the bar forces. Such an approach is called a Monte Carlo Simulation. Perform a Monte Carlo Simulation and discuss the sensitivity of your truss to the joint locations.

VI. Model Validation and Testing

A critical element of your design development will be the experimental validation of your modeling assumptions. In a typical design development process, a series of tests would be performed on individual components, such as the joint strength and sub-assemblies. Due to time constraints for this lab, only the final assembly of the truss will be tested. Assuming that your truss supports its own weight, apply additional loads to one or multiple joints by adding magnet-ball joint segments hanging from the structure. Use your truss analysis tool to predict how much extra weight can be applied to the structure before it collapses. For this analysis assume a nominal joint strength, i.e. do not consider a safety factor. Compare the predictions to experimental data and discuss the accuracy of your model, accounting for uncertainty of the joint strength and the joint locations.

VII. Required Deliverables

Two MATLAB codes (one for each sub-team, including the input files for your truss design), the slides of your final design presentation, and the written report must be uploaded to Canvas by the due date listed at the beginning of this document. Again, the following files should be uploaded:

1) Lab report in PDF format.
2) Slides of CDR presentation in PDF format.
3) Two m-files, one for each MATLAB code (all functions need to be contained in one m-file).
4) Input and output files for MATLAB codes.

The lab report and slides should be named as follows: <group####>.pdf

A. Critical Design Review

By the beginning of lab on the day of the CDR presentations, you will be required to have developed two designs (one per sub-team) and chosen one design that will enter the competition. The design process (from conceptual to detailed) and the analysis of both designs need to be presented at the Critical Design Review on up to 6 slides of information. These slides should:

1) Provide information about the model (essential free body diagrams, external loads, etc.),
2) Discuss the rationale for the safety factors chosen,
3) show the layout and analysis of the two candidate designs,
4) Provide rationale for down-selecting the designs,
5) Present sensitivity analysis results for the design that is selected for entering the design competition,
6) And demonstrate that the truss can be fabricated with the material available with NO CUTTING of the struts.

The review process should be no more than 10 minutes. While the CDR is informal (held at your lab station, presentations will be shown on the computer screen) the slides should be presented in a concise and precise manner (which typically requires a few dry-runs before presenting to the reviewers).

The reviewers will be determining whether your design assumptions appear to be reasonable as well as whether the proposed design assumptions appear to be reasonable as well as whether the proposed design is in compliance with the competition rules. Further, the reviewers will check whether the struts are constructed according to the design rules. Once the review is passed, the team will be allowed to proceed to the fabrication and integration steps. The slides shown at the CDR are part of the deliverables of this lab and as such will be considered in the final score for this lab.

B. Final Report

The report must be word processed **in AIAA format** Latex, MS Word, and Google Docs are all acceptable and submitted as a .pdf. The main body **should not exceed 8 pages** (this excludes the Title page, Abstract, Graphs, and Appendices). The AIAA required format of the report is defined in a report template document that can also be found on the Canvas course web-page. See section 8.2 for report grading details. Use these grading weights to distribute your approximate page counts.

Your Lab 2 report should specifically include:

Title Page. (Follow AIAA format)

Abstract. A concise summary of purpose, method, results, and any conclusions. The reader should be able to infer from the abstract whether the paper is relevant to their interests and whether to read the entire document.

Introduction. Discuss the objectives of the lab as you see them. This should include background "theory".

Design Analysis. This section should be broken into three subsections corresponding to section 5 of this lab description. The design lessons learned from each stage of model refinement should be discussed here. Through the discussion and illustrations, the reader should get a sense of the evolutionary path your design took. You may describe and discuss the design process only for the design that you have finally fabricated, build, and tested.

Truss Design. Provide a brief description and illustrations of your design. Make sure to present the designs and analyses of the two designs developed by the sub-teams and discuss the rationale for choosing the design you have built and tested. You should indicate where your critical joint locations are and what your expected safety factors are for these joints. Also briefly summarize the outcome of your final assembly and test.

Model Validation This section should briefly summarize the loading test performed at your final assembly.

Discussion. As usual, the discussion section should include your observations of agreement and disagreement of the experimental and theoretical portions of the lab. Focus more here on structural modeling issues (the limits of truss modeling assumptions, etc.) then on details of magnetic field behavior on the joints. Explain why your truss failed of was a success. Did fabrication imperfections slightly impact your design? Compare your test results of safety factor and the trade-offs between performance and risk in a design. Use this section to summarize these observations.

Conclusions. Summarize what was done and the results of the tests while providing insight into the significance of the results.

References. List references cited from the body of the report, e.g. the textbook or this lab description document. References should be cited in the text by numbers enclosed in square brackets. Example: "The experimental procedure provided on page 4 of [3] is used."

Appendices.(See AIAA format)

Note: For sections such as the introduction it is recommended that a key rule of technical writing: "context before content", be followed. That is, briefly state what the objectives are and which approach was followed to meet objectives, before entering into the technical content.

VIII. Grading

The total score for this design lab includes:

1)	Design Presentation	35%
2)	Final Report	50%
3)	MATLAB code	15%

A. Critical Design Review Presentation Slides

Category	Weight	Score	Contribution
Mechanical Modeling	0.20		
Safety Factor	0.10		
Truss Analysis	0.30		
Sensitivity Analysis	0.20		
Validation	0.10		
Style and Clarity	0.10		
Conclusions	0.05		
Total	1.00		

B. Final Report

Category	Weight	Scale	Contribution
Abstract	0.05		
Introduction	0.05		
Design Analysis	0.15		
Model Validation	0.15		
Design	0.10		
Discussion	0.10		
Conclusion	0.05		
Organization	0.05		
Flow	0.10		
Style	0.05		
Grammar	0.05		
Spelling and Typos	0.05		
References	0.05		
Total	1.00		

"Flow" measures smoothness of reading from start to finish and correlation of material from section to section, as well as adherence to guidelines of technical writing. Not conforming to the required format will lead to an overall reduction in score.

C. MATLAB code

The score for the MATLAB code is based on the functionality of the code (level of applicability to a generic 3-D truss, robustness, failure tolerance), the program structure (modularity, use of intrinsic MATLAB functions, efficiency), and the code organization (headers, comments).

IX. Appendix 1 - Rules and Guidelines for Designing and Fabrication of Struts

Note: The following rules and guidelines need to be **strictly** followed. Violating these design rules and fabrication guidelines will result in both a disqualification from the design contest and a score reduction for the lab grade.

Design Rules

1) Teams are **NOT** allowed access to their truss kits until after passing the Critical Design Review. Violating this rule will result in a 50% score reduction for the lab grade.
2) Teams are **NOT** allowed to join segments with sleeves or otherwise to create struts longer than 30" without additional members at that joint, i.e. a 30" section must connect to a new section.
3) To glue to magnets into the struts, only **Elmer's glue** and nothing stronger is allowed. Failing to comply with this requirement will result it a 50% point reduction in the lab grade.
4) Try to minimize how much glue you need and leave enough of your magnets exposed so you can pull them out with pliers. The magnets are a pretty tight fit anyway, so using little to no glue makes it much easier to switch polarity at a joint or fine tune the length. You can use a twisting motion, and a vice if needed, to remove properly attached magnets without cutting. (Or use a long thick wire to push the magnets out from the other side.)
5) Only use **glue** provided to secure individual members in the sleeves (only one sleeve per strut member.) Here it is also important to use as little as possible, as when too much is used it is easy to destroy the strut and the sleeve in the attempt to remove the sleeve. Failing to comply with this requirement will result in a 50% score reduction for the lab grade.

Truss Tube Kit Inventory: Sizes listed are nominal to a ± 0.5" accuracy. Length can be adjusted slightly with magnet depth and/or sleeve placement. 30 ball bearings are provided in Test Kits. Magnets and Sleeves will be checked out based off of need of design so **make sure you know how many of each are needed (and your group number) before you check out your kit.**

Size	Count	Size	Count	Size	Count
26"	1	16"	3	6"	19
24"	1	14"	5		
22"	1	12"	8		
20"	1	10"	16		
18"	1	8 "	19		

Do NOT CUT the struts. Check to see that you have all the correct struts as soon as you get your kit. Trading struts between group members is NOT ALLOWED.

Tips:

1) When assembling the truss, use tape to label your struts. This will help you build your truss quickly and accurately, and it is a life saver if your truss falls apart on build day. However, don't use too much tape as each piece you put on you have to remove before returning your kits.
2) **Design your truss based on the lengths of strut available.** This is an important constraint, and creating a truss that takes this into account will be much easier than trying to find struts that work after the fact.
3) Sleeves are 5.25" long, when constructing this gives you up to two inches of added length to your strut. Note: each rod must be at least $\frac{3}{4}$" inside the sleeve to provide proper support, otherwise there will be too much flex in the structure.