ASEN 2001 Lab 2:
Design, Construction, and Testing of a Truss Structure – Fall 2016

1. 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 method 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
- Uncertainty analysis and sensitivity Analysis
- Balancing risk and performance in aerospace designs

2. 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.

Monday	**Tuesday**	**Wednesday**	**Thursday**
Sept 26 Conceptual design analyses, Computational tool development	*Sept 27* Lecture	*Sept 28* ASEN 2002 Lab	*Sept 29* Lecture
Oct 3 Computational tool development	*Oct 4* Lecture	*Oct 5* ASEN 2002 Lab	*Oct 6* Lecture **Unit Exam 2**
Oct 10 Detailed Design, Sensitivity Analysis	*Oct 11* Lecture	*Oct 12* ASEN 2002 Lab	*Oct 13* Lecture
Oct 17 **Critical Design Reviews,** fabrication and integration	*Oct 18* Lecture	*Oct 19* ASEN 2002 Lab	*Oct 20* Lecture
Oct 24 Integration and test, **Design Demo**	*Oct 25* Lecture	*Oct 26* ASEN 2002 Lab	*Nov 27* Lecture
Oct 31 **Lab 2 due** **Lab 3 starts**	*Nov 1* Lecture **Unit Exam 3**	*Nov 2* ASEN 2002 Lab	*Nov 3* Lecture

Following a 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, including a MATLAB truss analysis tool.

At CDR (see schedule), the team will present the two designs developed by the sub-teams and provide a rational for down-selecting the design which is then to be fabricated and tested. Only one design per team will be built and will enter the design competition.

This combined experimental and design laboratory assignment will involve a number of different tasks, which should be evenly distributed amongst the 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 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 through D2L by 9:00 am on Oct 31.

3. Design/Build/Test Competition Rules

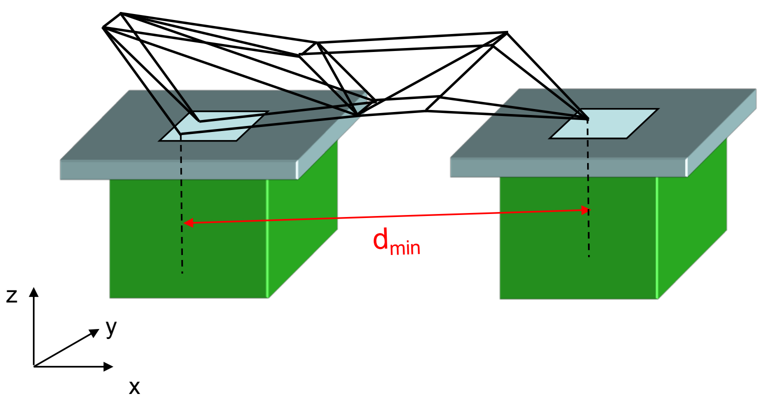


Figure 1: Basic geometry of competition truss and performance metric

The truss rests on a set of support mounted on two square base plates, one place 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 joint 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 points on the provided base plates as detailed in Figure 2. The structure must have either 3 points of contact (three balls on three rails) or 4 points of contact (two balls on two rails and two balls on two pads).
2. One of the base plates must be placed on a standard ITLL cart and 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 leveled relative to each other.
3. Teams will be provided with the following materials (note: there is no requirement to use all material provided):

    a. Carbon fiber rods

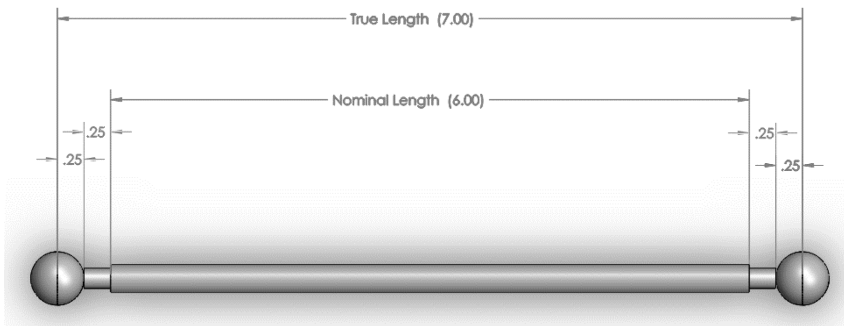
Length	Quantity	Length	Quantity	Length	Quantity
26-30"	2	18-20"	2	10-12"	18
24-26"	2	16-18"	3	8-10"	22
22-24"	2	14-16"	4	6-8"	17
20-22"	2	12-14"	8	Full	2

Note: While any rods cut this summer are near the lower limits of each category, remember that it is a range of lengths. For example, when you get a 24-26"strut, it is assured to be greater than or equal to 24", but it may not be 26".

b. 50 x ½" diameter steel balls with chrome plating

c. 2 x 12"x12" PVC base plate

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



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 score reduction for the lab grade.

4. Prior to the Critical Design Review, each team will have access to 10" (some groups roughly 6") pre-assembled bars along with a sufficient number of 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 at your Critical Design Review. The bars and ball joints MUST be returned to the ITLL lockers at the end of each lab section.

5. As part of CDR you will turn in your 10" or 6" preassembled struts, receive your building kit, mark your struts with the planned modifications and show them to a lab assistant for approval, and then you will receive your magnets. You will receive exactly as many magnets as you need for your design at this point, and any magnets requested after this point must have an acceptable explanation.

6. The truss geometry defined by the 3D node positions and member connectivity presented at the Critical Design Review may not be altered during fabrication and integration. Magnet pole orientations may be rearranged at the team's discretion however. For this reason, only the provided Elmer's glue should be used.

7. Prior to final testing, teams will be required to disassemble their structures and store their struts at the end of each lab section.

8. If the as-designed truss fails to support its own weight, the team receives a distance score of "0". (Note that this will not necessarily reflect negatively on the team's grade.)

9. Integrated trusses which do support their own weight will have their distance score measured by the instructors.

10. After final testing, teams will be required to remove any tape used to mark struts, and all magnets must be extracted. Failing to comply with this requirement will result in a 50% score reduction for the lab grade.

11. Any additional rules deemed necessary by the instructors will be added to this document on D2L and announced via email.

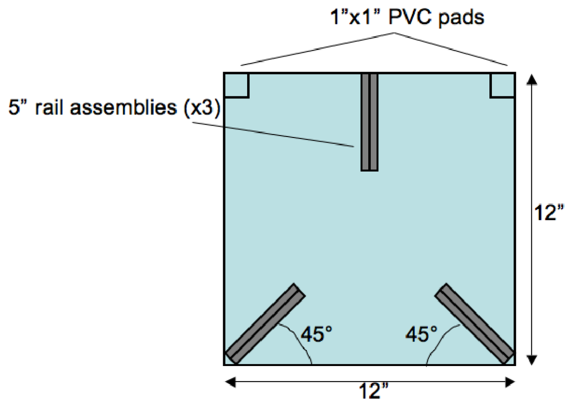


Figure 2: Approximate dimensions of PVC base plate

4. Joint Strength

A crucial design element is the joint composed of one ball joint and several magnets. The magnets are glued into hollow carbon fiber 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 of 4.8 N and a standard deviation of 0.4 N.

5. Design Analyses

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.

5.1. 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 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 step.

5.2. Detailed Design and Computational Analyses

Once the basic truss architecture is identified, a detailed layout of the truss is developed. This process is supported by computational truss analyses, which can efficiently capture the detailed geometry of a final design. An appropriate 3-D truss analysis tool should be developed based on the Method of Joints. This tool should be coded in MATLAB; the 2-D truss analysis code discussed in class may be used and expanded. For visualizing the geometry and the bar forces you may use a MATLAB routine *plottruss* available on D2L.

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 independently a MATLAB code. The codes of both sub-teams have to be uploaded through D2L, 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; ask a TA or the instructor for details.

5.3. Sensitivity Analysis

All engineering systems are subject to uncertainty, either because material or geometric parameters randomly vary (see joint strength information), 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 2.25 N. Considering that the variation of the joint strength is described by a normal (or Gaussian) distribution, select a safety factor and provide a rational 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 variation of the joint locations can be described via a normal distribution, one can analysis the truss for randomly varying joint locations and derive from these analyses a statistic on the bar forces. Such an approach is called Monte Carlo Simulation. Perform a Monte Carlo Simulation and discuss the sensitivity of your truss to the joint locations.

6. 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 subassemblies. 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. 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 these predictions to experimental data and discuss the accuracy of your model, accounting for uncertainty of the joint strength and the joint locations.

7. Required Deliverables

Two MATLAB codes (one for each sub-team, including the input files for your truss design), the PowerPoint slides of your final design presentation, and the written report must be uploaded through D2L by 9:00 am on October 31. The following files should be saved in a zip file:

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

The zip file should be named as follows: <group number>.zip.

7.1. Critical Design Review Presentation

By the end of the lab on October 17, 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 concept to detailed design) and the analysis of both designs need to be presented at the Critical Design Review on up to 6 PowerPoint slides. The slides should

1. provide information about the model (essential free body diagrams, external loads),

2. discuss the rational for the safety factors chosen,
3. show the layout and analysis of the two candidate designs,
4. provide a rational 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 and according to the competition rules.

The review process should be no more than 10 minutes. While the CDR is informal (be held at your lab station, presentation will be shown on 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 slides shown at the Critical Design Review are part of the deliverables of this lab.

The reviewers (instructors and/or TAs) will be determining whether your design assumptions appear to be reasonable as well as whether the proposed design is incompliance with the competition rules. Further, the reviewers will check whether the struts are cut according to the design rules. Therefore, you need to mark by tape where you will cut the struts. Once the review is passed, the team will be allowed to proceed to the fabrication and integrations steps. The slides for the critical design review are considered in the final score for this lab.

7.2. Final Report

The report must be word processed. The main body should not exceed 8 pages (this excludes the Title Page, Abstract, Graphs, and Appendices). The general guideline for lab report writing can be found on D2L. The required format of the report is defined in a report template document that can also be found at the D2L 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 more specifically include:

Title Page. (see guidelines)

Abstract. (see guidelines)

Introduction. Discuss the objectives of the lab as you see them. This should include background “theory” as described in the guidelines.

Design Analyses. This section should be broken into three sections corresponding to sections 5.1-2 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, built, and tested.

Truss Design. Provide a brief description and illustration of your designs. Make sure to present the designs and analyses of the two designs developed by the sub-teams and discuss the rational 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.) than on details of magnetic field behavior in the joints. Explain why your truss failed or was a complete success. Did fabrication imperfections significantly impact your design? Compare your test results with the maximum possible load predicted by your MATLAB code. Based on this comparison, discuss your choice of safety factor and the trade-offs between performance and risk in a design. Use this section to summarize these observations.

Conclusions. (see guidelines)

References. List of references cited from the body of the report, e.g. the textbook or 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 guidelines)

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 the objectives, before entering into the technical content.

8. Grading

The total score for this design lab includes:

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

8.1. 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 clearness	0.10		
Total	1.00		

8.2. Final Report

Category	Weight	Score	Contribution
Abstract	0.05		
Introduction	0.05		
Design Analyses	0.15		
Model Validation	0.15		
Design	0.10		
Discussion	0.10		
Conclusions	0.05		
Organization	0.05		

Flow	0.10
Style	0.05
Grammar	0.05
Spelling and typos	0.05
Referencing	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 confirming to the required format will lead to an overall lower score.

8.3. 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 function, efficiency), and the code organization (headers, comments).

Appendix 1 – Rules and Guidelines for Designing with 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 competition and score reduction for the lab grade.

Design Rules:

1. Teams are NOT allowed to cut or joint struts prior to passing their Critical Design Review. Violating this rule will result in a 50% score reduction for the lab grade. At the Critical Design Review, the locations where struts are cut need to be marked by tape. The tape should be removed after the struts are cut to length.
2. Struts may ONLY be modified such that a cut strut fits into the size range just below the original member. For example, an original strut in the 26-30" range may be cut as small as the 24-26" range. A strut in the 26-30" range may NOT be cut to less than 24". Violating this rule or modifying pre-assembled struts will result in a 50% score reduction for the lab grade.
3. The 'full' length struts may be cut to any length(s).
4. Teams are NOT allowed to join segments to create struts longer than 30" without additional members at that joint, i.e. joints whose sole purpose is to connect two collinear struts whose total length is greater than 30" are not allowed. Segments may be joined in this manner if and only if they create a strut shorter than 30". Violating the rule will disqualify the design.
5. To glue the magnets into the struts, only Elmer's glue (removable) and not permanent hot glue, such as gorilla glue, should be used. Failing to comply with this requirement will result in a 50% score reduction for the lab grade.

   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 change the polarity or fine tune a bar length. You can use a twisting motion, and a vice if needed, to remove properly attached magnets without cutting. Otherwise you may end up having to cut a strut shorter than you wanted to.

Fabrication Guidelines:

1. You must wear gloves and, if you are using the shop, a mask whenever you cut the carbon fiber rods. The material is a carcinogen, and it makes lots of tiny splinters when you cut it. Gloves will help keep you from itching like crazy after lab, and a mask is important if using a faster cutting tool.
2. At least one person in your group really should get access to the ITLL machine shop. If you did this freshman year you are still certified. Cutting the carbon fiber with a band saw or circular saw is much faster than using the tube cutters. It is an hour long, and more information is on the machine shop bulletin board or itll.colorado.edu. Talk to Mark Eaton in the ITLL machine shop for more info.

Tips:

1. When assembling the truss, use tape to label your struts. This will help you building your truss quickly and accurately, and it is a life saver if your truss falls on build day. However, don't use too much tape, because each piece you put on, you'll have to take off at the end.
2. Design your truss based on the lengths 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.