Project 1: Key Component

ME 104: Mechanical Systems Design

Overview:

In this project, you will individually design a single component, manufacture and test it, upload test data and video, and explain your design in a concise written report. You will design part geometry to minimize mass within constraints on loading, material, and manufacturing. You will use conceptualization methods, sketching, simple models, analytical methods, CAD modeling, numerical analysis, and functional prototype testing, iteratively, to design your component. You will fabricate the design using your personal 3D printer and perform tests to verify its strength and mass. Grades will be based on objective performance and the rationale for the design as communicated through the summary report.

Learning Goals:

1. How to select appropriate analysis tools and learn from results, iteratively, in the design process.
2. How to apply free-body diagrams, stress and buckling analysis, and finite-element analysis to design.
3. How to design components for mass efficiency.

Detailed specifications and constraints:

Loading: Your component will be an important structural element in a larger mechanical system (Figure 1). At the base of the system is a lever. The right end of the lever will be loaded by free weights that generate a force of 100 N downwards. The lever is hinged at the left end. A rope is tied to the lever part-way along its length. The rope extends vertically to the “loading component”. The rope passes through a hole in the loading component and is then knotted in place. The hole center is offset from the face of the loading peg. The loading component has two cylindrical features, or pegs, which measure 0.250 ± 0.005 inches in diameter and extend 0.25 ± 0.01 inches from the face of the loading component. Please see the SolidWorks model for more details. Your custom component will contact the loading component at these cylindrical features. Your custom component may also contact the face of the loading component, but must not contact any other aspect of the loading component or rope.

In the upper left corner of the structure is the “support plate”. The support plate has a grid of threaded holes at 0.25 inch intervals. Included with the testing rig are 10 small cylindrical tubes called the “support pegs”. You may attach support pegs to the support plate at any of the 280 possible locations, using the screws provided, and use these to support your component. Your custom component may also contact the primary, largest surface of the support plate, but must not contact any other aspect of the support plate or frame. Although there are two support plates on the frame, you will only use the one on the left.

After you have installed your component, the loading component must be located at precisely the location depicted in Figure 2. The cylindrical features of the loading component must be 2.00 ± 0.01 and 2.50 ± 0.01 inches to the right of the right-most column of threaded holes and 3.00 ± 0.01 inches below the top-most row of threaded holes. You will verify that your component meets this geometric requirement using the paper measurement grid we will provide. When the load is applied, the loading peg must not move more than 0.50 inches from this position, for example due to deflection or fracture of the component.

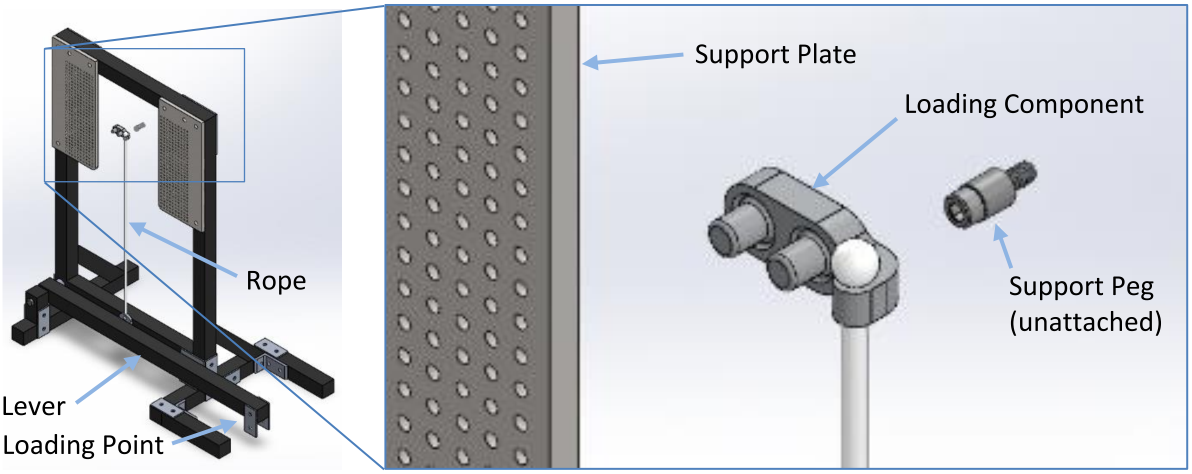

Figure 1. Testing rig overview. *Left Panel:* The testing rig will comprise a rigid frame with a lever at its base. The lever will be hinged at its left end, while weights will be hung from its right end. Part-way along the lever, a rope will be tied. The rope will extend vertically to the loading component. *Right Panel:* Your custom component will connect the loading component to (a) support peg(s) attached at any of the possible connection points on the support plate at left. The loading component has cylindrical features that your component can contact. One unattached support peg is shown for reference.

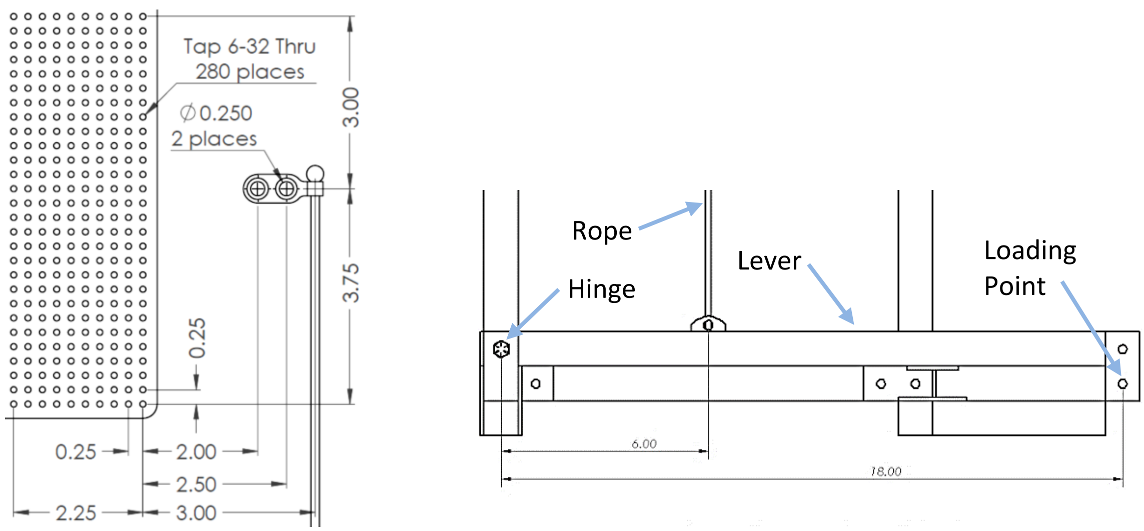

Figure 2. Schematics of the support plate, loading component and lever. *Left Panel:* Your part will be mounted to the support plate via (a) peg(s) and to the cylindrical features on the loading component. Support pegs can be attached to the support plate via a screw at any of the indicated locations, which are on a quarter-inch grid. Support pegs stick out from the indicated tapped holes, so there is no interference with your part in areas where you choose not to include a peg. The loading component will have two 0.250 inch cylindrical attachment pegs. The loading component must be located and oriented exactly as dimensioned in the drawing. *Right Panel:* The other end of the rope will attach to a lever at the indicated location, directly below the loading component. The lever will be hinged at left. On the right end of the lever, weights will be hung at the indicated location. During loading, nothing else can contact the lever. A SolidWorks assembly of the full rig is provided for verification of your parts in the detailed design phase.

You will gradually increase the load until your component breaks or a factor of safety of 2 is met. Free weights in small increments will be provided for this purpose. You will note the failure load and calculate the factor of safety. You will capture the full testing process on video.

Material and Manufacturing: You will fabricate your part by 3D printing PLA material using your personal 3D printer. The material properties of 3D printed PLA are anisotropic; parts are strongest under tensile loading in the directions along the main printing lines (parallel to the bed) and weakest under loads that pull layers apart (perpendicular to the bed) or shear them (in the plane of the bed). In the stronger loading directions, the material is ductile, the yield strength is about 50 MPa, the elastic modulus is about 3.6 GPa, the flexural strength is about 70 MPa, and the flexural modulus is about 3.8 MPa. In the weakest loading directions, the yield strength for pulling layers apart is about 20 MPa, and the yield strength for interlaminar shear is about 5 MPa. The density of PLA is about 1.24 g cm^{-3} (parts themselves can have lower mass depending on infill density). For those interested, the following papers provide more data:

1. Travieso-Rodriguez, J. A., Jerez-Mesa, R., Llumà, J., Traver-Ramos, O., Gomez-Gras, G., & Roa Rovira, J. J. (2019). Mechanical properties of 3D-printing polylactic acid parts subjected to bending stress and fatigue testing. *Materials*, **12**:3859. Article Link.
2. Tian, X., Liu, T., Wang, Q., Dilmurat, A., Li, D., & Ziegmann, G. (2017). Recycling and remanufacturing of 3D printed continuous carbon fiber reinforced PLA composites. *Journal of Cleaner Production*, **142**:1609-1618. Article Link.

SolidWorks does not include PLA as a default material, but the Acrylic material has similar elastic modulus, Poisson's ratio, and density. You can calculate factor of safety from the stress or buckling load factor result from FEA using the strengths above, even if the listed yield strength of the material in CAD is different.

Design Process:

You will use a process that combines sketching, low-fidelity prototyping, back-of-the-envelope analysis, finite-element analysis (FEA), and functional prototype testing, iteratively, to design your component. Lean into this design approach; it will provide you with a strong understanding of the design space, which will allow you to both arrive at a good design and explain it well in your report.

Outcomes and evaluation:

Component testing: You will test your component and record the results in the online spreadsheet linked from Canvas. You will provide the mass of your component, the estimated factor of safety, whether it sustained at least 100 N applied to the lever, and the maximum load applied before it broke (to calculate actual factor of safety). You will provide: a link to a video of the test, which should include a close-up of your part and depict the part and entire load during testing; a link to the gcode used to print your part, which the teaching team may use to spot-check performance; a photo of the component being weighed on a scale with 0.1 g precision; and a photo of the component being checked against the paper measurement grid to verify geometric compliance. Please use YouTube to share linked videos and Google Drive to share files and photos (with permissions set to "Stanford"). These data will be used to calculate the performance-based portion of your grade. Please be careful not to injure yourself during testing :-).

Performance-Based Grading: A portion of the project grade is based on objective performance. If the component meets the geometric requirements, you will receive full credit for `nominal' performance comprising 15% of your project grade, even if the component breaks during testing. An additional 15% of the project grade will be based on objective performance of the component relative to 'excellent' and 'heavy' component masses set by the teaching team. The total performance-based grade is calculated as

$$Performance\ Grade = 15\% \cdot Nom + 15\% \cdot \frac{1.2 \cdot (m_{heavy} - m_{part})}{(m_{heavy} - m_{excellent})},$$

where Nom is a binary pass (1) or fail (0) result, m_{part} is the mass of your part (or m_{heavy} if the part failed), m_{heavy} is a mass selected by the teaching team to represent a relatively low-performance design, and $m_{excellent}$ is a mass selected by the teaching team to represent an excellent design. To emulate real-world conditions, we won't set 'excellent' or 'heavy' values in advance; you will need to use your design and analysis skills to determine for yourself what you think is possible for this scenario. Please be assured that we will select reasonable values, and that if all designs are excellent then everyone will receive the top performance grade. Notice that parts with mass near the excellent value will receive a grade bonus.

Design Awards:

1. The lightest-weight component that holds the required load.
2. The component with the best ratio of actual factor of safety to mass.
3. The best report, with emphasis on concision and use of mechanics concepts.

Summary Report: Please submit a five-page summary report explaining your design, submitted as a single PDF in response to the Canvas assignment.

This is a short-form technical report. Please carefully read the topic reading on technical writing for an explanation of the expected writing style, communication goals, content tips, and process suggestions. In the past, you may have been asked to write to fill space or to describe your emotional journey, but that is not the expectation here. Please use as few words as possible to precisely describe the important facts and logic of your design using the concepts and frameworks of mechanical systems design that we describe in this course. Please avoid argument by anecdote or intuition. Please avoid descriptions of early prototypes unless they provide a compelling illustration of a key idea in your final design.

We expect the analysis portions of your report to be easy to follow and logically consistent. Through the design process, especially at early stages, you will use a variety of handwritten brainstorming and analysis techniques, an iterative process that involves missteps (a necessary and helpful feature of our exploration). After you complete the design process, please generate a separate, clear summary of the most important simplified analyses for your report. We are expecting to be convinced by this graphical and mathematical explanation of how the part is loaded, how it can fail, and the implications for key design choices.

We have high expectations for the quality of the writing in these reports. You should plan to thoroughly edit your report several times prior to submission. We recommend that you make an appointment for a consultation with the Stanford School of Engineering Technical Communications Program on the week the report is due and pace yourself such that you have a complete draft to review at that time:

https://engineering.stanford.edu/students-academics/technical-communication-program

The report should be divided into the following sections:

1. **Summary Page:** Please include the following on a single page (50% of report grade)
    a. ***Image:*** A clear, aesthetically pleasing image of your final design.
    b. ***Description and Rationale:*** 400 words or fewer describing the design's primary features and why they are appropriate for this scenario. We're looking for a very clear, convincing explanation for each major design decision, based on mechanical systems design concepts. We expect high-quality writing, resulting from several rounds of editing.
2. **Back-of-the-Envelope Analysis:** Please include on one page each (25% of report grade)
    a. ***Free body diagrams:*** On one page, please provide FBDs of your entire component and simplified versions of each of its major features. Please draw forces and moments in their expected directions (vector form). Please clearly state any assumptions and justifications for these assumptions. Please include estimates of the values of each resultant load.
    b. ***Inverse failure analysis:*** On one page, provide a clear version of the analysis you used to determine the values of each critical design parameter needed to achieve the desired factor of safety against each important failure mode. Please perform derivations symbolically and provide parameter values in SI units (meters).
3. **Computational Analysis:** Please include on one page each (25% of report grade)
    a. ***Stress distribution:*** On one page, please provide a CAD screen shot depicting the stress distribution in your component. The legend should be legible, with SI units (Pa). Describe the loading and constraints you used, and why. Explain any differences between the patterns of stress found and those expected based on back-of-the-envelope analysis.
    b. ***Buckling results:*** On one page, please provide a CAD screen shot depicting the first buckling mode for your component. The buckling load factor should be legible. Please describe the loading and constraints you used, and why. Explain any differences between the deformed shape found and those assumed in your back-of-the-envelope analysis.

Project Grade: The overall project grade will be calculated as:

$$Project\ Grade = Performance\ Grade(30\%) + Report\ (70\%)$$