Names: Team Number:

MEEN 305 – Project 1
Design, build, and test of a topology optimized lightweight beam
Due October 30, 2025, by 11:59 PM

Project 1 is a **team** assignment on the application of the **deformation and failure analysis concepts** to design and structural optimization of a beam.

BACKGROUND AND MOTIVATION – Many human-made structures utilize beams with sophisticated topologies and cross-sections, see below. Additionally, many animals have bones with similarly complex shapes, see the jawbone of the below badger skull.

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DESIGN REQUIREMENTS – You are tasked to design a lightweight horizontal beam (see sketch in **Fig. 1**).

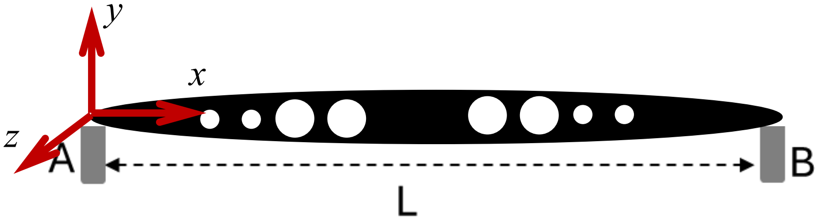

Figure 1. Sketch of a lightweight beam (frontal view)

- The goal is **to minimize the use of materials while meeting the safety requirements against failures**. You will fabricate your design via 3D printing.
- You need to design the shape of your beam, including the cross-section type (solid circular, rectangular, H, I, T, square tube, circular tube, etc.), taper (i.e. $h(x), b(x), d_i(x), d_o(x), b_f(x), t_w(x), etc.$), and any other weight reducing elements (e.g. holes). You will need to justify your choices using von Mises stress analysis.
- The total length of the beam must 9".
- The span between the two supports is $L = 8"$.
- The beam must be designed to support the following loading conditions:
  - Loading 1: A concentrated load of 5 lb is applied at the midspan.
  - Loading 2: The 5 lb load is removed. Your beam is then rotated $90°$ onto its side. Next, a concentrated load of $(2 + Team\ \#)$ lb applied at $(2 + \frac{Team\ \#}{5})$ inches from support A.
- The design factor of safety is 1.5 for all possible failure modes.

ANALYSIS REQUIREMENTS

- You need to write a computer program that automatically solves the statics problem for a simply supported beam subject to a single concentrated applied load between the supports. The program needs to calculate reaction forces and automatically generate plots of the shear force diagram $V_y(x)$ and bending moment diagram $M_z(x)$. The units of the plots must be clearly labeled as well as the name or symbol of the independent and dependent variables being plotted. The user inputs to the program must be the span, load magnitude, and load location.
- The program must also take the basic tapered geometric dimensions of the beam as input, e.g. (i.e. $h(x), b(x), d_i(x), d_o(x), b_f(x), t_w(x), etc.$). The program must compute and automatically plot the section modulus $S(x)$ and second moment of area $I_z(x)$ with appropriate units labeled. The program should also automatically plot the outer dimensions of cross-section viewed from the front ($x - y$ plane) and top ($x - z$ plane).
- The relevant material properties must be a user input into the program.
- The program must compute and automatically plot von Mises stress $\sigma_{vm}(x)$ and factor of safety $FoS(x)$.
- The program must compute and automatically plot vertical deflections $v(x)$.
- The program must compute and automatically plot slope deflections $\theta_z(x) = v'(x)$.

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- Your program should automatically calculate the weight of the beam. You can neglect the weight of the beam in your analysis, but you must justify this assumption and ensure that it is clearly commented in the program.
- The computer program can be written in any language you like, including Python, MATLAB, or Excel.
- You should use your program to optimize your beam's topology and geometric cross-sectional design. This will involve a LOT of trail-and-error. If you'd prefer to avoid the trial-and-error approach, then you can alternatively use appropriate parameterization of the dimensions combined with built-in optimization tools. For example, if you are designing the height of a rectangular shaped beam, you can parameterize this as $h(x) = H_{L/2} \times \left(\frac{x}{L/2}\right)^n$. With this parameterization, you could ask the built-in optimizing tool (e.g. Goal Seek in Excel) to minimize the standard deviation of $\sigma_{vm}(x)$ by changing n. The standard deviation will go to zero when $\sigma_{vm}(x)$ is constant with respect to x. Once you are happy with your value of n, you can optimize $H_{L/2}$ by asking the built in tools to find the value of $H_{L/2}$ that outputs a minimum factor of safety of 1.5.
- Lastly, you should use your engineering judgement and intuition to constrain unrealistic designs that are artifacts of the idealized analysis. For example, the beam's cross-section CANNOT taper to zero at the supports, even if the idealized analysis says it can. The thickness of a tubular cross-section CANNOT be paper-thin, even if the idealized analysis says it can.
- At minimum, you should try at least 20 design iterations that meet all design requirements. Of those 20 design iterations, a subset of them should be ruled out based on your engineering judgement of their designs being unphysical. Of the remaining design iteration, the "best" or "optimal" design is the one with the minimum weight.

BUILD REQUIREMENTS

- You should develop a CAD model of your final "optimized" beam design.
- This CAD model is then used to **3D print** your "optimized" beam using a **polymer-based material**. You can select any of the materials available at the MEEN Rapid Prototyping Lab. You can also use other facilities, e.g., FEDC in Zachry Complex, Soft Mater, etc., to 3D print your design. Make sure you justify the material selection. You should consider cost, mass density, printability, and mechanical properties in your material selection.
- You need to document the printing process in terms of printing orientation, infill density, etc., and whether additional support structures are needed. You need to discuss any fabrication challenges and material/dimensional imperfections you may encounter during the fabrication. Also, discuss any final refinement that is done. If possible, please include photographs of the fabrication process.

TESTING REQUIREMENTS

- You need to record a video of your team demonstrating the load-bearing capacity of your beam under the two above loading conditions.
- For each loading condition, measure and calculate the deformation. A horizontal string or background grid paper can be used as a baseline to measure deflections from.
- The supports should each be 8" apart and **at least** 0.5" wide.
- If you have access to a 5-gallon bucket, that is the ideal way to apply the load. Fill the bucket with the necessary amount of water to produce the desired load. Then hang the bucket from your beam. Hint: Do this outside in case your beam fails.

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BASIS FOR GRADE - Your team's grade will be based on the accuracy and detail of your analysis, design rationale and justification, fabrication process, and demonstration of load bearing ability of your beam design. The goal is to minimize the use of materials and structural weight while meeting all other design requirements. You will need to submit a project report with the following information:

- Report should be typed and nicely formatted, e.g. title page, page numbers, section headers, equation numbers, table/figure numbers, figure/table captions, etc.
- Report should have a one paragraph abstract followed by the following sections:
    1. Design Requirements
    2. Theory and Analysis
    3. Build
    4. Test
    5. Discussion
    6. Author Contributions
    7. Appendix – Design Iterations
- In the **Design Requirements** section, list the specific requirements for your team and FBD.
- In the **Theory and Analysis** section, type out the key equations and their key assumptions. Briefly explain their implementation/parameterization in your program and built-in tools used.
- Detailed engineering drawings of your final "optimized" beam design, e.g. from SolidWorks.
- Provide a brief (few sentences) justification for why you chose your final geometric design and the rationale for your material selection. Put this in the **Build** section.
- Provide detailed documentation of your 3D printing fabrication strategies, including rationale and justification of selecting printing factors. You can also include a discussion on fabrication challenges you encountered. Put this in the **Build** section. No other text needed.
- Upload your test demonstration video as well as a short tutorial video on how to use your computer program to YouTube and include the link in the **Test** section of the report. This can be public private link only accessible to the instructor and graders. You may include video of the build process, but it is NOT required. Make sure to get approval before recording in any of the rapid prototyping labs. No other text needed in the **Test** section of the report.
- In the **Discussion** section, provide a table with a comparison of the theoretically predicted and experimentally measured values of the beam's weight and maximum deflection under both loading conditions. Include the percent error between theory and experiment. Provide a brief discussion (about a paragraph or two) of the sources of error in the theory (e.g. assumptions, neglecting weight of beam, linear elasticity) and sources of experimental error (e.g. load inaccuracies, measurement error, dimensional tolerances exceeded, etc.).
- Provide at least 20 screenshots of your 20 design iterations. No need to format these nicely. Just drop them into the **Appendix** section. No need to have Figure labels, captions, or text for these. Include a table of the predicted beam's weight for each of the 20 design iterations.
- In the **Author Contributions** section, describe the tasks and responsibilities of each member and the work coordination among all members of your team.
- Only one team member will upload the report and your program on behalf of the entire team.
- Each team member must complete an individual peer assessment form (provided on the next page) and upload to CANVAS.

PEER ASSESSMENT - Be sure to balance the workload of this project evenly among team members. After the project is completed, an individual peer assessment (only visible to instructors and graders) will be completed by the student to voice praises or concerns about project contributions from their fellow teammates.

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Student Self and Peer Evaluation for MEEN 305 Project 1

This form will be used to assess the performance of all the members of your group. Your responses are to be confidential and only known by the graders and yourself. Do not discuss your responses with your group members. Type your team number in place of "#".

TEAM: #

Based on the following scale, fill in the number of points earned by each group member for each category using the following scale:

5 – Excellent	**4 – Good**	**3 – Fair**	**2 – Poor**	**1 – Did Nothing**

Team Member Name	Assisted with analysis	Assisted with fabrication	Assisted with testing	Assisted with writing the report	Completed the assigned tasks that were given by group	Actively responded to group communications	Total
1.							
2.							
3.							
4.							
5.							
6.							

If you have any additional comments that were not addressed in the table, write them here. This is an additional opportunity to respectfully voice praises or concerns about your group members.

When finished, please edit the name of this document by replacing the "#" with your team number. Save and submit to CANVAS.