Term Project Final Report
March 2026
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1. Introduction

1.1 Background

Rock climbing carabiners are load-bearing connectors used to attach ropes and harnesses during climbing. Because they are critical safety components, they must be designed to withstand significant tensile loads without structural failure. At the same time, minimizing weight is important because climbers carry multiple carabiners as part of their equipment.

Carabiners are commonly manufactured from high-strength aluminum alloys due to their favorable strength-to-weight ratio. Research by Sentanu and Muflikhun analyzed carabiner performance using finite element analysis and modeled the component using aluminum 6061. Their work demonstrated how FEA can be used to evaluate stress distribution, deformation, and potential failure regions in carabiner designs before physical testing (Sentanu & Muflikhun, 2022).

FEA is therefore a useful approach for evaluating how carabiner geometry influences structural performance. By applying representative loads and constraints, we can identify stress concentrations and assess whether the component meets strength requirements while minimizing material usage.

1.2 Loading Conditions and Boundary Setup

The carabiner is subjected to loading along its major axis. In the model, the carabiner is supported at one contact location while a tensile load is applied at the opposite contact point to simulate force transfer through the connector.

A load of 7 kN is used for the analysis. This value was selected based on previous research evaluating carabiner performance using finite element analysis, where a similar load was applied to represent tensile loading conditions in climbing equipment (Sentanu & Muflikhun, 2022).

Figure 1: Carabiner illustrated with force load and fixed pin-support

Figure 2: Reference loading condition in real world.
https://www.alpinesavvy.com/blog/retreat-anchors-sport-climbing

1.3 Design Objectives and Constraints
Objective:
- Minimize mass

Constraints:
- No yielding
- Limit deflection to 1.5mm

2. Baseline Model

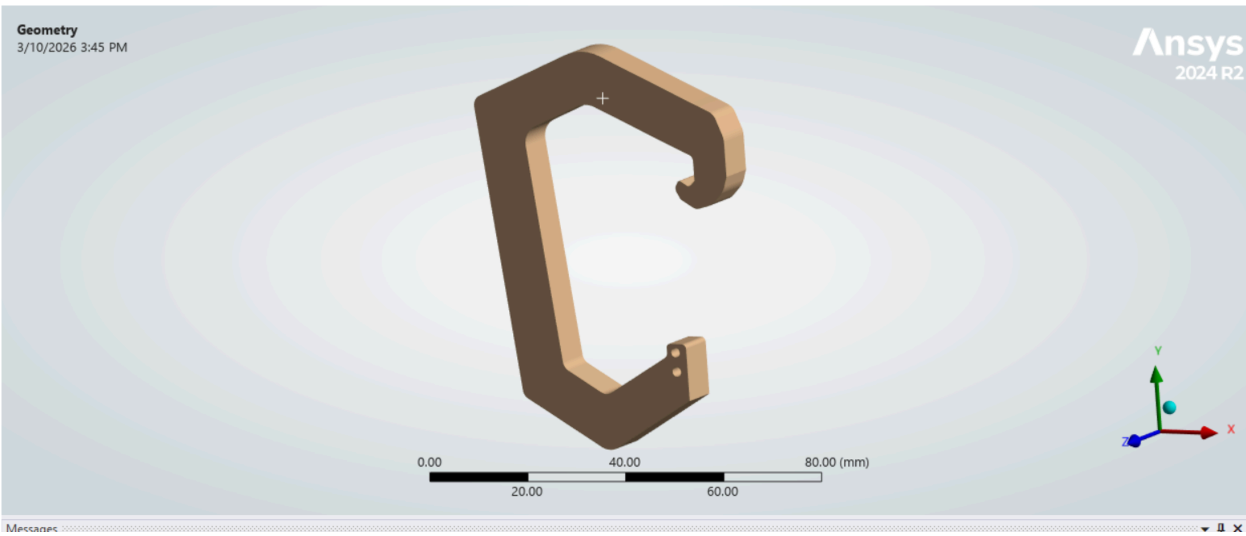
2.1 Geometry and Model Setup


Figure 3: Baseline model created in spaceclaim.

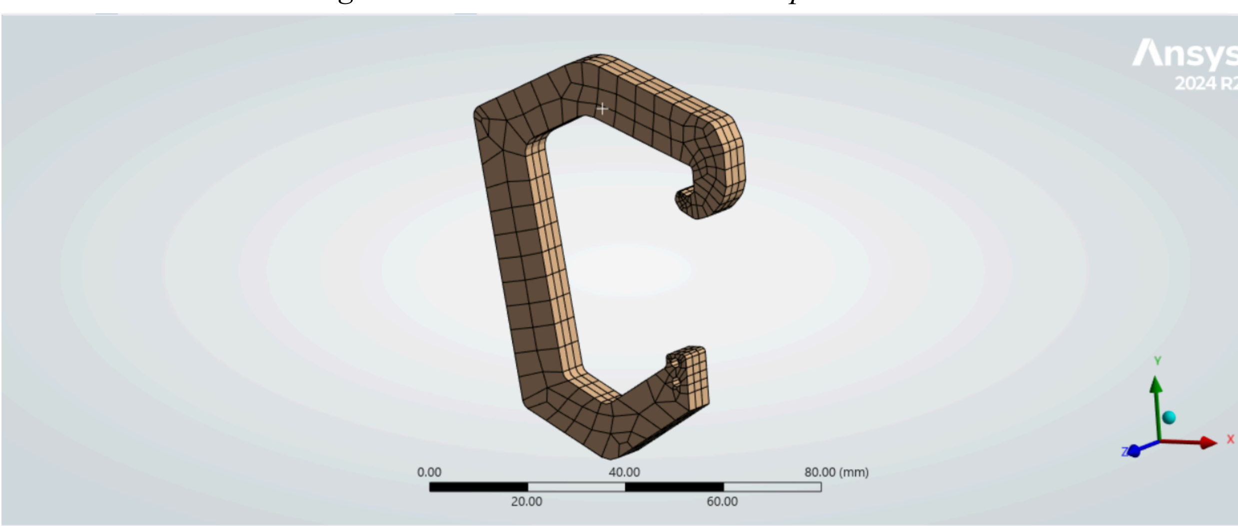
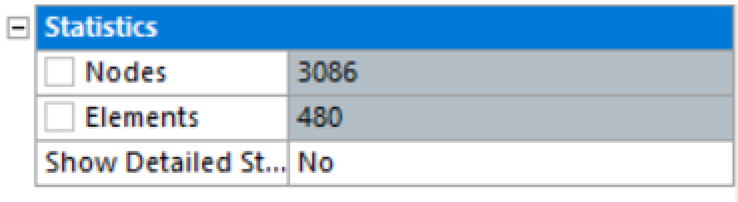


Figure 4: Generated mesh on baseline model.



Statistics	
Nodes	3086
Elements	480
Show Detailed St...	No

Figure 5: Node and element quantity of baseline model; 3086 nodes, 480 elements.

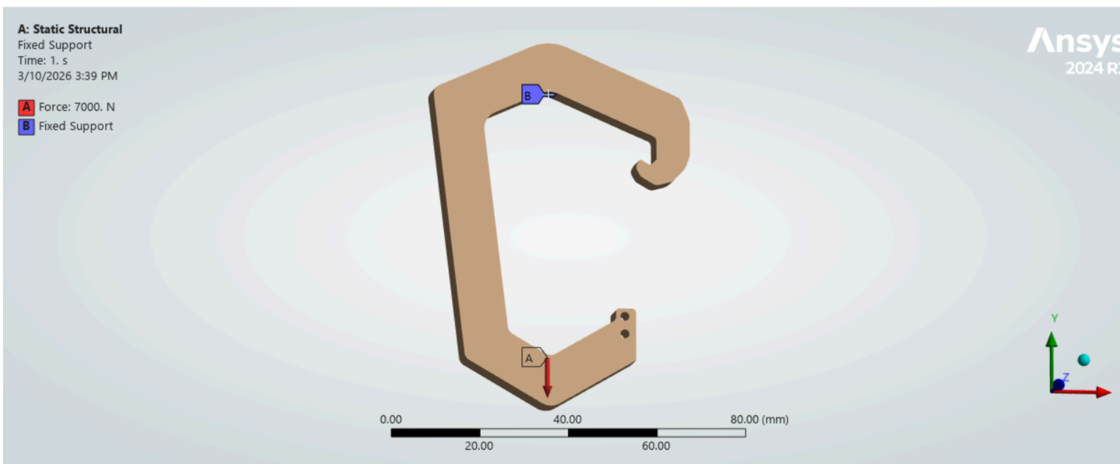


Figure 6: Loading conditions illustrated in mechanical. 7kN force acting on bottom of carabiner, fixed support acting opposite of force on top of carabiner.

2.2 Material Properties

Material	**Young's Modulus**	**Poisson Ratio**	**Yield Strength**
Aluminum 6061	609040 MPa	0.33	259 MPa

Table 1: Material properties of carabiner.

2.3 Mesh Convergence Study

Resolution set to 6

Element Size (mm)	# of nodes	Max Total Deformation (mm)	Max Equivalent Stress (MPa)
5	3698	0.90025	1272.6
2.5	7999	0.90498	1348.5
1.25	24175	0.90727	1553.3
0.5	172390	0.9076	1568.9

Table 2: Tabulated results of mesh convergence analysis.

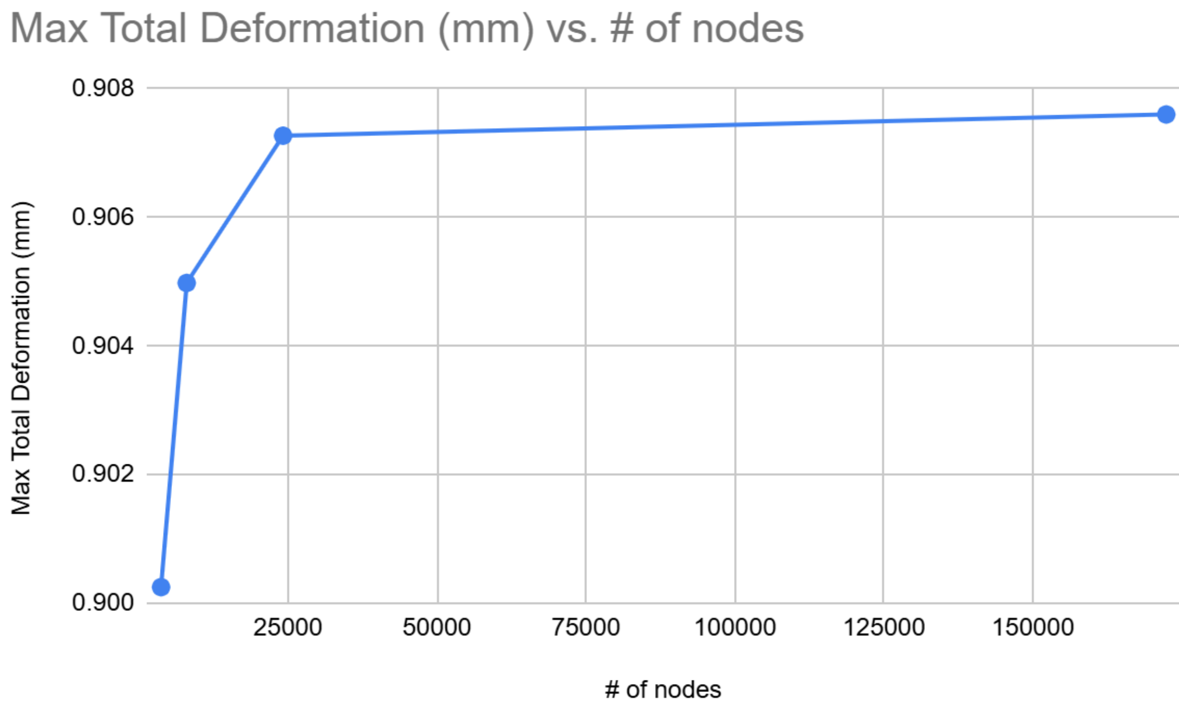


Figure 1: Max deformation vs number of nodes plot.

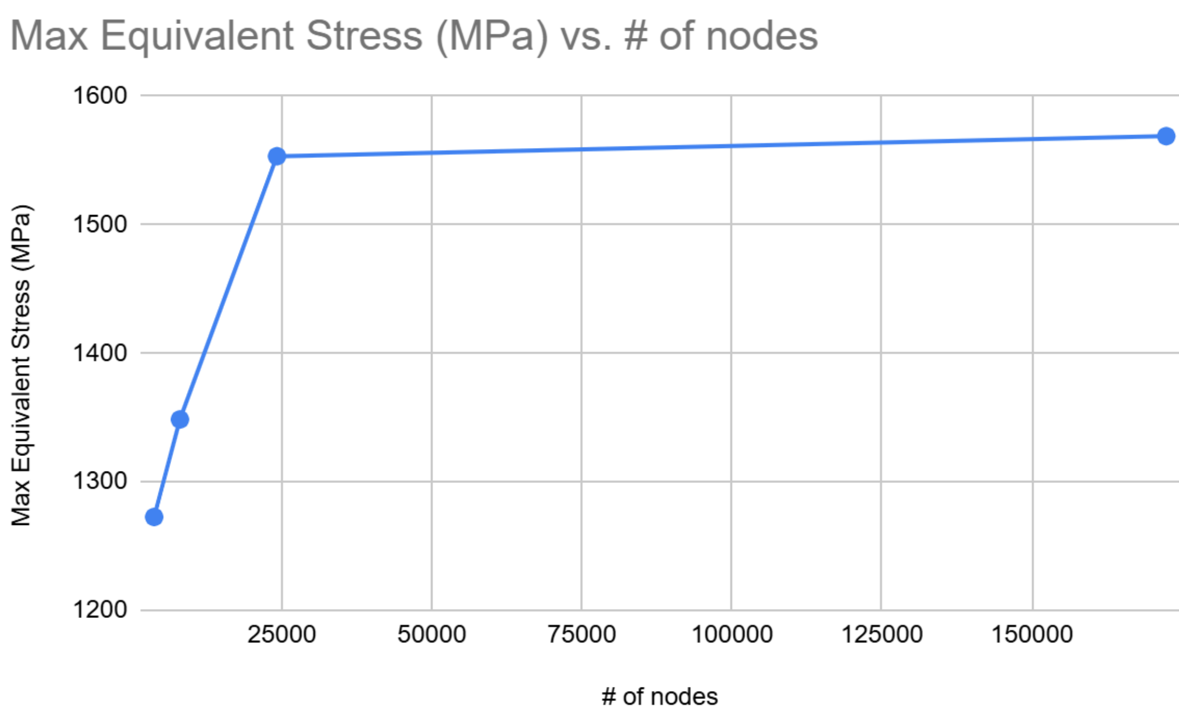


Figure 2: Max equivalent stress vs number of nodes plot

A mesh convergence analysis was completed by refining the mesh and comparing the resulting deformation and equivalent stress values. The results showed that the change between the 1.25 mm mesh and the 0.5 mm mesh was very small. This indicates that the model was already close to convergence at 1.25 mm.

Because the finer 0.5 mm mesh required significantly more nodes and longer computation time, the 1.25 mm mesh was selected for the analysis. This mesh gives nearly the same results as the finer mesh while being much more efficient computationally.

2.4 Baseline Results

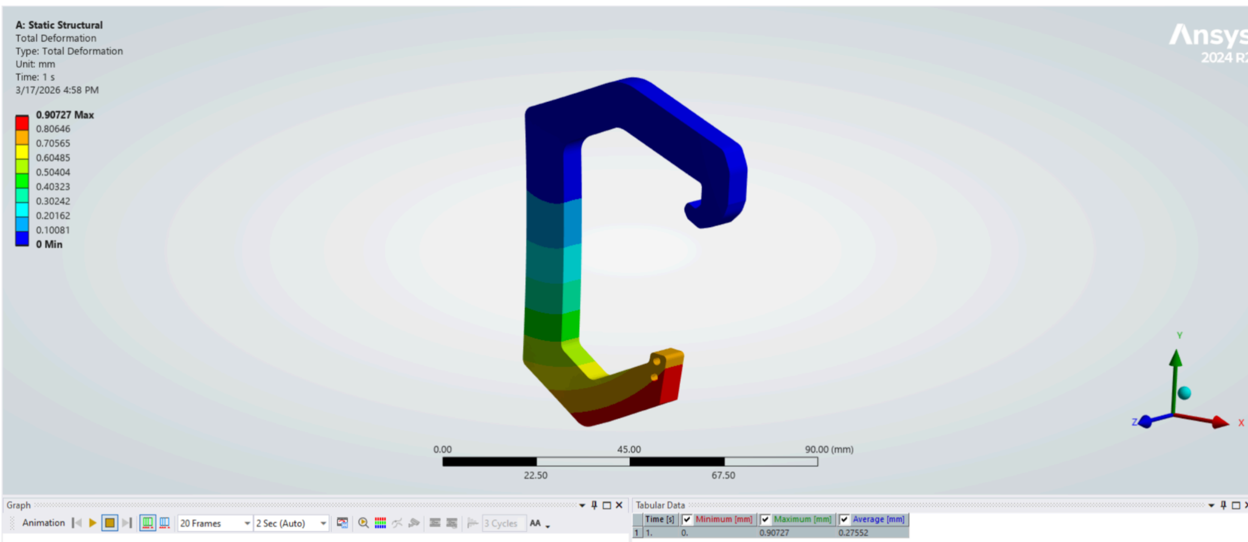


Figure 7: Total deformation with element size 1.25mm. Max deformation of 0.90727 mm.

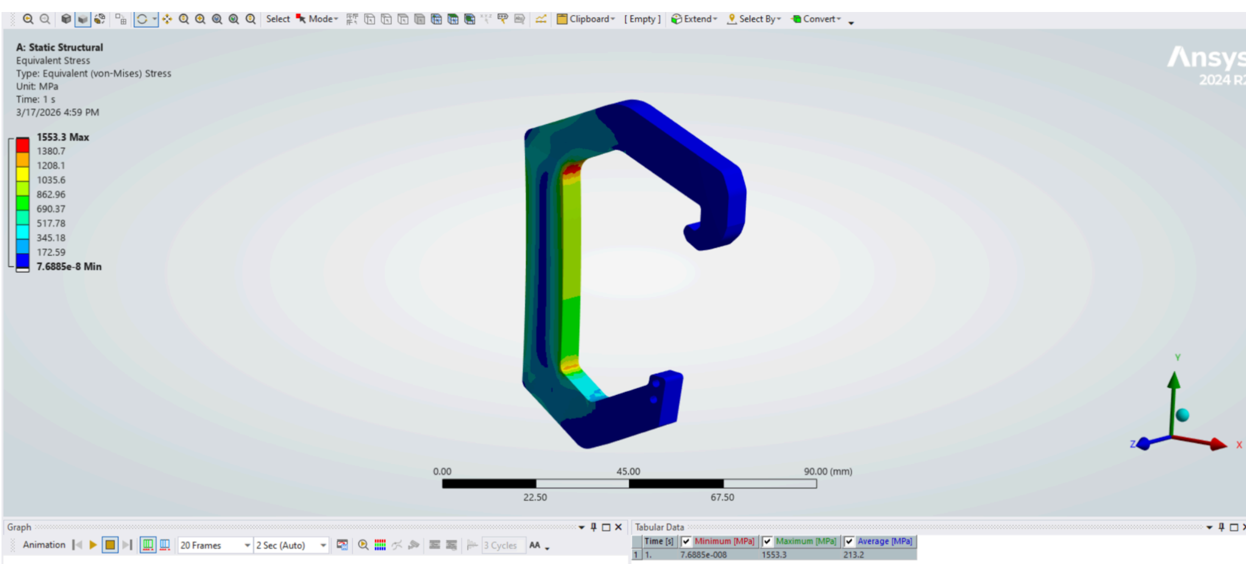


Figure 8: Maximum von-mises stress with element size 1.25mm. Maximum stress of 1553.3 MPa.

3. Optimized Design

3.1 Design Modifications

The baseline model was updated by simplifying the geometry and rounding sharp edges where stress concentrations were observed. Material was removed from low-load regions to reduce mass and added in high-stress areas to improve load distribution. The same mesh settings, material properties, and boundary conditions were used as the baseline model to allow for a direct comparison.

3.2 Model Setup (Updated Geometry)

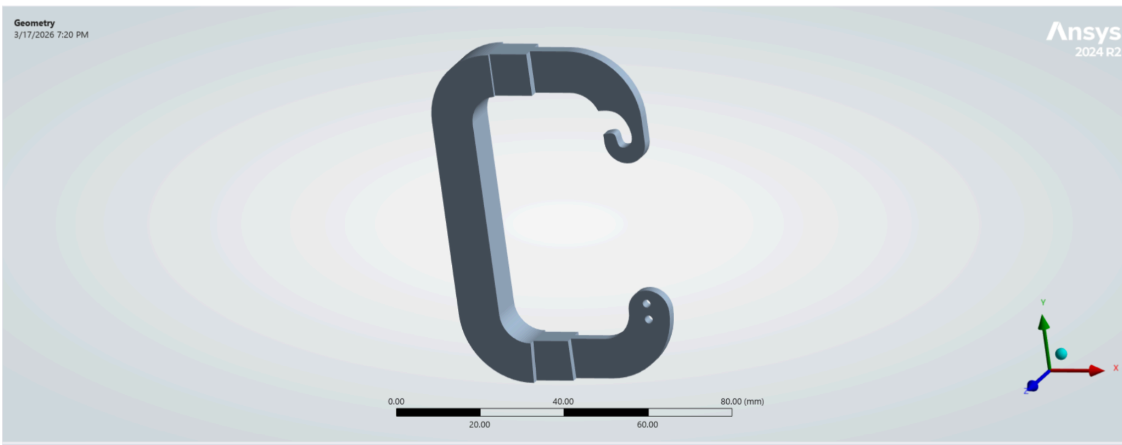


Figure 9: Updated model made in spaceclaim.

Figure 10: Updated model with mesh element set to 1.25 mm and resolution set to 6.

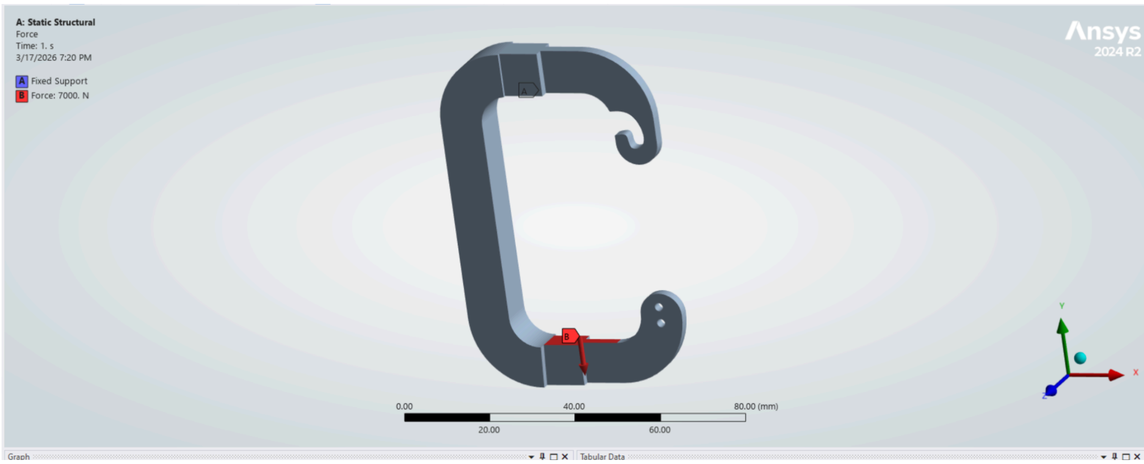


Figure 11: Updated model with the same loading condition as baseline. Fixed top, 7kN facing downward.

3.3 Results Under Primary Load (7 kN)

Figure 12: Updated model with maximum deflection of 1.1345mm.

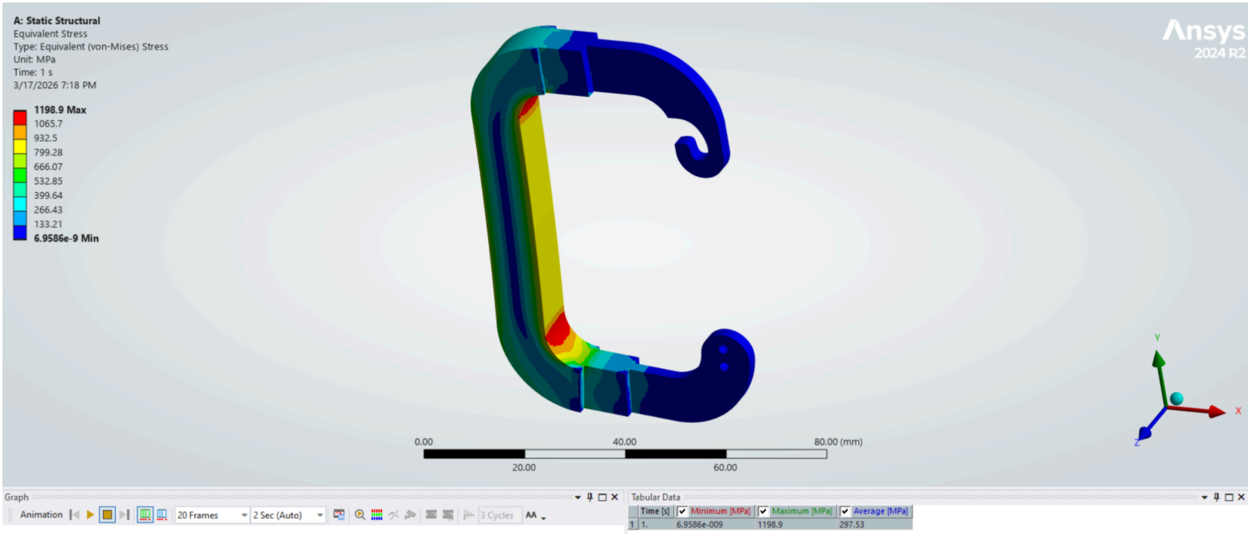


Figure 13: Updated model total equivalent stresses. Maximum of 1198.9 MPa.

3.4 Secondary Load Case (1 kN Analysis)

A consistent trend was observed where, despite multiple design iterations, the maximum stresses remained above the yield strength. This is likely due to the large loading condition applied in the model. To evaluate performance under a more realistic scenario, the updated model was reanalyzed using a reduced load of 1 kN instead of 7 kN. Under this condition, the model satisfied the yielding constraint.

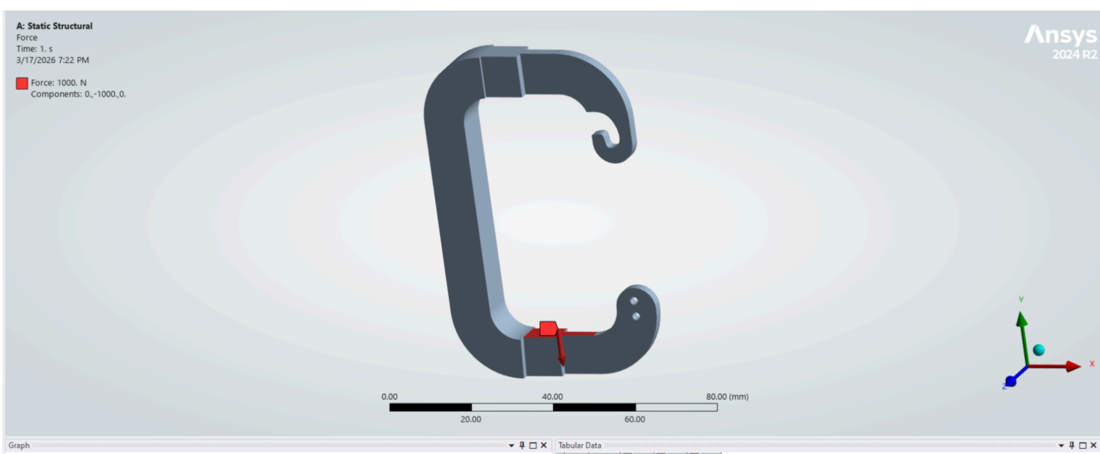


Figure 14: Secondary loading condition on updated model, same fixed support with 1kN downward force.

Figure 15: Secondary loading condition deflection results. Maximum deflection of 0.16192 mm (within the constraints)

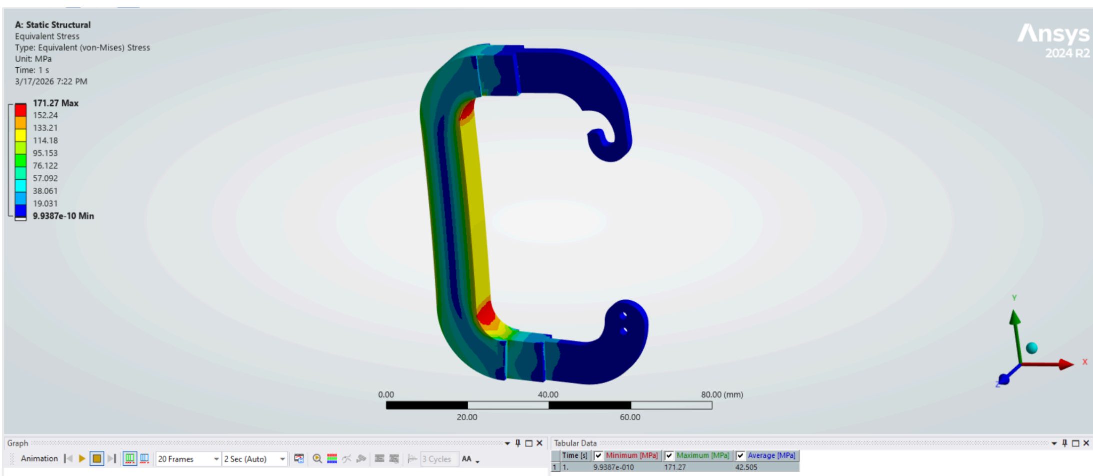


Figure 16: Secondary loading condition total equivalent stresses. Maximum of 171.27 MPa (not yielding).

4. Performance Comparison

4.1 Quantitative Comparison of Designs

Model	Total Volume (mm^3)	Mass (g)	Max Deflection (mm)	Max Von-Mises Stress (MPa)	Yielding?
Baseline	13500.05	36.45	0.90727	1553.3	Yes
Updated	11619.2	31.37	1.1345	1198.9	Yes

Table 3: Tabulated results of design change on objectives and constraints.

4.2 Visualization of Results

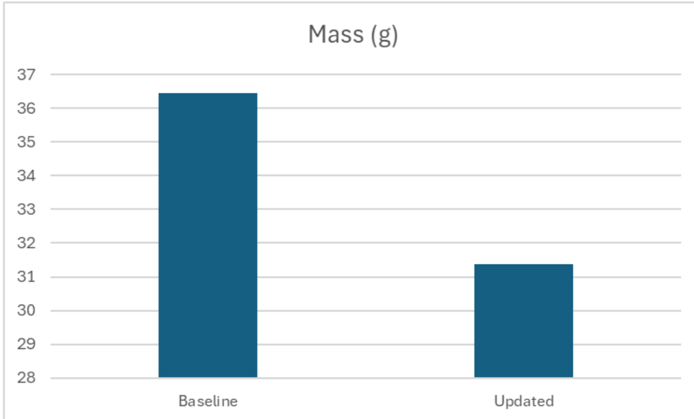


Figure 17: Objective bar plot. Updated model over 5 grams lighter than baseline.

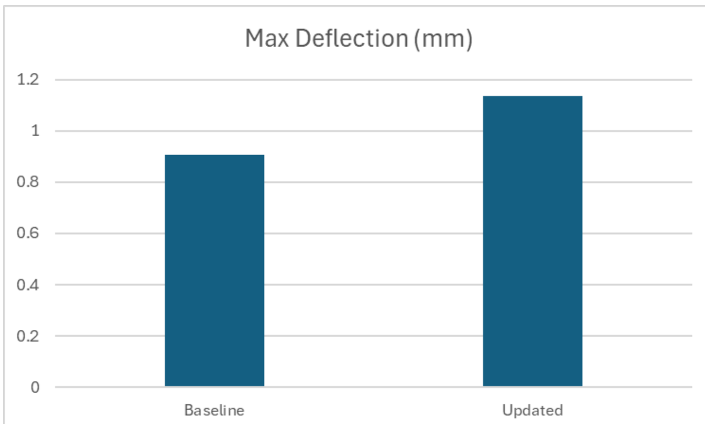


Figure 18: Constraint bar plot. Maximum deflection larger in updated model but still within constraint of 1.5mm.

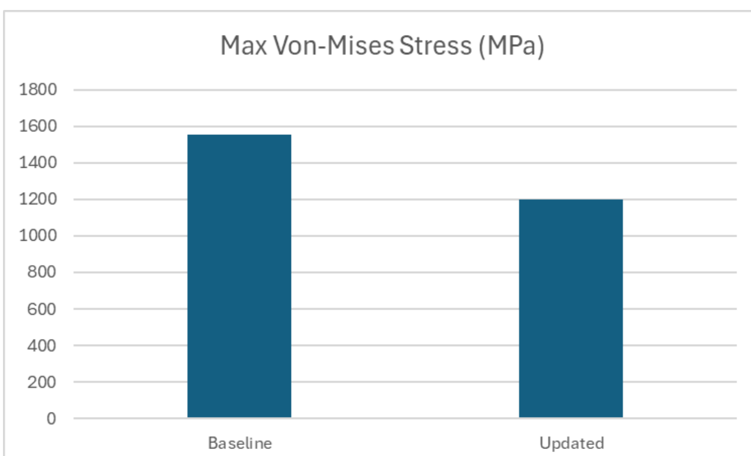


Figure 18: Constraint bar plot. Maximum stress seen by carabiner, updated model experiencing over 350MPa less than baseline.

5. Discussion and Conclusions

5.1 Key Findings

The updated design was successful in reducing the maximum stress while also lowering the overall mass. Although this came with a slight increase in deflection, the value remained within the allowable limit of 1.5 mm, making this a reasonable trade-off. However, the design was not able to satisfy the no-yielding constraint under the 7 kN loading condition. When a more realistic load of 1 kN was applied, the updated model did not yield, suggesting that the original loading case represents an extreme scenario rather than typical use conditions.

5.2 Challenges and Limitations

One of the main challenges encountered during this project is that carabiners are already highly optimized components, making it difficult to achieve significant improvements without trade-offs. Additionally, the model consistently showed yielding under the applied load, which limited how much improvement could be made through geometry changes alone. The iterative nature of the design process also started to add up in terms of computation time, since every small change meant rerunning the FEA again.

5.3 Future Work

For future work, smoothing the sharp edges could help reduce stress concentrations and better align with design for manufacturing, since sharp features are difficult to machine. Material selection could also be revisited, with options like titanium potentially improving strength while maintaining low weight. Finally, applying a more realistic loading condition, such as simulating a rope contact instead of a point load, would better represent real-world performance.

Bibliography:

Sentanu, D. A., & Muflikhun, M. A. (2022). Design and evaluation of carabiner using finite element analysis. Jurnal Rekayasa Mesin. https://rekayasamesin.ub.ac.id/index.php/rm/article/view/989/602