Optimization of a Climbing Carabiner

Sebastian Fiorini, Richard Matthews, Nicholash Bedi, Levi Johnston, Rafa Narciso | Under the guidance of Christopher Kohar

ANSYS

UNIVERSITY OF WATERLOO

Purpose of Study

Carabiners are a phenomenal tool for climbers due to their ability to sustain large tensile loads while being light weight and compact. It was believed that it was possible to further reduce a carabiner's weight while maintaining impressive tensile strength capabilities. A study was done to examine how the cross-sectional areas and profile shape affected a carabiner's ability to bear tensile loads.

Objective

To determine the effect of varying the shape of the Neutrino carabiner and optimize parameters with the goal of maximizing the strength-to-mass ratio.

Finite Element Model

Governing Equations

- System is in equilibrium, therefore:

$\sum \vec{F} = 0, \sum M = 0$

- The meshes will create multiple elements that will be axial loaded and thus follow Hooke's Law:

$\sigma = eE$, where $\sigma = \frac{F}{A}$

Original CAD Model of Neutrino

Initial Setup

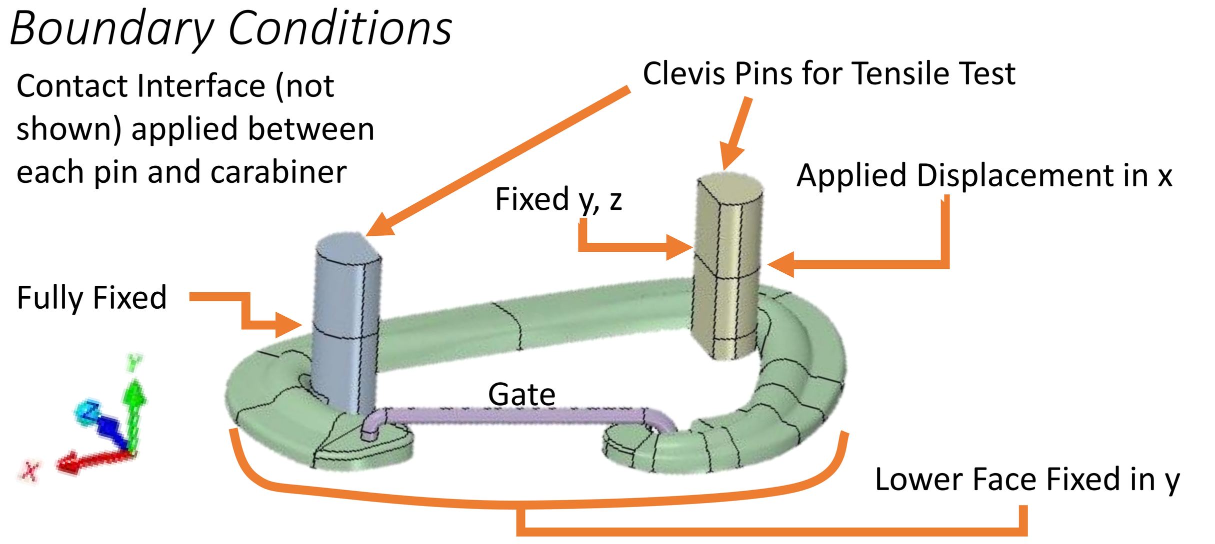
- Pins were added in the model assembly that are meant to represent the steel clevis pins of tensile tests
- Known contact surfaces were set to have a frictional surface with a coefficient $\mu = 0.15$
- Model was cut in half due to symmetry

Material Properties [1]

Aluminum 7075 was used for the carabiner, steel was used for the pins and gate

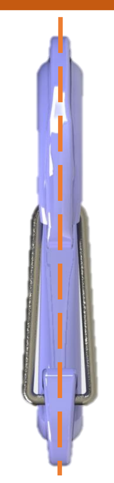
	Aluminum 7075	Structural Steel
Density	2810 kg/m³	7850 kg/m³
Tensile Yield Strength	503 MPa	250 MPa
Tensile Ultimate Strength	572 MPa	460 MPa
Modulus of Elasticity	71.7 GPa	200 GPa
Poisson Ratio	0.333	0.3

Boundary Conditions



Assumptions and Simplification

- Complete symmetry along the flat plane
- The force exerted by the gate when not engaged is negligible
- Analysis stays within the linear elastic region
- The bending in the clevis pins is negligible
- Contact method is accurate
- Stress at small displacements correlates to a higher failure load
- The gate does not restrict rotations

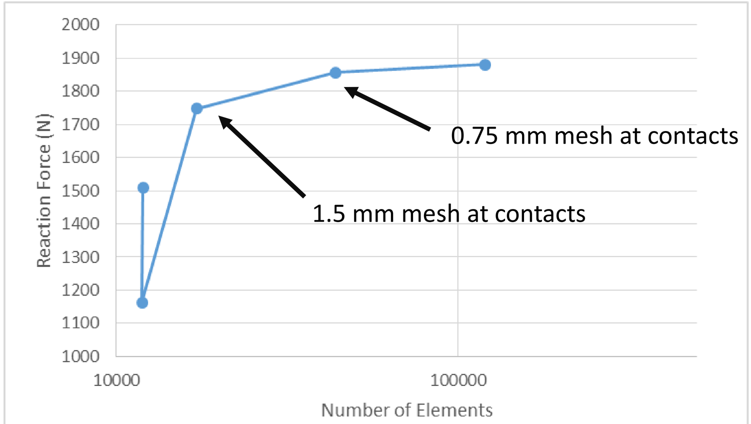


Plane of Symmetry

Models and Mesh Discretization

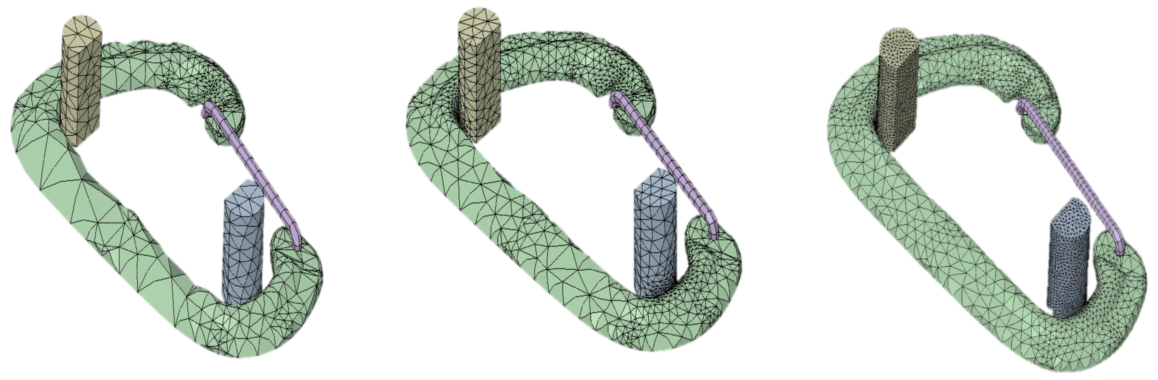
Mesh Convergence Test

- Various meshes were tested at a displacement of 0.5 mm



Convergence of Meshing Size

- Refining the mesh has little effect beyond contact mesh of 1 mm



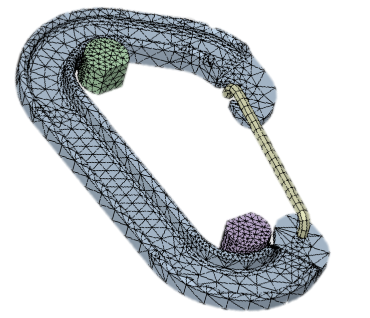
Coarse Mesh	Medium Mesh	Fine Mesh
3 mm size at contacts, Lowest global setting	1.5 mm at contacts, Middle global setting	0.5 mm at contacts, Highest global setting
Nodes: 1.85E4	Nodes: 2.70E4	Nodes: 1.74E5
Elements: 1.19E4	Elements: 1.72E4	Elements: 1.20E5

Simplified Model

- The model was simplified to have the following properties:
  - Constant cross sectional area
  - Constant thickness along a simpler profile
- This model was used for the parametric study

Parametric Study Mesh

- A mesh was created in a similar fashion for the parametric study, with specific contacts having finer meshes than the rest of the body
- From the mesh convergence, a mesh size of 1 mm at the contacts was chosen

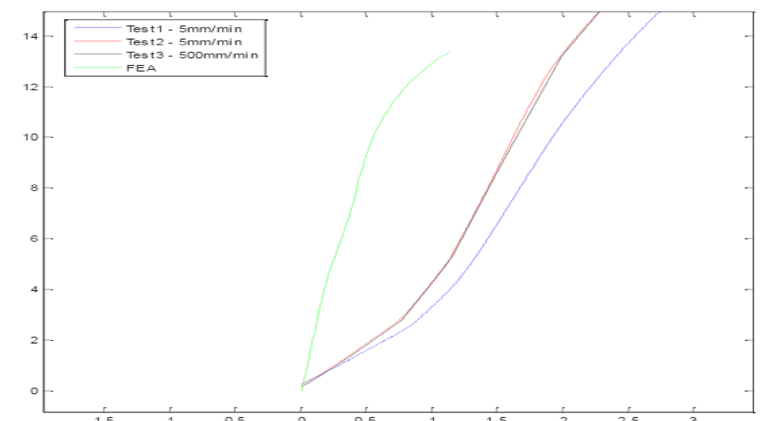


1 mm at contacts, Middle setting

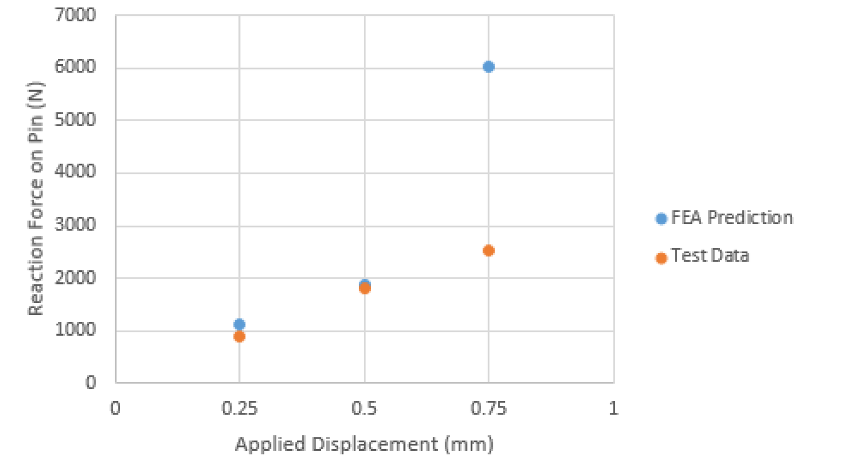
Validation

Load vs. Displacement

- Displacements of 0.25 , 0.50, and 0.75 mm were applied to the FEA model
- The resultant forces on the pins was compared to the force seen in the experimental data shown below



Force (N) vs Displacement (mm) Experimental Data [2]



Comparing FEA model to Experimental Data

- The model is invalid beyond 0.5 mm since stresses exceeded the yield stress, and so the elastic behaviour no longer accurately represents the system
- Lowest error of 3.8% for an applied displacement of 0.5 mm, and therefore 0.5 mm was used in the parametric study

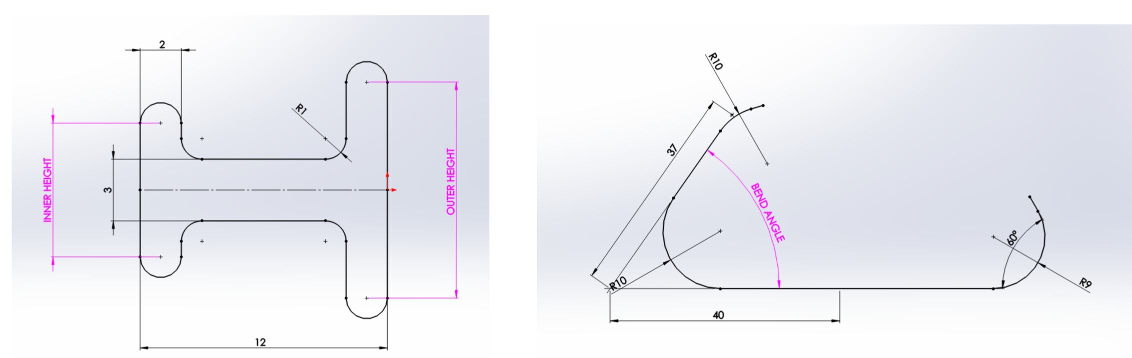
Parametric Study

- 25 models were made such that the sum of the inner and outer height were kept constant in order to keep the cross sectional area constant

Variation of Carabiner Parameters

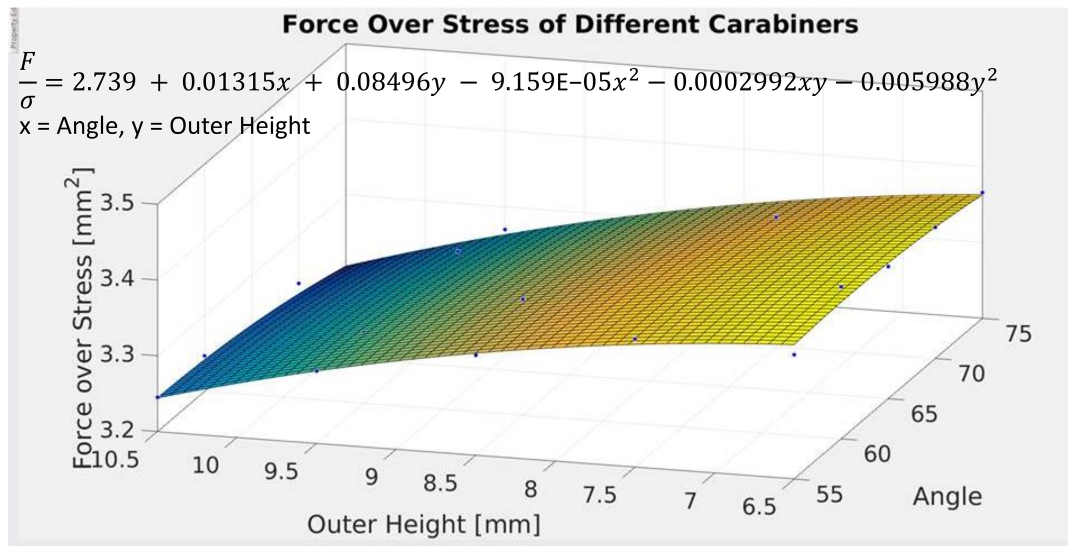
Parameter	Range	Increment	Default
Inner Beam Height	6.5 – 10.5 mm	1.0 mm	8.5 mm
Outer Beam Height	10.5 – 6.5 mm	1.0 mm	8.5 mm
Bend Angle	55 – 75°	5°	60°

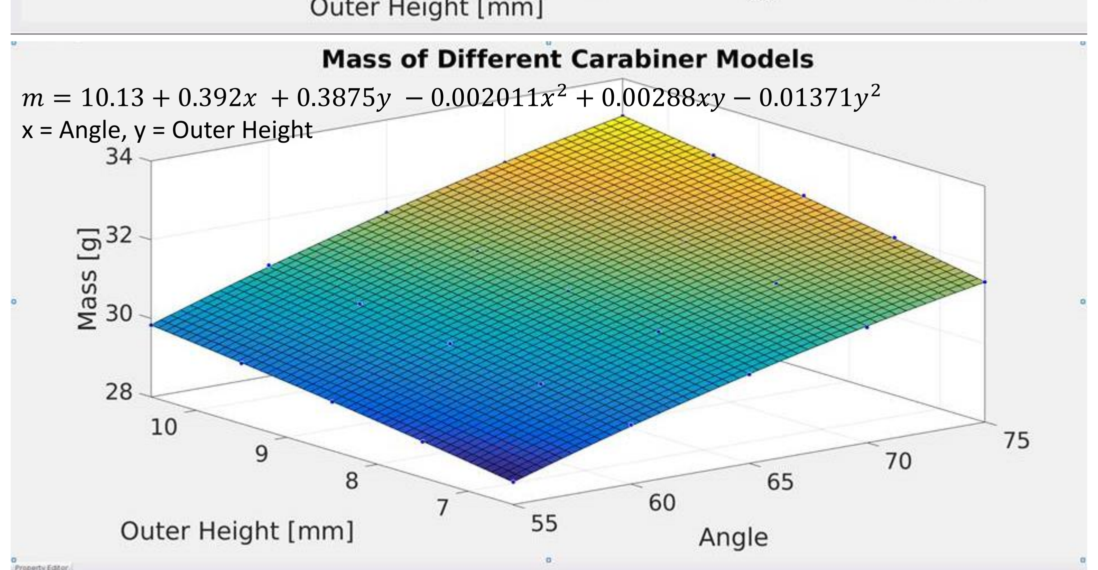
- These profiles are the simplified drawings used to create the simplified models



Simplified Model Profiles

- A constant displacement of 0.5 mm was applied at the upper pin, and the force reaction of the pin and the max stress were recorded
- Boundary conditions of 55 - 75° for angle and 6.5 - 10.5 mm were chosen to keep overall carabiner design similar to validation model





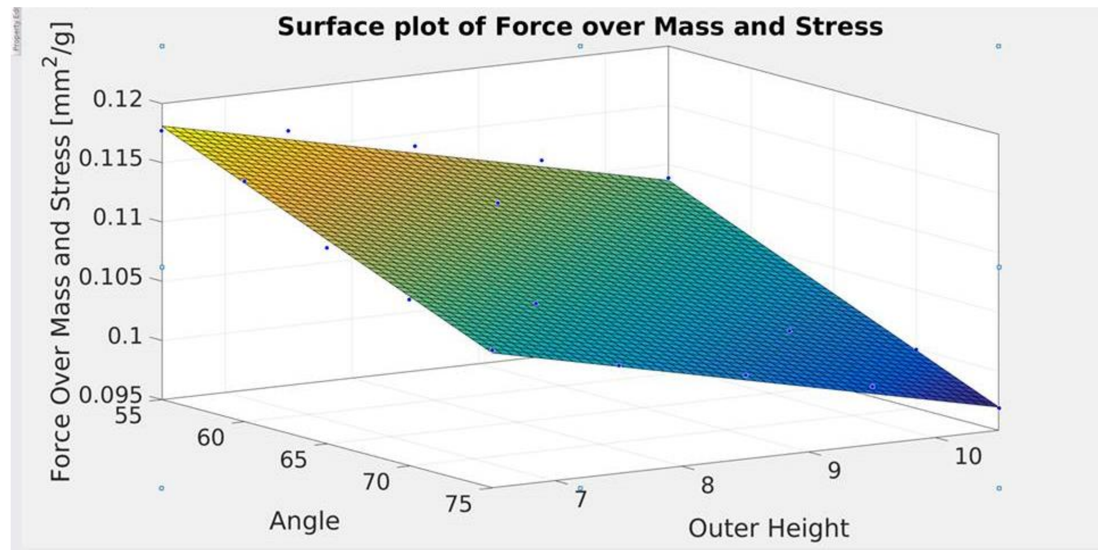
Results

- To optimize for mass and strength, a parameter, Z, was created, which considers the mass and the force to induced stress ratio of the carabiner:

$$Z = \frac{Force}{Max\ Stress * Mass}$$

- Thus Z should be maximized in the ideal carabiner
- Using a linear surface regression function in Matlab, a plane was generated:

$$Z = f(x, y) = 0.166 - 0.000584x - 0.00236y$$



$R^2 = 0.991$, first order surface is sufficient

- The carabiner closest to the maximum of the plane is carabiner 1

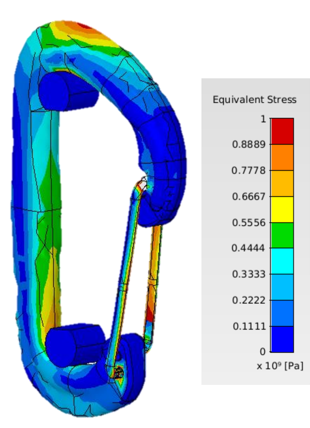
Inner Height (mm)	10.5
Outer Height (mm)	6.5
Bend Angle (deg)	55
Mass (g) (total size)	28.58
Force (N) (half model)	1100
Stress (MPa)	327

Conclusions

- The simulated ideal carabiner is very similar to the Neutrino model, which had a bend angle of approximately 60° and inner height of 9.8 mm
  - This suggests that the parametric study was successful in finding the ideal model of a carabiner
- The assumption of linear elastic behaviour was only valid for displacements up to 0.5 mm, limiting the analysis of small applied loads
- Overall, the project was a valuable learning experience in FEA which emphasized the importance of quality assumptions and simplifications, which can lead to faster and better results

Future Considerations

- Use quasi-static loading or dynamic loading to solve for displacements
- Mesh the carabiner to use hexahedral meshes as opposed to tetrahedral meshes
- Use a software that is capable of solving for larger displacements on complex structures
- Model plastic deformation to be able to predict failure load of carabiners
- Limitations of purely elastic model are shown (right) for displacement at 1 mm displacement, where stresses exceed yield point of 503 MPa



Acknowledgements

Special thanks to Professor Chris Kohar and Ping Zhang for their invaluable support and knowledge.

References

[1] ASM, *Metals Handbook*, Vol.2 - Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, ASM International 10th Ed. 1990.

[2] Alex Strait, *A Comparison of Tensile Testing and FEA Modeling for the Black Diamond Neutrino Carabiner.* June 9, 2015. Online: https://app.box.com/s/3wv5fz4uv8lgmx06jfia2bet0yurfl6x

[3] Steven Welsh, *The Effect Of Damage on the Strength of Climbing Carabiners*, University of Strathclyde, Glasgow, Scotland, April 2013