Evaluation of Composite Materials for Heliostat Cost Reduction

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1. **Motivation**
2. **Reference heliostat model**
3. **Characteristic wind loads**
4. **Selection of pultruded structural composites**
5. **Technoeconomic analysis using equivalent deformation**
6. **Summary and discussion**

Motivation

- Composites have become high-volume and mainstream
- DOE cost target: $50/m²
- Steel is the largest, most volatile material cost in a heliostat
- Challenge: heliostats are a dynamic system with high stiffness requirements

Images from:

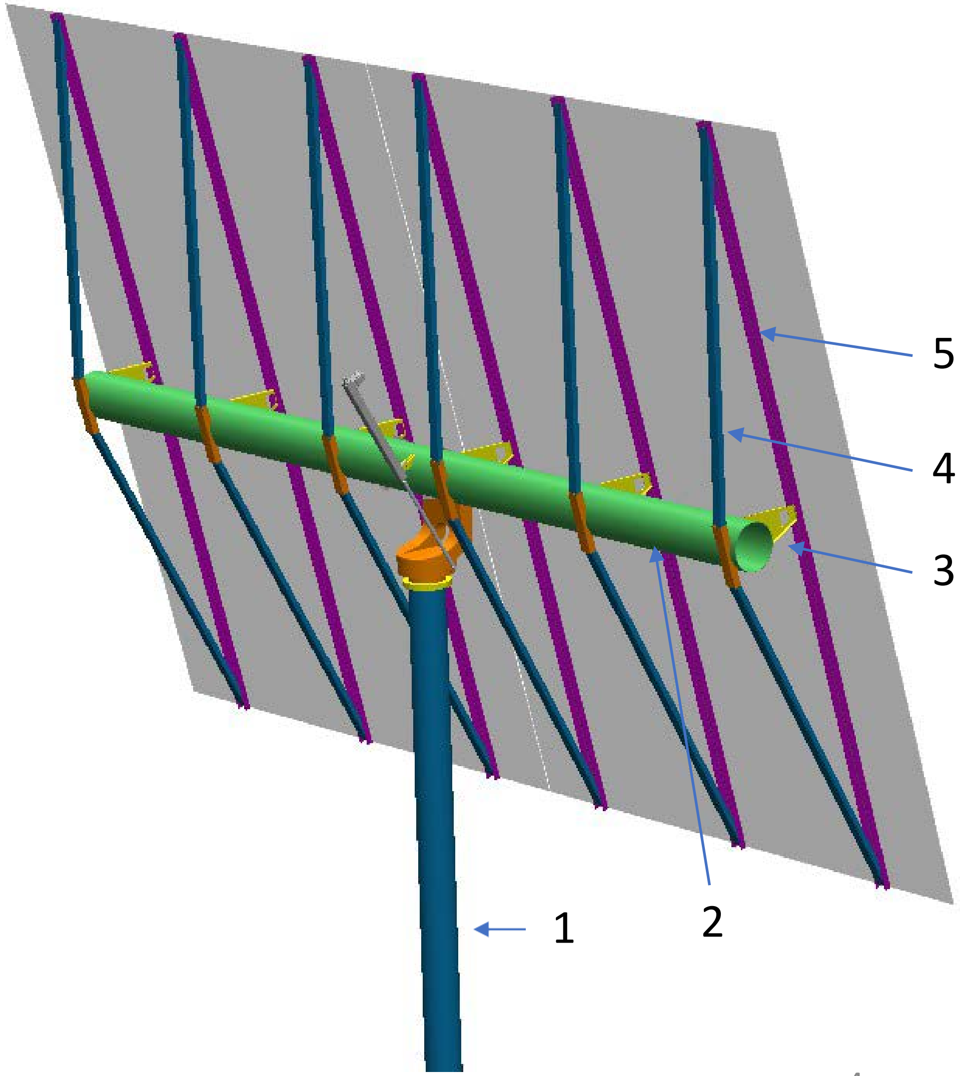
FetchCFD, "Boeing 787 3D Model," FetchCFD. https://fetchcfd.com/view-project/1834 (accessed Jul. 05, 2023)

. J. Ayre, "114 Miles = 2017 BMW i3 Official US EPA-Certified Range," CleanTechnica, Aug. 16, 2016. https://cleantechnica.com/2016/08/16/114-miles-2017-bmw-i3-official-us-epa-certified-range/ (accessed Jul. 05, 2023).

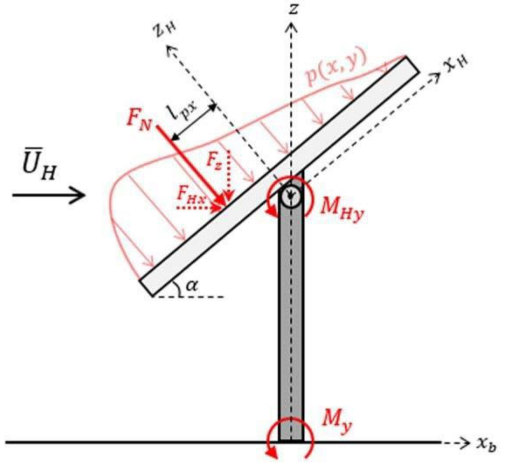
"Bauer Vapor X3.7 Grip Hockey Stick - SENIOR," B&R Sports. https://brsport.com/products/bauer-vapor-x3-7-grip-hockey-stick-senior (accessed Jul. 05, 2023).

Reference heliostat model

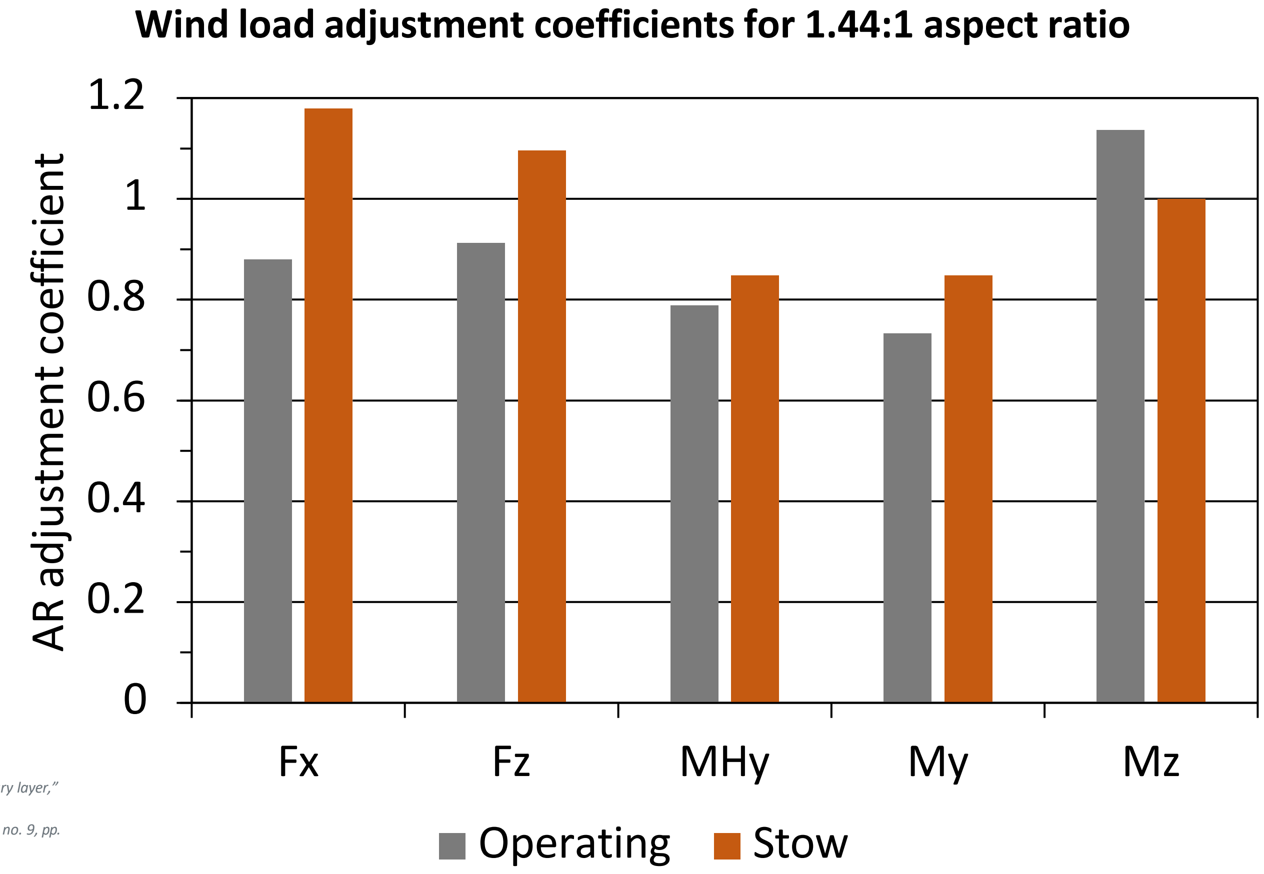
- Generic 25m² pedestal-type heliostat
  - Aspect ratio: 1.44
  - Elevation axis height: 2.50m
- Components analyzed:
  - Pylon (blue, 1)
  - Torque tube (green, 2)
  - Facet center support (yellow, 3)
  - Facet end support (blue, 4)
  - Purlin (purple, 5)



Wind loads: base calculation



- Loads per ASTRI Heliostat Design Wind Load Calculator (version v1d; see Emes et al, 2019)
  - Operation: 21 m/s
  - Stow: 45 m/s
  - Turbulence intensity: 26%
  - Chord length: 5m (1:1 aspect ratio)
- Adjustment of wind loads for aspect ratio (AR) using empirical curve fits from Pfahl et al (2011)
  - Operating loads -> evaluate deflection
  - Stow loads -> evaluate factor of safety


Wind load adjustment coefficients for 1.44:1 aspect ratio

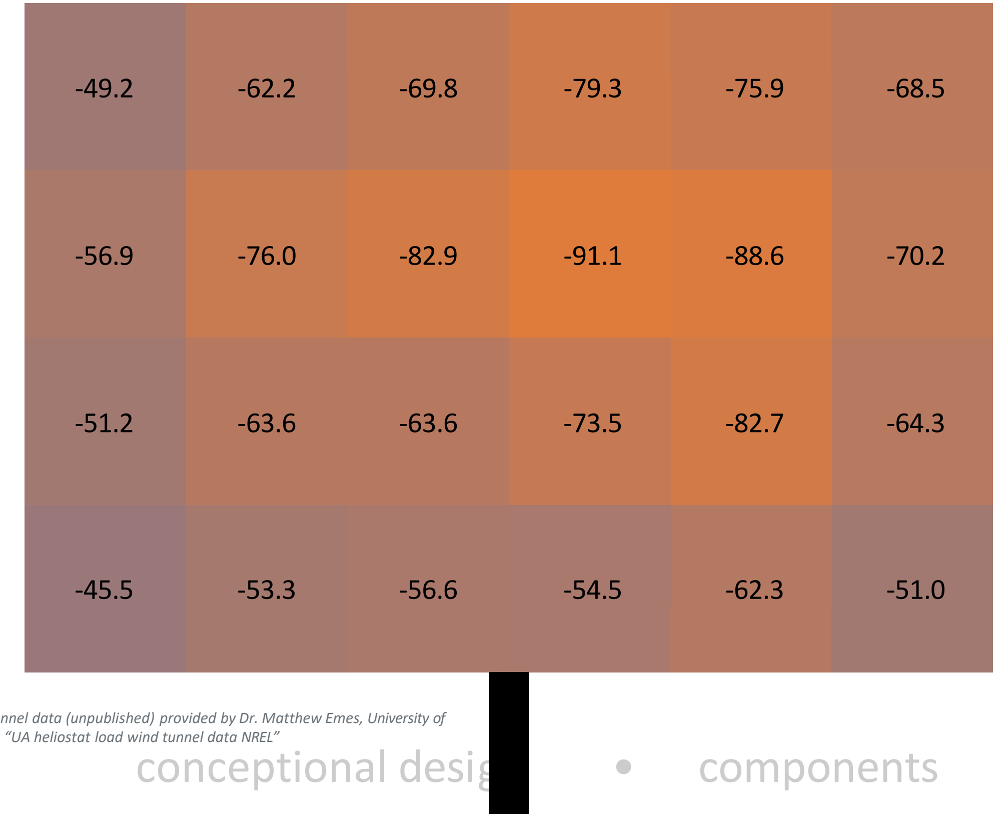
Heliostat image from M. J. Emes, A. Jafari, F. Ghanadi, and M. Arjomandi, "Hinge and overturning moments due to unsteady heliostat pressure distributions in a turbulent atmospheric boundary layer," Solar Energy, vol. 193, pp. 604–617, Nov. 2019, doi: 10.1016/j.solener.2019.09.097.

Wind load adjustment coefficients from Table 3 of A. Pfahl, M. Buselmeier, and M. Zaschke, "Wind loads on heliostats and photovoltaic trackers of various aspect ratios," Solar Energy, vol. 85, no. 9, pp. 2185–2201, Sep. 2011, doi: 10.1016/j.solener.2011.06.006.

Wind loads: representative distributions

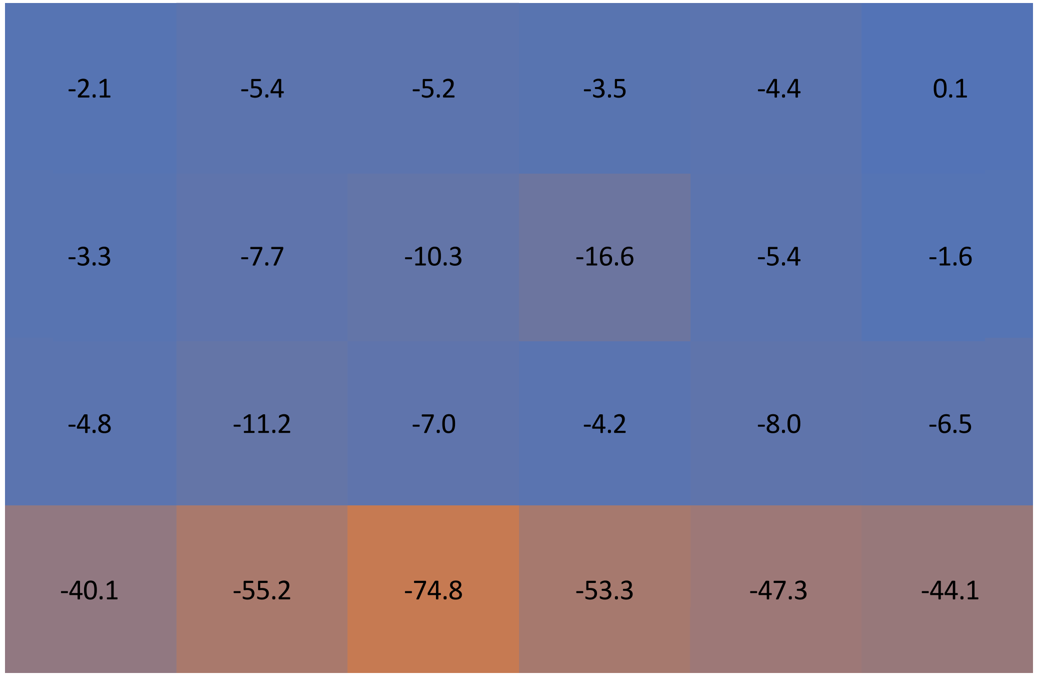
- Source data: University of Adelaide wind tunnel, scale model heliostat, 24 differential pressure taps[1]
- Purpose: Quantify transient torques into mirror facet backing structure. Design Wind Load calculator gives summary loads only.

Differential pressure distribution on mirror surface, upright orientation (Pascals)



-49.2	-62.2	-69.8	-79.3	-75.9	-68.5
-56.9	-76.0	-82.9	-91.1	-88.6	-70.2
-51.2	-63.6	-63.6	-73.5	-82.7	-64.3
-45.5	-53.3	-56.6	-54.5	-62.3	-51.0

Differential pressure distribution on mirror surface, stow orientation (Pascals)



-2.1	-5.4	-5.2	-3.5	-4.4	0.1
-3.3	-7.7	-10.3	-16.6	-5.4	-1.6
-4.8	-11.2	-7.0	-4.2	-8.0	-6.5
-40.1	-55.2	-74.8	-53.3	-47.3	-44.1

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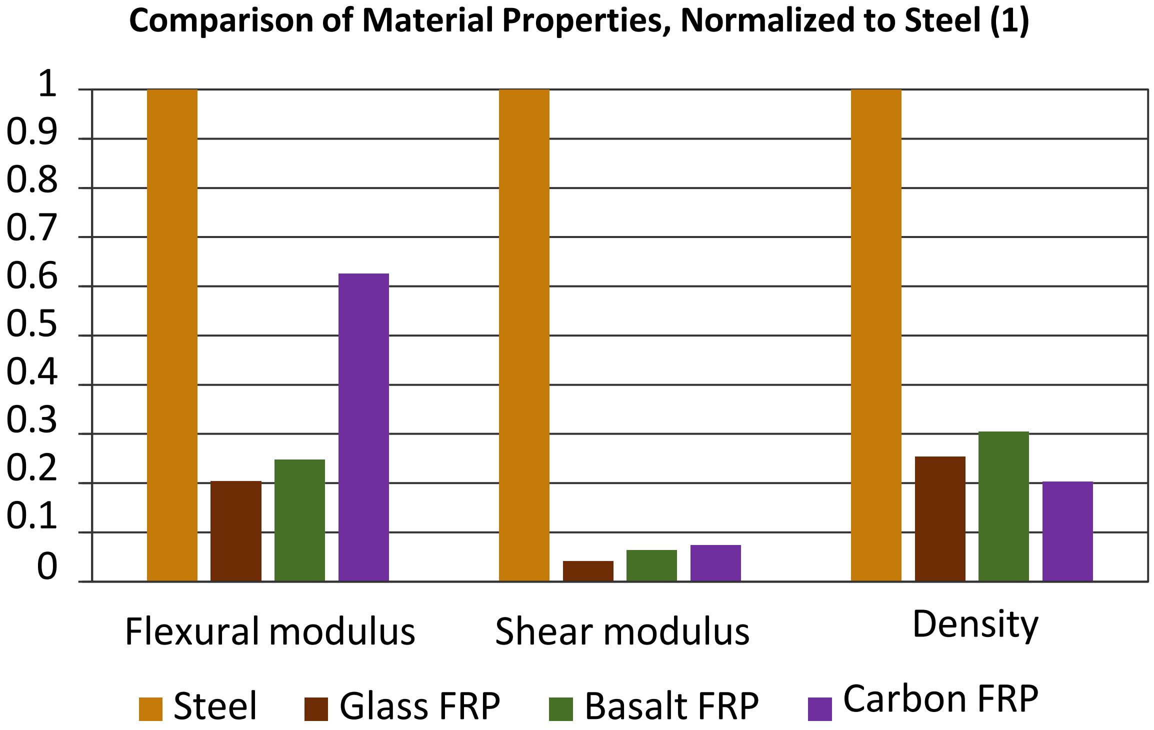
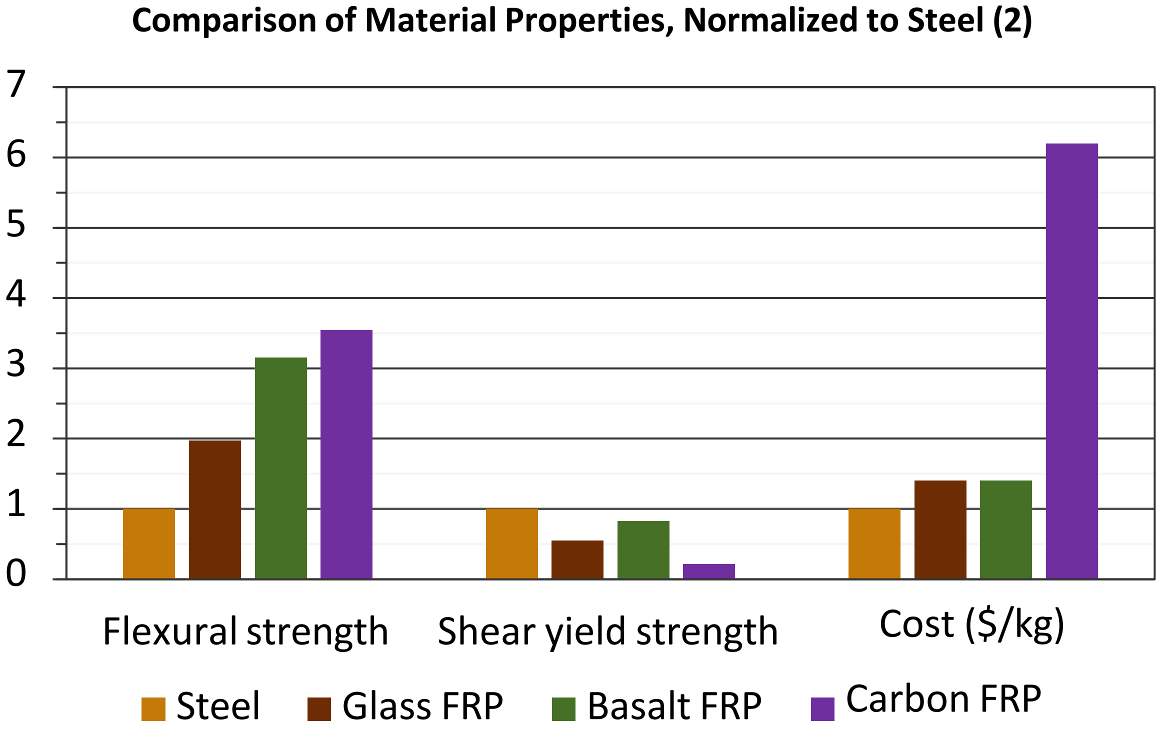
[1] *Wind tunnel data (unpublished) provided by Dr. Matthew Emes, University of Adelaide. "UA heliostat load wind tunnel data NREL"*

Materials and properties

- Baseline: Steel AISI 1020[1]
- Composites: Unidirectional fiber pultruded composites (UFPs)
  - Fibers investigated: E-glass[2], Basalt[3], Carbon[4]
- UFPs are the lowest-cost, highest-volume, most dimensionally-consistent composites for this application



Comparison of Material Properties, Normalized to Steel (1)



Comparison of Material Properties, Normalized to Steel (2)

1-4: See material property references slide (end of presentation)

Technoeconomic analysis method

- Worst-case orientation & load
- Re-size each component for pultruded composites
  - Constant shape, total deflection
- Evaluate weight, cost, FOS
- Limits:
  - No change to heliostat design
  - Facets not considered structural
  - First-pass analysis of composites' feasibility; **not a comprehensive, dynamic analysis**

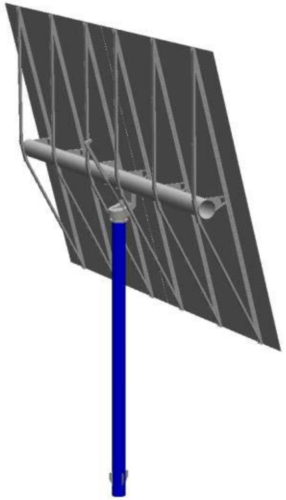
Sample summary calculation, steel vs glass FRP torque tube

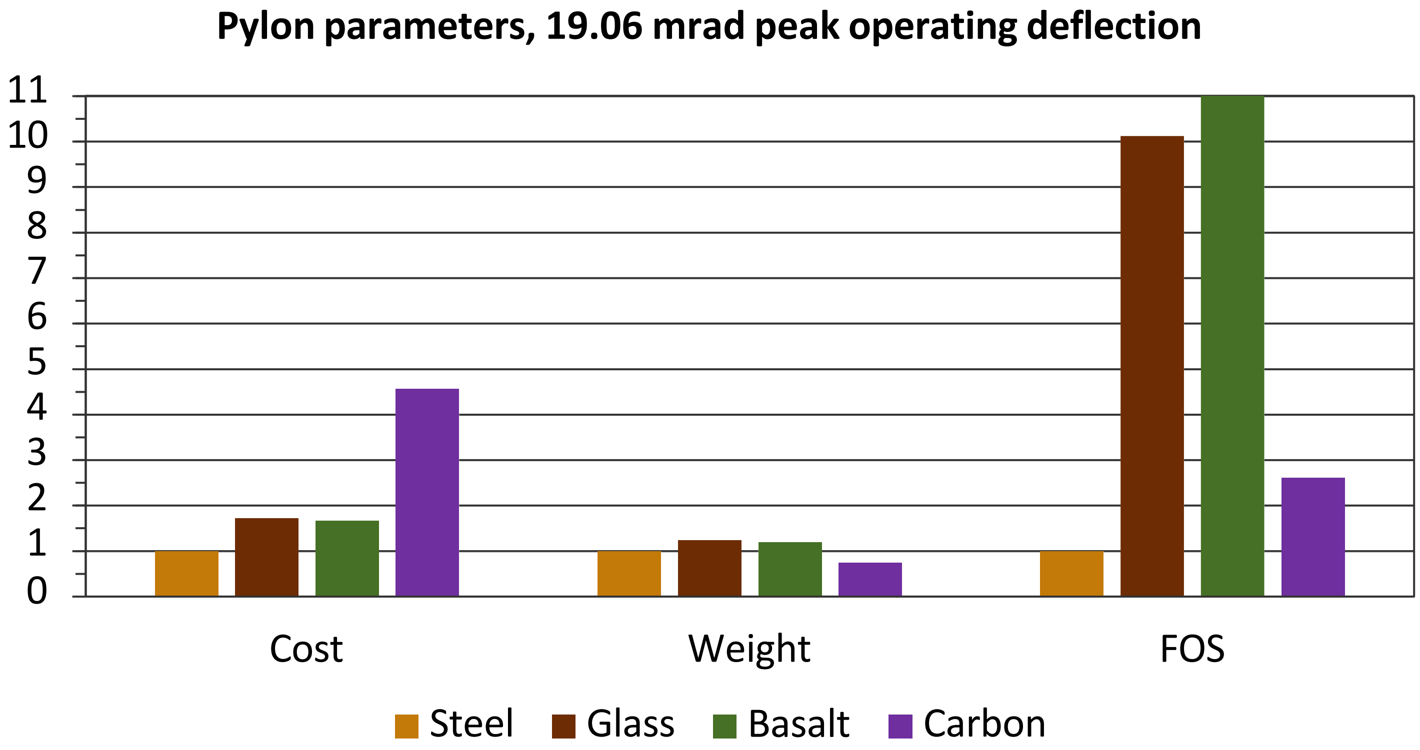
Material	Steel	Glass FRP
OD (mm)	250.0	513.5
Wall (mm)	2.7	5.5
Bending angle (mrad)	1.37	0.25
Torsion angle (mrad)	0.95	1.65
Total deflection (mrad)	1.67	1.67
Cost ($)	167.33	251.26
Weight (kg)	86	92
FOS	4.3	30.3

Results and discussion

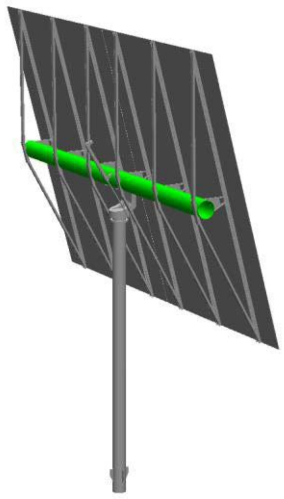
Pylon

- High torsional deflection (twist) at pylon base
- Design for stiffness = overdesign for stress
- Proposed composite material: continuous filament-wound tube

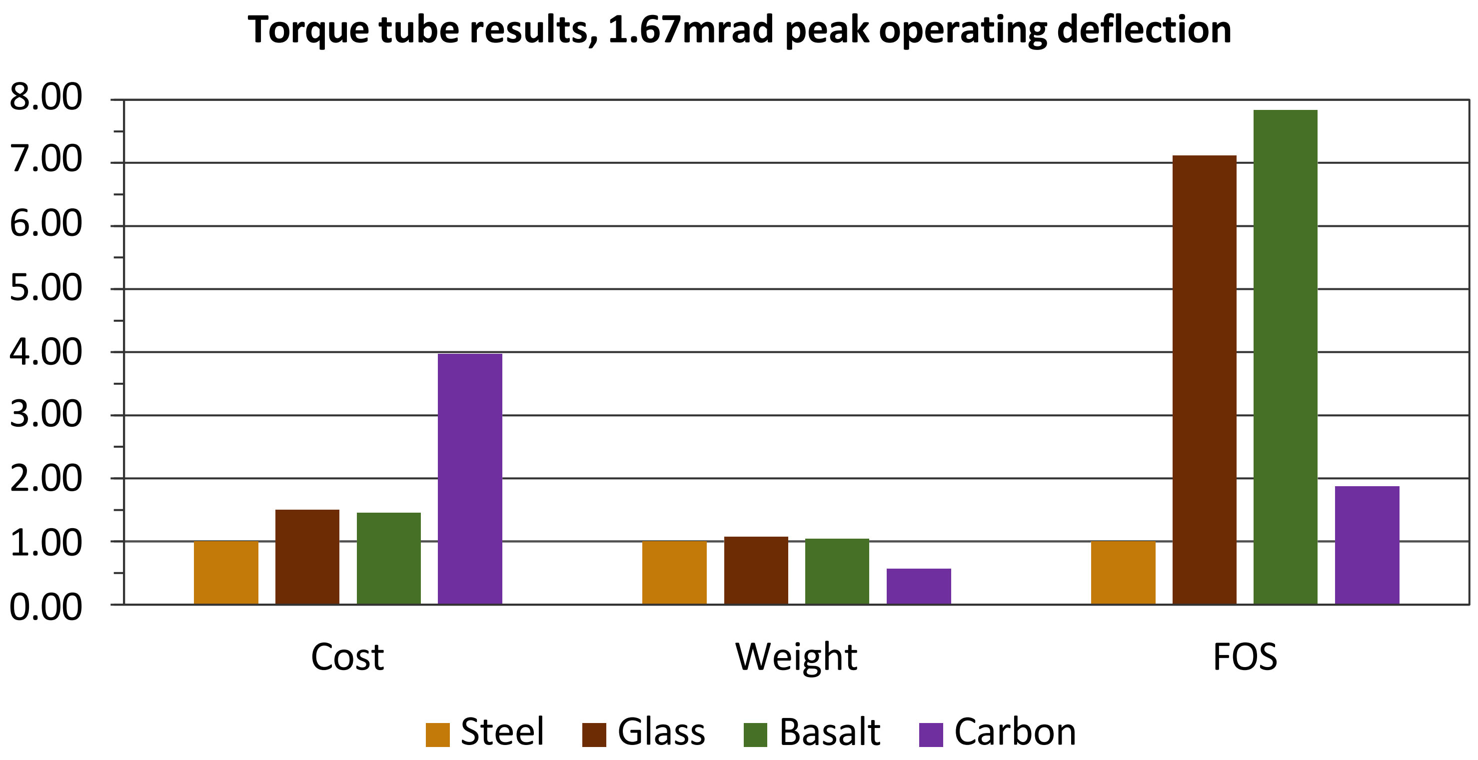


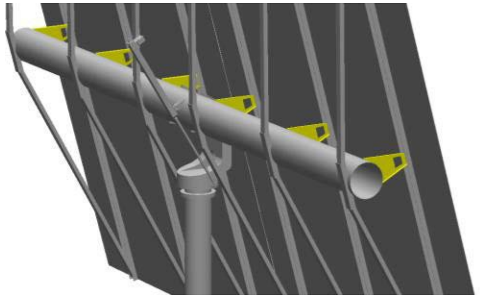


Torque tube



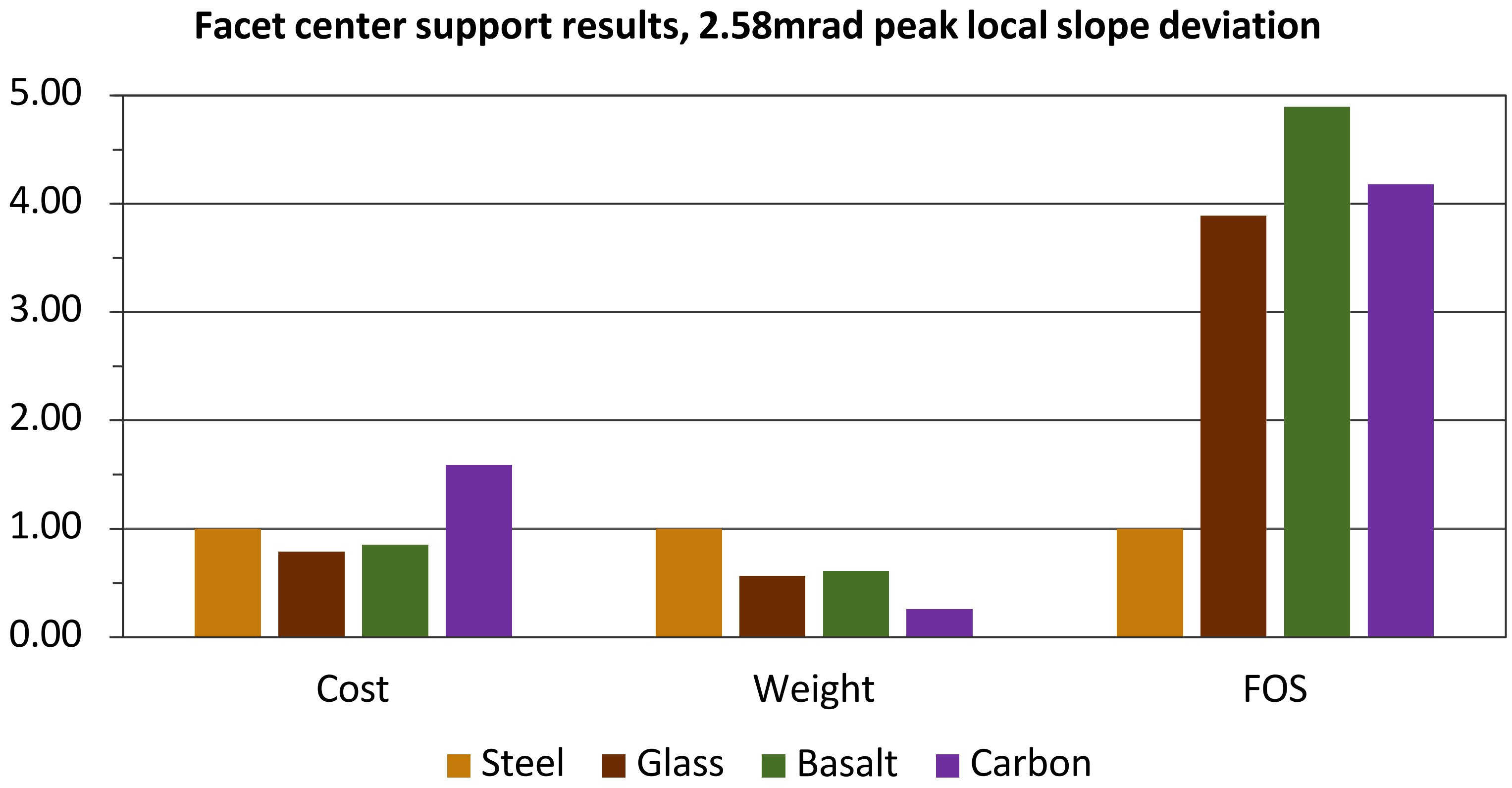
- High torsional deflection (twist) at elevation drive attachment point
- Continuous filament-wound tube potentially suitable


Torque tube results, 1.67mrad peak operating deflection

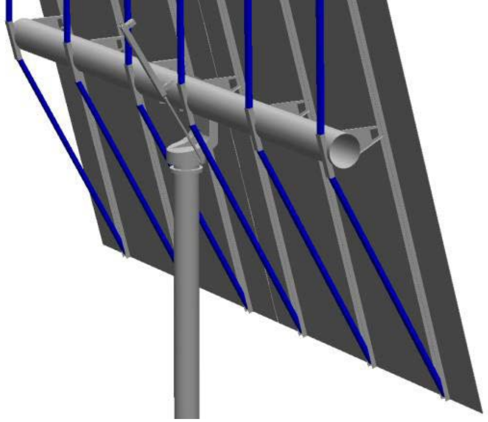


Facet center support

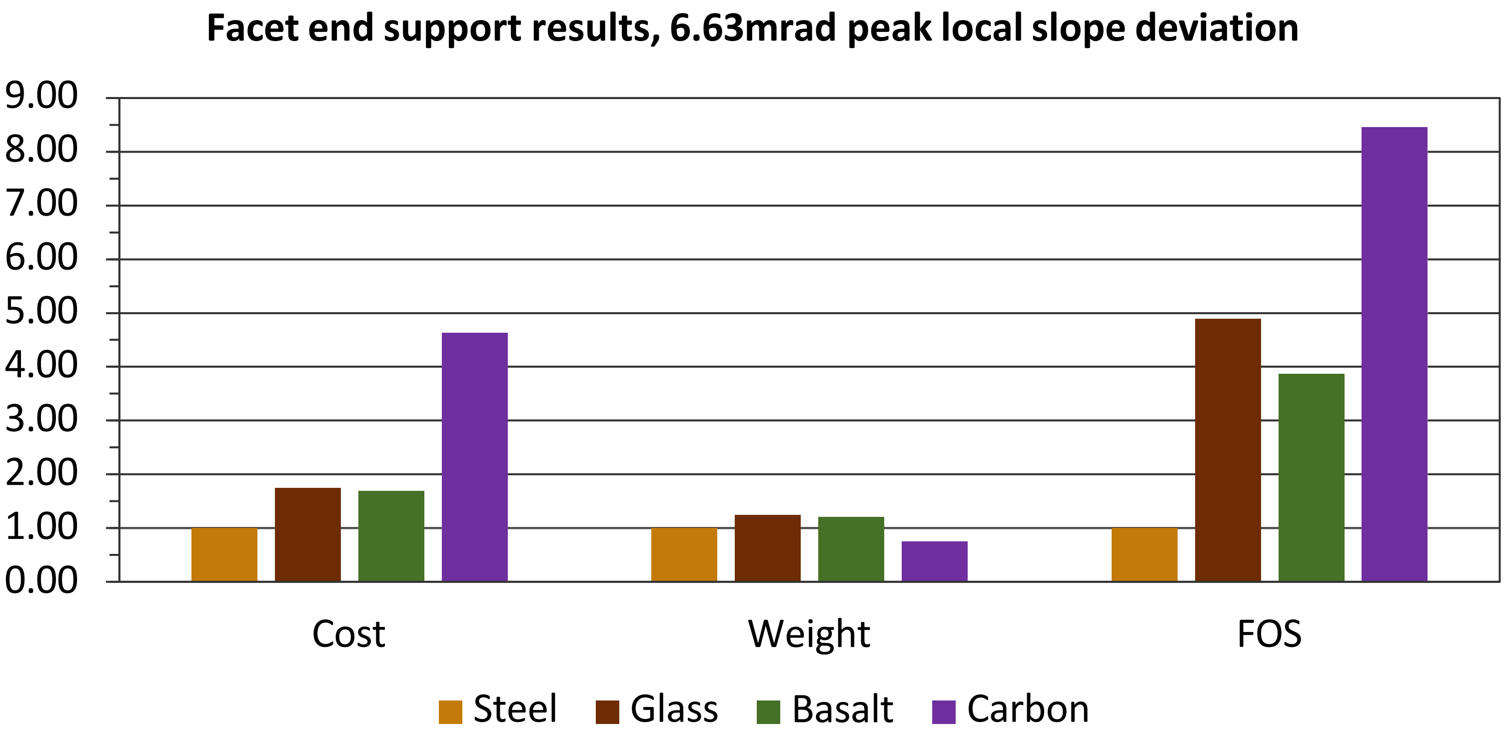
- All loads are compressive (buckling in small flange region)
- Short length limits deflection
- Good fit for pultruded UD composites



Facet end support

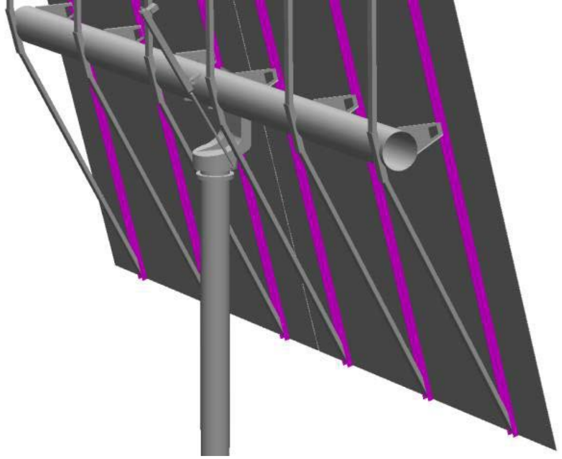


- Most deflection is twist at attachment point to purlin
- Result sensitive to mirror stiffness and attachment method to heliostat structure
  - Opportunity to use composite facets

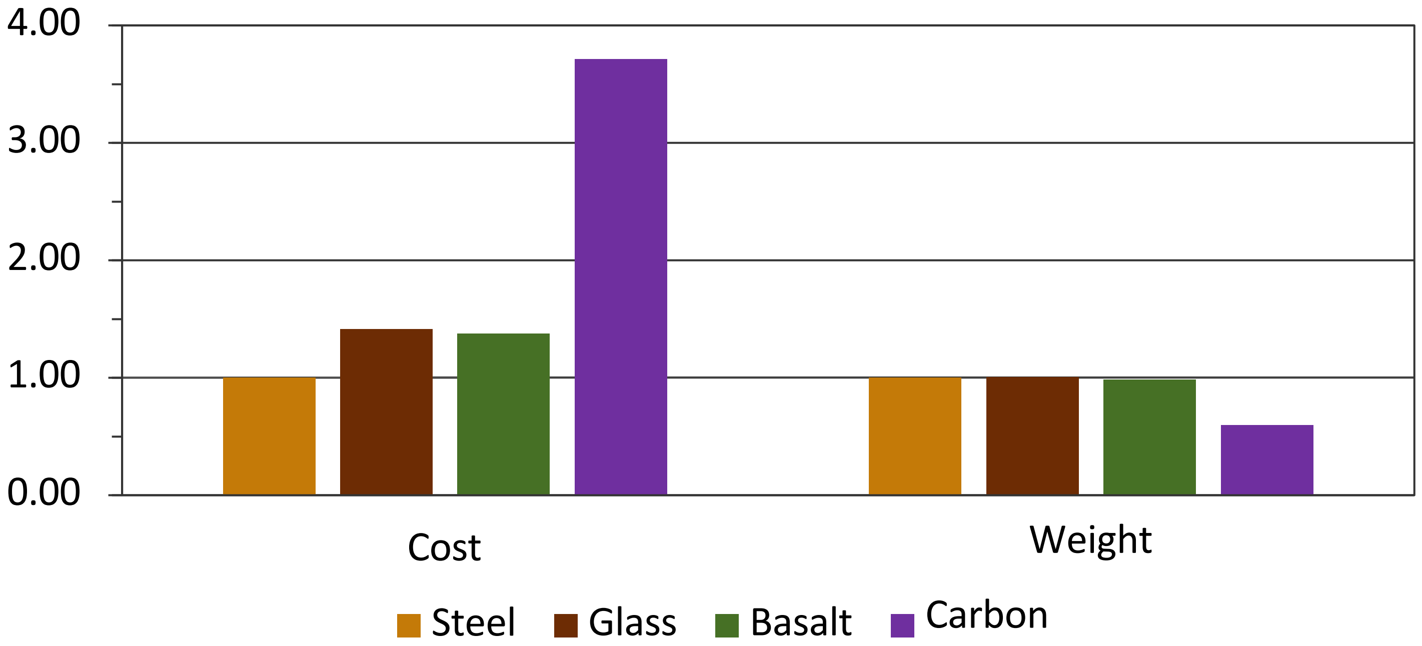


Purlin

- Most deflection is midspan twist (between attachment to center & end facet supports)
- Result sensitive to mirror stiffness and attachment method to heliostat structure



Facet backing results, 9.90mrad peak local slope deviation



Conclusions

- Unidirectional fiber pultrusions (UFPs) lack torsion rigidity for application to pylons, torque tubes for common T-shape designs
- Weaknesses of UFPs indicate the need to study:
  - Structural facets to reduce complexity of supporting assemblies and reduce deflection
  - Advanced pultruded or filament-wound beams for torsional stiffness
  - Lattice and truss structures optimized for low shear modulus of UFP beams

Thank you

Q&A

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NREL/PR-5K00-87044

Material property references

1. Steel

- Mechanical properties: “AISI 1020 Steel, cold rolled.” https://www.matweb.com/search/datasheet.aspx?matguid=10b74ebc27344380ab16b1b69f1cffbb&ckck=1 (accessed Jul. 06, 2023).
- Cost: Adjusted to May 2023 via producer price index ID PCU3312103312100 (St. Louis Fed. “Producer Price Index by Industry: Iron and Steel Pipe and Tube Manufacturing from Purchased Steel: Iron and Steel Pipes and Tubes, from Purchased Iron and Steel”) from April 2022 cost on M. C. News, “Mechanical Tubing Report - Metal Center News.” //www.metalcenternews.com/editorial/current-issue/mechanical-tubing-report/44964 (accessed Jul. 01, 2023).

2. Glass FRP

- Elastic, tensile, and flexural properties: Avient Glasforms 1000 Technical Data Sheet (https://catalog.ides.com/Datasheet.aspx?I=19843&FMT=PDF&E=301883)
- Shear properties: J. T. Mottram, “Shear Modulus of Standard Pultruded Fiber Reinforced Plastic Material,” Journal of Composites for Construction, Accessed: Jun. 21, 2023. [Online]. Available: https://www.researchgate.net/publication/248879057_Shear_Modulus_of_Standard_Pultruded_Fiber_Reinforced_Plastic_Material
- Cost: Mean of three extruded fiberglass products:
  - “[Hot Item] Fiberglass FRP GRP Glassfibre Pultrusion Tubes,” Made-in-China.com. https://qhdedao.en.made-in-china.com/product/IKOmkSNlSVpC/China-Fiberglass-FRP-GRP-Glassfibre-Pultrusion-Tubes.html (accessed Jul. 10, 2023)
  - “[Hot Item] Fiberglass FRP Pultrusion Profile, FRP Tube/Angle/Channel/Beams,” Made-in-China.com. https://59world.en.made-in-china.com/product/tESUwjVxhghc/China-Fiberglass-FRP-Pultrusion-Profile-FRP-Tube-Angle-Channel-Beams.html (accessed Jul. 10, 2023).
  - “[Hot Item] FRP Pultrusion Tubing (Fiberglass Tube),” Made-in-China.com. https://njlf-frp.en.made-in-china.com/product/peYJKfmCqBrt/China-FRP-Pultrusion-Tubing-Fiberglass-Tube-.html (accessed Jul. 10, 2023).

3. Basalt FRP

- Mechanical properties: K. Protchenko, F. Zayoud, M. Urbański, and E. Szmigiera, “Tensile and Shear Testing of Basalt Fiber Reinforced Polymer (BFRP) and Hybrid Basalt/Carbon Fiber Reinforced Polymer (HFRP) Bars,” Materials (Basel), vol. 13, no. 24, p. 5839, Dec. 2020, doi: 10.3390/ma13245839.
- Cost estimated equivalent to E-glass FRP based on “Basalt Fiber Properties, Advantages and Disadvantages,” Build-on-Prince.com. https://www.princelund.com/basalt-fiber.html (accessed Jul. 01, 2023).

4. Carbon FRP

- Mechanical properties: A. Bussiba, I. Gilad, S. Lugassi, S. David, J. Bortman, and Z. Yosibash, “Mechanical Response and Fracture of Pultruded Carbon Fiber/Epoxy in Various Modes of Loading,” Crystals, vol. 12, no. 6, Jun. 2022, Accessed: Jun. 21, 2023. [Online]. Available: https://www.mdpi.com/2073-4352/12/6/850
- Density: Avient Glasforms 2000 Technical Data Sheet (https://catalog.ides.com/Datasheet.aspx?I=19843&FMT=PDF&E=301884)
- Cost: D. Brosius and R. Deo, “Impact of Technology Developments on Cost and Embodied Energy of Advanced Polymer Composite Components,” Inst. for Advanced Composites Manufacturing Innovation (IACMI), Knoxville, TN (United States), IACMI/0001-2018/2.5, Jan. 2018. doi: 10.2172/1437162.

Appendix: Composites state of the art

- Significant work has been published examining the use of composite facets including installed heliostats by Abengoa (sandwiched panels creating a structural mirror).
  - Liedke, P., A. Pfahl, J. F. Vasquez-Arango, and E. Holle, 3rd generation rim drive heliostat with monolithic sandwich panel. *AIP Conference Proceedings* 2018
  - Fadlallah, S., Anderson, T., Nates, R., Fluid-structure interaction analysis of a lightweight sandwich composite structure for solar central receiver heliostats, *Mechanics Based Design of Structures and Machines*, 2022
  - https://www.abengoa.com/export/sites/abengoa_corp/resources/pdf/en/gobierno_corporativo/informes_anuales/2012/2012_Volume1_AR_8.pdf, Accessed 5/21/2023
- Composite materials have been explored for structural components in other industries to cut cost and enhance reliability but this has not been done for heliostats
  - Brosius, D., Deo, R., Impact of technology developments on cost and embodied energy of advanced polymer composite components, DOE report 2018
  - Godat, A., Légeron, F., Gagné, V., Marmion, B., Use of FRP pultruded members for electricity transmission towers, *Composite Structures, 2013*
- Cost of composite materials have generally been too expensive for bulk applications like structural components but cost has reduced significantly
  - Shama, R., Simha, T., Rao, K., Ravi, K., Carbon composites are becoming competitive and cost effective, Infosys.com, 2015