Structural Sizing of a 50-m-Tall Thermoplastic Composite Solar Array Truss Tower Structure for the Lunar South Pole

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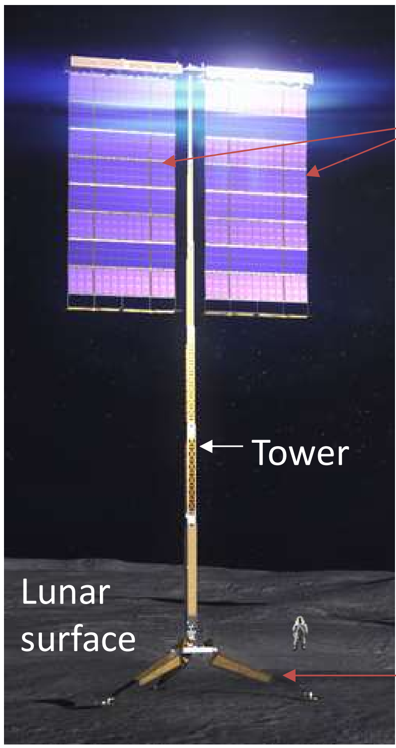
Outline

- Background and motivation
- Thermoplastic Space Point Design (TSPD): 50-m-tall tower
- Moonquake loads
- Structural sizing routine
- Example trade study
- Detailed design development & finite element analysis
- Joint sizing using cohesive zone elements
- On-going validation effort
- Summary

Background: Why Towers at the Lunar South Pole?



Solar panels
- Fixed to top of tower
- Gravity deployed

Tower base
(assumed fixed)

- Low Sun angles at the lunar south pole → need to elevate solar arrays on ridge lines
- Higher elevation (taller tower) → more continuous illumination
  - Shorter towers require batteries (heavy)
  - Tower height system level trade study[1]:
    50 m truss vs. 15 m tube (10 kW constant supply)
    - 24% mass savings
    - 14x volume savings
  - For >20 m, truss towers are >3x lighter than telescoping tube towers[2]
- Mass and volume are critical! **$1.2M/kg** delivered to the Lunar south pole[3]
- Towers are also needed for communications, navigation, & science payloads

[1] Tiffin and Mahlin 2023
[2] Doggett et al. 2023
[3] Astrobotic

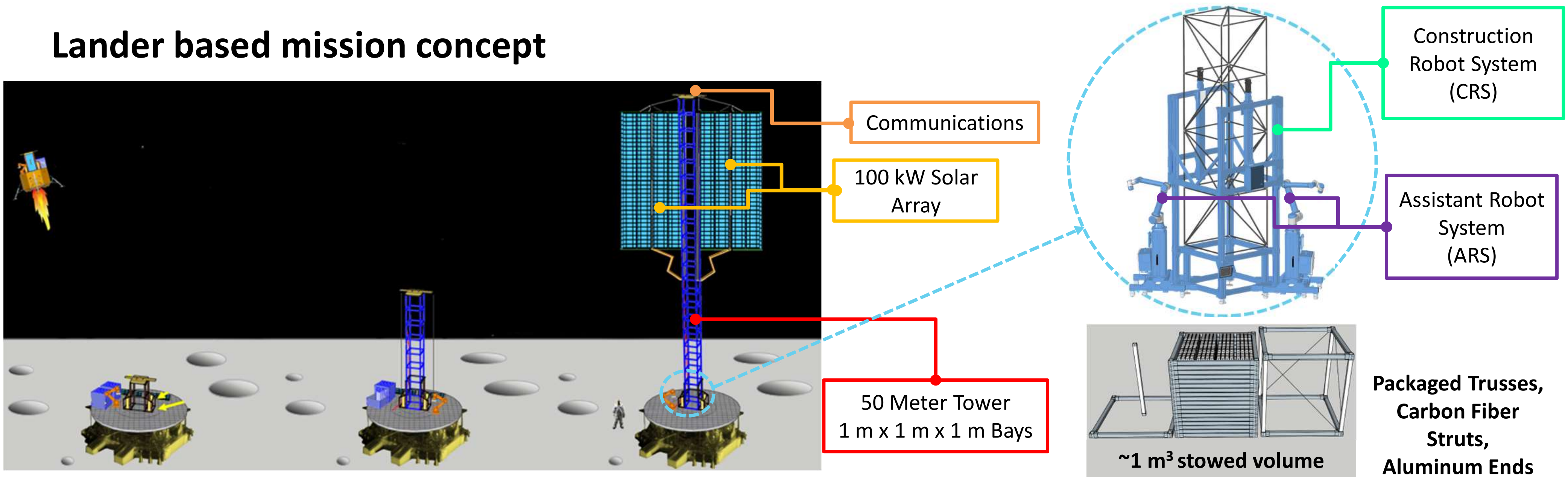
Need structurally efficient truss towers

Background: Tall Lunar Tower (TLT) Project

The Tall Lunar Tower (TLT) project developed designs, models, and autonomously assembly technology for a tall tower at the lunar south pole

Demonstrated with an engineering development unit (lab environment)

Lander based mission concept



Prepare Assemble Power

TLT developed concept for robotic truss tower assembly

Thermoplastics Development for Exploration Applications (TDEA) Thermoplastic Space Point Design (TSPD)

Objective

- Demonstrate a thermoplastic composite (TPC) welding approach for assembly a of truss structure relevant to a 50-m-tall solar array tower

Assumptions

- Solar array & other payloads = 1000 kg point mass
- Fixed base (lander compliance ignored)
- Design to moonquake (base excitation)
- ‘L’ shaped structural members (compact packaging)
- Same truss connectivity as used in TLT
- Compatible with robotic assembly

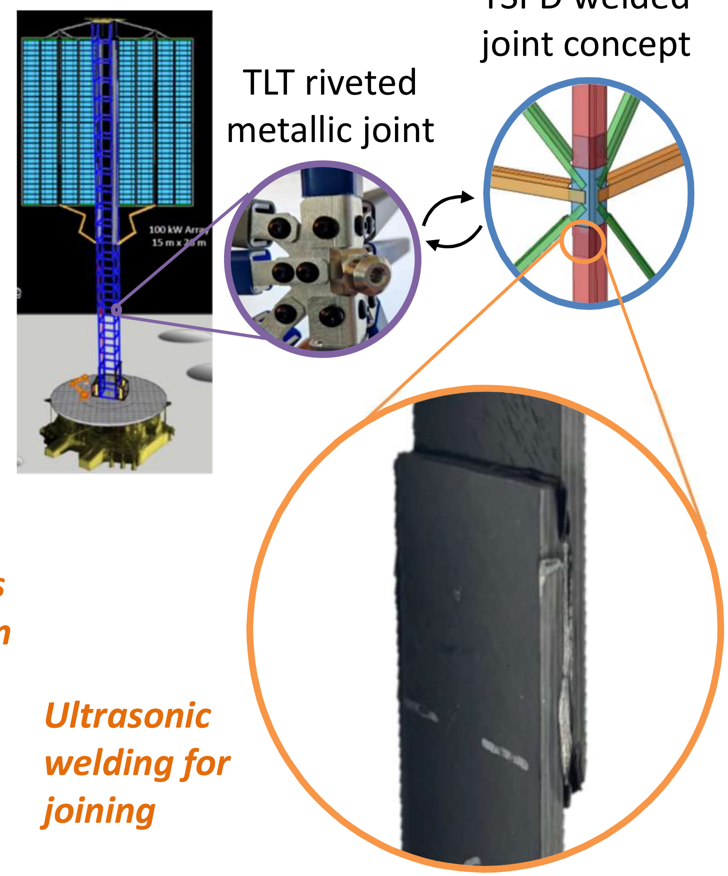
Accomplishments

- Structural sizing approach
- Parametric studies on material & member cross-section
- Design & analysis for structural members and joints
- Coupon-scale test data

Focus of this presentation

Future work

- Manufacturing and test validation



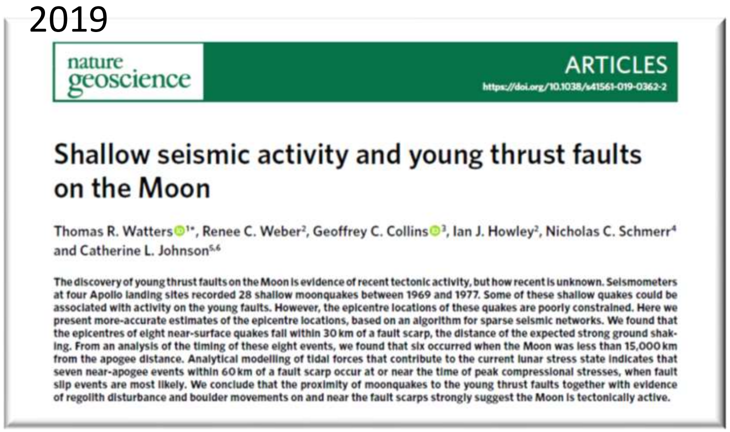
Moonquakes – Evidence of Hazard

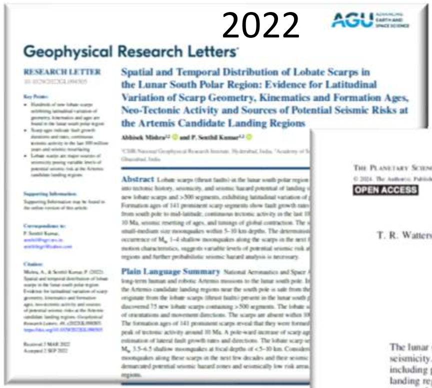
Moonquakes measured by Apollo seismometers – four sources:

1. Deep moonquakes: most frequent, low severity
2. Meteoroid impacts: ~10% of recorded events, variable severity
3. Shallow moonquakes: ~28 events over 8 years (rare), can be severe
4. Artificial (human-related) impacts

Shallow moonquakes characteristics:

- Low attenuation → events **carry over long distances**[1]
- Scattering diffuses the energy → can **last for more than 1 hour**[2]
- "The potential of **strong seismic events** from active thrust faults should be considered when preparing and locating permanent outposts and pose a **possible hazard to future robotic and human exploration** of the south polar region"[3]





Moonquake loads on towers must be considered!

[1] Heiken et al. 1991
[2] Oberst and Nakamura 1985
[3] Watters et al. 2024

TSPD Moonquake Load Condition

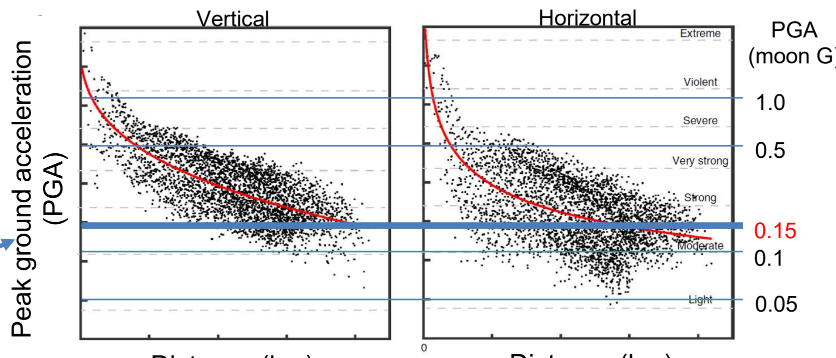
Moonquake data sources

- Apollo data insufficient to characterize moonquake hazard
- Recent numerical simulations predict peak ground acceleration (PGA)[1,2]

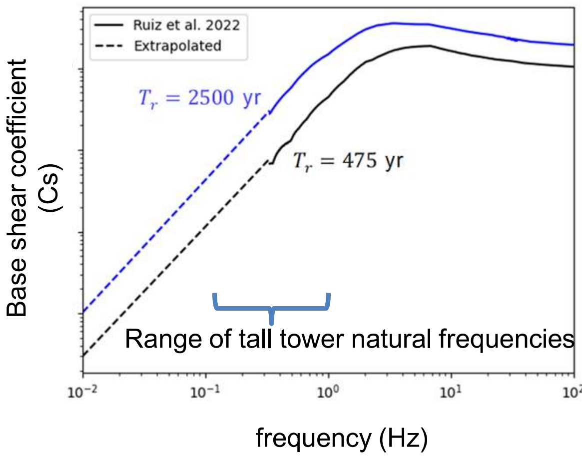
TSPD moonquake load assumptions

- Two loading assumptions considered:
    1. Harmonic base excitation $\ddot{u}_g/g_M = 0.15$; corresponds to PGA at ~30 km from epicenter[1] (g_M = lunar gravity)
    2. Uniform hazard spectrum (UHS), $T_r = 475$ yr (10% probability of exceedance in 50 yr)[2]
- Further dynamic analysis needed; new data available[3]
- Seismic instruments are high priority payload for upcoming lunar missions

Epicenter at Mandel'shtam scarp (near equator), M_w=6.3 at 350 m depth



Adapted from: Watters et al. 2019, Fig. 3



[1] Watters et al. 2019
[2] Ruiz et al. 2022
[3] Watters et al. 2024

TDEA evaluated tower designs with two assumed moonquake load conditions

Preliminary Structural Sizing Routine

Objective: rapid (analytical) truss tower sizing for preliminary design

Approach: extend sizing approach proposed by TLT team[1] (red are additions)

Residuals defined for 3 margins :

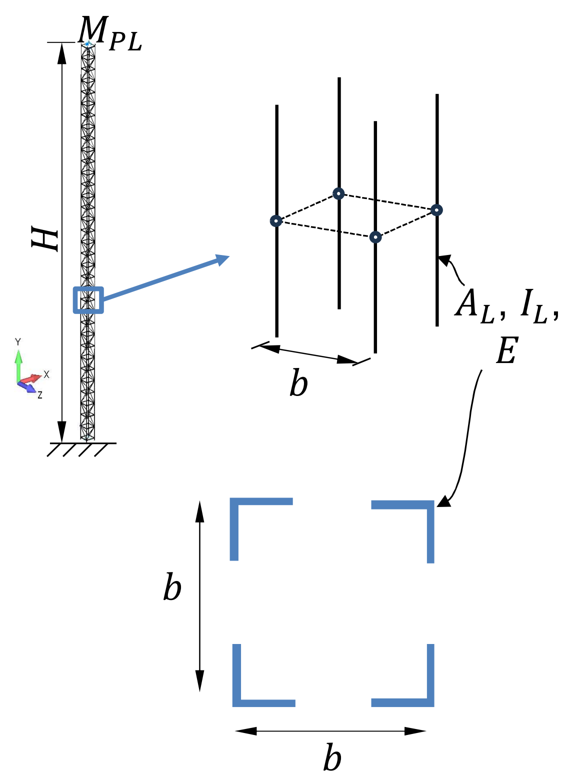
1. Tower Euler buckling

$$R_{TE} = \underbrace{\frac{\pi^2 E I_{\text{truss}}}{4H^2 FS}}_{\text{Tower buckling capacity}} \overbrace{- \underbrace{M_{\text{eff}} g_M}_{\text{Gravity}} - \underbrace{M_{\text{eff}} S_{A,v}}_{\text{Moonquake (vertical)}}}^{\text{Load}}$$

$$M_{\text{eff}} = M_{PL} + 0.3 M_{\text{truss}}$$

$$M_{\text{truss}} = A_L H \rho J \underbrace{\left(4 + 4\beta_{ah} + 5\sqrt{2}\beta_{ad}\right)}_{\text{Mass of bracing members (horizontal, diagonal)}}$$

Joint mass factor



$$I_{\text{truss}} = 4I_x + A_L b^2$$

[1] Doggett et al. 2023

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2. Longeron Euler buckling

$$R_{LE} = \underbrace{\frac{\pi^2 E I_L}{b^2 FS}}_{\text{Longeron buckling capacity}} - F_L$$

Max. in longeron, occurs near base due to resonance in first mode

$$F_L = \frac{M_{\text{eff}}}{4}\left(g_M + \underbrace{\ddot{u}_v}_{\text{Vertical moonquake acceleration}}\right) + \frac{H}{2b} \underbrace{C_S(\omega_n)}_{\substack{\text{Horizontal moonquake} \\ \text{base shear coefficient} \\ \text{Frequency dependent for UHS}}} \overbrace{(M_{PL} + 0.23 M_{\text{truss}})}^{\text{Effective mass as cantilever}} g_M$$

[1] Doggett et al. 2023

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2. Longeron Euler buckling $$R_{LE} = \frac{\pi^2 EI_L}{b^2 FS} - F_L$$

3. Longeron strength $$R_{LS} = \underbrace{\frac{X_c A_L}{FS}}_{\text{Longeron strength}} - F_L$$

Total residual:

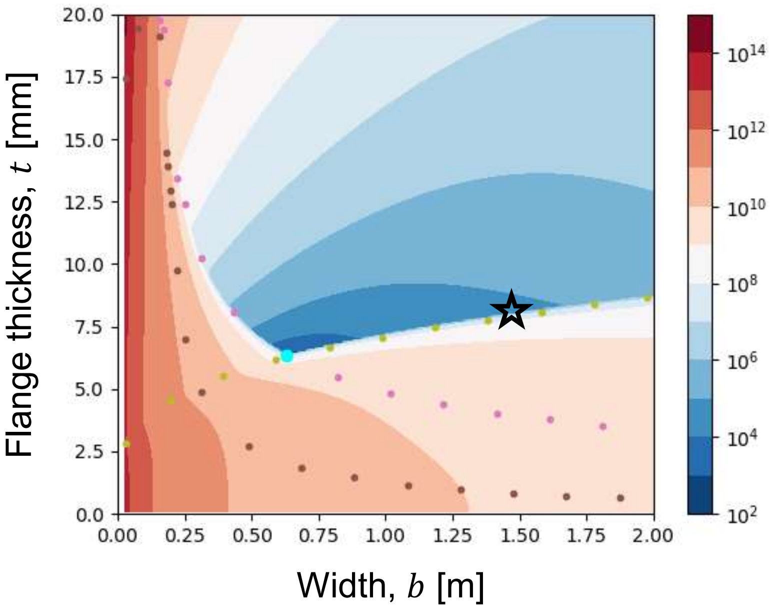
$$\mathbb{E} = \sum_{i=TE,LE,LS} \left[R_i \underbrace{\left(k_s + \mathbb{H}(-R_i)(1 - k_s) \right)}_{\text{Scale error slowly for positive margins}} \right]^2$$

Solve for:
Tower width: b
Member thickness: t

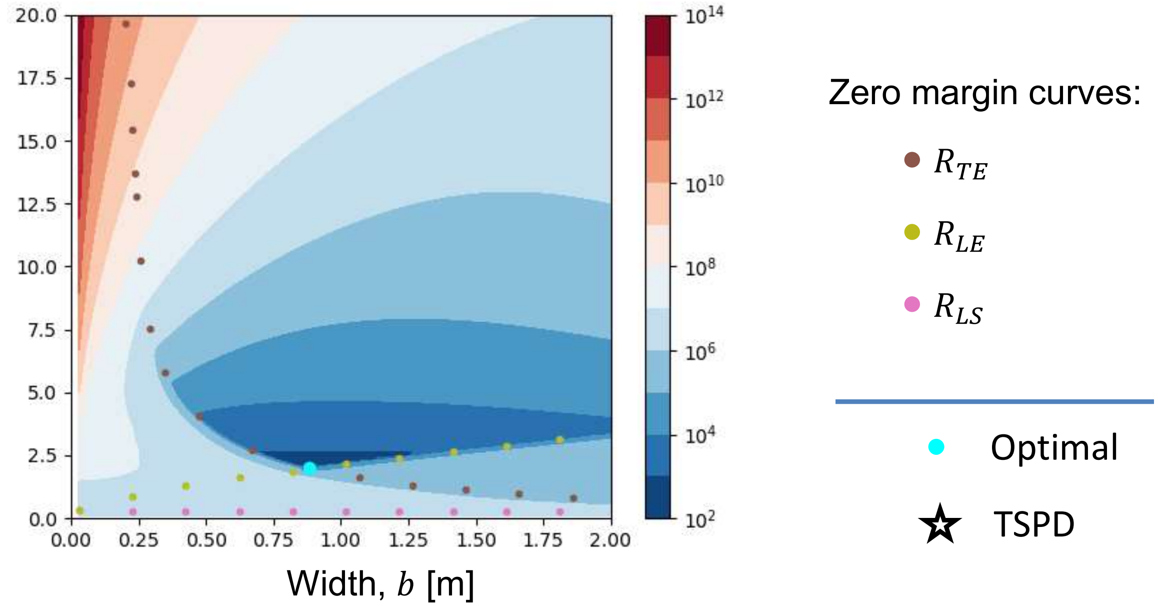
[1] Doggett et al. 2023

Sizing Results for Two Moonquake Load Assumptions

Harmonic ground motion: $\ddot{u}_g/g_M = 0.15$



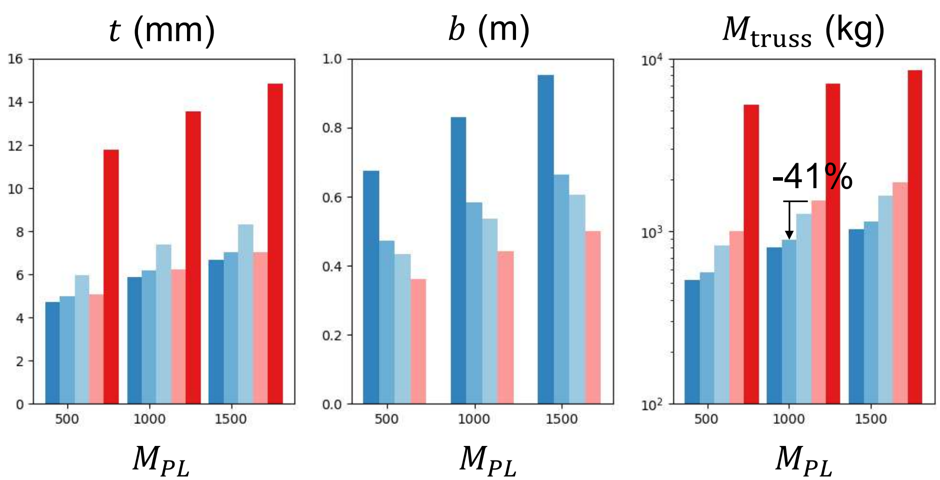
UHS: $T_r = 475$ years



- Sizing routine identifies optimal designs (blue dots)
- Harmonic ground motion and UHS are driven by different margins
- TSPD sized to harmonic excitation; has larger than optimal width b (selected prior to these results being available)

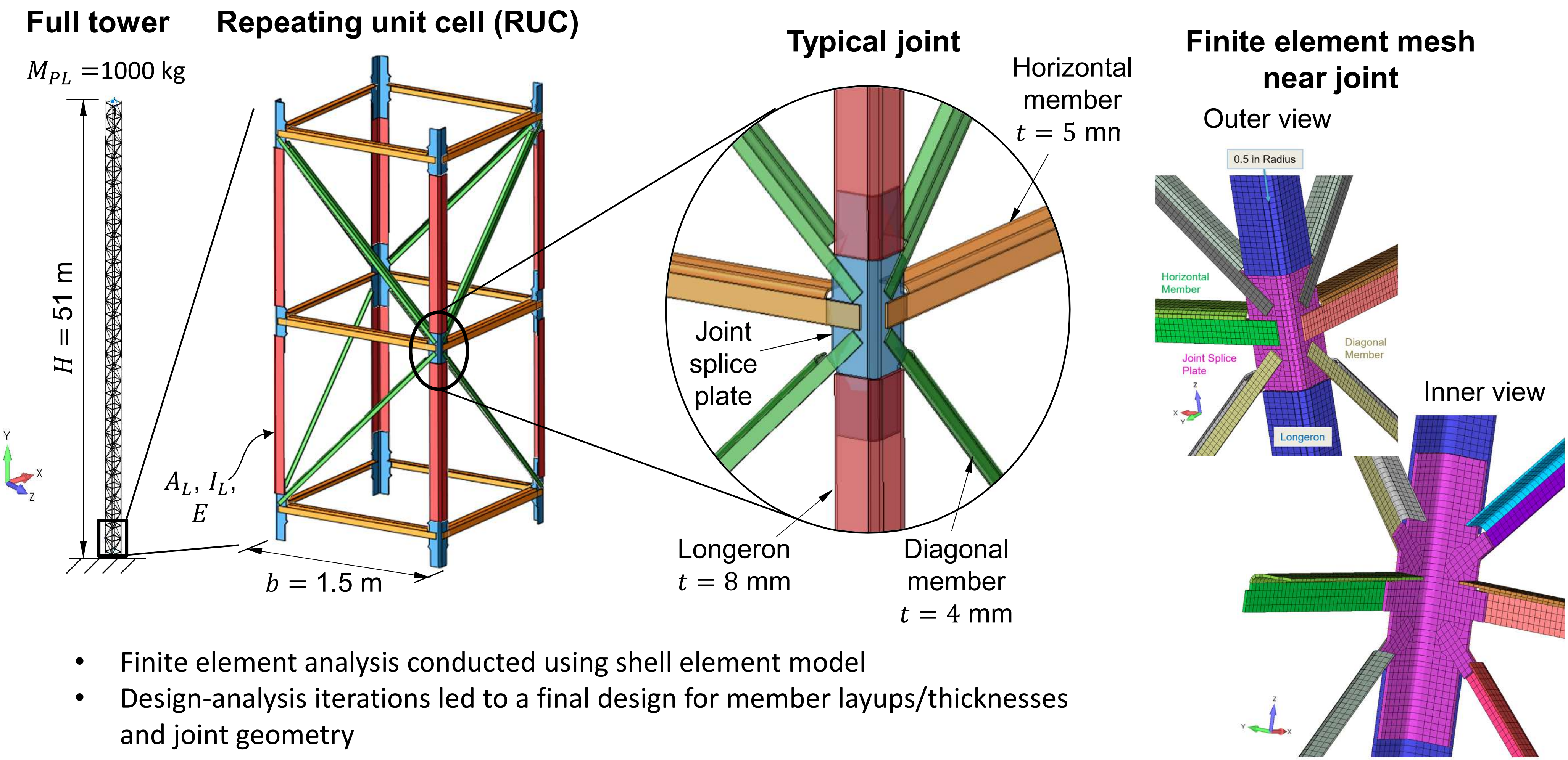
Trade Study: Effect of Material

Material		E [GPa]	Strength [MPa]	ρ [kg/m^3]
HM63/8552	HM fiber, 0° bias 'hard' layup	162.0	300	1600
TC1225, Hard	SM fiber, 0° bias 'hard' layup	92.9	393	1600
TC1225, QI	SM fiber, quasi-isotropic	45.0	324	1600
AL 7075-T6	Aerospace grade aluminum	71.7	538	2700
AL 1100	In-situ grade aluminum	68.9	24	2700



- t and M_{truss} increase with payload and more flexible materials
- Using 'TC1225 Hard' in place of AL 7075-T6 yields a 41% reduction in M_{truss}
- High-stiffness fibers (HM63/8552) provide an additional 9% mass reduction
- M_{truss} for towers made from in-situ aluminum is an order of magnitude higher

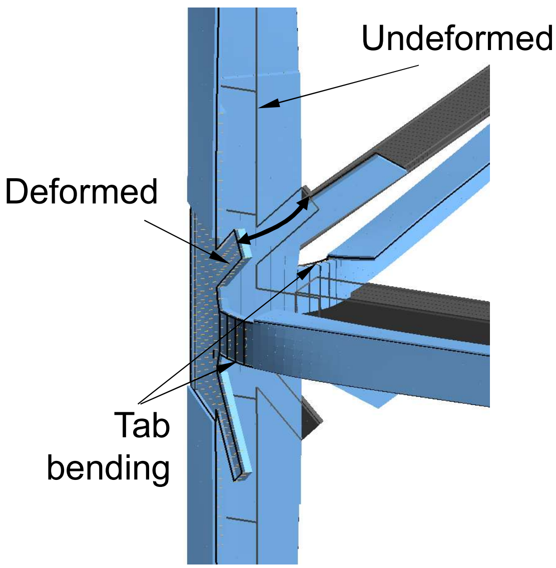
Detailed Design and Analysis of the TSPD



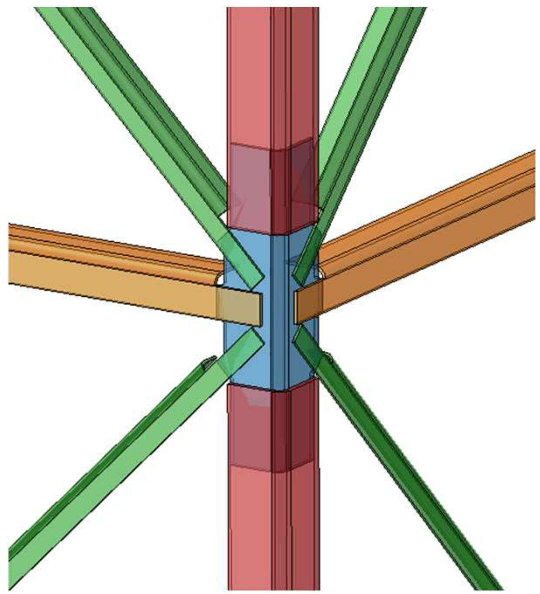
- Finite element analysis conducted using shell element model
- Design-analysis iterations led to a final design for member layups/thicknesses and joint geometry

Joint Stiffness Critical to Successful Design

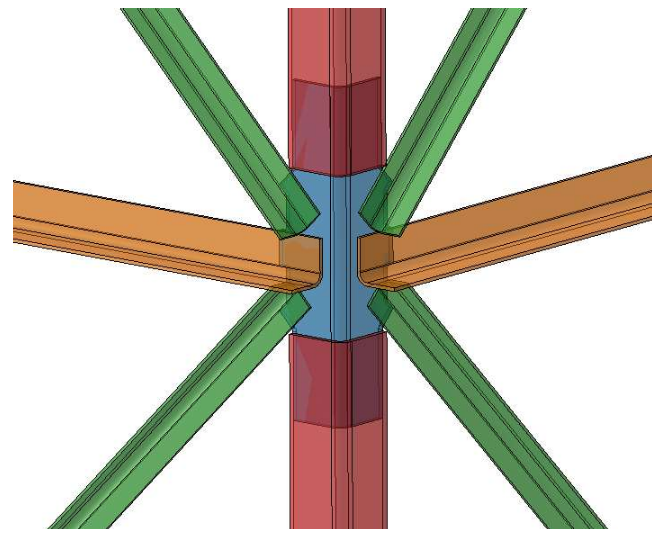
Early design: long tabs allow welding access
Local buckling mode (twisting)



Final design: welding closer to outside corner



Alternative orientation of horizontal and diagonal members: no significant improvement

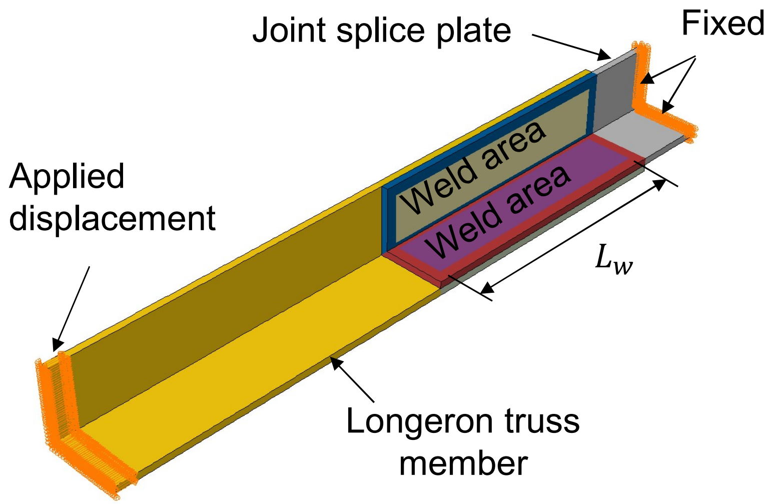


Joint stiffness:

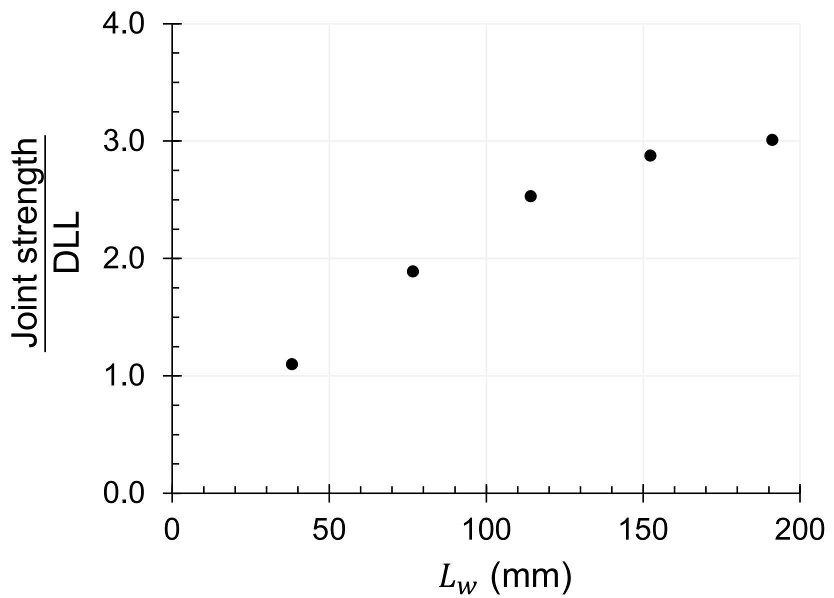
- ***Not directly considered in preliminary design***
- ***Critical to positive margin in buckling***

Joint Sizing

Joint model overview



Joint strength vs. overlap length



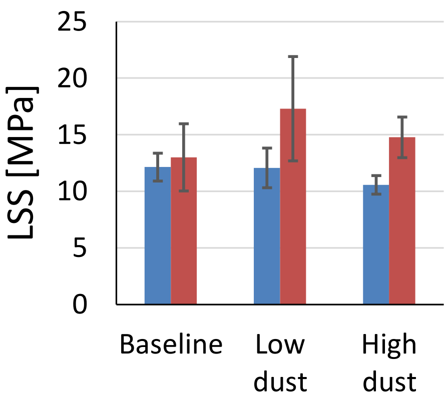
- Joint model developed with simplified boundary conditions and a single layer of cohesive elements represented the weld
- Joint overlap length predicted based on assuming interlaminar fracture toughness for the weld
- Results support selection of joint overlap length

On-Going Validation Effort

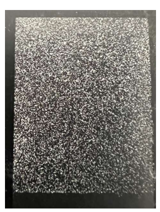
Effect of lunar simulant contamination

Objective:
- Quantify knockdown of lunar simulant dust contamination in ultrasonically weld joints

Status:
- Completed baseline and 'low' dust welds and lap shear strength (LSS) test
- Welds with dust show same or better strength



'Low' dust on surface

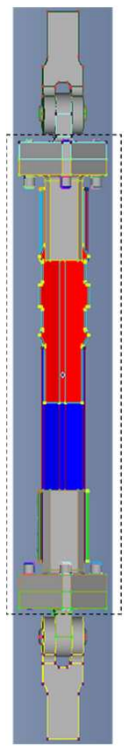


Vertical joint sub-element test

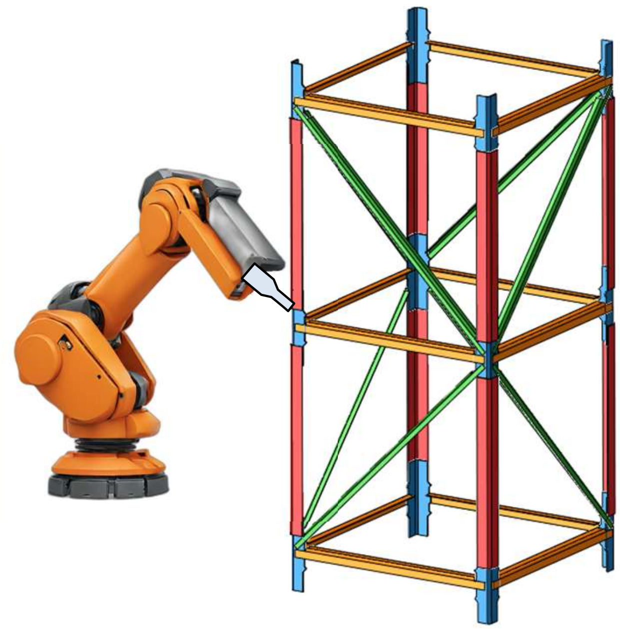
Objective:
- Build, test, and validate a representative vertical joint

Status:
- Designed test specimen and load introduction
- Predicted stiffness and strength using a 3D finite element model
- Manufacturing 'L' sections using automated fiber placement and autoclave consolidation at NIAR

Test setup



RUC manufacturing demo



Objective:
- Build a repeating unit cell (RUC) of the truss tower to gain experience with manufacturing scale-up

Summary

- Developed an all-thermoplastic composite truss tower concept for solar array and other relevant payloads at the lunar south pole
- Extended an existing truss tower structural sizing routine to account for longeron strength and moonquake loads
- Sized the truss tower welded joints using a cohesive zone model
- Thermoplastic composites and welding processes show promise for in-space and on-surface assembly of large structures