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CENTER 5500

Data-Driven Optimization of Interlocking Metasurface Design

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Sandia National Laboratories

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Presented by Nathan Brown –

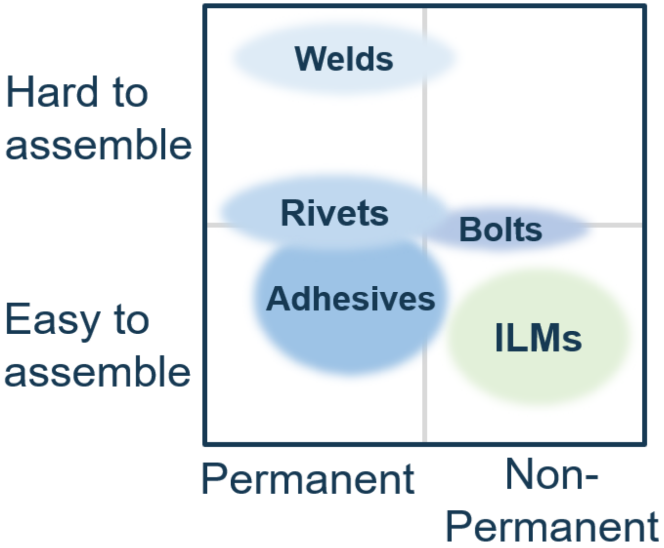
What are interlocking metasurfaces (ILMs)?

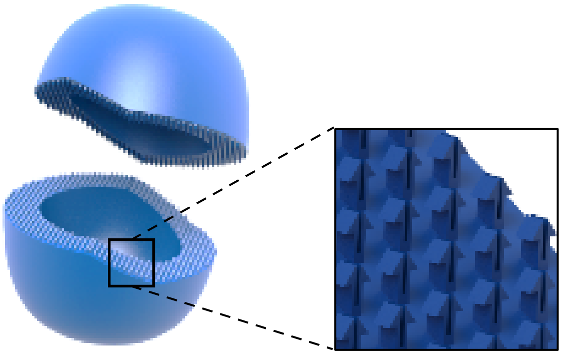
Robust
Architected
Non-Permanent
Integrated

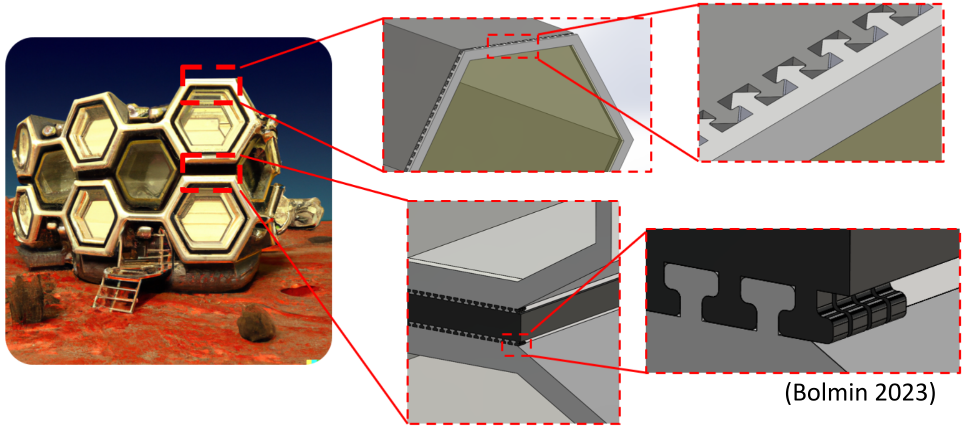
joining technology suitable for

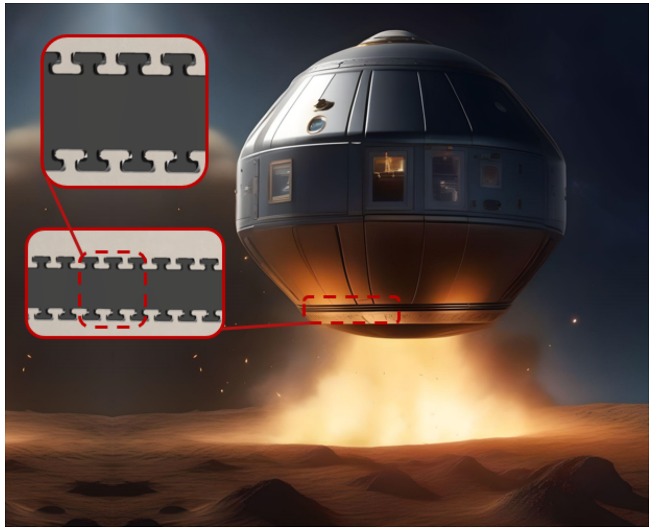
complex surfaces
dissimilar materials
extreme environments

ILMs overcome many limitations of existing joining methods

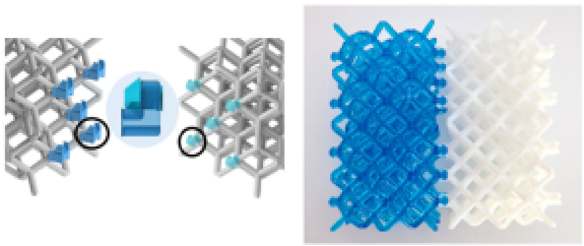








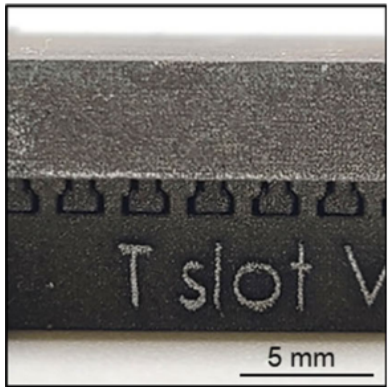
(Bolmin 2023)

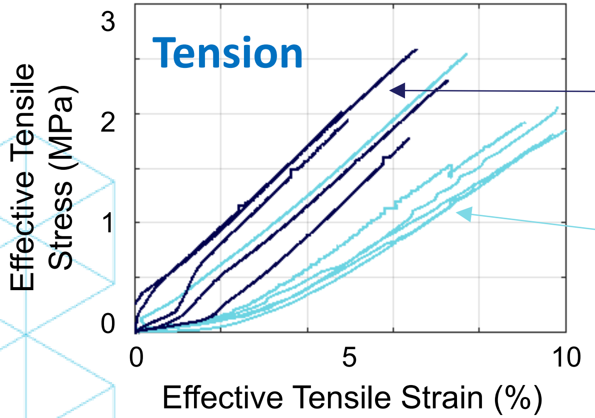


Tailoring Mechanical Performance

- Robustness controlled by ILM's **unit cell design,** constitutive material, and unit cell interaction

Failure Criteria

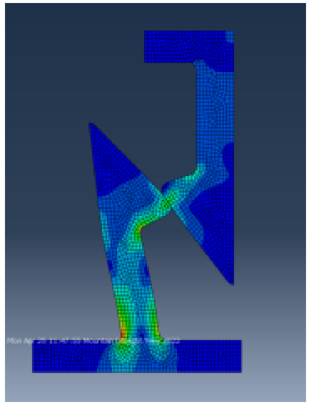


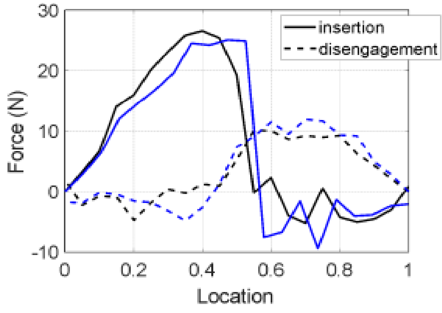


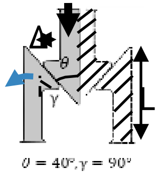
Snapping T-slots

Sliding T-slots

Remateability





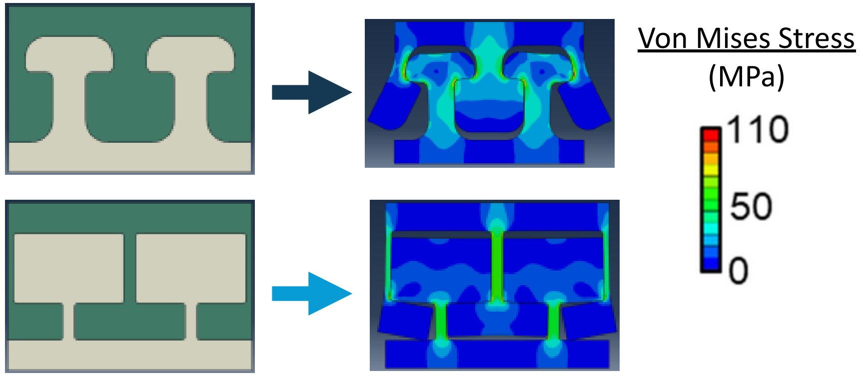


$\theta = 40°, \gamma = 60°$

$\theta = 40°, \gamma = 70°$

$$F > \frac{3EI}{l^3}\Delta \frac{\mu + \tan(\theta)}{1-\mu \tan(\theta)}$$

Stress Uniformity



Design Methodology Comparison

- Evaluate ILM unit cell performance and capabilities of 4 distinct design methods

Human Intuition
- Expertise
- Experiences
- Nature

Parametric Opt.
- Geometrically parameterize a design
- Optimize parameters according to objectives and constraints

Genetic Algorithm
- Elementally Discrete domain (voxelized design)
- Evolutionary algorithm: Cross-populating and mutations

Conditional Diffusion Model
- Single-shot generation
- Conditions based on objectives/constraints
- Thermo-mechanical properties

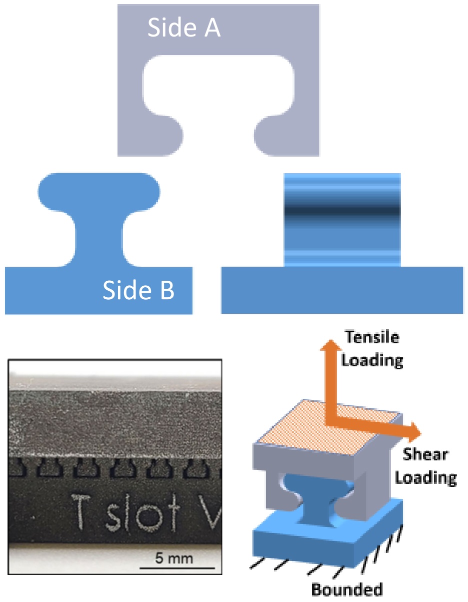
Direct design comparison in tension and shear, including experimental validation

Rapid unit cell generation with emphasis on generalizability

Topology Comparison Methods

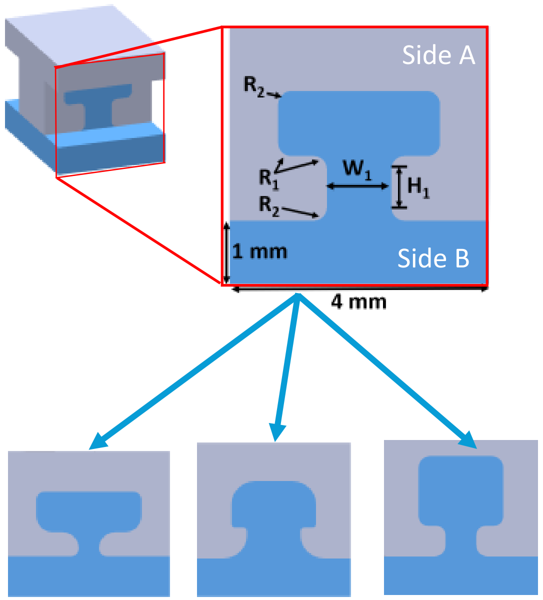
Human Intuition

- "Sliding T-slot"
- Based on designer's expertise
- No additional optimization



Parametric Optimization

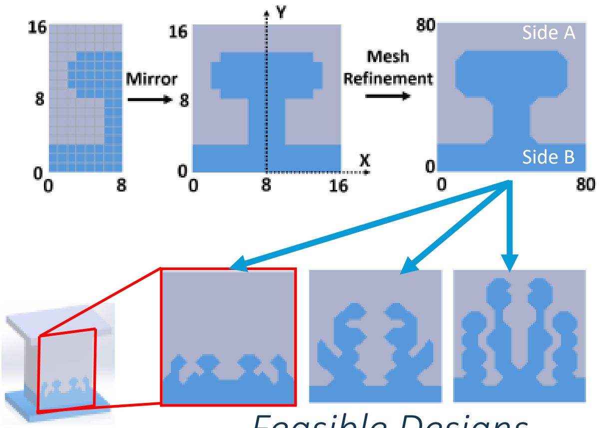
- Parameterized T-slot
- Gradient-based optimization
- Maximize Strength: Tension, Shear, Weighted-sum



Feasible Designs

Genetic Algorithm

- Evolutionary optimization
- 16x8 mirrored discretized design domain
- Single and Multi-Objective Optimization (Tension/Shear)



Feasible Designs

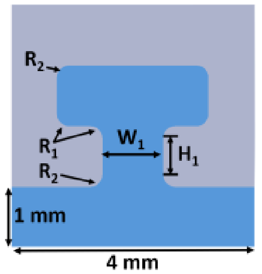
Iterative Evolution

Design Results

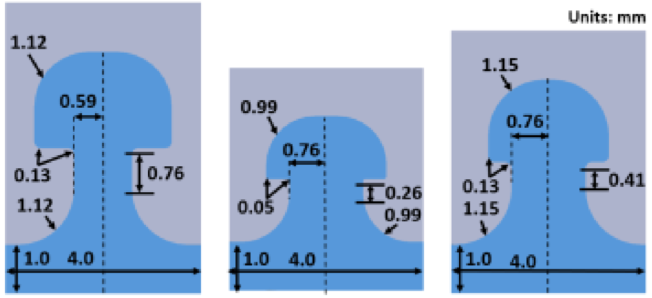
Parametric Optimization

- Parametrization limit uniqueness between topologies
- Differences in height and width

Initial Design



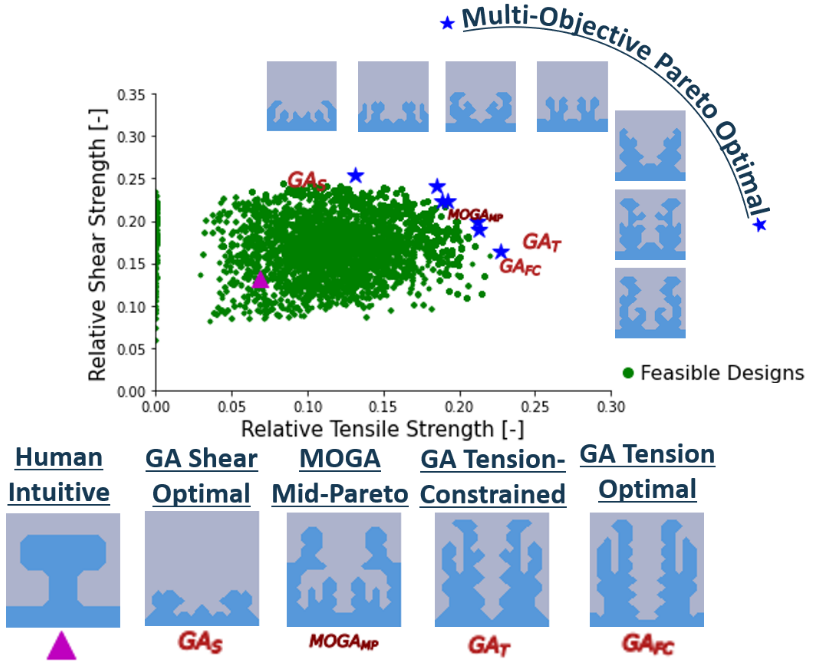
Optimized Designs



Tension Shear Weighted-Sum

Genetic Algorithm

- Considerable changed in topology corresponding to objective
- Non-intuitive designs
- **Tension:** Tall, Dendritic **Shear:** Short, sturdy



MOGA: Multi-Objective Genetic Alg.
Constrained: Mimics "infinite" unit cell tessellation

Design Results

Parametric Optimization

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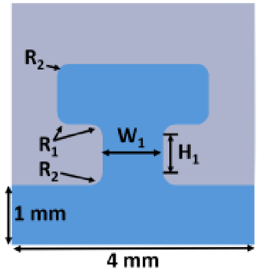
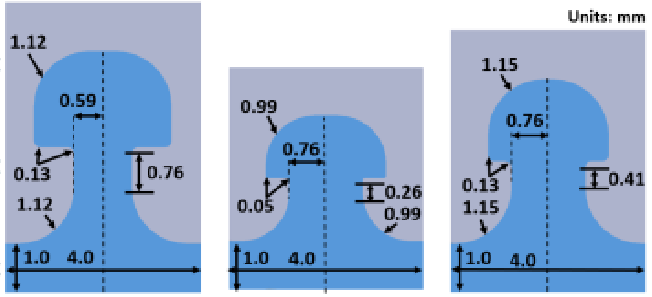


Optimized Designs



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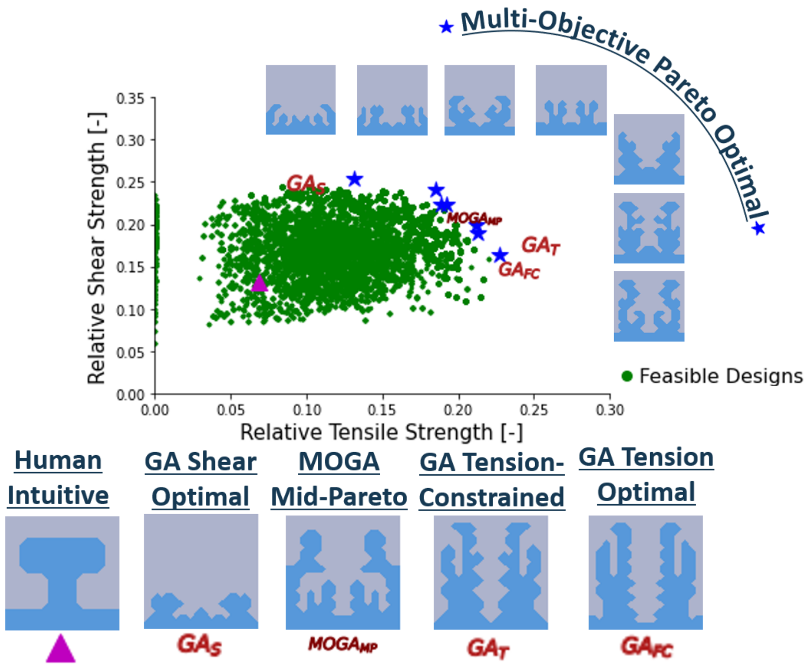

MOGA: Multi-Objective Genetic Alg.
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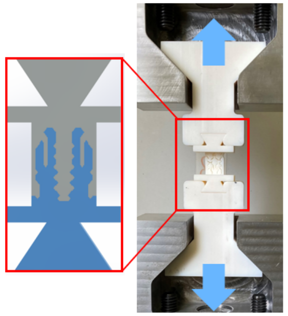
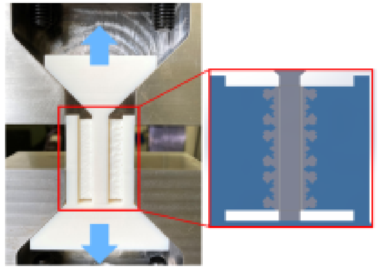
Experimental Testing

- Tested in 1x1, 1x3, and 1x1 Fully Constrained configurations
- Extruded 2D surfaces

Tension Testing



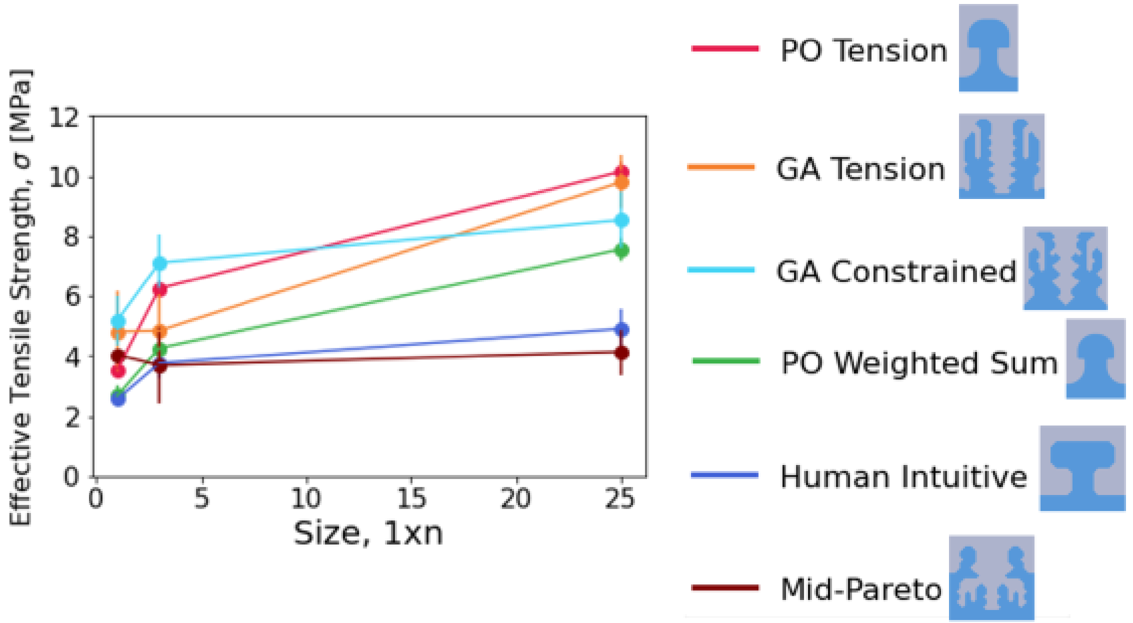
Shear Testing



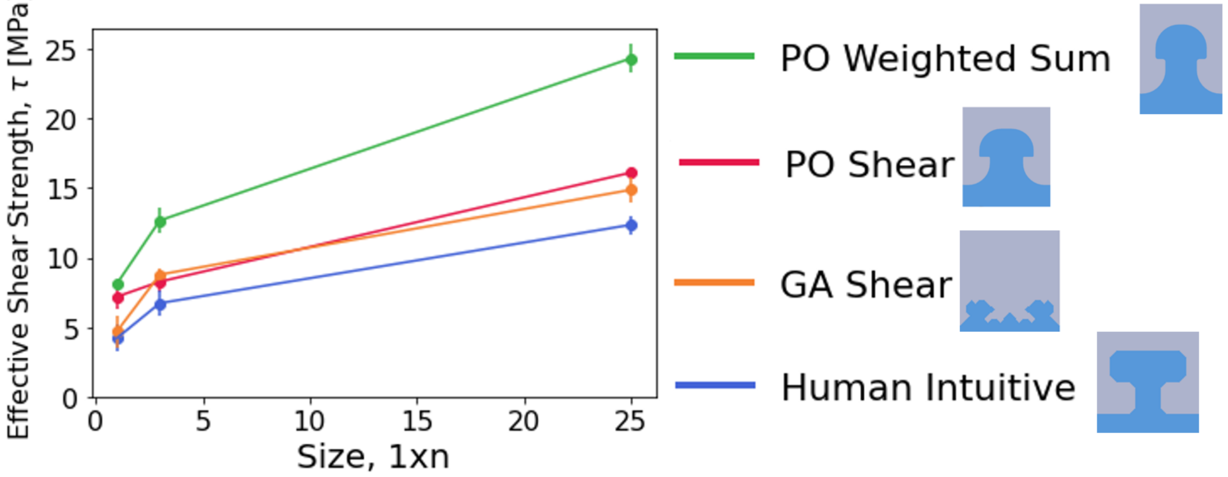
Experimental Results

- Both optimization method result in considerable strength increase
- Effective strength increases with tessellation size → Unit Cell Interactions

Tension



Shear



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- Evaluate ILM unit cell performance and capabilities of 5 distinct methods

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Parametric Opt
- Ge…
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- …ntally Discrete
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Conclusion: **The unit cells of ILMs can be optimized to achieve considerable increases in strength for various tessellation sizes**

Conditional Diffusion Model
- Single-shot generation
- Conditions based on objectives/constraints
- Thermo-mechanical properties

Direct design comparison in tension and shear, including experimental validation

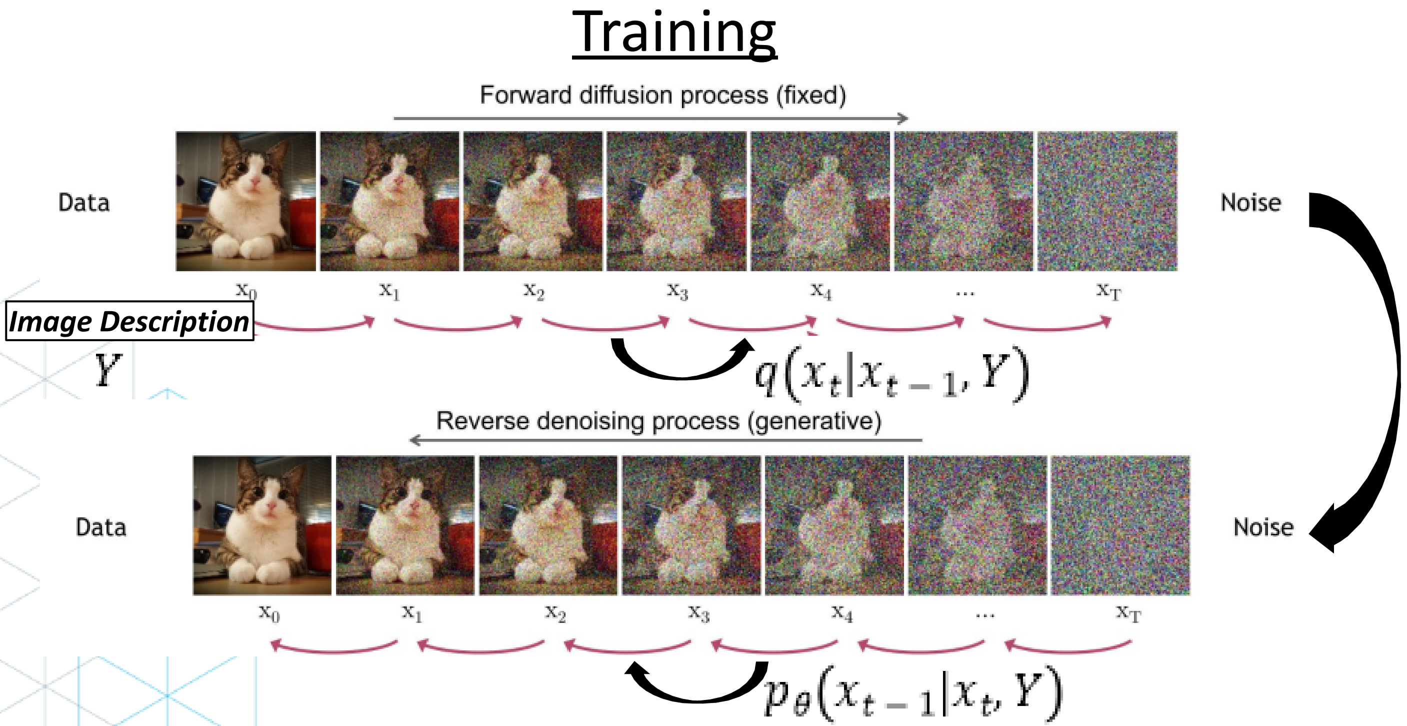
Rapid unit cell generation with emphasis on generalizability

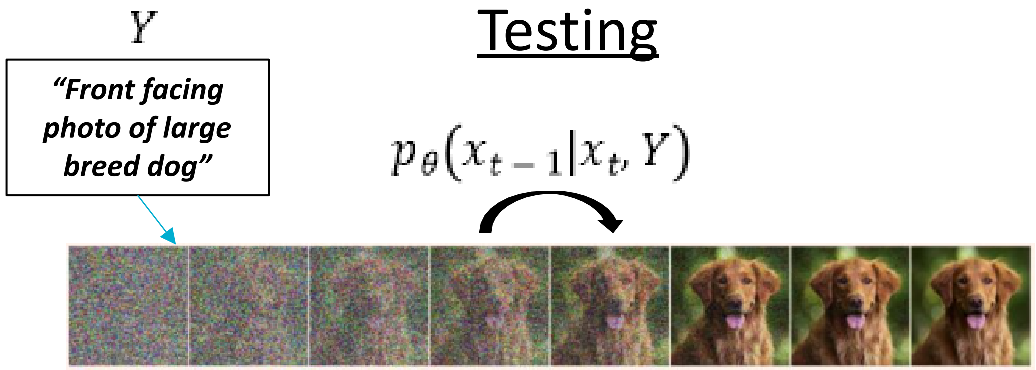
Condition Diffusion Models (CDMs)

- **CDM**: Generative AI method to generate data by iteratively refining random noise, guided by specific conditions or inputs, to produce highly realistic/practical outputs
- Commoly used for "text-to-art" generation →


(MidJourney)

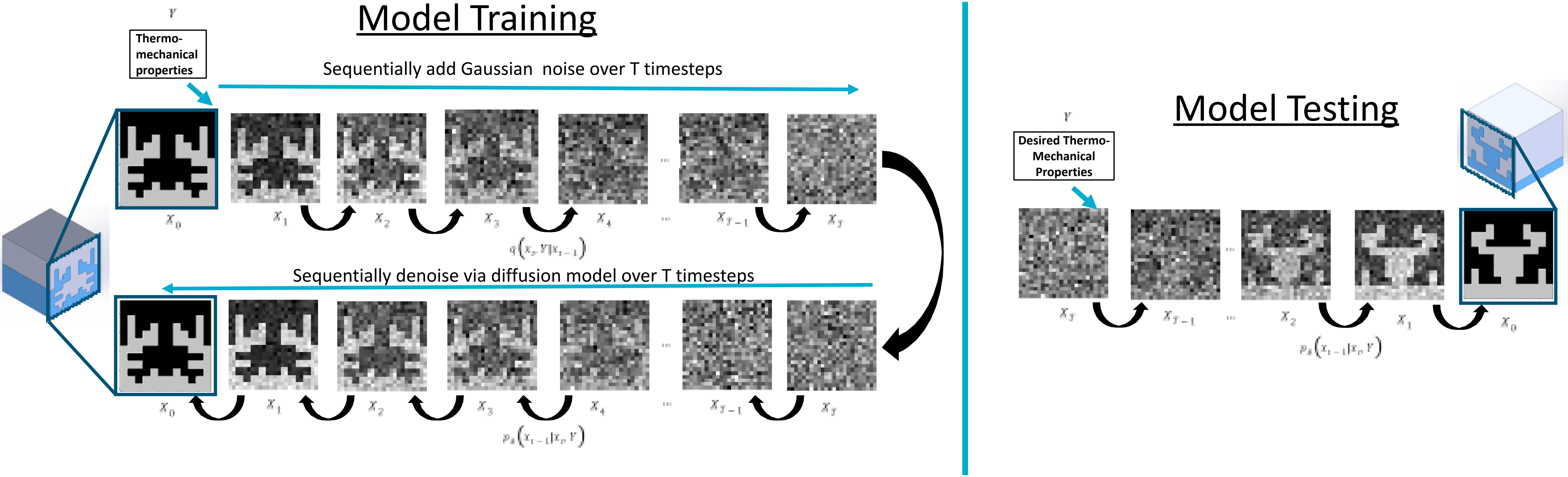

(Gemini)





CDMs as an Engineering Design Tool

- Use the denoising process to go from complete noise to a viable design candidate
- Replace "text-description" with performance criteria → Desired Thermo-mechanical properties



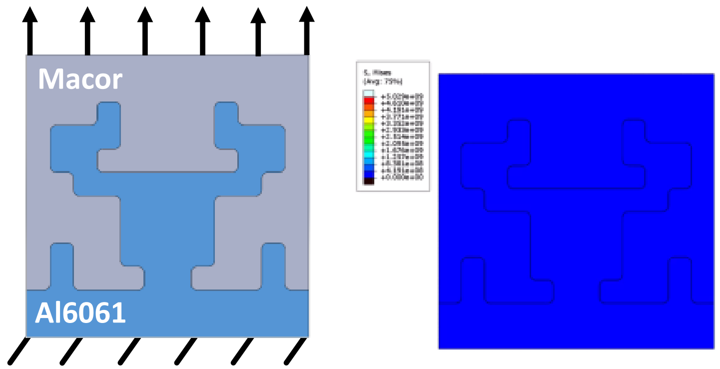
Generating Training Data

- Training data comprised of **ILM unit cell design** and **corresponding thermo-mechanical properties**
  - Randomly generated ~28k designs and determine properties using finite element analysis (FEA)
  - Voxelized 12x12 (mirrored) design domain, each element either *Macor*, Al6061, or void

Thermo-Mechanical Properties

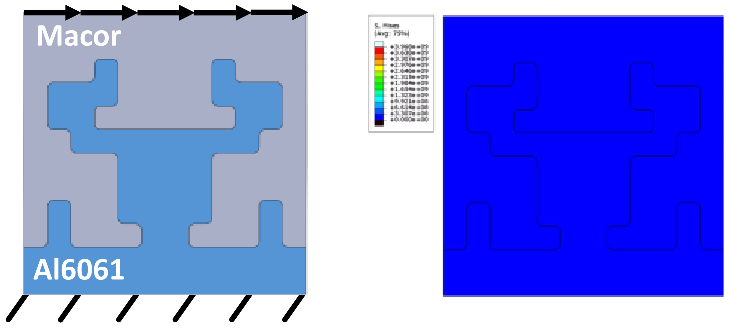
1. Tensile Resultant Force

- Top surface resultant force at material yielding



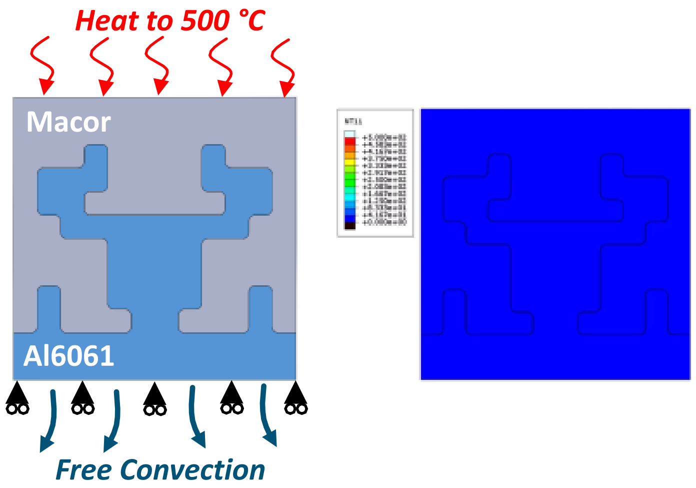
2. Shear Resultant Force

- Top surface resultant force at material yielding



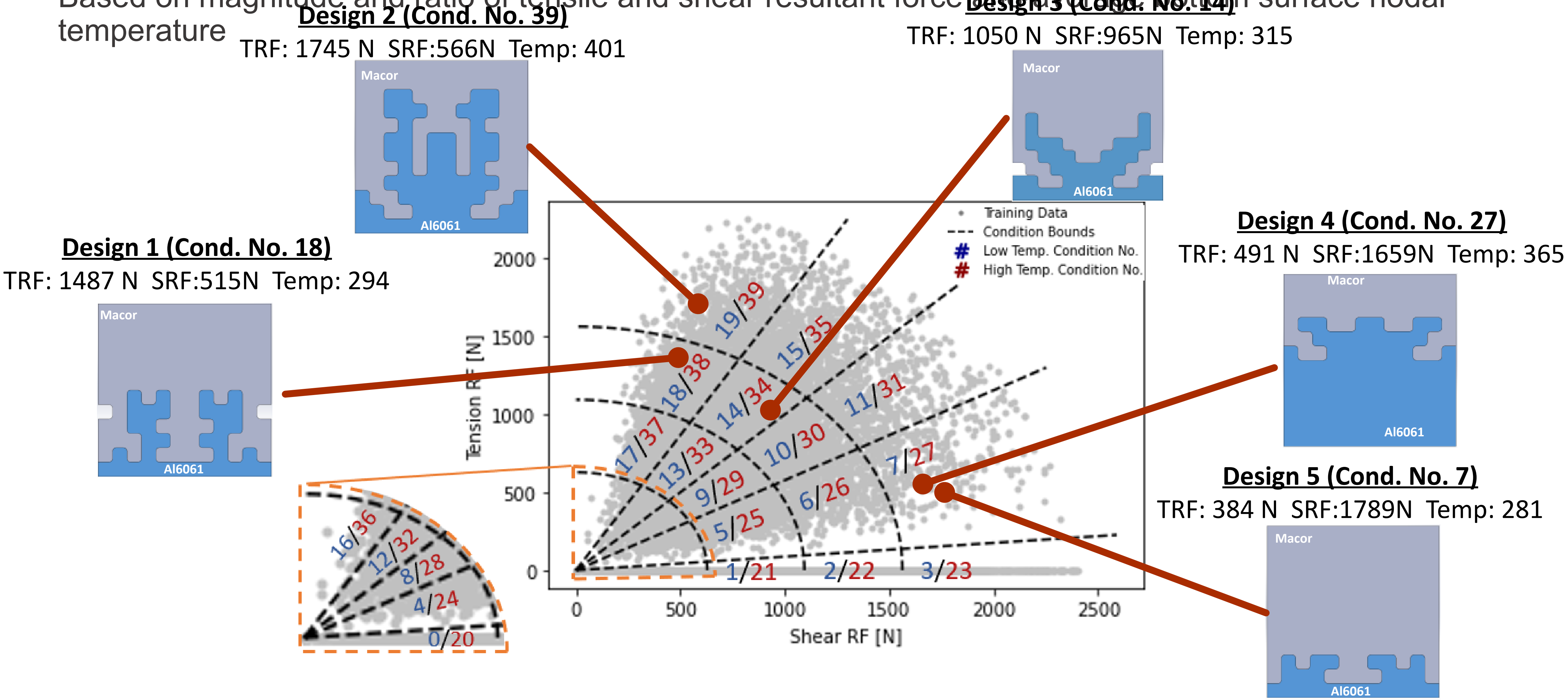
3. Heat Mitigation

- Average bottom surface nodal temperature



Putting the “Conditional” in CDM

- **40 individual conditions numbers** determined based on thermo-mechanical responses of 28k training samples
- Based on magnitude and ratio of tensile and shear resultant force and average bottom surface nodal temperature



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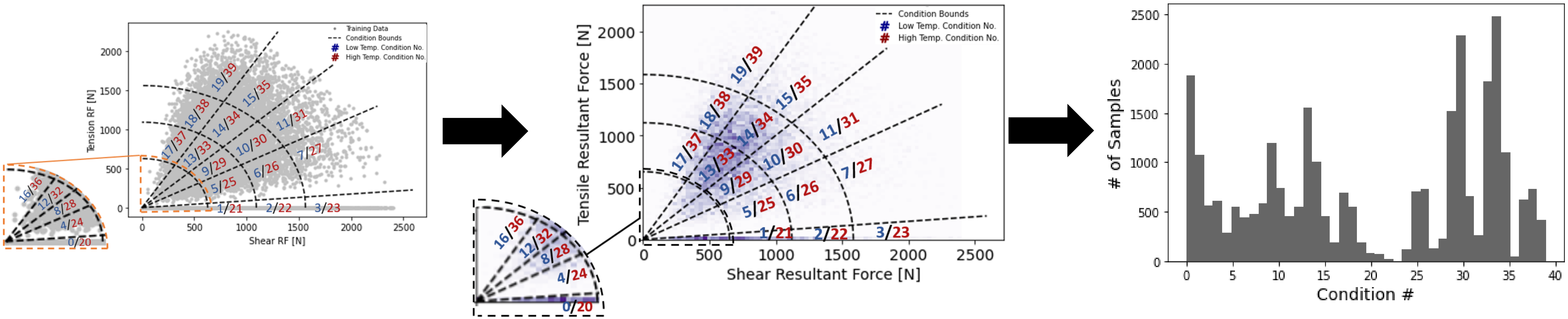
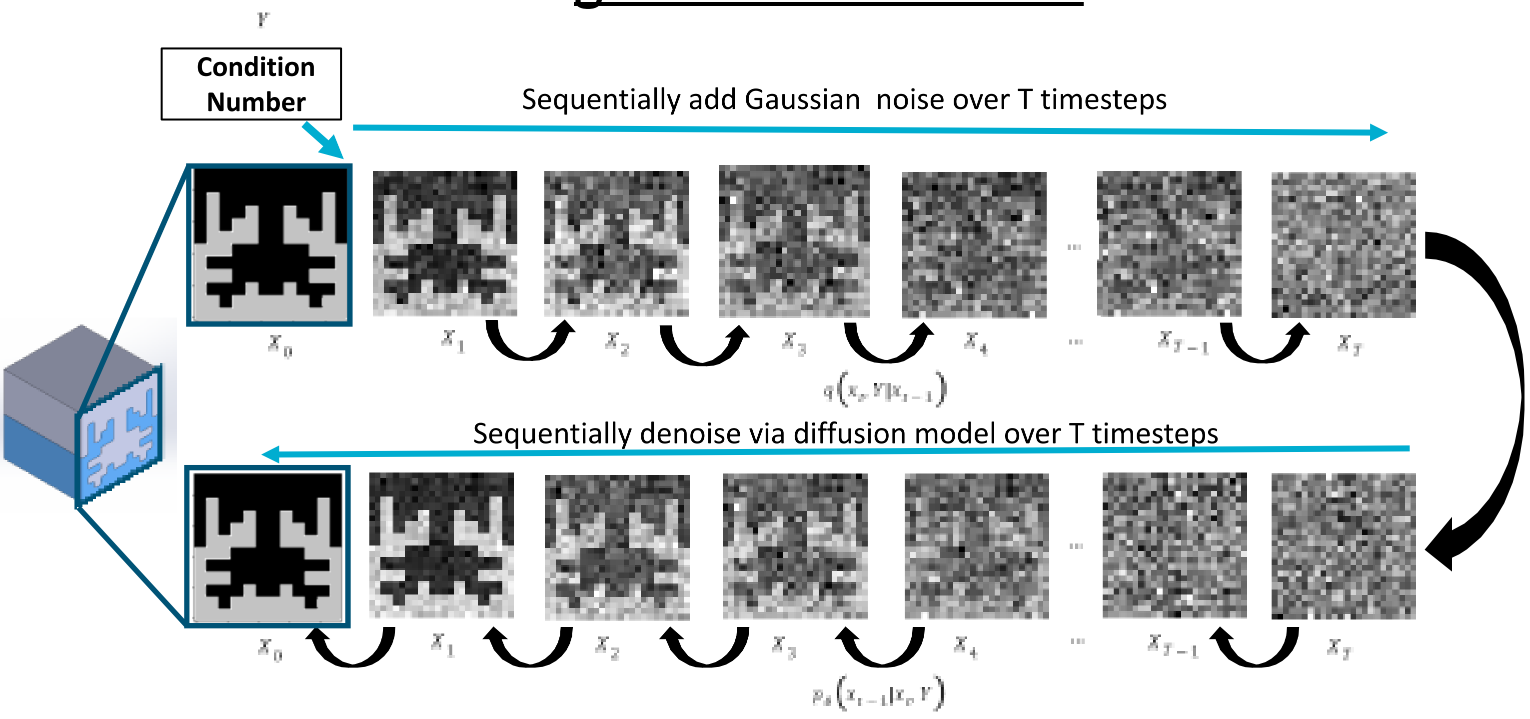


CDMs as an Engineering Design Tool

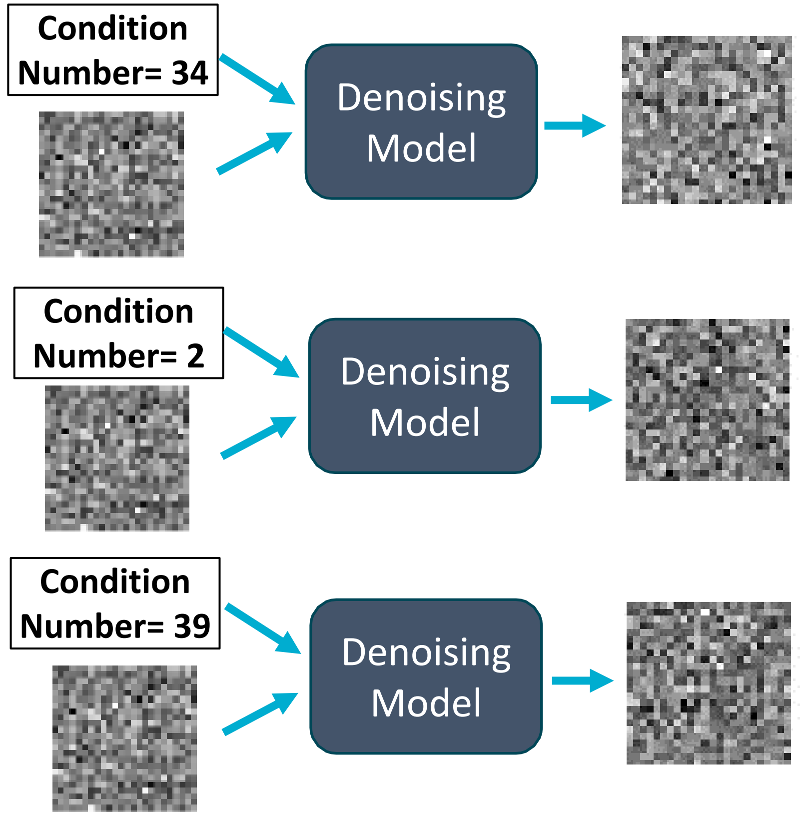
- Feed the 28k unit cell designs and accompanying condition number through the noising and denoising process

Model Training w/ 28k randomly generated unit cells



Model Testing

- Pick condition # based on desired thermo-mechanical properties



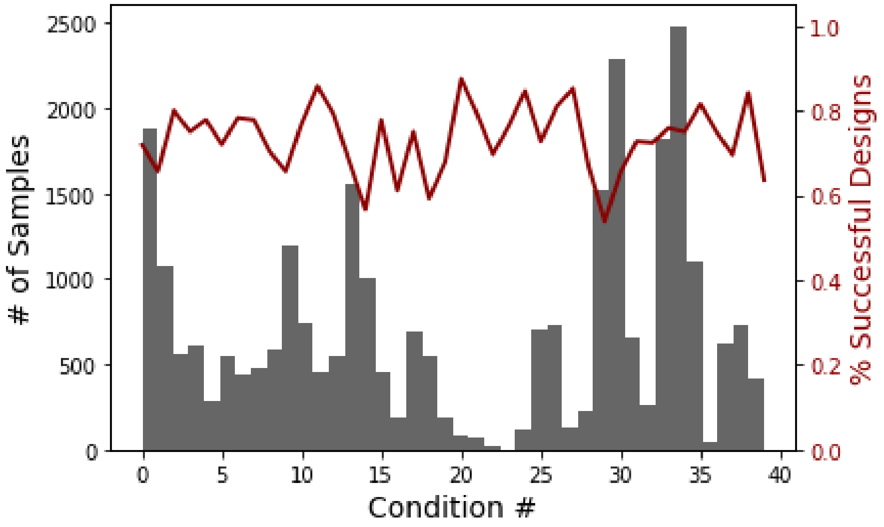
Generalized Design Generation

- The model was prompted to generate designs based on 1000 random condition numbers
  - Generate design via CDM → Tested Design via FEA → Compare FEA result to condition bounds

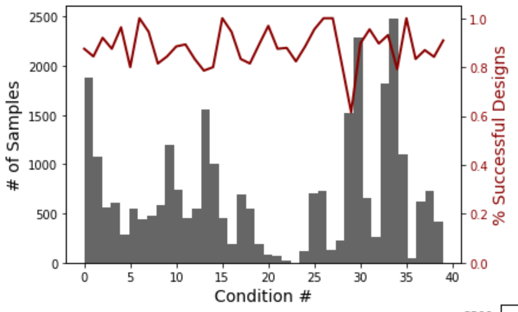
Conditions	Avg. Success Rate
All Conditions	73.3%
Angle	86.0%
Magnitude	88.2%
Thermal	95.6%

- The ability to achieve desired properties does not appear to be condition number dependent!

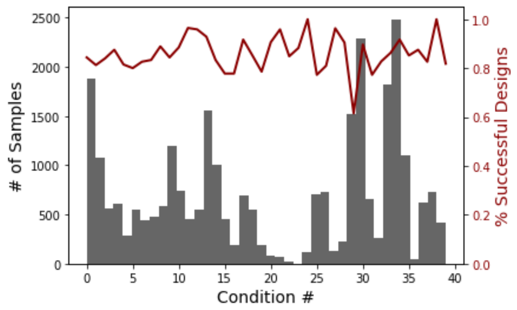
All Conditions



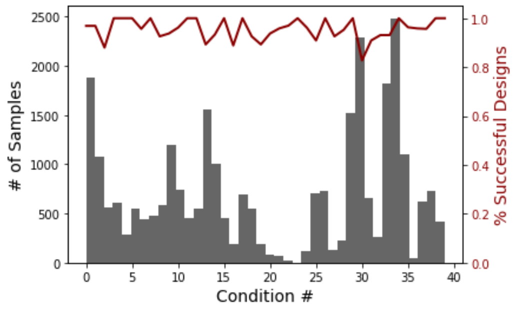
Magnitude



Angle

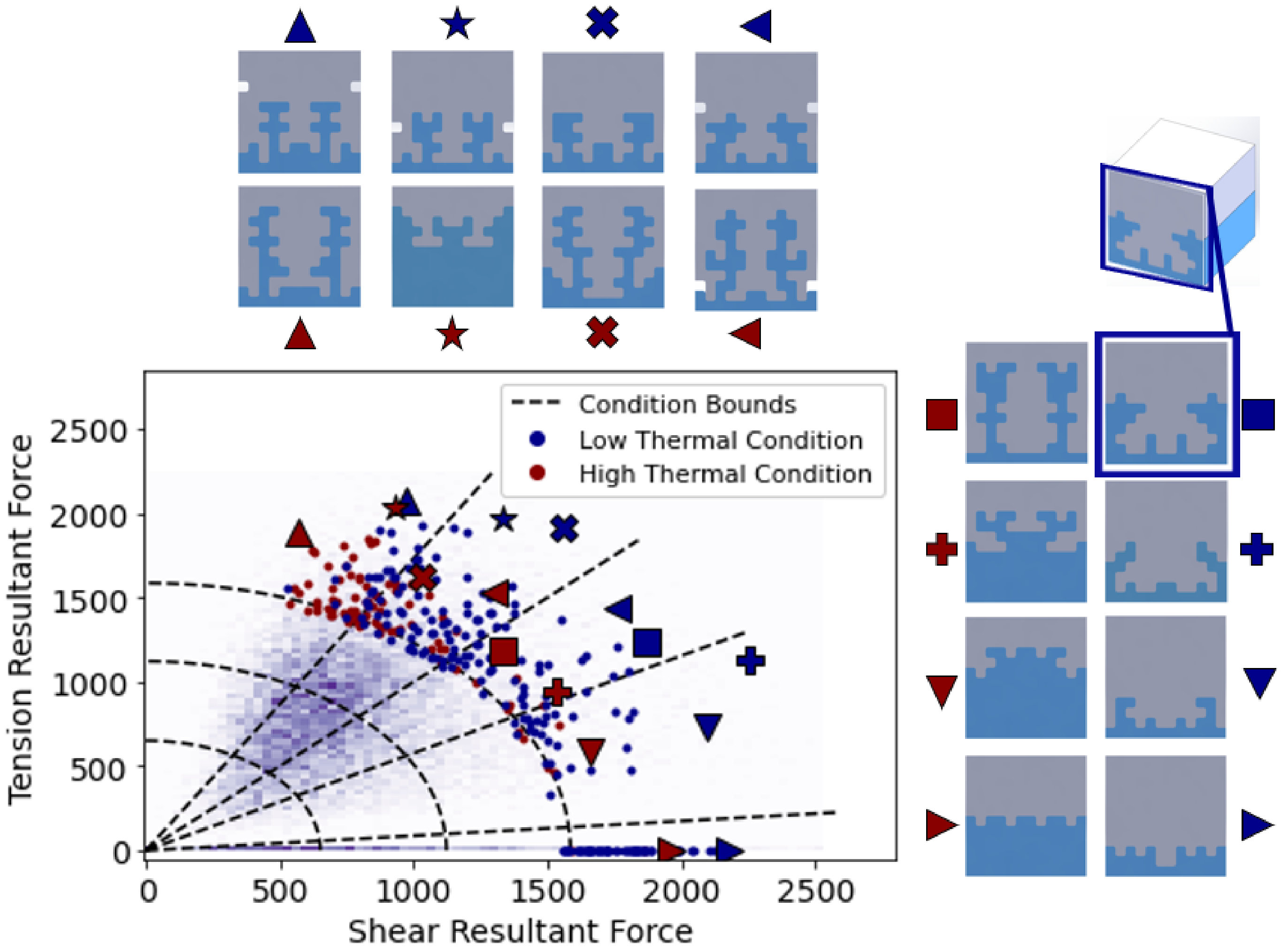


Heat Transfer



“Pareto Front” Approach – 40 conditions

- Testing the model to produce extremes results in plethora of high performing design solutions
- Able to produce designs with high mechanical strength while achieving varying thermal responses



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Conclusion: The unit cells of ILMs can be optimized to achieve considerable increases in strength for various tessellation sizes

Direct design comparison in tension and shear, including experimental validation

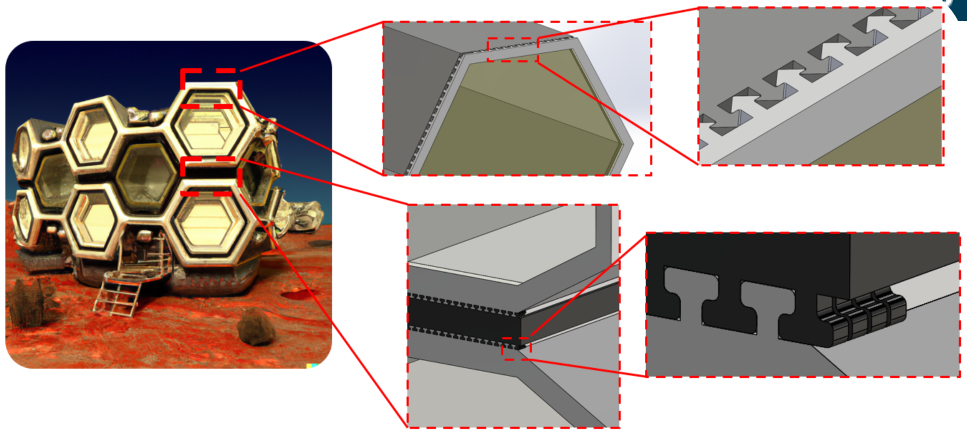
Conditional

Engage… …age

Conclusion: Conditional Diffusion Models can serve as a generalized engineering design tool, accommodating design rules.

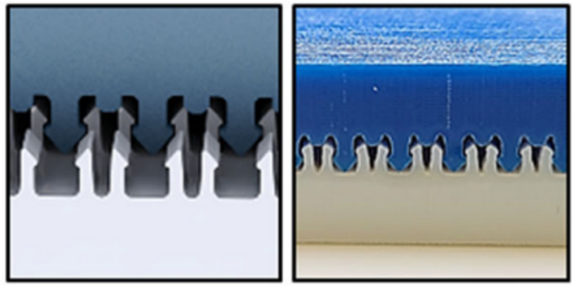
Rapid unit cell generation with emphasis on rematability

Conclusions

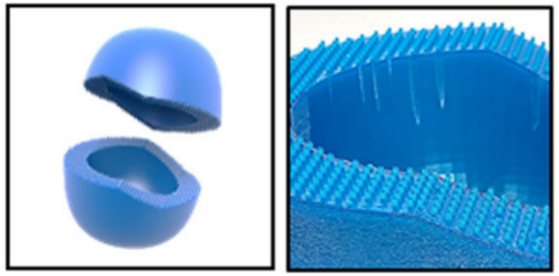


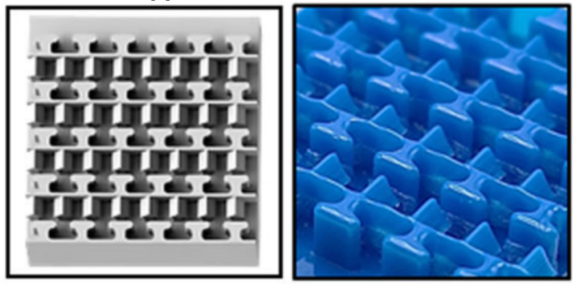
- Interlocking metasurfaces (ILMs) are a mechanically robust, non-permanent, environmentally durable alternative to traditional joining technologies

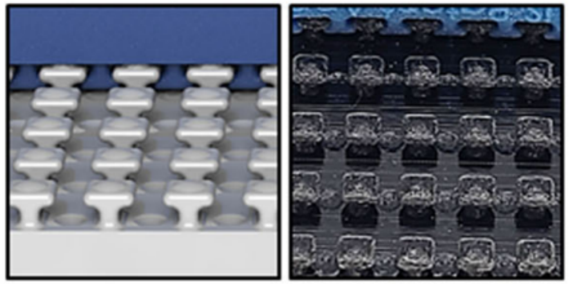
- ILMs' mechanical (and thermal) properties are dependent on feature topology



- ILMs can be optimized using a host of design methodologies
  - **Human intuition:** Fastest
  - **GA and PO:** Well established methods to achieve high performing solutions
  - **CDM:** Serve as generalizable tools for complex design







Thank you!

Questions?

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