Modelling and optimisation of rapid tow shearing for composite reflective mirrors in space-based laser communication systems

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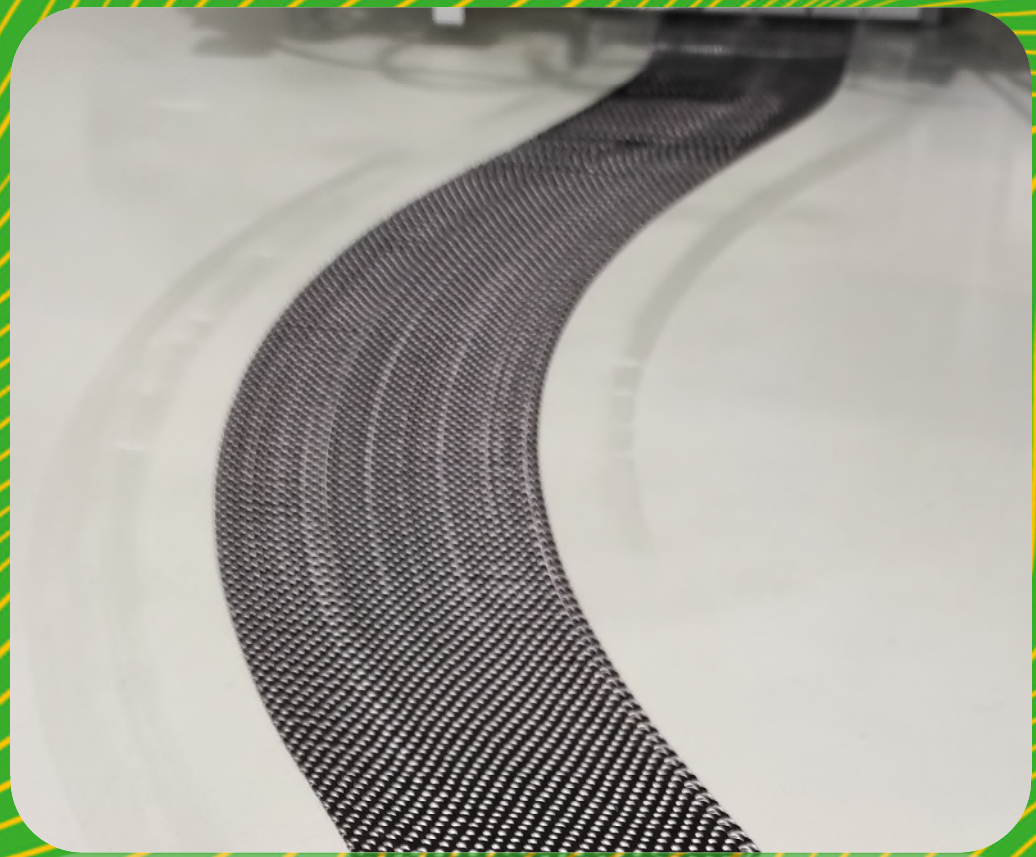

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Outline

- Introduction
- Project objectives and specifications
- Challenges in design
- Novel Solution – Rapid Tow Shearing (RTS)
- Structural and thermal analysis
- Material selection
- Optimised straight fibre design vs RTS design
- Surviving launch loads and manufacturing feasibility
- Summary

The need for lightweight space reflective mirrors

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- **Current challenge**:
  - Space telescopes and laser communication systems require highly reflective, low-mass mirrors
  - Traditional materials (aluminium, beryllium) are:
    - Heavy (~20 kg/m²), increasing launch costs
    - Expensive due to manufacturing complexity
    - Sensitive to thermal expansion, causing distortion
- **Space mission requirements**:
  - Withstand extreme temperatures
  - Survive launch loads with minimal distortion

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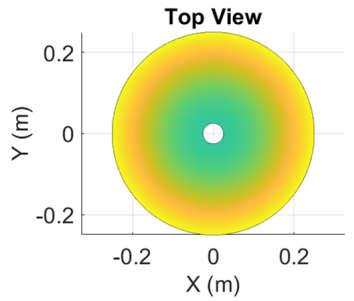
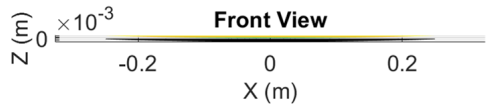
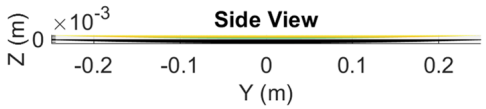
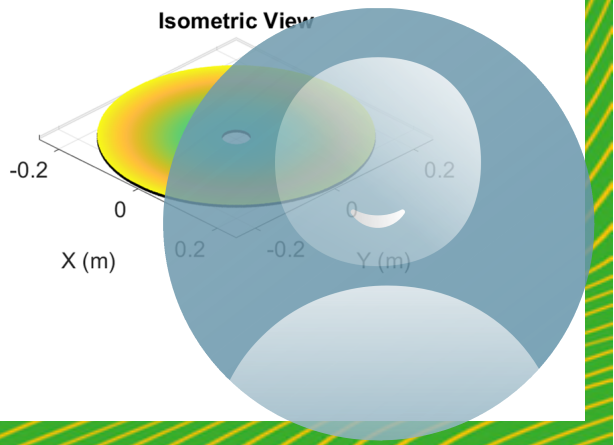
Project objectives and specifications

- **What are we trying to achieve?**
  - Develop a 0.5m diameter spherical mirror with an 8m radius of curvature and an f/8 focal ratio
  - Second reflection opening: 50 mm
- **Key performance targets**:
  - Areal density: ≤10kg/m²
  - Thermal endurance: 60,000 cycles
  - (-65°C to 125°C)
  - Optical performance:
    - ≤1µm RMS surface roughness
    - ≤10µm RMS thermal distortion









Challenges in design

- **Structural vs thermal performance trade-off**:
  - Launch phase:
    - Resonance frequency > 140 Hz to avoid amplification of loads
    - Must withstand 15g axial and 4g lateral loads (Failure Index <0.5)
  - Operation phase:
    - Target: <10 µm RMS distortion across temperature cycles
    - Needs low hygrothermal distortion (≤20µm RMS)
- **Traditional composite designs struggle to meet both requirements**:
  - QI laminates provide stiffness but have high thermal distortion
  - We need an optimised fibre steering approach to balance both needs

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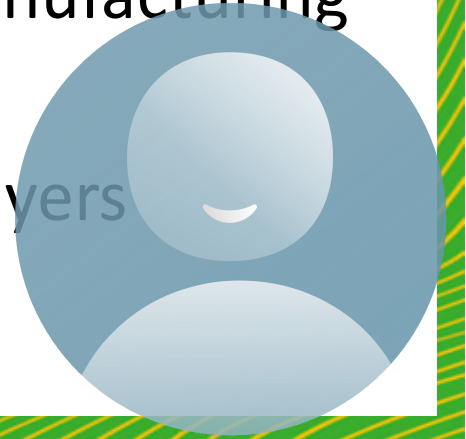
Novel Solution – Rapid Tow Shearing (RTS)

- **What is RTS?**
  - First automated process for defect-free curved fibre placement
  - Shears tapes instead of bending, avoiding wrinkles, gaps, and overlaps
  - RTS allows for custom fibre paths and weight reduction in aerospace structures
- **Why use RTS for space reflective mirrors?**
  - Improves structural performance by placing fibres along optimal load paths
  - Reduced mass & distortion by optimising fibre paths

Structural and thermal analysis

- **Simulation methods used:**
  - **Thermal-structural analysis (Abaqus)**:
    - Launch phase: Dynamic and static analysis (acceleration, resonance, vibration)
    - Operation phase: Hygrothermal and thermal distortion evaluation
  - **Curing simulation (Marc Mentat, CHILE model)**:
    - Residual stress & thermal distortion analysis during manufacturing
- **Optimisation process**:
  - Design variables: Fibre paths, fibre angle and number of layers
  - Objective: Minimise mass & distortion during operation

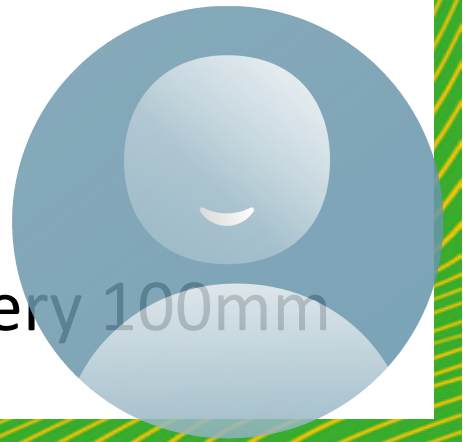


Material selection – IM7/8552 composite

- **IM7/8552 composite**
  - **Pros**: High strength established cure kinetics data and constitutive models
  - **Cons**: High hydrothermal shrinkage
- **Alternative material**: M55J/EX1515
  - **Pros**: High Stiffness fibre with cyanate ester resin, offering better thermal and hygrothermal stability
  - **Cons**: High cost material
- **Decision**:
  - RTS optimised layups with IM7/8552 for performance validation
  - Is it possible to use RTS technology to make conventional material usable for the space application?

Optimised straight fibre design vs RTS design

- **Straight fibre layup configuration**:
  - Stacking sequence: $[0/90/\pm45]_{2s}$
  - Total thickness: 2.1mm (16 plies)
  - Manufacturing approach: standard UD tape layup
- **RTS layup configuration:**
  - **[45/45*/-45/-45*/0/0*/**90**/90/0*/0/-45*/-45/45*/45]**
  - RTS plies are highlighted in red
  - Shearing path control:
    - Reference length: 600mm
    - Control Points: Start & end of each path, and points every 100mm



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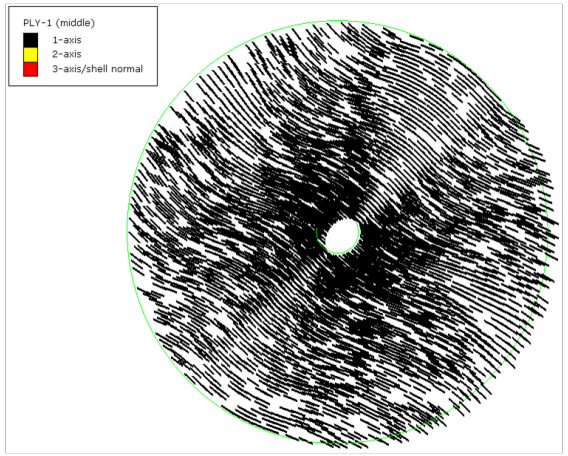
Orientation distributions for the RTS plies

45º



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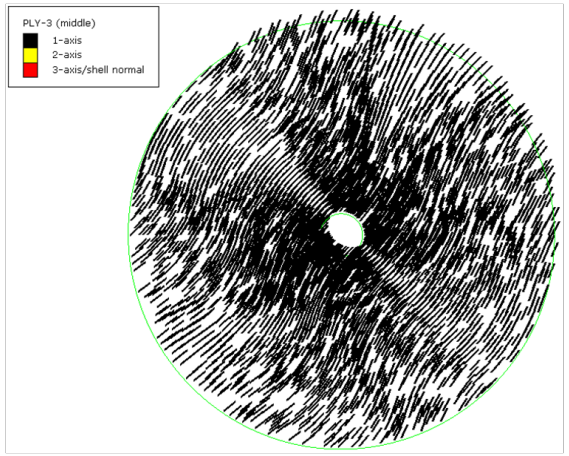

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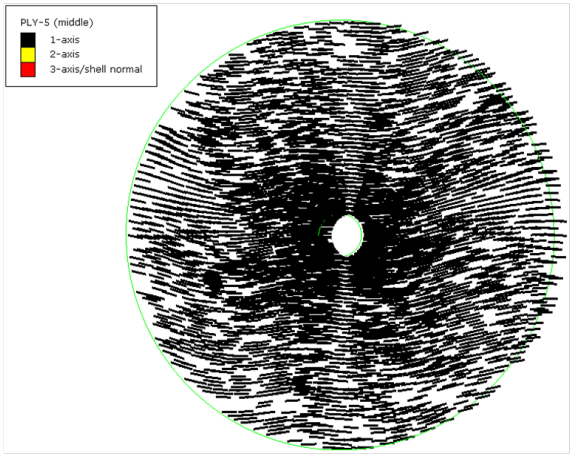

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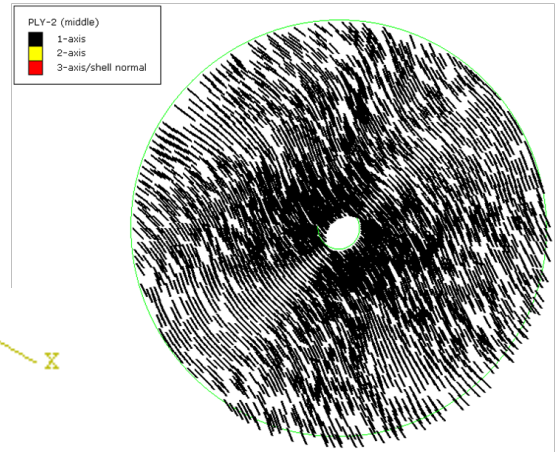

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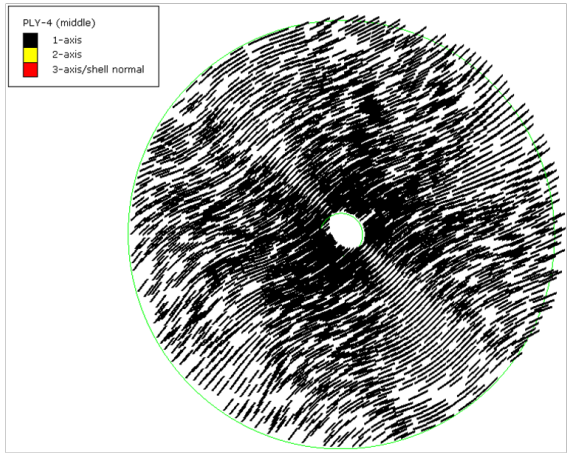

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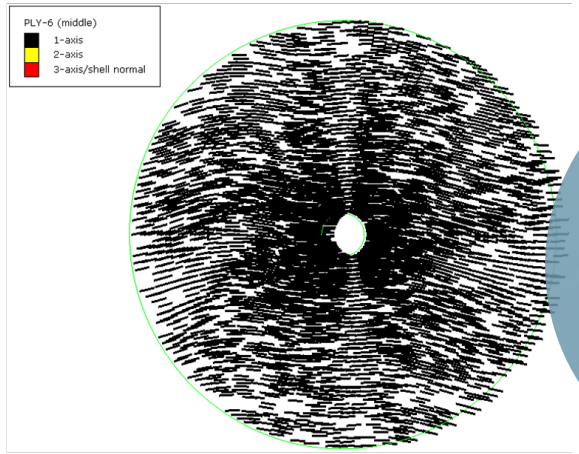


Optimised straight fibre design vs RTS design

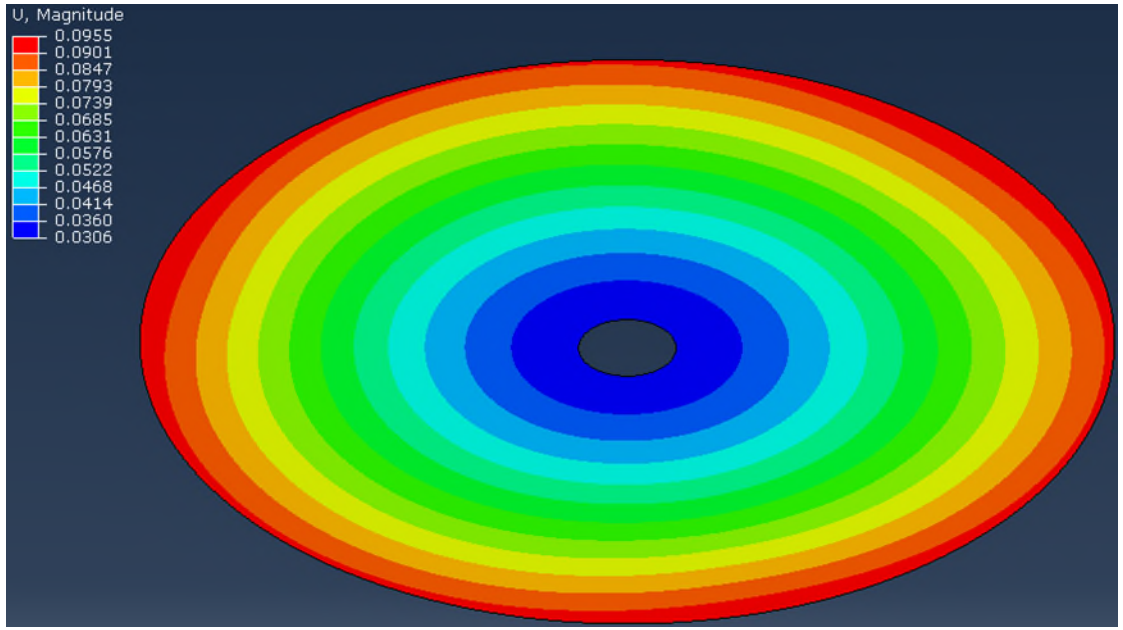
- Performance Comparison

Metric	Straight fibre layup	RTS layup	Improvement
Mass (kg/m^2)	3.31	2.97	↓ 11%
Resonance Frequency (Hz)	152.7	150.5	~Equal
Thermal distortion (RMS) (μm)	69.3	67.8	↓ 2%

Optimised straight fibre design vs RTS design

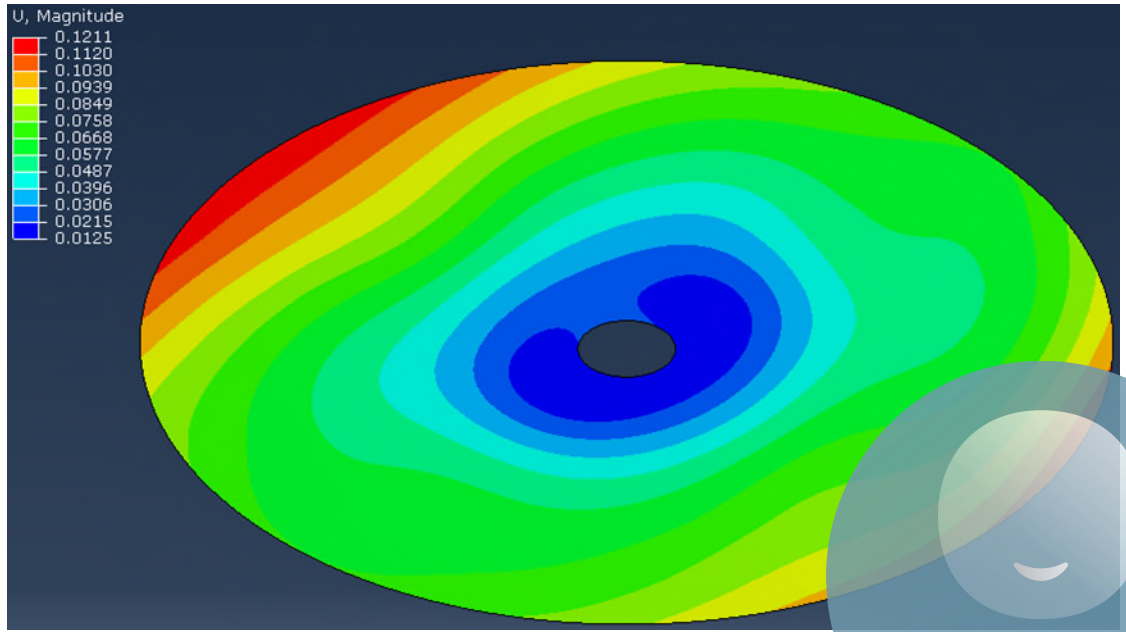
- Thermomechanical analysis results: Displacement contour plots

Straight fibre case



RMS: 69.3µm

RTS case



RMS: 67.8µm

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Surviving launch loads

- **Structural safety verification**:
  - Tsai-Wu failure index (FI):
    - <0.01 under 15g axial / 4g lateral loads
    - <0.08 under random vibration (90g equivalent static load)
- **Key insight**:
  - Stiffness-driven design: conservative strength margins
  - Intermediate modulus fibre used due to cost (demo, not flight)
  - Lower mass = lower inertial loads, better launch survivability
  - RTS composites outperform traditional laminates in launch conditions

Manufacturing feasibility

- **Forming simulation (Aniform)**:
  - Verify the manufacturability of straight-fibre layup in shallow-curvature components
  - Simulations confirm no significant fibre deviations from the designed orientations
  - No wrinkles or fibre deviations detected (smooth curvature)
- **RTS path validation**:
  - Minimum steering radius: 173mm
  - Well within RTS manufacturing capability, which supports steering radii as small as 50mm

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Summary

- **Proof of concept achieved**:
  - Simulations confirm feasibility for space mirror applications.
  - Proven launch survivability under extreme conditions.
- **Next steps**: bridging simulation to reality
  - Experimental validation: Testing physical prototypes to confirm simulation accuracy.
  - Manufacturing & evaluation:
    - Produce straight-fibre & RTS composite mirrors.
    - Compare surface distortion to assess optical precision
  - Explore cyanate ester-based composites for improved hygrothermal stability.

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Key takeaways

- **Why RTS composites?**
  - Lighter weight: Reduces overall spacecraft mass, increasing payload efficiency.
  - Comparable or superior structural performance: Maintains high strength and stiffness, even under extreme conditions.
  - RTS composites allow for precise fibre steering, achieving complex geometries without compromising structural integrity

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Acknowledgements

- This work is supported by the UK Space Agency under the NSIP Programme. (KS1-040)

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2025-04-09
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Yang N, Stamatopoulos G, Skordos A. (2025) Modelling and optimisation of rapid tow shearing for composite reflective mirrors in space-based laser communication systems. International Conference on Manufacturing of Advanced Composites 2025 (ICMAC 2025), 9-10 Apr 2025, Coventry, UK

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