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Mcinnes, C. J., Pirrera, A., Kim, B. C., & Groh, R. (2023). *Fiber Steering for Mass-Efficient Thin Plate Structures*. Abstract from Society of Engineering Science Annual Technical Meeting 2023, Minneapolis, Minnesota, United States.

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University of BRISTOL
Bristol Composites Institute

Fiber Steering for Mass-Efficient Thin Plate Structures

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Society of Engineering Science Annual Technical Meeting 2023

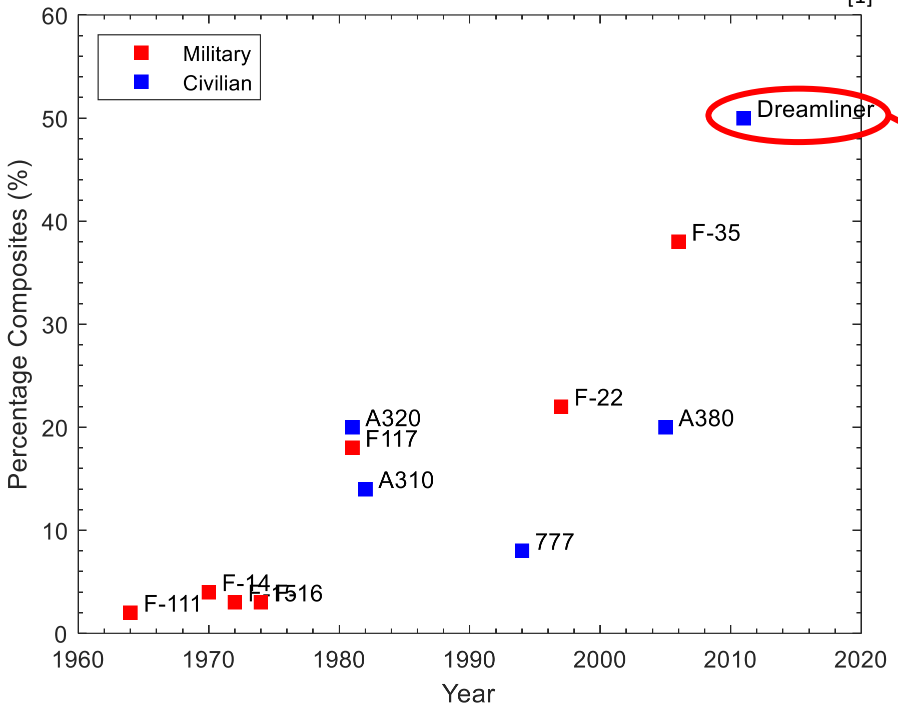
11th October 2023

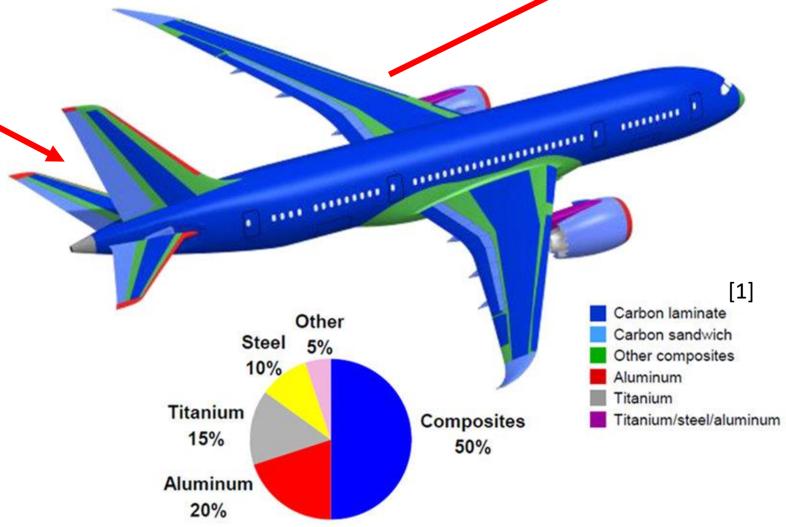
University of BRISTOL
EPSRC Centre for Doctoral Training in Composites Science, Engineering and Manufacturing

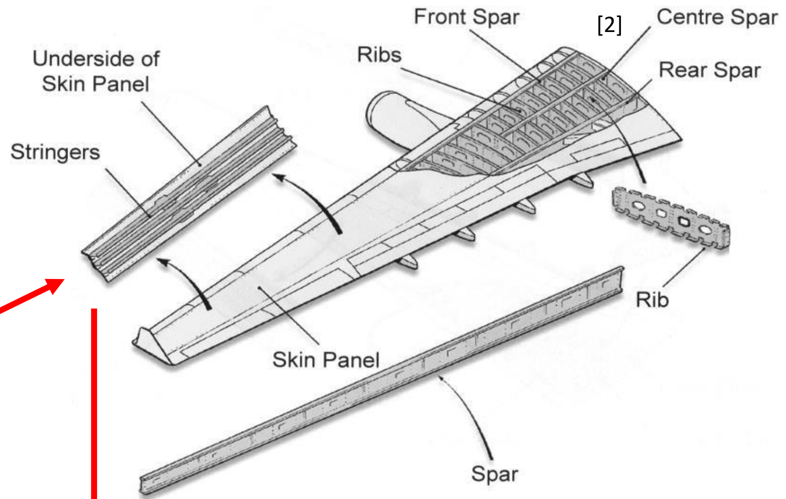
UKRI Engineering and Physical Sciences Research Council

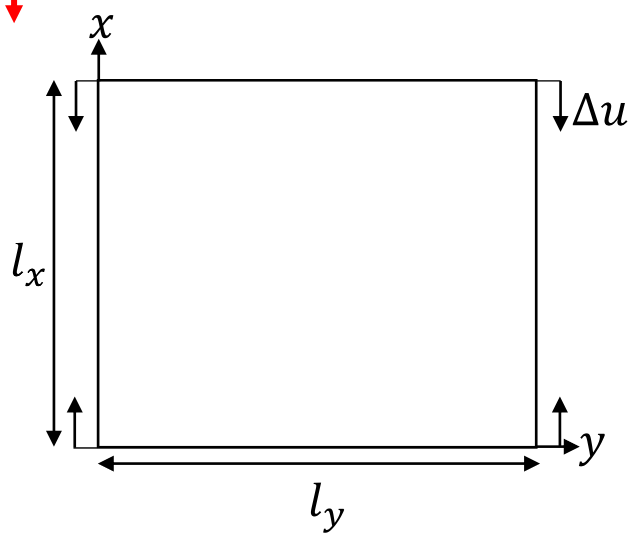
Motivation: Lightweight Structures

- Increasing use of advanced composites in aerospace structures
- **Mass efficiency is a key design driver**
    - Larger payload capacity
    - Lower fuel burn
    - New economic opportunities





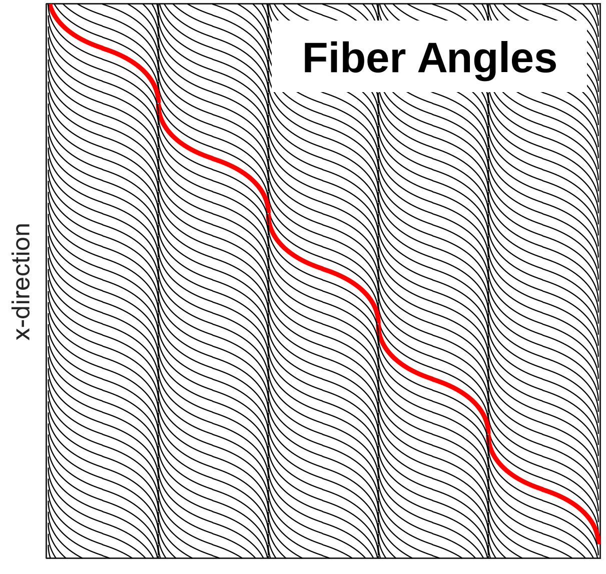




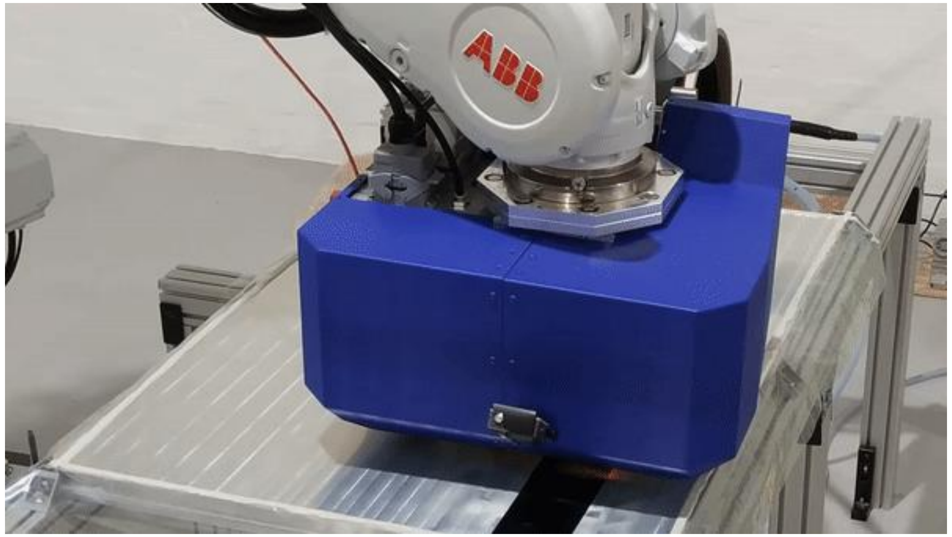
[1] R. Wanhill, Carbon Fibre Polymer Matrix Structural Composites, Springer, 2016
[2] Tiwari et al., Automated inspection using database technology within the aerospace industry, Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture, 2008

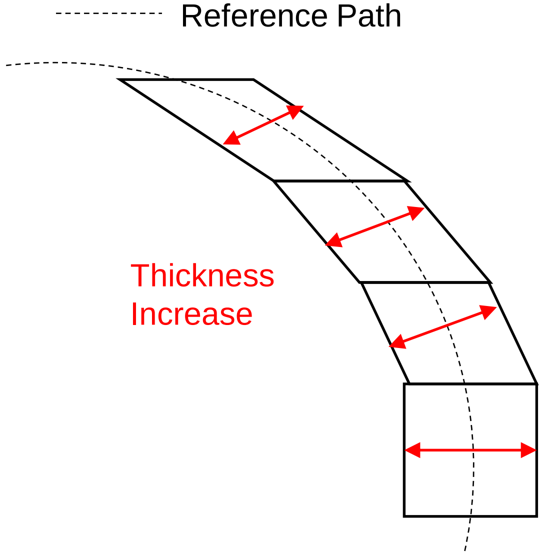
Context: Fiber-Steered Composites

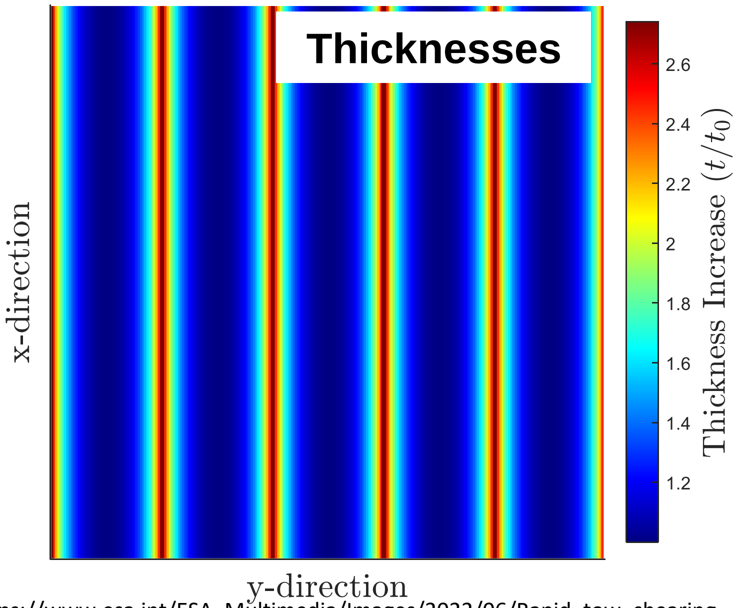
- Steering of composite material tapes produces **non-constant fiber angle across a ply**
- **In-plane shearing of material tows by Continuous Tow Shearing (CTS)** process along curvilinear reference eliminates potential defects and allows tessellation
- CTS process exhibits **nonlinear orientation-thickness coupling** $(t = t_0 \sec\theta)$ and allows **periodic fiber steering**



[2]



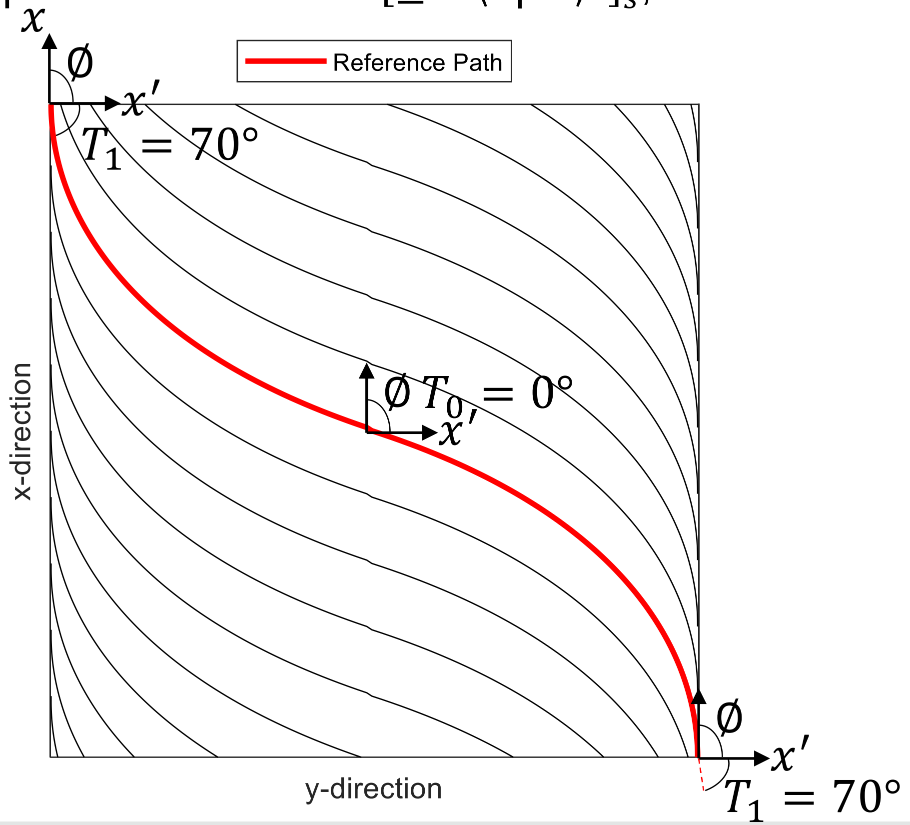


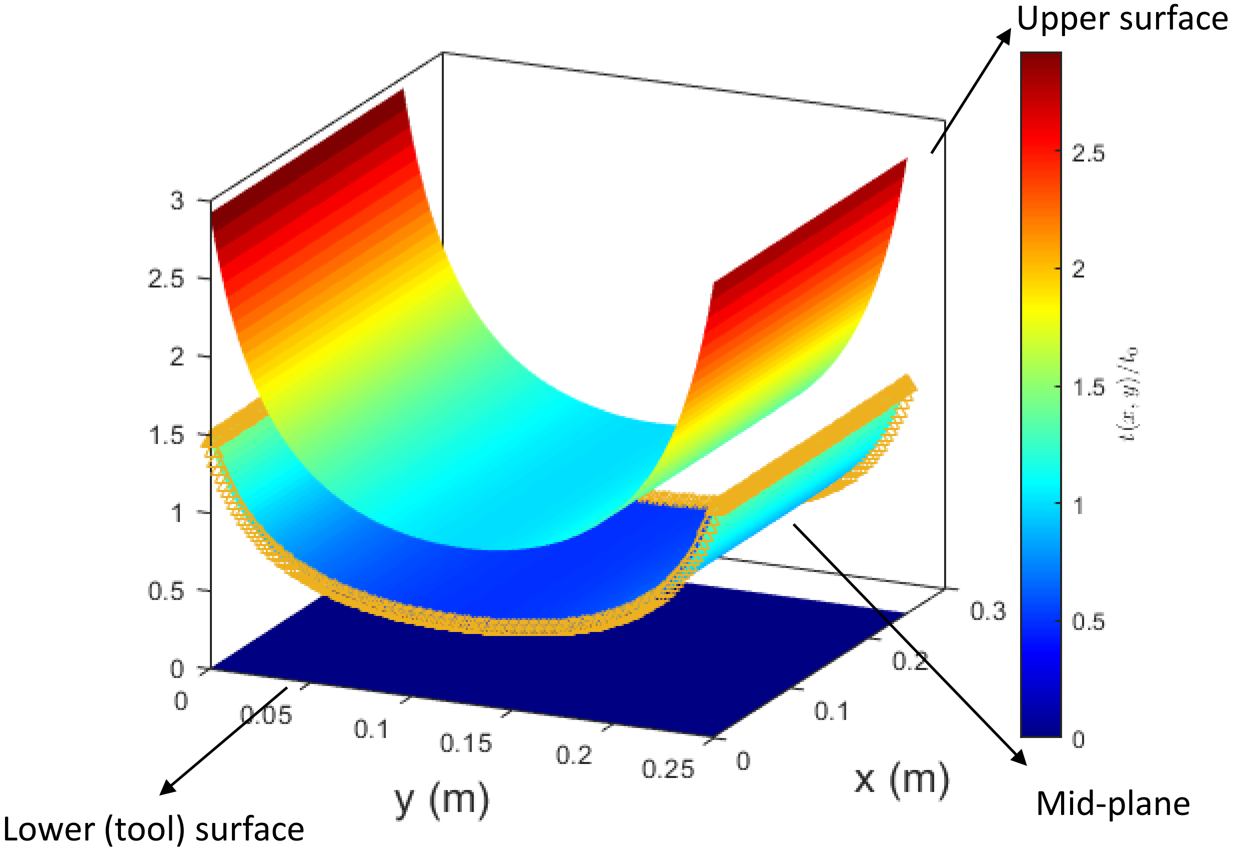


[2] European Space Agency. (2022, May 31). *Rapid tow shearing*. Retrieved from https://www.esa.int/ESA_Multimedia/Images/2022/06/Rapid_tow_shearing

Method: Finite Element Model

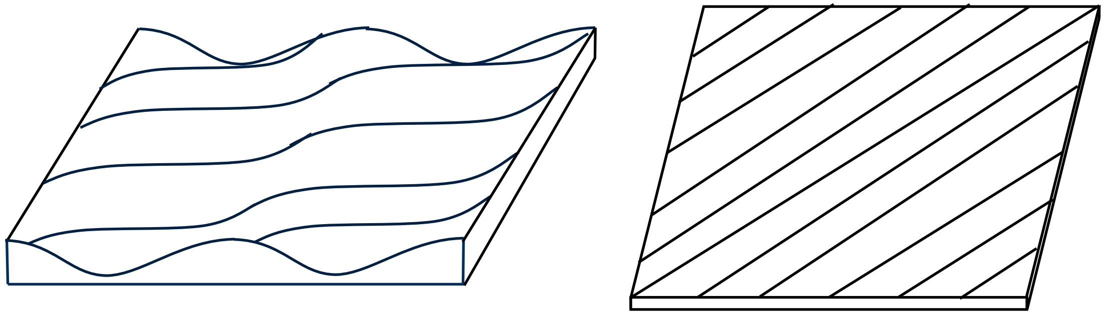
- **Finite Element Method** employed in commercial solver (**ABAQUS**)
  - **Element-wise angle and thickness algorithm** for computation of unique composite sections
  - **Continuum shell elements** (SC8R) necessary **for application of simple support conditions to curved mid-plane**
- Example discretization of $[\pm 90\langle 0|70\rangle^1]_s$,





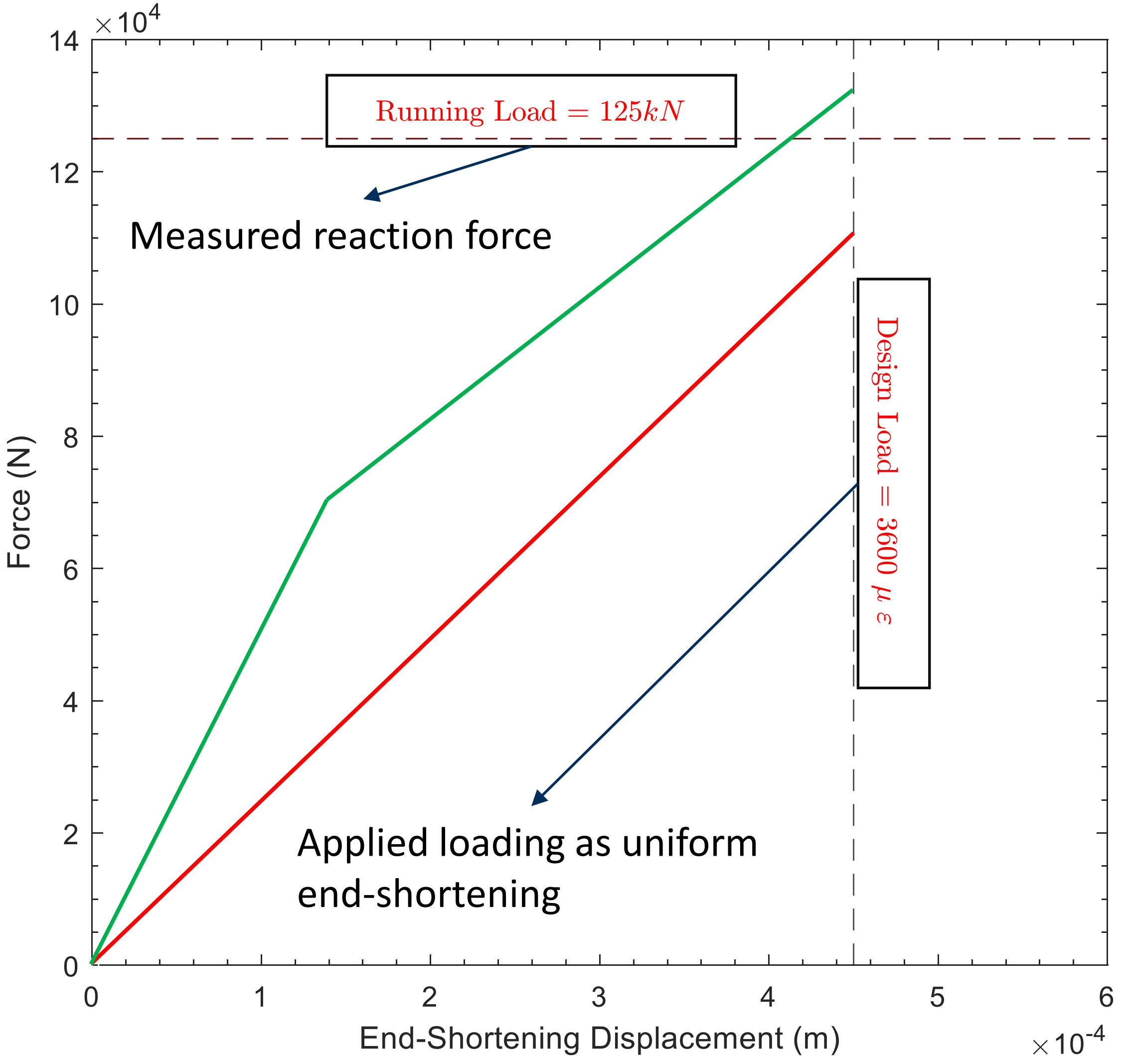
Objective: Design Problem

- Application
  - **Simply supported square aspect ratio panel $(l_x = l_y = 0.25m)$ under uniaxial compression**
- Hypothesis

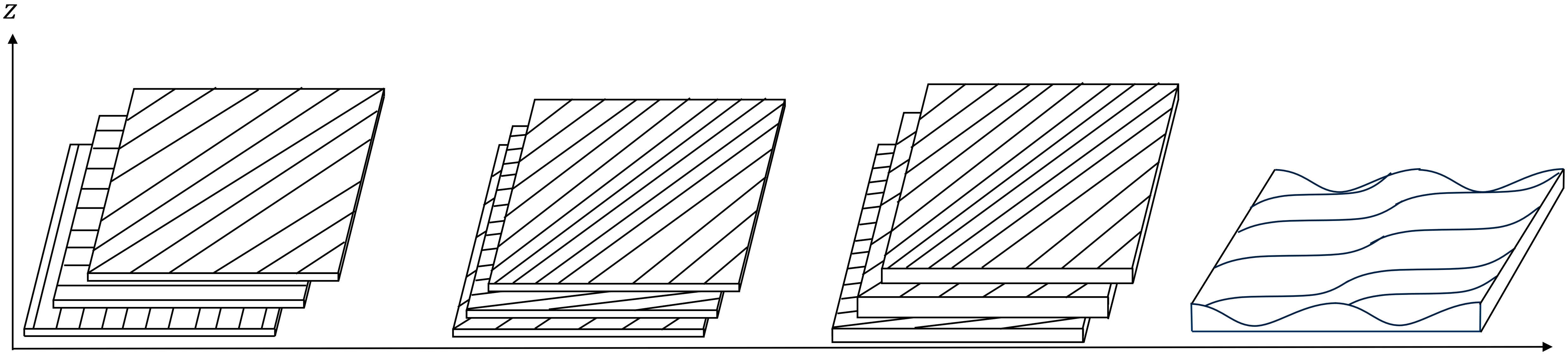


$m^{CTS} < m^{ST}$

- Constraints
  - Design load
  - Minimum load-carrying capacity
  - Tsai-Wu failure criterion
  - Solution stability assurance
  - Balanced and symmetric layups



Method: Elastic Tailoring Potential by Orthotropic Materials

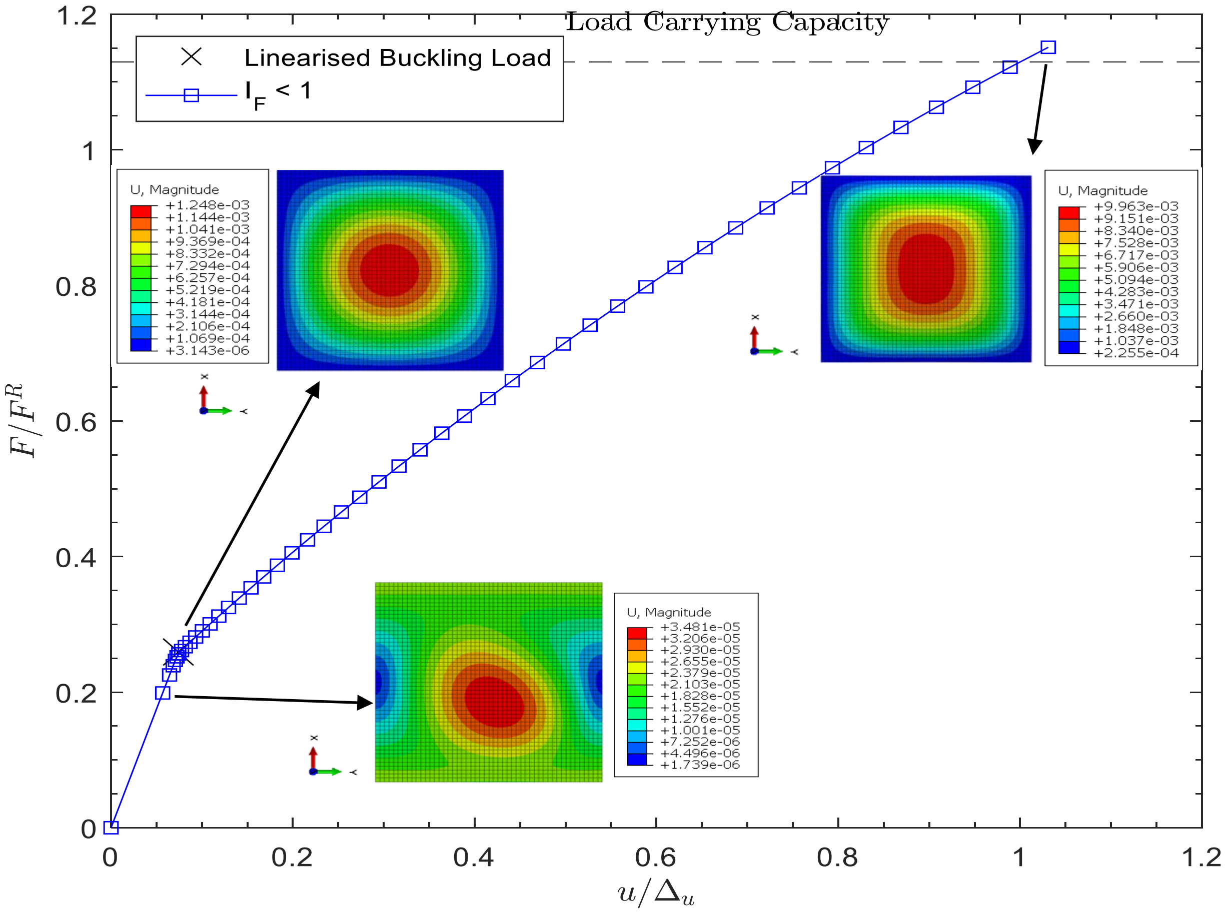


Traditional Angles | Angle Ply | Thickness-Tailored Angle Ply | Fiber-Steered

Tailoring Method	Ply Angles (θ^k)	Ply Thickness (t^k)
Traditional Angles	$[0°, \pm45°, 90°]$	t_0
Angle Ply	$[0°, 1°, 2°, \ldots, 90°]$	t_0
Thickness-Tailored Angle Ply	$[0°, 1°, 2°, \ldots, 90°]$	$t_0 \sec(\vartheta^k)$
Fiber-Steered	$f(x, y)$	$t_0 \sec(\theta^k(x, y))$

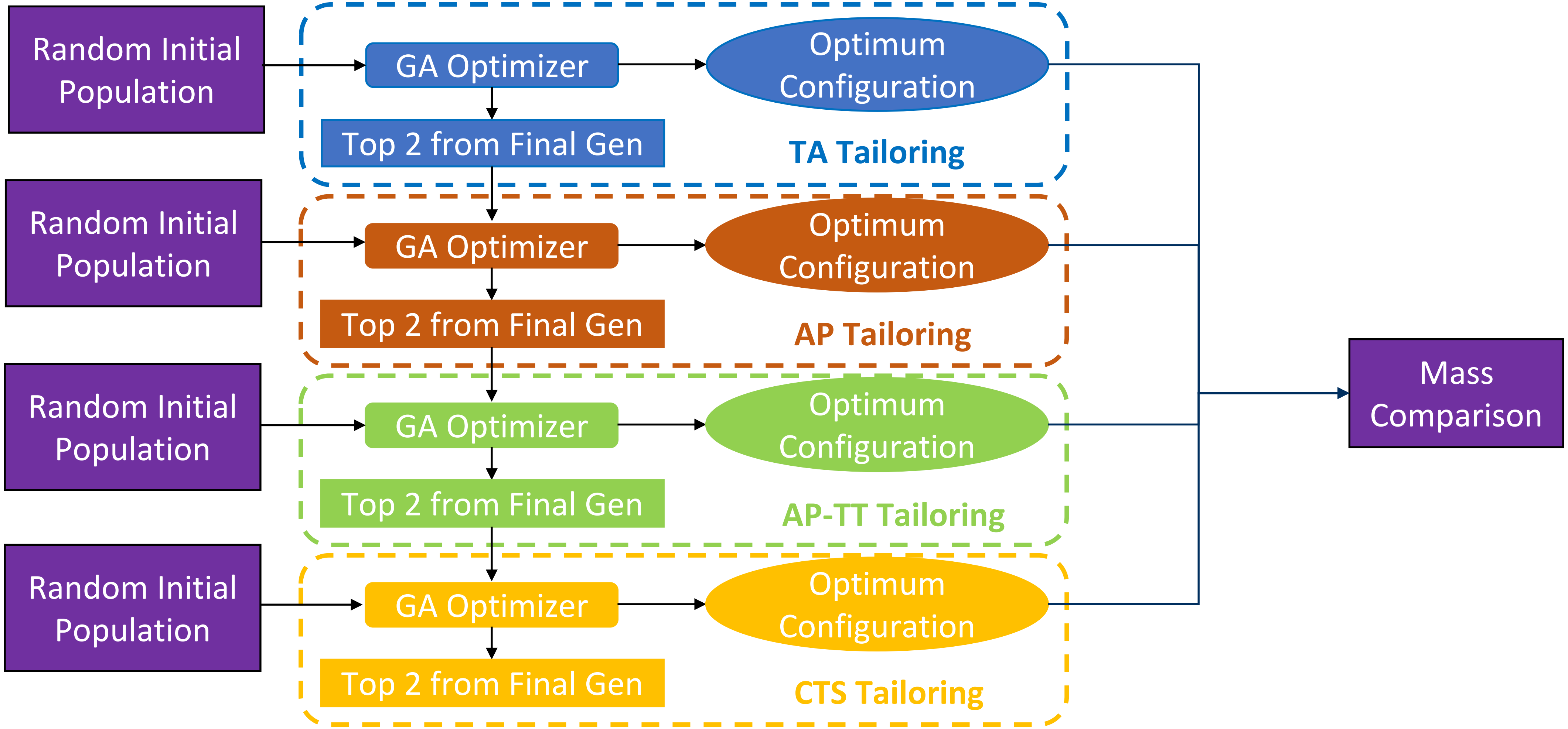
Method: Nonlinear Performance Evaluation

- Linear Buckling Step → $m, \lambda_u, \Phi(x,y)$
- Linear Static Step → P_{cr}
- Nonlinear Riks Step → $F, u, I_F(x,y)$
- Structural Stability → $n_{-\lambda}$
- Load Carrying Capacity Estimation → $F^{3600\mu\varepsilon}$
- Stiffness Evaluation → k_x^{pre}, k_x^{post}
- Fitness Evaluation



$$\min_{\alpha} m(\alpha) \cdot \max\left(1, {F^R}/{F^{3600\mu\varepsilon}}\right)^1 \cdot \max\left(1,\ \max\left(I_F(x,y)\right)\right)^1 \cdot \max(1,\ 1 + n_{-\lambda})^1$$

Method: Optimization Process

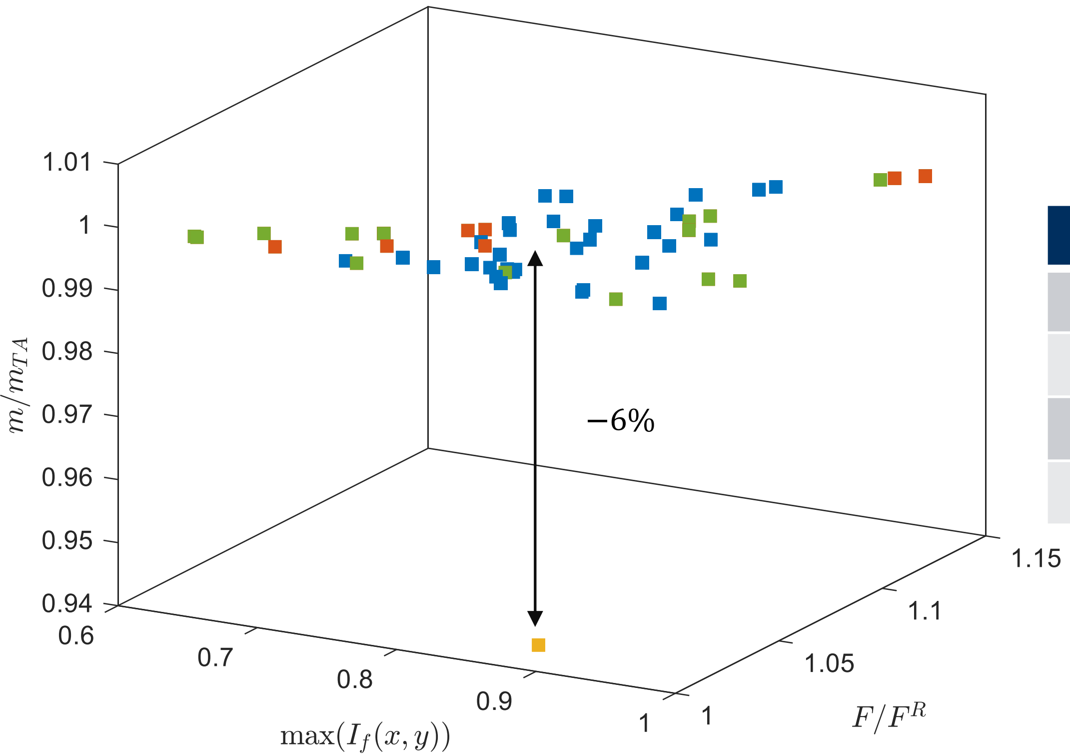


Results: Key Findings

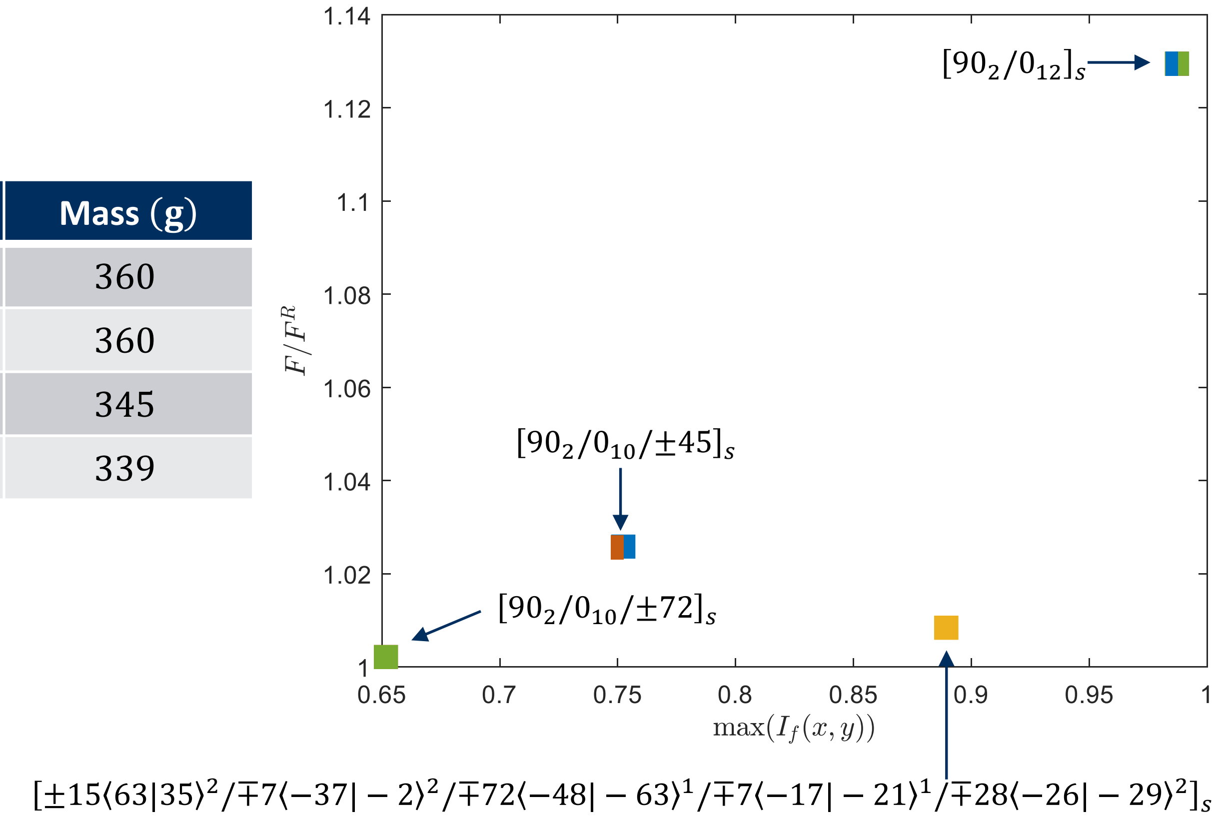
1. **Mass efficiency achievable** by elastic tailoring with orthotropic materials
2. Mass **penalty when fiber steering** by CTS process is high (up to $\sim 3\times$)
3. Fiber steering can result in structural mass efficiency but is **not a catch-all design method**
4. Significant **potential for programmable ply thicknesses** by CTS process

Results: Square Aspect Ratio, $F^R = 0.5kN/mm$

- Dataset extreme value identification as $\left(I_F(\max(F^R)), (\max(F^R))\right)$ and $(\min(I_F), F^R(\min(I_F)))$
  - Several coincident extreme values due to layered optimization methodology



Optimization	Mass (g)
TA	360
AP	360
AP-TT	345
CTS	339



Results: Square Aspect Ratio, $F^R = 0.5kN/mm$

Optimization	Optimized Layup
TA	$[90_2/0_{12}]_s$
AP	$[90_2/0_{12}]_s$
AP_TT	$[\pm 69/\pm 5/\pm 19/\pm 3]_s, [(t_0 \sec 44)_2/(t_0 \sec 70)_2/(t_0 \sec 10)_2/(t_0 \sec 44)_2]_s$
CTS	$[\pm 15\langle 63\|35\rangle^2/\mp 7\langle -37\| -2\rangle^2/\mp 72\langle -48\| -63\rangle^1/\mp 7\langle -17\| -21\rangle^1/\mp 28\langle -26\| -29\rangle^2]_s$

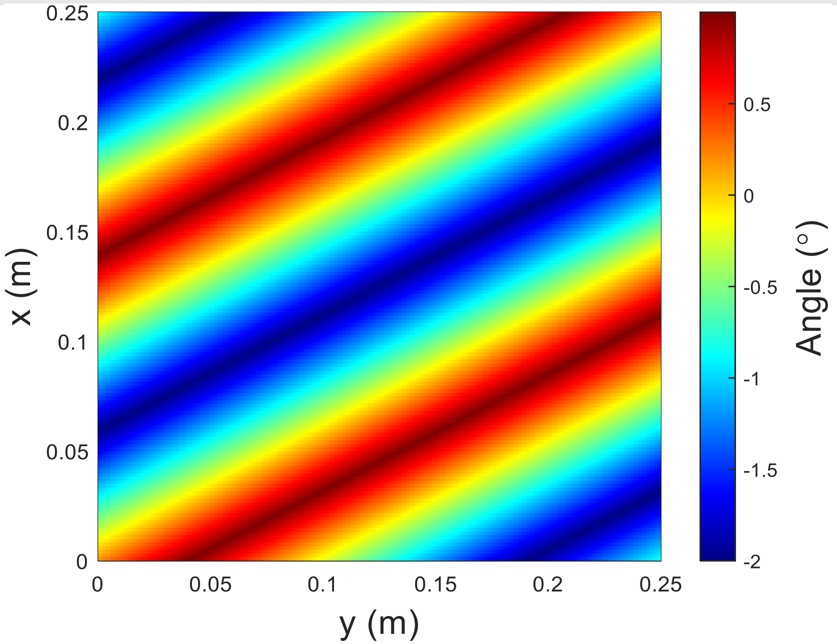
Ply 1

Ply 3

Ply 5

Ply 7

Ply 11



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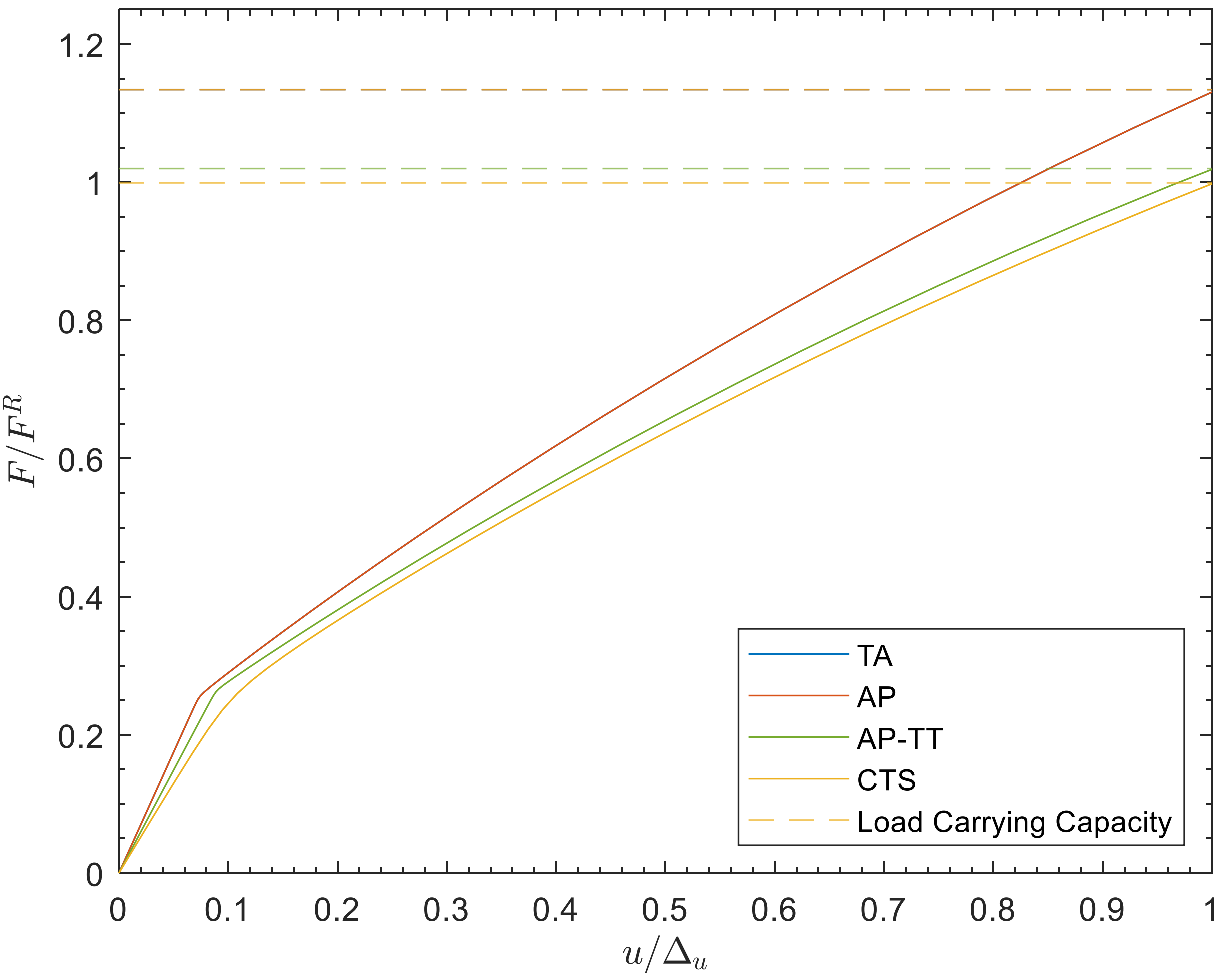
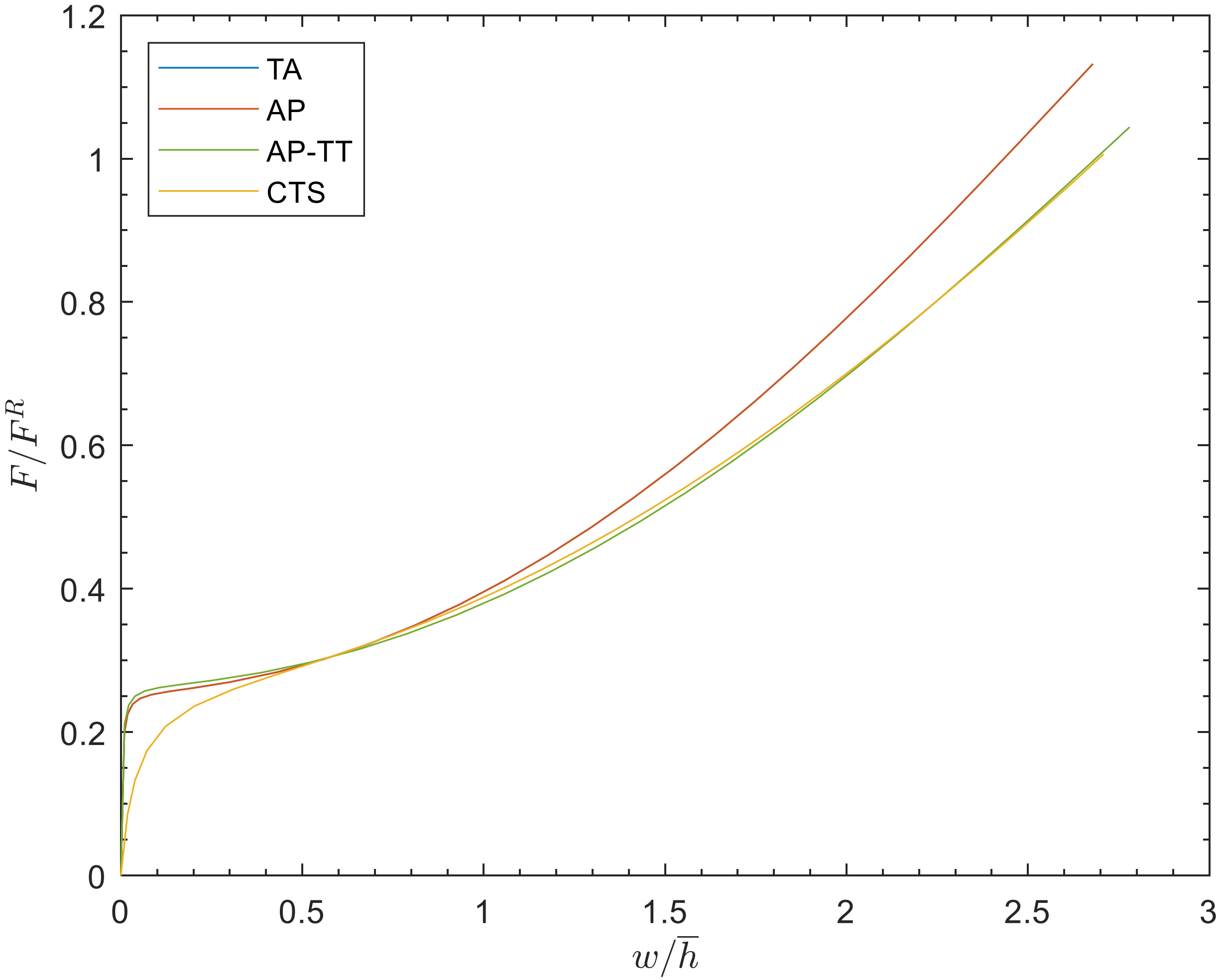
CTS	$[\pm 15\langle 63\|35\rangle^2/\mp 7\langle -37\|-2\rangle^2/\mp 72\langle -48\|-63\rangle^1/\mp 7\langle -17\|-21\rangle^1/\mp 28\langle -26\|-29\rangle^2]_s$

Optimization	m (g)	N_{plys}	$k_x^{pre}\left(\frac{GN}{m}\right)$	$k_x^{post}\left(\frac{GN}{m}\right)$	$P_{cr}(kN)$	$\max\left(I_F^{3600\mu\varepsilon}(x,y)\right)$	$F^{3600\mu\varepsilon}/F^R$
TA	360	28	0.97	0.26	32.4	0.99	1.13
AP	360	28	0.97	0.26	32.4	0.99	1.13
AP_TT	345	16	0.83	0.23	33.4	0.96	1.02
CTS	339	20	0.72	0.23	36.0	0.89	1.01

Results: Square Aspect Ratio, $F^R = 0.5kN/mm$

- Load-displacement history (L) and equilibrium curve (R) of optimized structural configurations

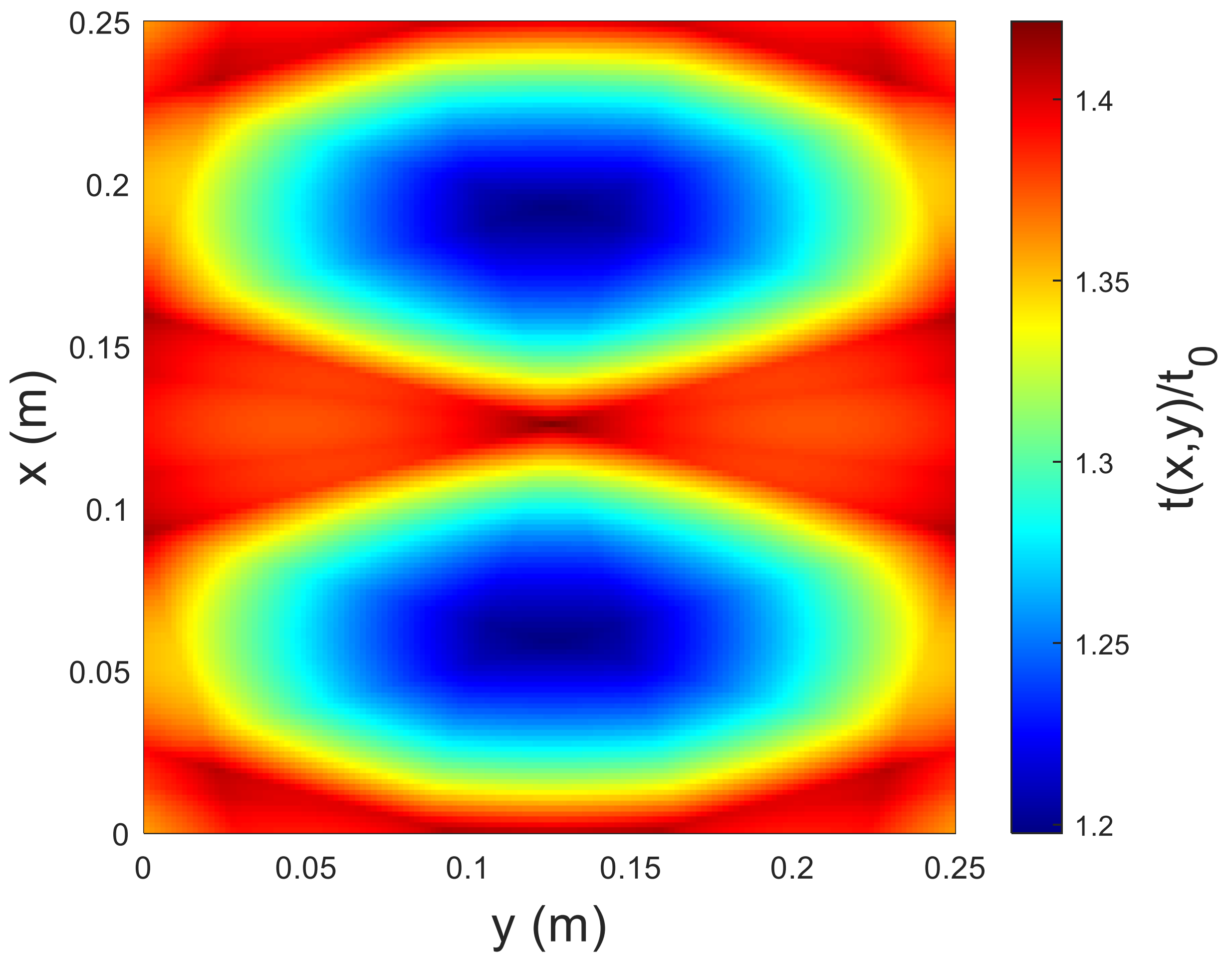




Conclusions & Future Work

- **Mass efficiency achievable by elastic tailoring with orthotropic materials**
- **Mass penalty when fiber steering by CTS process is high (up to 3x)**
- **Fiber steering can result in structural mass efficiency**
- **Significant potential for programmable ply thicknesses by CTS process**

- Aspect ratio change
- Increased minimum load carrying capacity



Acknowledgements

- This work was supported by the Engineering and Physical Sciences Research Council through the EPSRC Centre for Doctoral Training in Composites Science, Engineering and Manufacturing [grant number EP/S021728/1]
- This work was carried out using the computational facilities of the Advanced Computing Research Centre, University of Bristol – http://www.bris.ac.uk/acrc/

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Questions?

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