Damage Tolerance of Tow-Placed, Variable Stiffness Laminates

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Main Goal

Development of methodologies to predict the structural integrity of fibre-steered laminates

Experimental Investigation

- Material testing
- Progressive damage leading to structural collapse
- Structural damage produced by low-velocity impacts

Numerical Simulations

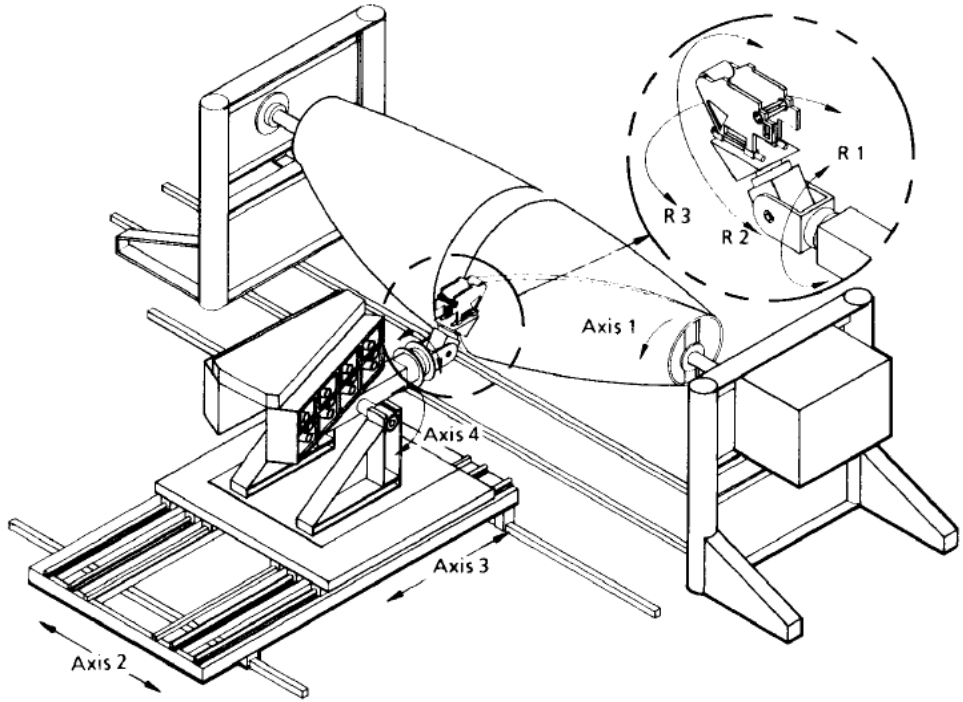
- Physically-based constitutive models able to represent damage onset, progress and failure
- Finite Element Analysis
- Micromechanical models

Tow-Placed, Variable-Stiffness Laminates

Tow- Placement Technology

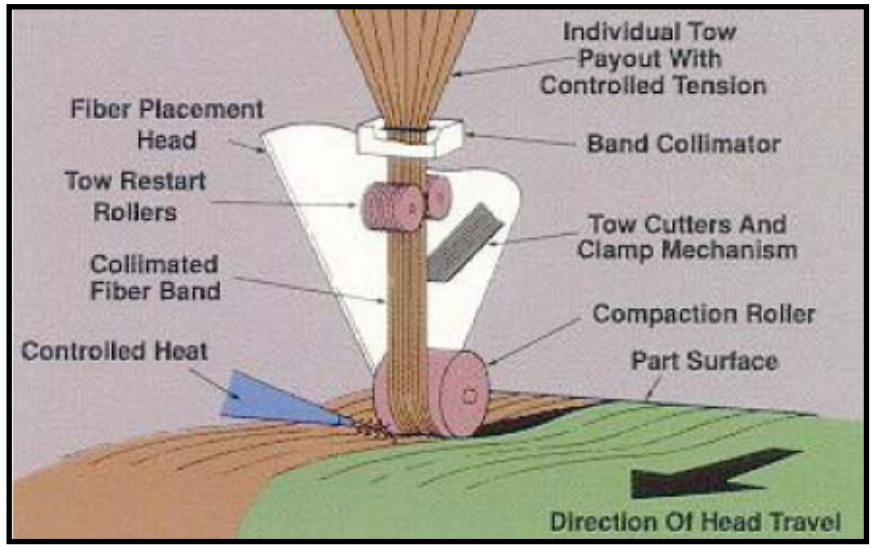
Tow-Placement Systems
(e.g. Cicinnati, Hercules, Automated Dynamics)

- 7 degrees of freedom
- Full automation
- Off-line programming and simulation
- Fabrication of parts over 10m in length
- Multi-purpose tow-placement head



Tow-Placed, Variable-Stiffness Laminates

Tow- Placement Technology: Tow-Placement Head



Tow: ~3mm wide bundle of (graphite, fibreglass, kevlar…) fibres pre-impregnated with "tacky" termoset epoxies, i.e. adheres to a surface.

Tow-Placed, Variable-Stiffness Laminates

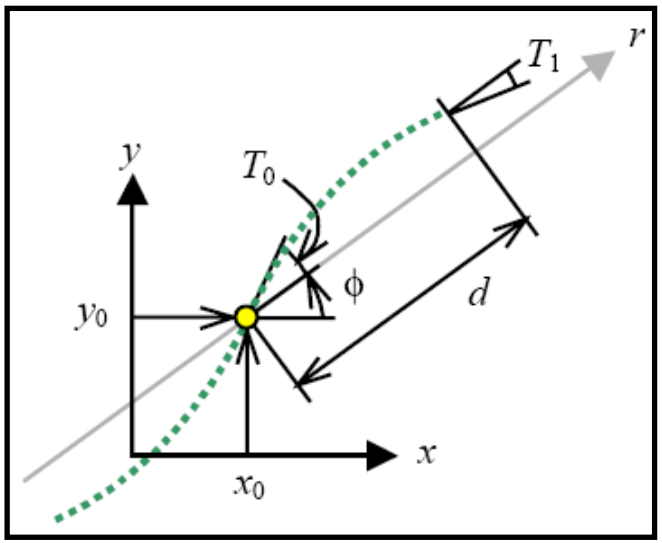
Tow-Placement Technology: Advantages

- **Individual tow handling**
  - 16 to 32 tows are fed individually
- **Tow cut and restart capabilities**
  - Path overlapping can be prevented
- **Differential payout system**
  - Curved tow-paths are allowed (75cm min. turning radius to avoid fibre-buckling)
- **Controlled compaction & Low-tension positioning**
  - Curved tow-paths
  - Concave surfaces are possible (within the limits of the placement head dimensions)
- **Precise output control**
  - Part design is accurately reproduced. “Exact” replicas can be manufactured
- **Reduced material scrap and post-cure machining**
  - Tow-cut capability used to handle part edges
- **Speed**
  - Up to 7 times faster than hand-layup
- **Design flexibility**
  - “Comparable” to hand-layup

Tow-Placed, Variable-Stiffness Laminates

Current Designs

Linear variation of the fibre orientation angle: $\varphi(r) = (T_1 - T_0)\frac{r}{L} + T_0$



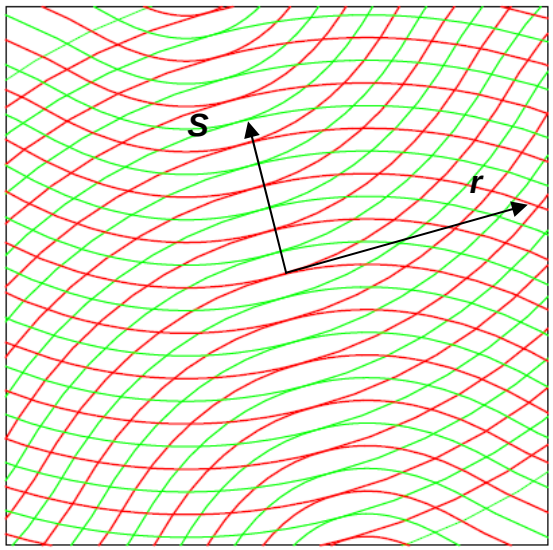
Notation: $\Phi\langle T_0 \mid T_1 \rangle$

Examples: $0\langle 30 \mid 60 \rangle, 90 \pm \langle 75 \mid 30 \rangle_2, \left[\pm 45 / 90 \pm \langle 0 \mid 45 \rangle_2 \right]_S$

Tow-Placed, Variable-Stiffness Laminates

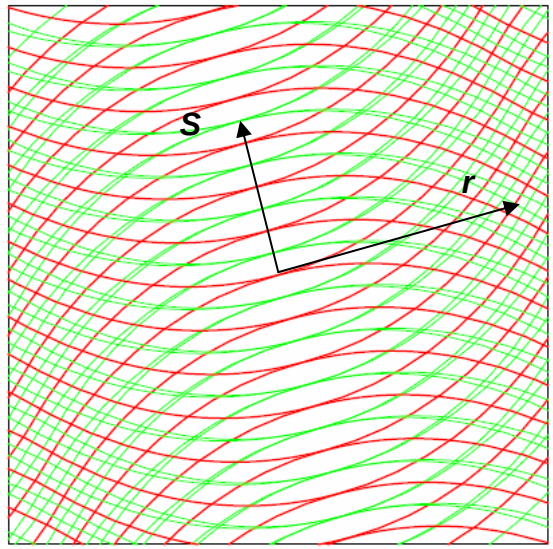
Construction Methods

Parallel Tow Paths



- Two-dimensional stiffness variation

Shifted Tow Paths

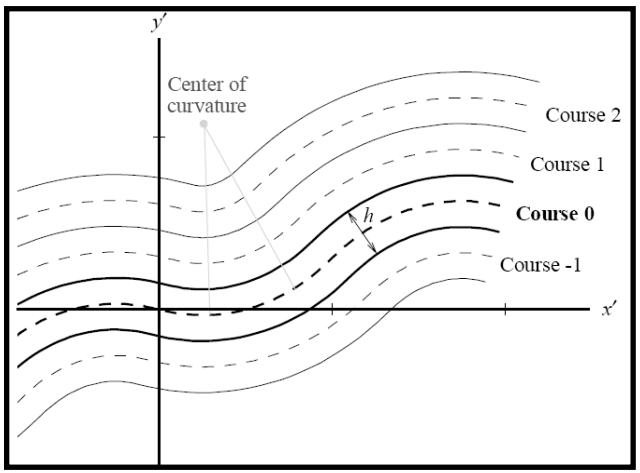


- One-dimensional stiffness variation (along the r-direction)

Tow-Placed, Variable-Stiffness Laminates

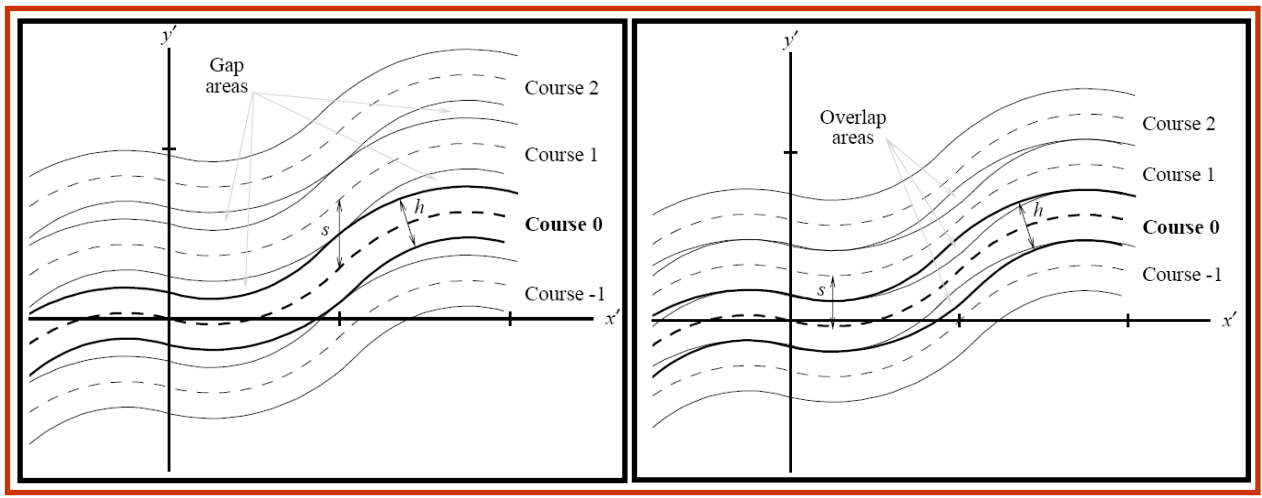
Construction Methods

Parallel Tow Paths



- No overlaps or gaps

Shifted Tow Paths

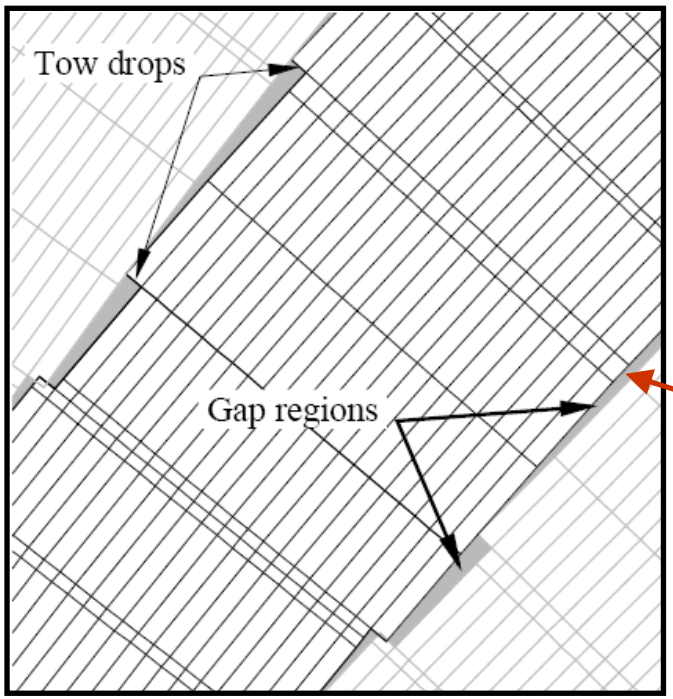


- Gaps or overlaps

Tow-Placed, Variable-Stiffness Laminates

Shifted Tow-Paths

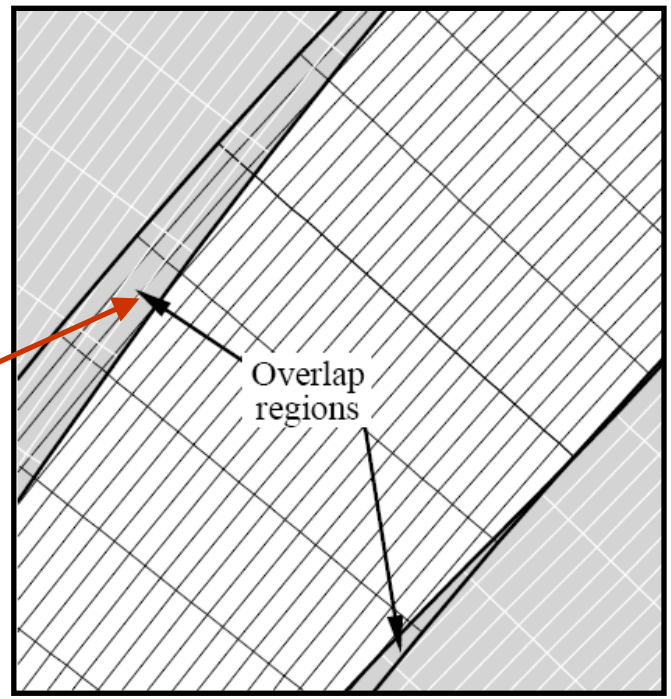
Tow-Drop Method



Constant Thickness

Weak spots!
Onset of damage

Overlap Method

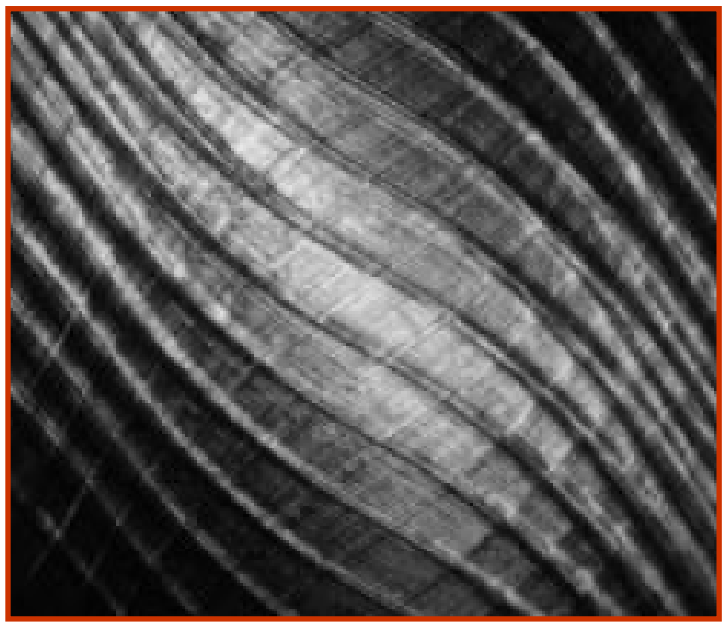


Thickness Build-up

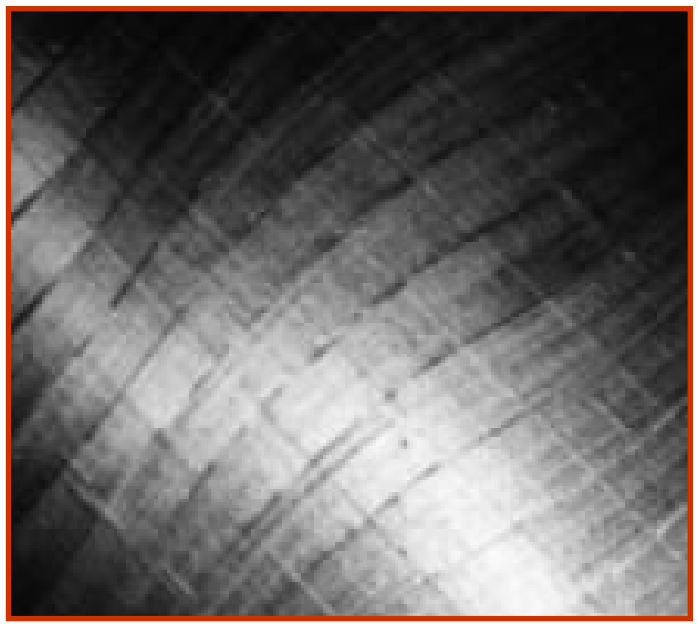
Tow-Placed, Variable-Stiffness Laminates

Shifted Tow-Paths

Overlap Method



Tow-Drop Method



Approach

1. Global progressive failure analysis of tow-steered laminates
   - Physically-based failure criteria (*e.g.* LaRC04)
2. Homogenization of *tow-drop* and *overlap* regions by the *Method of Inclusions*.
   - Development of a visualization tool capable of describing the exact tows+matrix geometry, perform homogenization and export to FEM (if necessary)
3. In-depth failure analysis of *tow-drop* and *overlap* regions.
   - Micromechanical analysis
4. Structural experiments
   - Static and impact tests on critical configurations. Focus on *tow-drop* and *overlap* regions.
   - Characterization of the damage onset, progression and failure behavior.
5. Validation of numerical simulations.
6. Optimization of tow-steered laminates for damage propagation and failure.

Failure Analysis of Tow-Steered Laminates

Example: 20 layer panel under tension load

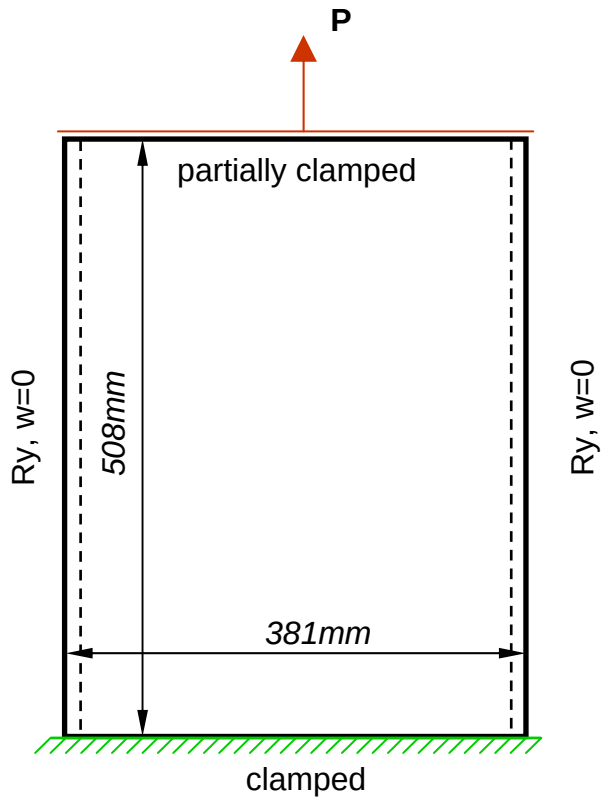
Layups, optimized for compressive buckling loads:

Straight-fibre

$$\left[\pm 45_2/\pm 30/\pm 45/\pm 15\right]_S$$

Parallel, Shifted (tow-drop & overlap)

$$\left[\pm 45/0\pm\langle 45|60\rangle_2/0\pm\langle 30|15\rangle/0\pm\langle 45|60\rangle\right]_S$$



AS4/9773 graphite-epoxy

E_{11}	E_{22}	G_{12}	ν_{12}	t
130GPa	9.2GPa	5.1GPa	0.36	0.1905mm
X^T	X^C	Y^T	Y^C	S^L
2.1GPa	1.2GPa	29.0MPa	157.9MPa	91.0MPa

Failure Analysis of Tow-Steered Laminates

Results

Configuration		Compressive Buckling		First Ply Failure			
		Load (kN)	Diff. %	LaRC03 (kN)	Diff. %	Tsai-Wu (kN)	Diff. %
Straight-Fibre		52	-	105	-	98	-
Parallel		54	3.8	143	36	120	22
Shifted	Tow-Drop	62	19.2	190	80	170	73
	Overlap	94	80.8	450	328	400	308

Damage Tolerance of VS Laminates

Acknowledgements

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