Thin ply technology advantages*

An overview of the TPT-TECA project

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Ecole polytechnique fédérale de Lausanne (EPFL), Switzerland

In partnership with North-TPT, FHNW, RUAG Technology, RUAG space, and Connova

* Including a few drawbacks
Introduction to Project TPT-TECA

**Goal:**
Characterize, optimize and demonstrate the technical and economical advantages of the Thin-ply technology developed by North TPT

*Industrial / academic collaboration project*

**Mechanical performance**
- Prediction models
- Optimal design of benchmark parts

**Material development**
- Production technology & implementation

**Rheo-kinetics testing and modeling**
- Process cycle optimisation

**Together ahead. RUAG**
- Bearing strength
- Satellite panel demonstrator part

**Fachhochschule Nordwestschweiz**
- Helicopter structural part demonstrator
- Evaluation of production time and cost savings

**Commission pour la technologie et l'innovation CTI**

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**EPFL**
- École Polytechnique Fédérale de Lausanne

**North TPT**
- Thin-ply technology

**Connova**
- Material development
Introduction to Project TPT-TECA

WP1 Resin development
Createx

WP2 Material & process optimization
FHNW

WP3 Optimal ply thickness
EPFL / RUAG Tech.

WP4 Mechanical characterization
EPFL

WP5 Optimal scarf joint design
EPFL

WP6: vacuum bag process optimization

WP7 Application benchmarks:
performance & system cost comparison
Brühlmeier, RUAG Space

Go / No Go: suitable baseline performance & no critical issues

End: March 1st 2012

Project timeline 24 months

Go / No Go: compatibility with process, advantages of thin-ply

Today

Thin-ply composites: performance and system cost optimization

End: March 2014
Study of ply size effects

Method:
- Comprehensive study of composite properties and ‘thin ply’ effects
- Properties at Lamina/Laminate/Element levels (same as Mil Hdbk 17)
- Resin and fibre fixed (same batch):
  UD prepreg TP80ep toughened epoxy / 55%vol M40JB, autoclave production
- Tests performed at three ply thicknesses: 30g/m2, 100g/m2, 300g/m2
- Constant laminate thickness and specimen dimension, only change ply thickness
- Scaling: Ply or sub-laminate repetition (+ half-angle / optimized laminates)

Questions to be addressed:
- Will thin plies make my part stronger – qualitatively?
- How to simulate / predict ply size effects?
- Design methods towards part level modeling and design?
ThinPly composites: design performance advantages

Click one of the icons below to learn more about Thin Ply composites performance in a specific area

Lamina & Laminate
Open Hole & Fatigue
Bolted joint & Ageing
Impact Damage Resistance
Part Design & Analysis

... or just continue reading normally to have a full overview
### WP4 test matrix

<table>
<thead>
<tr>
<th>Properties</th>
<th>Test</th>
<th>Related standard ( guideline )</th>
<th># specimen tested / produced</th>
<th>Specimen type</th>
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<tr>
<td>Element level</td>
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<td>Checklist</td>
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<tr>
<td>Simulation</td>
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</tr>
<tr>
<td>Design</td>
<td></td>
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</tbody>
</table>

#### Measurements:
- Strain gages
- Acoustic emission
- Digital image correlation
- C-Scan

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**Intro**

**Ply and interface failure**

**Ply size effect**

**Lamina level**

**Laminate level**

**Element level**

**Checklist**

**Simulation**

**Design**
Lamina properties TP80ep/M40JB 55%vol

<table>
<thead>
<tr>
<th>Property</th>
<th>Direction</th>
<th>Symbol</th>
<th>Unit</th>
<th>Test</th>
<th>Related standard</th>
<th>Thin (30g/m²)</th>
<th>SDEV</th>
<th>[%]</th>
<th>Intermediate (100g/m²)</th>
<th>SDEV</th>
<th>[%]</th>
<th>Thick (300g/m²)</th>
<th>SDEV</th>
<th>[%]</th>
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<td>Tensile modulus</td>
<td>E1</td>
<td>[GPa]</td>
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<td></td>
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<td>2.22 ± 14</td>
<td>6.22</td>
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<tr>
<td>Ultimate tensile strain</td>
<td>σ_1</td>
<td>[%]</td>
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<td>891 ± 0.63</td>
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<td>891 ± 0.63</td>
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<td>0.27</td>
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<td>1.01 ± 0.04</td>
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<td>0.08 ± 0.01</td>
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<td>15.0 ± 8</td>
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<td>213 ± 7.23</td>
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<td>784 ± 120</td>
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<td>0.00 ± 0.06</td>
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<tr>
<td>Shear chord modulus</td>
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<td></td>
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<td>97.8 ± 2</td>
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<td>97.8 ± 2</td>
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<td>Maximum shear stress at 0% offset</td>
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<td>4.06 ± 0.14</td>
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<td>4.06 ± 0.14</td>
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<td>ε_p</td>
<td>[%]</td>
<td></td>
<td></td>
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<td>83.2 ± 2.05</td>
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<td>83.2 ± 2.05</td>
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<td>83.2 ± 2.05</td>
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<td>Maximum shear stress at 2% offset</td>
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<td>1.8 ± 0.05</td>
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<td>Maximum shear stress at 0.2% offset</td>
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<td>[GPa]</td>
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<td></td>
<td></td>
<td>50.2 ± 1</td>
<td>1.99</td>
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<td>50.2 ± 1</td>
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<tr>
<td>In-plane shear stress</td>
<td>τ_2</td>
<td>[GPa]</td>
<td></td>
<td></td>
<td></td>
<td>46.8 ± 0.04</td>
<td>3.42</td>
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<td>46.8 ± 0.04</td>
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<td>46.8 ± 0.04</td>
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<td>Total in-plane shear stress</td>
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<td>[GPa]</td>
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<td>1.29 ± 0.04</td>
<td>3.42</td>
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<td>1.29 ± 0.04</td>
<td>3.42</td>
<td></td>
<td>1.29 ± 0.04</td>
<td>3.42</td>
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</tr>
</tbody>
</table>

Overall no change in intrinsic lamina properties except **compression**.
Lamina level ‘thin ply’ effects

Compressive strength UD 0° (ASTM D5467*)

- Thin Ply leads to a more uniform microstructure and improved 0° compressive strength

Thick 300 g/m²

Intermediate 100 g/m²

Thin 30 g/m²
Laminate properties

Quasi isotropic laminate tensile test (ASTM D3039) [45°/90°/-45°/0°]ns

- Failure mode transition from progressive transverse cracking & delamination to quasi brittle failure
- For thick ply (n=1), onset of damage at ~50% of ult. strength
- Nearly no damage in thin ply before failure

Acoustic emission damage monitoring

Thin 30g/m² & Interim. 100g/m²

Thick 300g/m²
Laminate properties

Quasi isotropic laminate tensile test (ASTM D3039) \([45^\circ/90^\circ/-45^\circ/0^\circ]\)ns

- Thin Ply “ply-level” scaling not better than Thick => Thin ply effect is not an intrinsic ply property.
- Strong effect of number of ply thickness is related to the number of sub-laminate repetition:
  - Thick, \(n=1\): progressive damage, low onset of damage
  - Intermediate, \(n=3\): mixed failure (delamination and macro “through” crack), improvement in strength and damage onset
  - Thin, \(n=10\): brittle failure with one macro “through” crack, best strength and damage onset, behaves like an homogeneous brittle solid
- Half angle laminate slightly weaker than standard QISO
Open Hole Tensile fatigue

Open Hole Tensile: static and fatigue [45°/90°/-45°/0°]ns (ASTM D5766 & D7615, R=0.1)

- Strong improvement in fatigue life @316MPa (10k vs 1M cycles)
- Lower ultimate strength. No damage around hole means no stress concentration relief but better predictability (Wisnom & al, Mollenhauer)

Fatigue criterion = -10% stiffness
Open Hole Compression

Open Hole Compression $[+45°/90°/-45°/0°]_n$ (ISO 14126 / ASTM D6484)

- **OHC Strength [MPa]**
  - QI_thin: 255.0
  - QI_int: 229.7
  - QI_thick: 215.9
  - QI_thinOPT: 236.8
  - QI_thinPL: 186.8

+18%
Bolted joint bearing strength

Single lap bearing test*, Hot Wet condition (ASTM 5961), fastener type EN-6115
ThinPregTM80EP 55%vol M40JB as produced @20°C and Hot Wet cond. 95%RH/70°C, test 90°C

Thick Ply 300g/m2 n=2
Intermediate 100g/m2 n=5
Thin Ply 30g/m2 n=18

As produced, 20°C
Hot Wet 90°C

\( \sigma_{br\_ult} = 156 \text{ MPa} \)
\( \sigma_{br\_ult} = 476 \text{ MPa} \)
\( \sigma_{br\_ult} = 573 \text{ MPa} \)
\( \sigma_{br\_ult} = 294 \text{ MPa} \)
\( \sigma_{br\_ult} = 584 \text{ MPa} \)
\( \sigma_{br\_ult} = 372 \text{ MPa} \)

- Strength improvement for as produced @ 20°C \(\rightarrow +18\%\)
- Strength improvement for Hot Wet @ 90°C \(\rightarrow +58\%\)

*+[+45°/90°/-45°/0°]ns
**Structural element properties**

<table>
<thead>
<tr>
<th>Structural Element</th>
<th>Test Method</th>
<th>ASTM Reference</th>
<th>Value</th>
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</thead>
<tbody>
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<td>Fatigue limit</td>
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<tr>
<td>Fatigue limit</td>
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<tr>
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<td></td>
<td>380</td>
</tr>
<tr>
<td>Ultimate strain</td>
<td></td>
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<td>146</td>
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</tbody>
</table>

- **OHT**: lower ult. strength but higher onset of damage, more brittle
- Strong improvement of most properties, delamination and damage in off axis plies are nearly suppressed
- Much improved hot wet properties as weakening of the matrix is less critical in thin plies (still no delamination)
- No damage means a better predictability and durability.
Low energy impact

- Rectangular specimen clamped on the short sides; bending is dominant
  - $QI [0^\circ/+45^\circ/90^\circ/-45^\circ]_{ns}$, 300 x 140 x 2.4 mm
  - Thick (300 g/m$^2$) $n=1$, Intermediate (100 g/m$^2$) $n=3$, Thin (30 g/m$^2$) $n=10$

- Energy: 11.5 J & 18J

- Transition of failure mode from delamination to fiber failure

- An optimal ply thickness can be found to achieve the smallest damage area

- Thin-Ply technology allows tailoring the material properties with respect to impact induced damage
‘Thin ply’ effects at different scales

**At the lamina level**
- More uniform microstructure, lower local variation of fiber Vf and finer voids
- Improved longitudinal compressive strength

**At the laminate level**
- Delay or suppression of delamination as damage / failure mechanism
- Delayed transverse cracking => apparent increase of transverse tensile strength
- Increased QI laminate onset of damage and ultimate strength
- Increased laminate fatigue strength *But more brittle, sensitive to stress concentrators!* 

**At the structural component level**
- Notched tests: improved onset of damage and fatigue life increase; more brittle response but better predictability
- Bolted joint strength: strong strength improvement in hot-wet conditions
- Impact effects: from delamination to fiber failure, optimal ply thickness is « intermediate ».
Will thin plies make my part stronger?

If it has one or more of the following features:

- Compressive strength critical
- Free edges
- Open holes (damage onset)
- Fastener connections
- Fatigue and impact loading
- Delamination cracks are the main concern
- Optimization is limited by ply thickness

... the answer is probably yes!

But how to quantify the benefits in a predictable manner?

Need new analysis models and better design & optimization methods to deal with potentially more design degrees of freedom.

.. but as the failure modes are simpler, predictability should be easier to reach too!

Read further for on going developments towards that goal...
Simulation of ‘thin ply’ effects

- Goal: capture the transition in dominant failure mode in order to understand and predict ply size effects
- Hypotheses: no change in lamina and interface properties

3D modeling of quasi isotropic unnotched tensile test in Abaqus Explicit
Damage models: cohesive interfaces between plies, cohesive elements for transverse cracking, continuum damage model for fiber failure

Work in progress

All data = from testing!
Simulation of ‘thin ply’ effects

- First results on thick ply QISO unnotched tension

- Cohesive elements = transverse cracking (all layers)

- Blue dots = fibre failure

- Blue = undamaged >>> Red = delamination

Damage sequence:

- Cracking of 90° & 45° plies, delamination 90° / -45° plies from free edges
- Shear failure of 45° plies, delamination 0° / -45° from free edges
- Fiber failure in 0° plies
Simulation of ‘thin ply’ effects

Thick, n=1 – EXPERIMENTAL (c-scan)

Thick, n=1 – NUMERIC (CSDMG)

Intermediate, n=3 – NUMERIC (CSDMG)

Intro

Lamina level

Laminate level

Element level

Simulation

Design

Conclusion

250 MPa

300 MPa

350 MPa

400 MPa

450 MPa

500 MPa

550 MPa

600 MPa

650 MPa

700 MPa
Simulation of ‘thin ply’ effects

- Damage energy, QISO unnotched tension
  - Work in progress

Good predictions for thick ply composites (300g/m2) for both onset of damage and ultimate strength.

Future: parametric study, extension to open hole and other cases
Towards part level modeling and design

- Even though ply size effects might be captured by detailed 3D FE modeling, computation cost makes it unsuitable for part level analysis; we need a way to up-scale the analysis (i.e shell models).

- Homogenization and parametric meso-scale analysis could provide laminate level failure envelopes for shell models. Specific strategy needs to be developed for free-edge crack stability analysis though.

- As delamination and transverse cracking are less an issue, standard shell models and laminate theory might be closer to the reality of Thin Ply composites than standard composites!

### Table

<table>
<thead>
<tr>
<th>Model</th>
<th>First ply failure</th>
<th>0° ply failure</th>
<th>Experiment</th>
<th>Damage</th>
<th>Ult strength</th>
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</thead>
<tbody>
<tr>
<td>CLT no damage</td>
<td>287 MPa</td>
<td>819 MPa</td>
<td>Thin ply 30g/m²</td>
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<td>847 MPa</td>
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<td>CLT with damage</td>
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<td>609 MPa</td>
<td>Thick ply 300g/m²</td>
<td>248 MPa</td>
<td>595 MPa</td>
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</table>

*Example: QISO unnotched tensile test, Classical laminate theory analysis*

Open questions:

- Ply size effects in standard impact tests and compression after impact?
- Transverse crack propagation in laminates?

Next steps:

- Optimization of scarf joints, ply size effects without free edges (tubes)
- Design optimization of two demonstrator parts; project continuation?
Next steps within TECA project

**Scarf joint optimization**
- Parametric FE
- Experiment

**Thin ply effects without free edges**
- Test and FE on tubular specimens

**Thin ply Design Guidelines**
- Simple design rules
- Where to use thin ply?
- Failure envelopes (limit cases)

**Demonstrator Design & Opt**
- Performance & production time / cost optimization to benefit from thin-ply effects and complex building block production approach

**Demonstrator Production & testing**
1) Satellite sandwich panel CE/M55
2) Helicopter part (gear box support structure)
Perspectives (new project?)

- Moving further towards Part level performance prediction & design criteria

  - Detailed «ply level» 3D FE modeling
    - Parametric meso-scale study
    - Homogenization for large n
    - Failure criteria
    - Free edge crack stability analysis
    - In-situ strength
    - Shell models
    - Ply size effect with/without free edges

  - Computation time

- Combined experimental / modeling work based on realistic demonstrator parts is required. Performance vs cost vs complexity (=1/quality) optimum need to be identified for representative cases

- Open for collaboration for a continuation project

*This may look complex, but Thin ply composites behaviour is simpler (less damage mechanisms) than traditional composites. Current designs methods do not consider much damage but 1st ply failure*
Thank you