Characterization of a filament wound thin-ply composite for a cryogenic tank for liquid hydrogen

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Background

Hydrogen as fuel

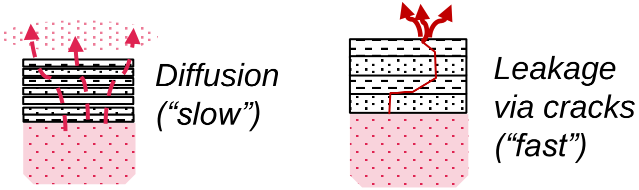
- Low weight & high energy - suitable as fossil free fuel for aircraft
- High energy/kg but too large volume if not kept liquid at -253°C

Composite tanks

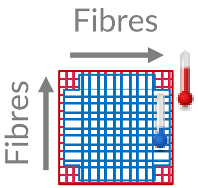
- Carbon fibres provide lowest weight
- Thin plies required to prevent thermal cracking

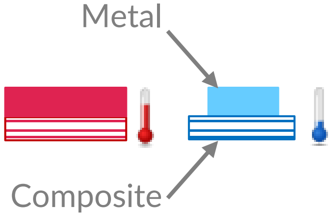
Challenges

- Small hydrogen molecules make it hard to prevent leakage



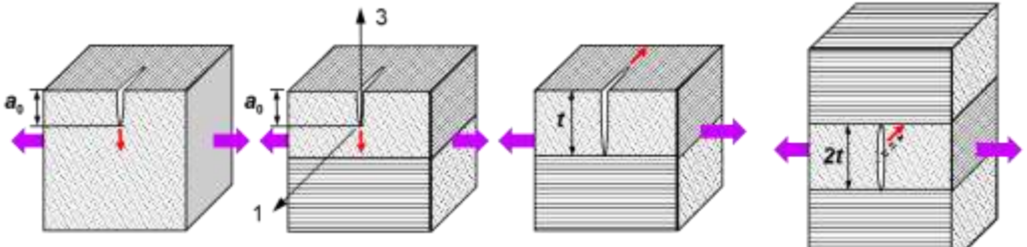
- Large thermal stresses in cryogenic tanks





Thin plies for linerless design

Thin composite bands in angle-ply layup used to prevent matrix cracking

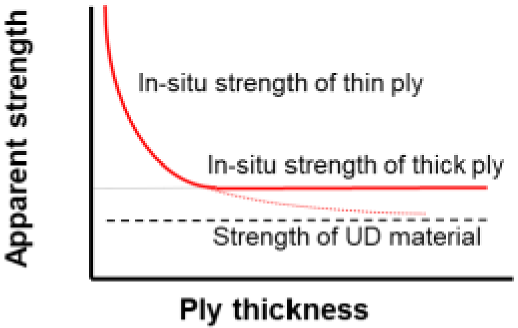


UD material	*Thick ply*	*Thin ply*
$Y_t = Y_0$	$Y_t \approx 1.6 \cdot Y_0$	$Y_t \sim Y_1 / \sqrt{t}$

Dvorak & Laws (1987)
Camanho et al. (2006)

Olsson, TR12-001,
Swerea SICOMP

In-situ strength of thin plies



Thin-ply strengths Y_1 and S_1 functions of G_{Ic} and G_{IIc}

LH2-Tanks project

Two year Swedish project on linerless CFRP tanks for liquid hydrogen (2021-2023)

Requirements

Material selection

Specimen manufacture

Material testing at RT and cryo temp

Sizing

Detailed design

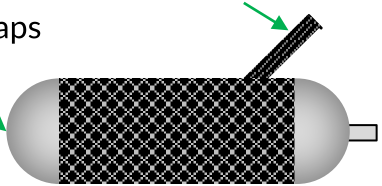
Tank manufacture

Tank cyclic testing in cryo temp

Tank burst testing in cryo temp

Guidelines for future

Demonstrator tank

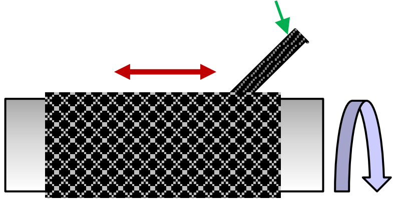


Partners: **RISE**, Oxeon, Konvegas, Chalmers University, Linköping University

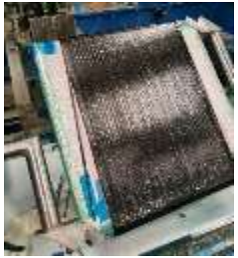
Funding: Swedish Energy Agency (project P2021-90061) Co-funding: Oxeon, Konvegas

Composites made by filament winding

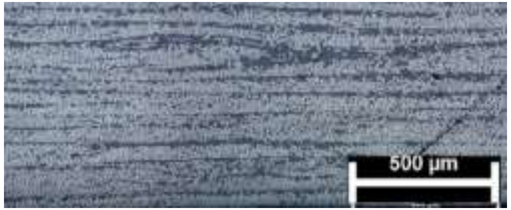
Wet filament winding



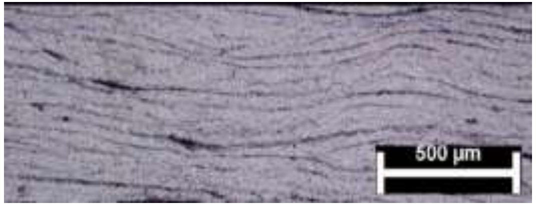
Angle-ply
layups



“Almost”
UD layup



~2%
voids



$(\pm 41°)_n$: FVF≈54%

$(\pm 0.5°)_n$: FVF≈57-61%

- UD-plies not homogenous – filaments separated by resin rich regions
- Material is a result of winding – data for the composite must be measured

Aim: determine properties of UD material as a basis for design of optimum layup

Testing at various temperatures

- Limited to tensile testing
- Focus on matrix dominated properties

Material tests at RISE

RT & -150°C (using LN2)

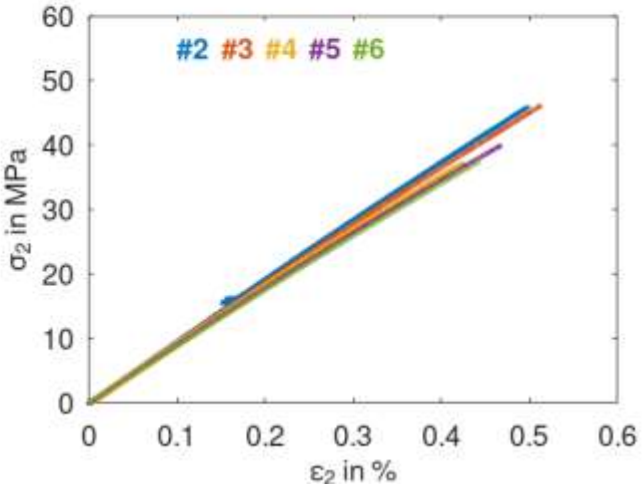
https://www.instron.com

Material tests at INTA

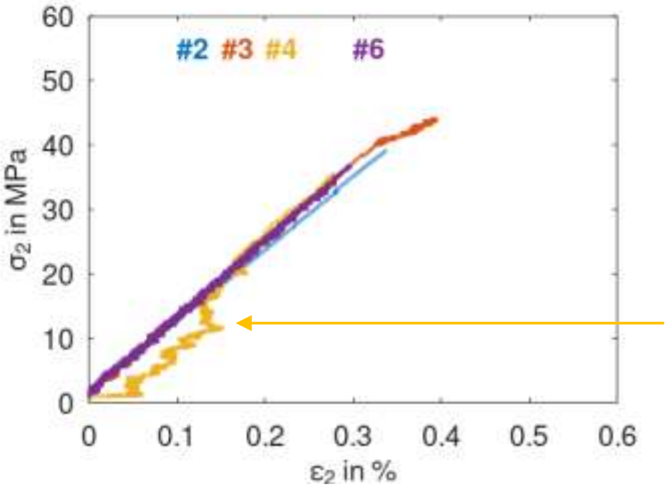
-253°C=20 K (using He)

Picture by INTA

Transverse tensile tests



RT
$$\boxed{\begin{aligned} E_2 &= 9 \pm 4\%\,\mathrm{GPa} \\ Y_t &= 41 \pm 9\%\,\mathrm{MPa} \end{aligned}}$$



Initial icing problems?

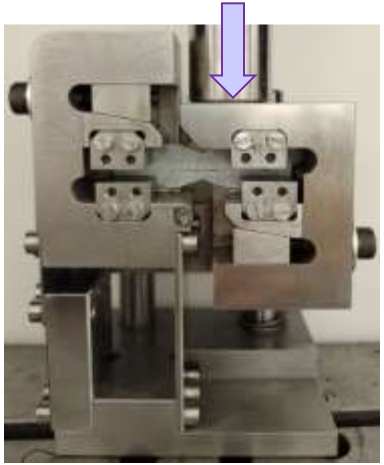
-253°C
$$\boxed{\begin{aligned} E_2 &= 12 \pm 6\%\,\mathrm{GPa} \\ Y_t &= 39 \pm 7\%\,\mathrm{MPa} \end{aligned}}$$

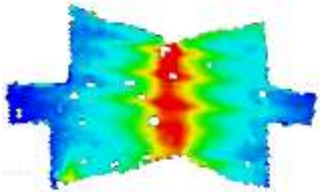
$(\ldots = \mathrm{Mean} \pm \mathrm{CoV})$

- E_2 increases about 30% at cryogenic temperature
- No increase in strength Y_t at -253°C, **maybe** due to higher defect sensitivity caused by a more brittle matrix behaviour

Shear test methods

Iosipescu (V-notch) test
RT

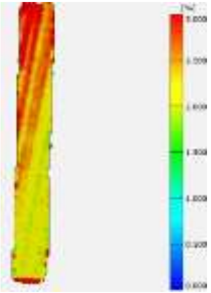




Increased notch angle for more uniform strains

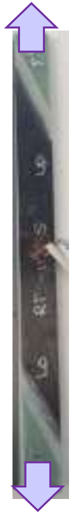
Neumeister & Melin (2003)

<u>10° off-axis tension</u>
RT & 20 K

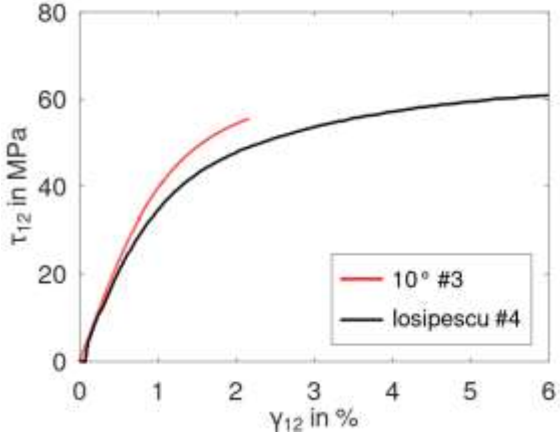


Oblique tabs for more uniform strains

Sun & Chung (2003)

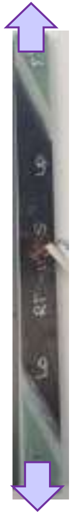


Effect of test method at RT

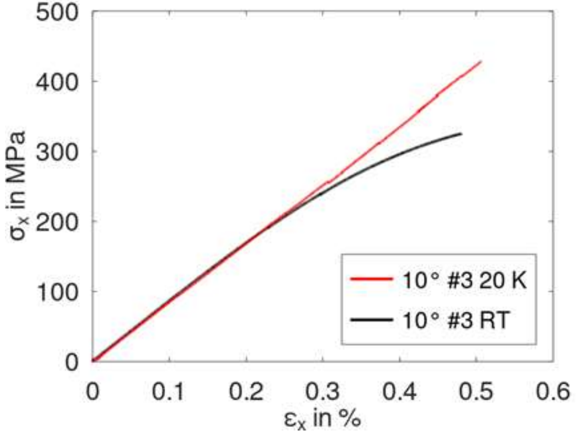


- Comparable shear modulus
- Premature failure in 10° test due to added transverse tension

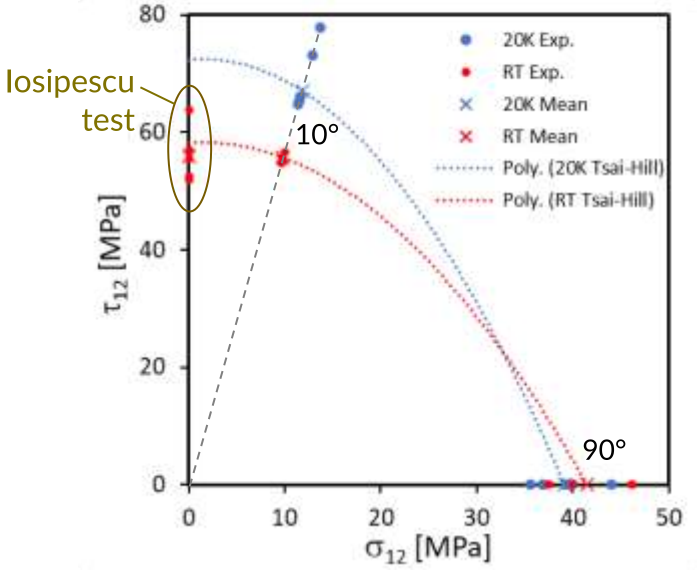
Shearing by 10° off-axis tension



Effect of temperature



Corrected strength in pure shear by using Tsai-Hill criterion for 10° and 90° data



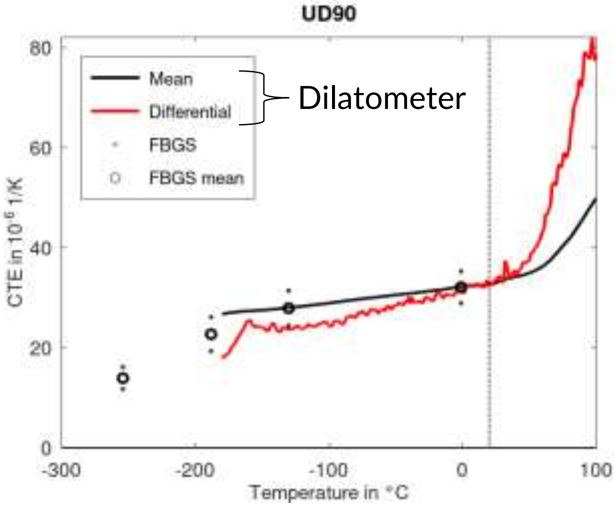
- Nonlinear shear effects very small at 20 K
- Shear strength increases significantly at 20 K

CTE tests

Measured at Netzsch with dilatometer between -180°C and +100°C

https://analyzing-testing.netzsch.com

Measured at INTA with biaxial fibre optic sensors (FBGS) during cooling from RT to -253°C



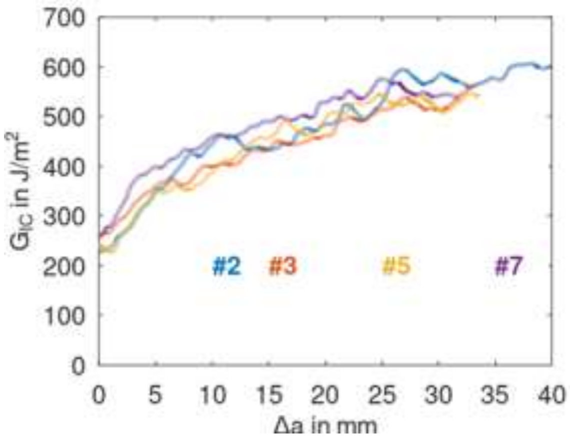
Dilatometer

- Mean CTE varies almost linearly between -200°C and T_g
- CTE drops sharply below -200°C

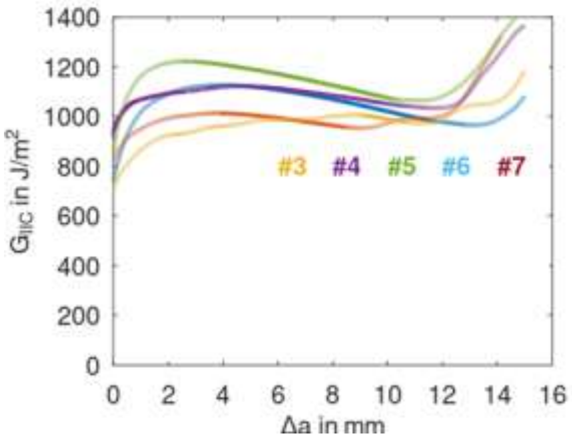
Intralaminar toughness tests

- *Intra*laminar toughness required to estimate in-situ strengths
- Measured as *inter*laminar toughness in $(\pm 0.5°)_n$ specimens as angle-ply layup causes severe intralaminar fibre bridging
- Toughness measured by DCB and ENF, but only at RT

DCB Mode I tests



ENF Mode II tests



Conclusions for our design

- Micromechanics used to correct material properties for differences in FVF between UD test coupons and real tank
- Variation in CTE replaced by an average CTE from T_g (93°C) to service temperature (-253°C)

Composite cylinder with titanium end caps for simplified manufacture

Adhesive joints between composite and end caps, with axial rods as “safety belts”.

- To avoid adhesive joint failure the composite layup was selected to match its CTE in the hoop direction to the titanium end caps (and not to maximize laminate strength).

Thin-ply/LH_2 activities at RISE