HYDROTHERMAL AGEING OF AIRCRAFT COMPOSITES

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The Central Aerohydrodynamic Institute named after N.E. Zhukovsky (TsAGI)

– theoretical and applied aerospace research facility

Modern russian jet **Irkut MC-21**

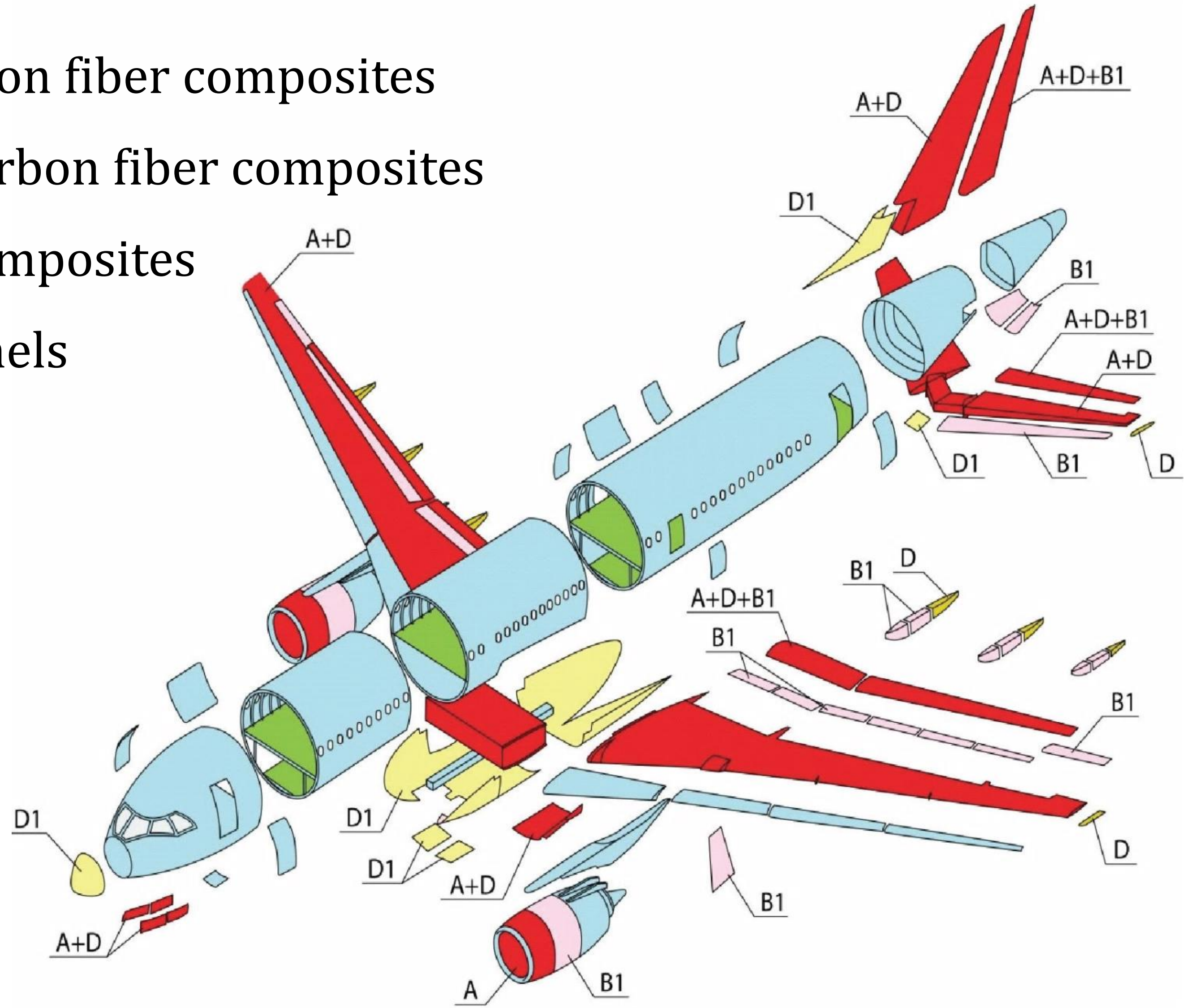
A – primary carbon fiber composites

B – secondary carbon fiber composites

D – glass fiber composites

– FRP floor panels

– metals



- 34% composites
- 132 – 211 passengers
- up to 6 400 km range

Plan of the presentation

1. Hydrothermal effects
2. Qualification of composite structures
3. Maximum operating temperature
4. Operating moisture content
5. Realistic hydrothermal factors

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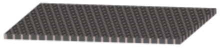
Hydrothermal effects on composites

On the resin:

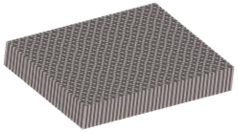
- Plastification
- Swelling
- Destruction
- Secondary curing

On the lamina:



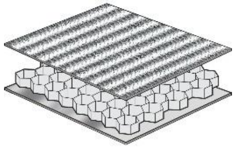
- Reduction of properties, mainly matrix governed

On the laminate:



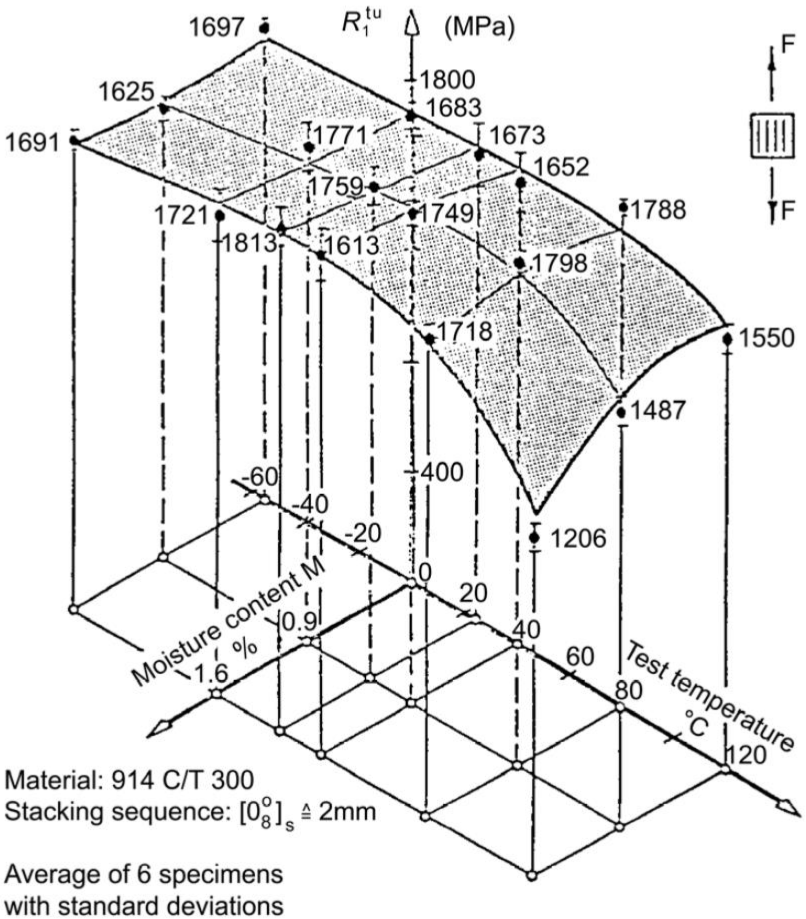
- Internal hydrothermal stress

On the construction:

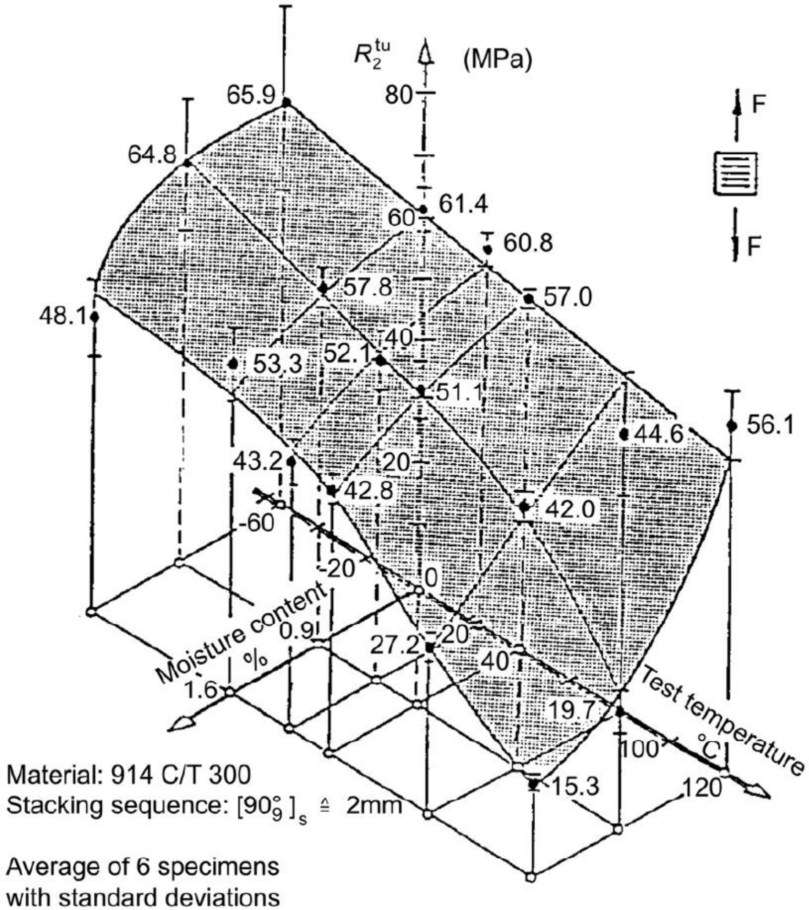


- Moisture affects bond-line (adhesive) - may lead to disbondings
- Moisture ingress in the honeycomb core
- Galvanic corrosion, mainly Al and carbon-epoxy

Mechanical lamina properties as a function of temperature and moisture content



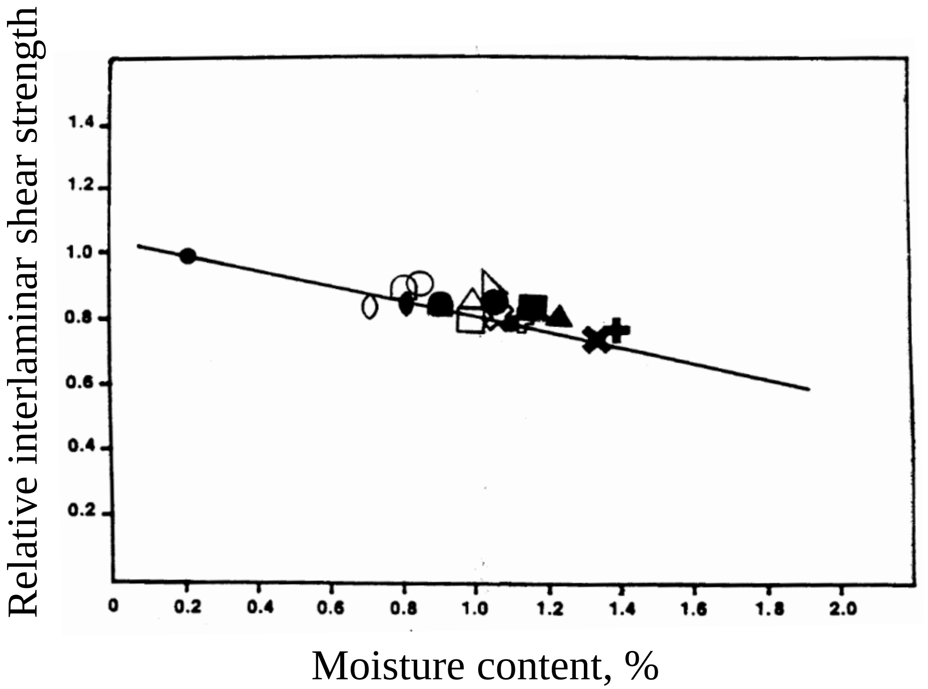
Longitudinal tensile strength



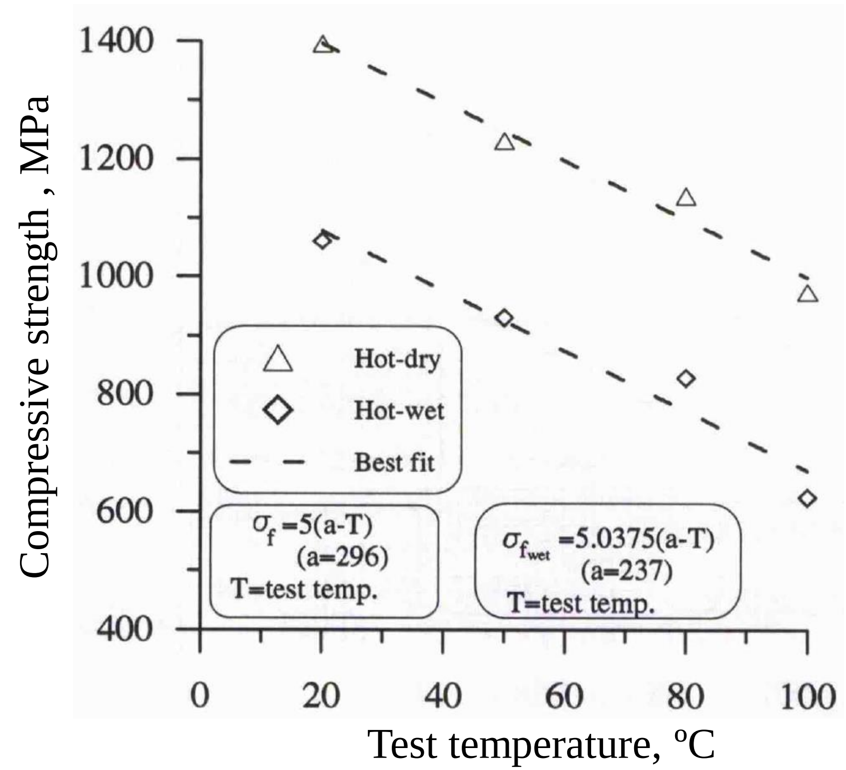
Transverse tensile strength

Structural materials handbook - Part 1: Overview and material properties and applications, ECSS-E-HB-32-20, 2011.

Mechanical lamina properties as a function of temperature and moisture content



MardoianG.H., EzzoM.B. Flight service evaluation of composite helicopter components – 1990.



TürkmenD. Compressive behaviour of CFRP laminates exposed in hot-wet environments – 1996.

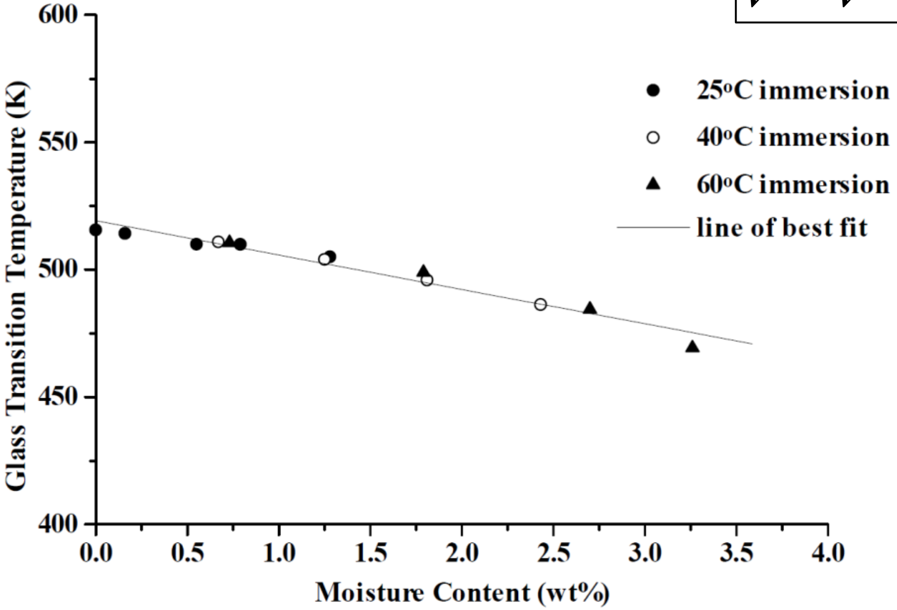
Lamina properties degradation model

Shan, Meijuan, et al. "A progressive fatigue damage model for composite structures in hygrothermal environments." International Journal of Fatigue 111 (2018): 299-307.

$$\boxed{g = \frac{T_g - T}{T_g^0 - T_0}}$$

$$E_1 = E_1^0 g^{0.04}$$
$$E_2 = E_2^0 g^{0.5}$$
$$G_{12} = G_{12}^0 g^{0.5}$$
$$\nu = \nu^0$$

$$X_T = X_T^0 g^{0.04}$$
$$X_C = X_C^0 g^{0.54}$$
$$Y_T = Y_T^0 g^{0.5}$$
$$Y_C = Y_C^0 g^{0.5}$$
$$S_{12} = S_{12}^0 g^{0.5}$$



T_g – glass transition temperature
T – temperature
index 0 – reference data

A S Maxwell at. al. Review of accelerated ageing methods and lifetime prediction techniques for polymeric materials, NPL Report DEPC MPR 016, 2005

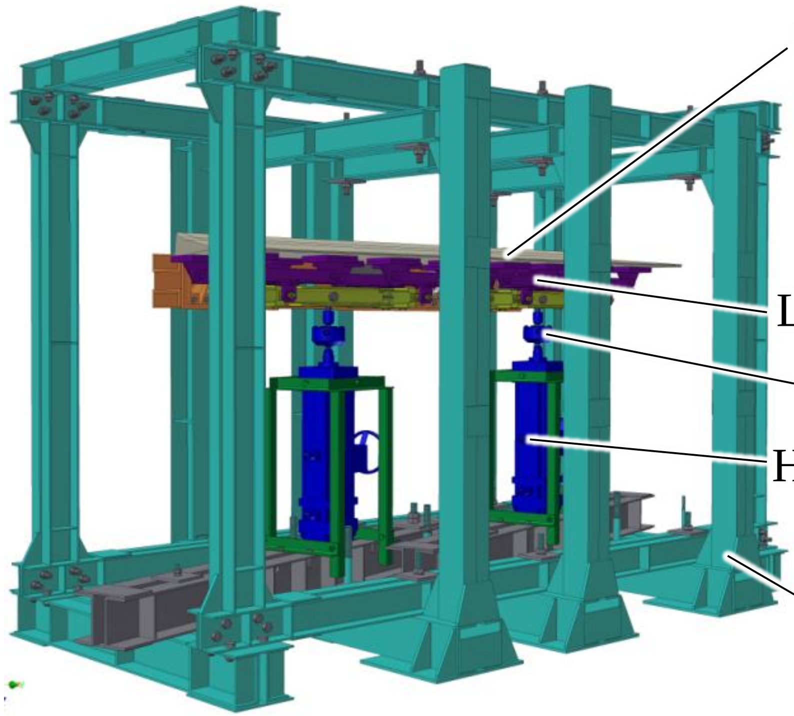
Plan of the presentation

1. Hydrothermal effects
2. **Qualification of composite structures**
3. Maximum operating temperature
4. Operating moisture content
5. Realistic hydrothermal factors

Test conditions
for hydrothermal qualification of composite structures

High temperature Moisture conditioning	High temperature Dry	Room temperature Dry
+ High realism	+ Time efficient	+ Time efficient
− Time consuming Special equipment	− Building-block approach Special equipment	− Building-block approach

Control surfaces test set up



Test Object

Lever-Loading System

Dynamometer

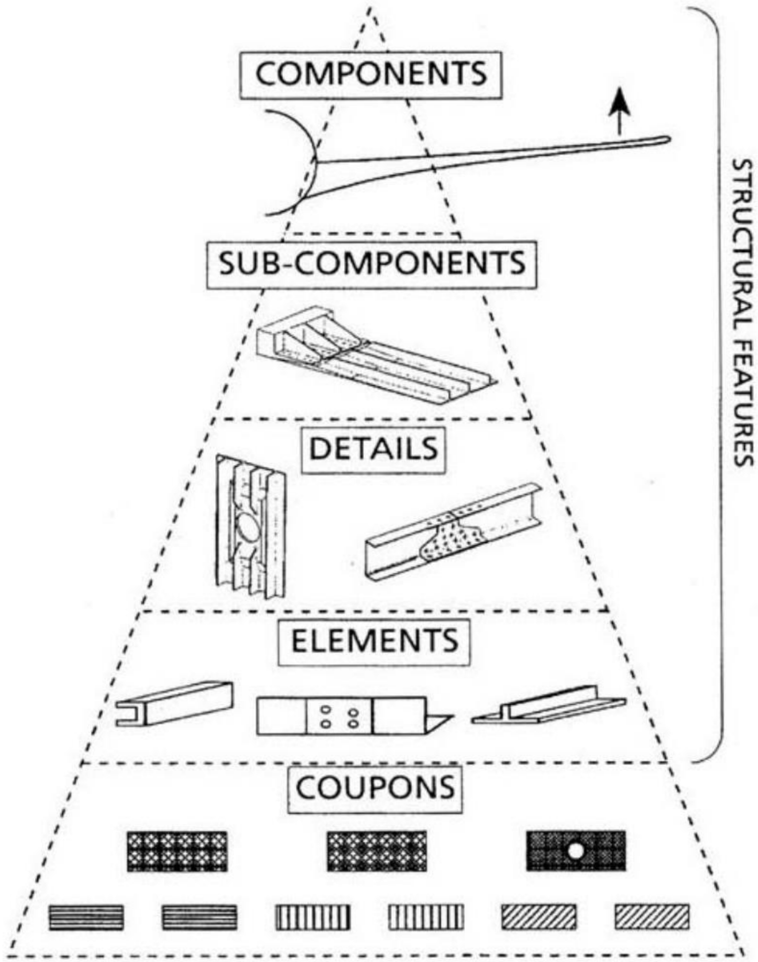
Hydraulic/Electric Ram

Test-bench

Climatic cabinet
Hot-wet and cold conditions

Infrared heating

Building-block approach

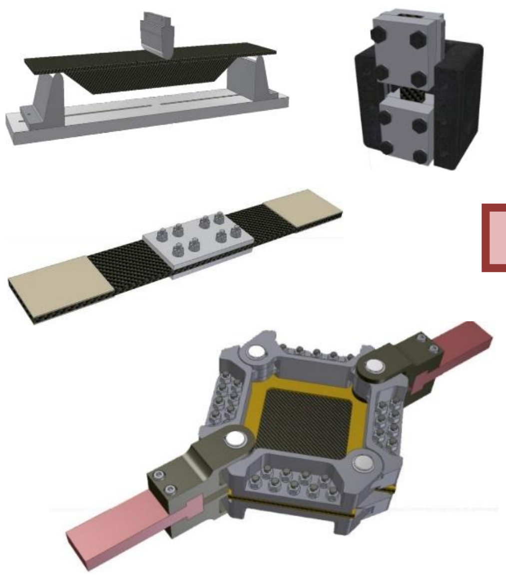


Overload Factors assure structural strength in all operating conditions

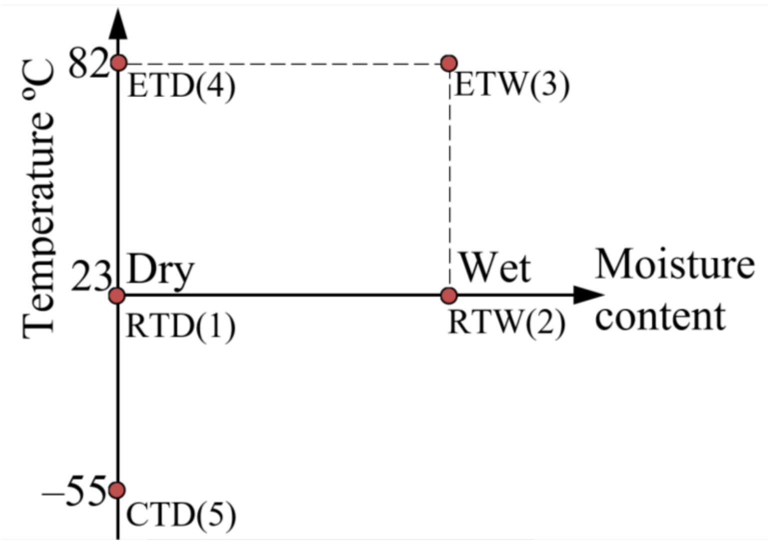
Overload Factors:
K_{WT}, K_{var}, K_{dam}

Building-block approach

Test elements



Test conditions for hydrothermal qualification



Environmental compensation factor

$$K_W = \frac{X_W}{X}$$

$$K_T = \frac{X_T}{X}$$

$$K_{WT} = \frac{X_{WT}}{X}$$

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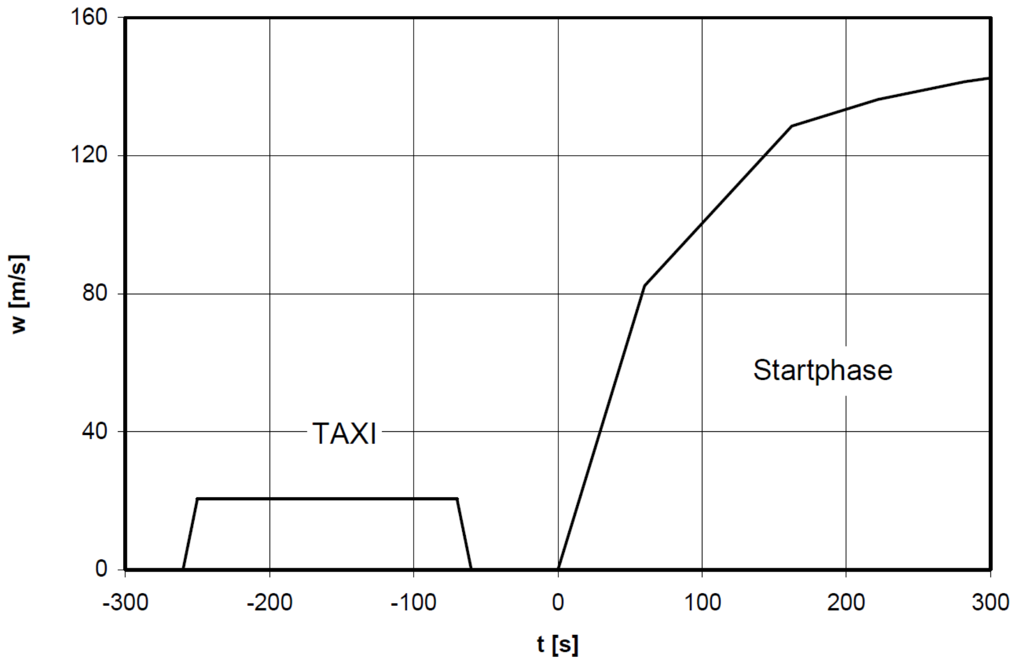
Maximum operation temperature

For most paint colors a default critical structural temperature is 82°C (180°F)

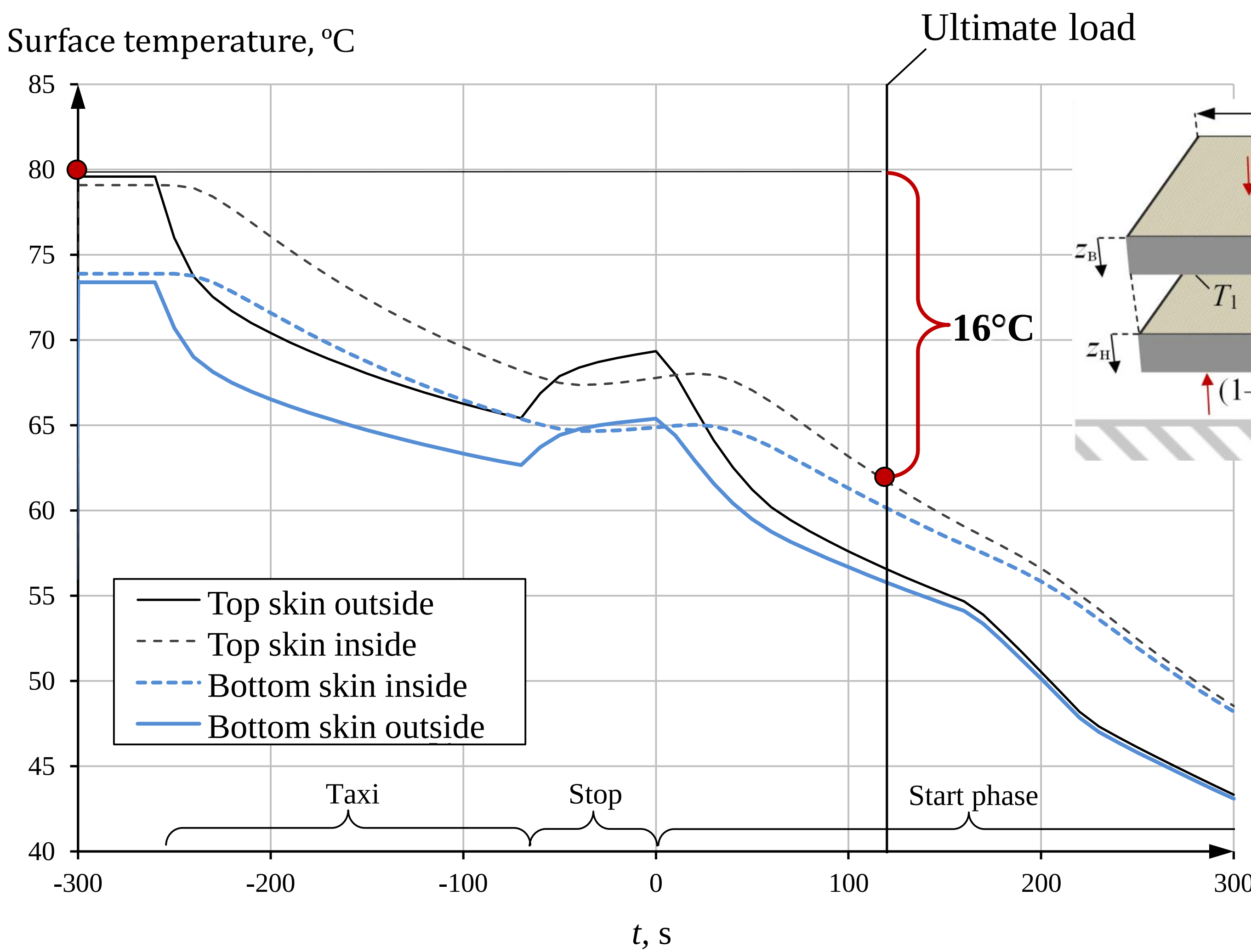
"Static Strength Substantiation of Composite Airplane Structure"
PS-ACE100-2001-006, December 2001

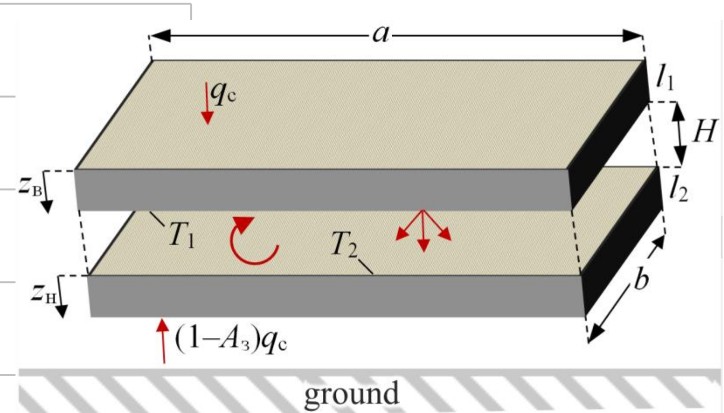
Air flow velocity
for take off scenario



Rolfes, R., J. Tessmer, and K. Rohwer. "Models and tools for heat transfer, thermal stresses, and stability of composite aerospace structures." *Journal of thermal stresses* 26.6 (2003): 641-670.

Transient cooling of wing box during take off scenario





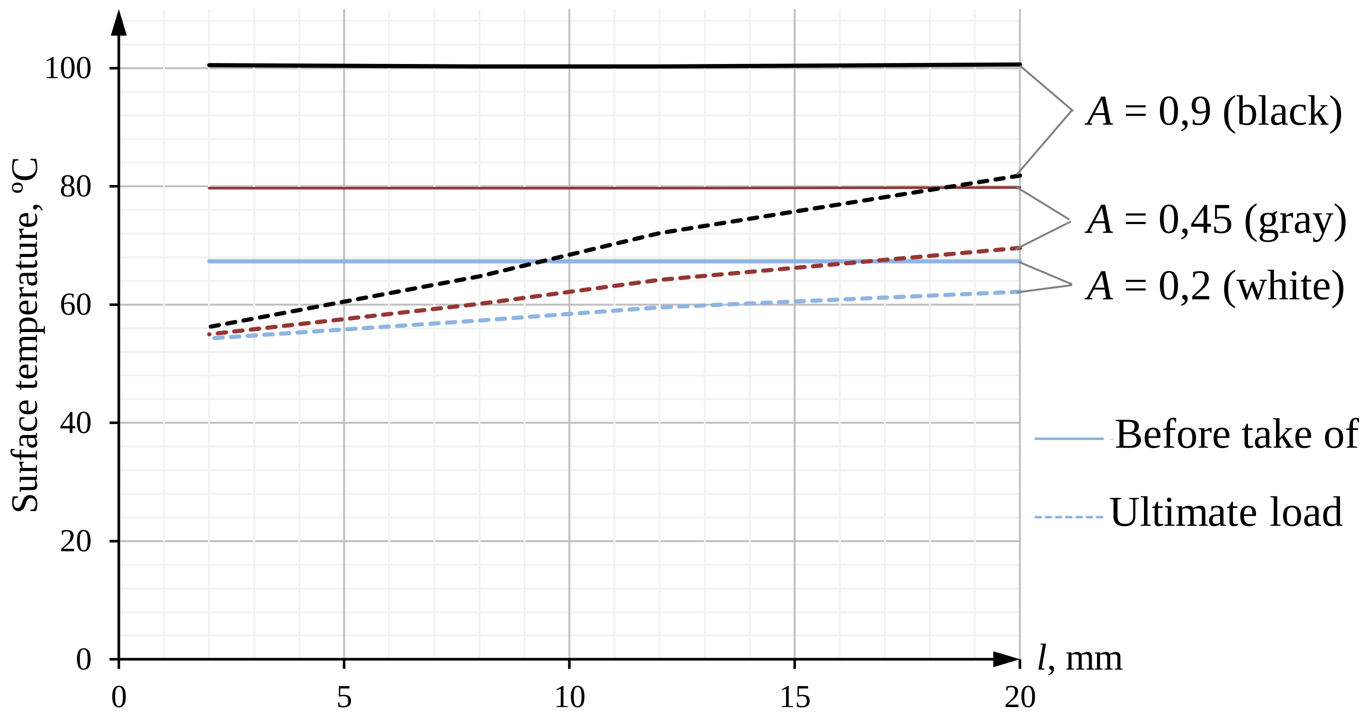
$l_1 = l_2 = 8$ mm, $q_c = 1082$ W·m^{-2},

$A = 0.45$, $T_{air} = 56$ ºC,

$h_0 = 8.5$ W·m^{-2}°K^{-1}, $A_g = 0.73$,

$T_g = 75$ ºC, $q_{12} \neq 0$, $h_{12} = 0$

Composite skin temperatures due to solar heating and takeoff cooling



Takeoff cooling reduces
the maximum operating temperature of thin components

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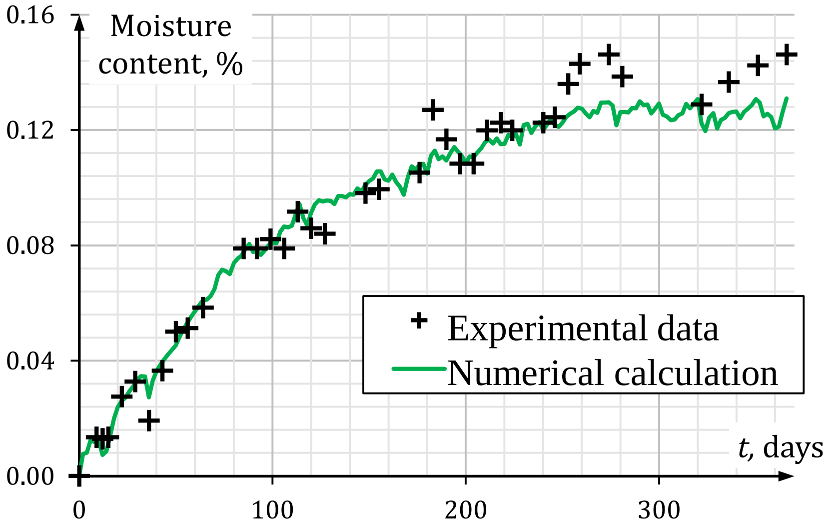
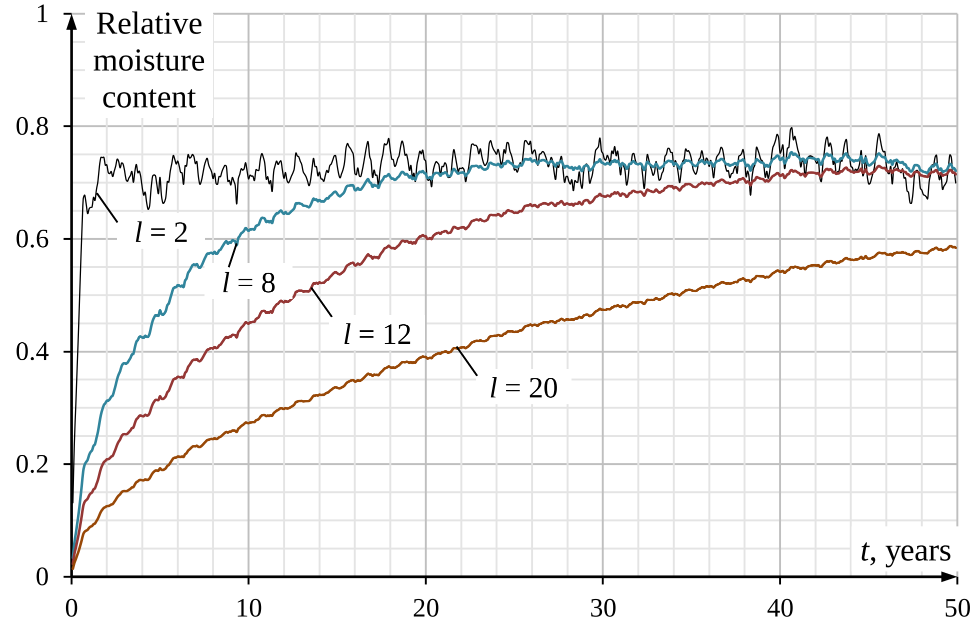
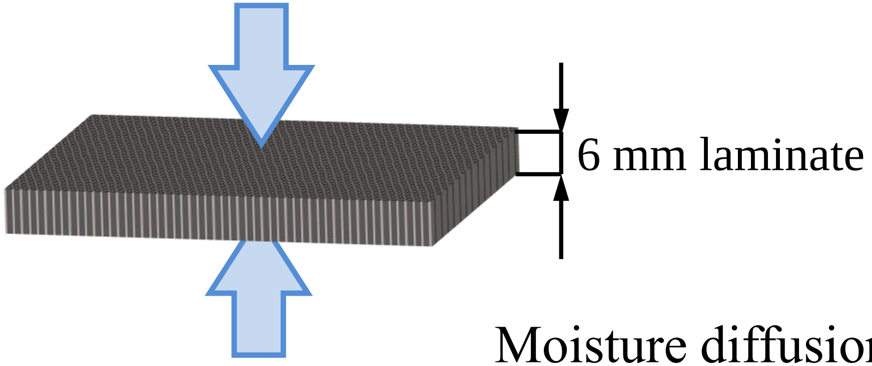
Moisture absorption in hot-wet climate (Sochi, Russia)

Calculated and experimental moisture contents



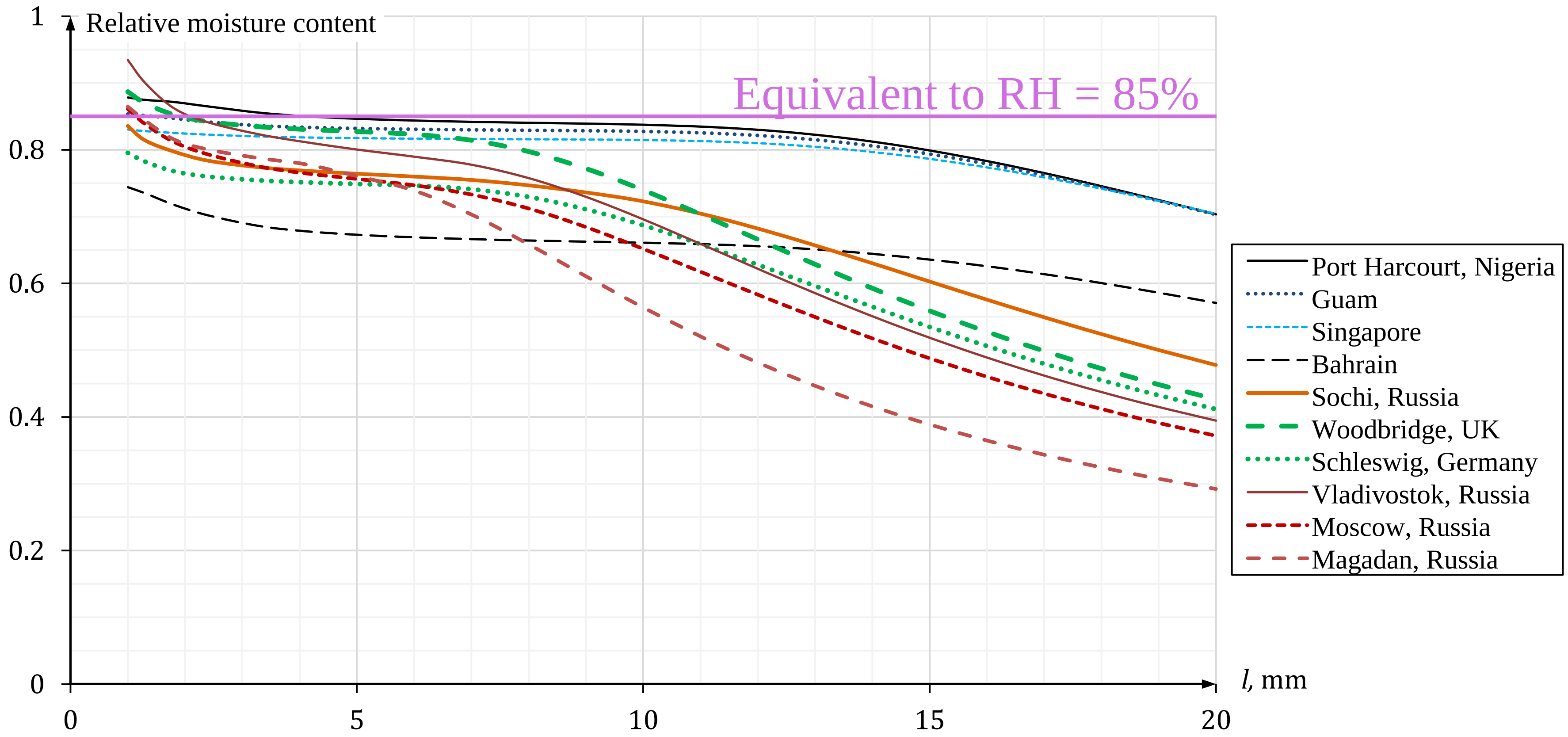
Moisture absorption modeling for diff. thicknesses





Moisture diffusion obeys the Fick's law

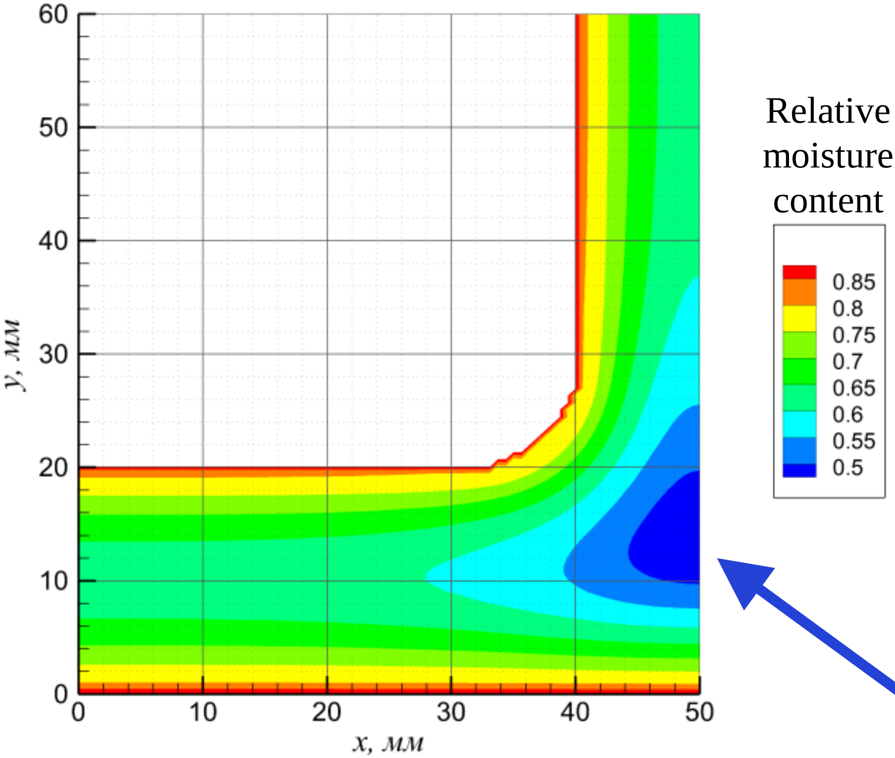
Moisture content resulting 30 years of operation

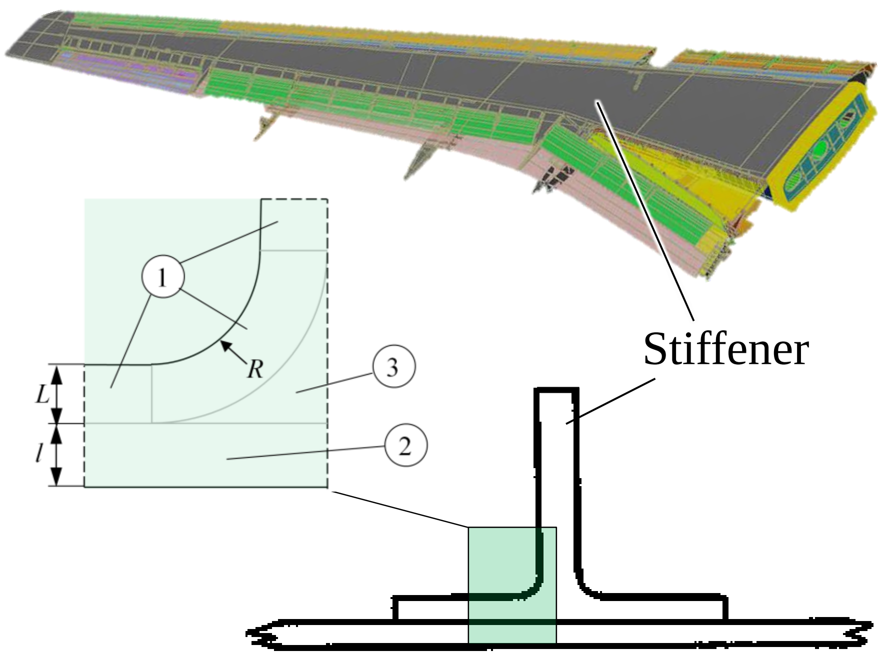


More than 10 mm thick laminates does not reach the equilibrium moisture level

The effect of stiffener on moisture distribution

(Port Harcourt, Nigeria)

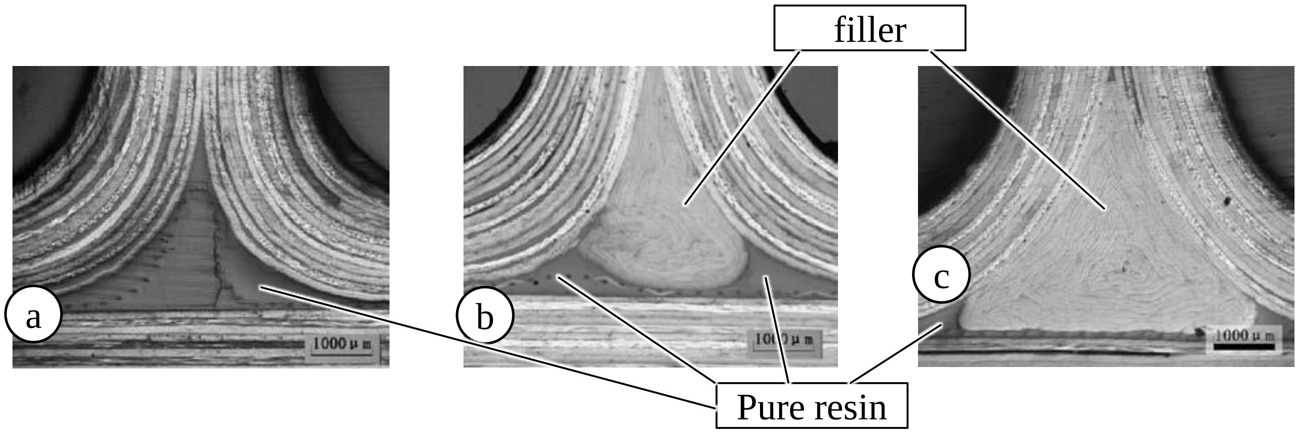


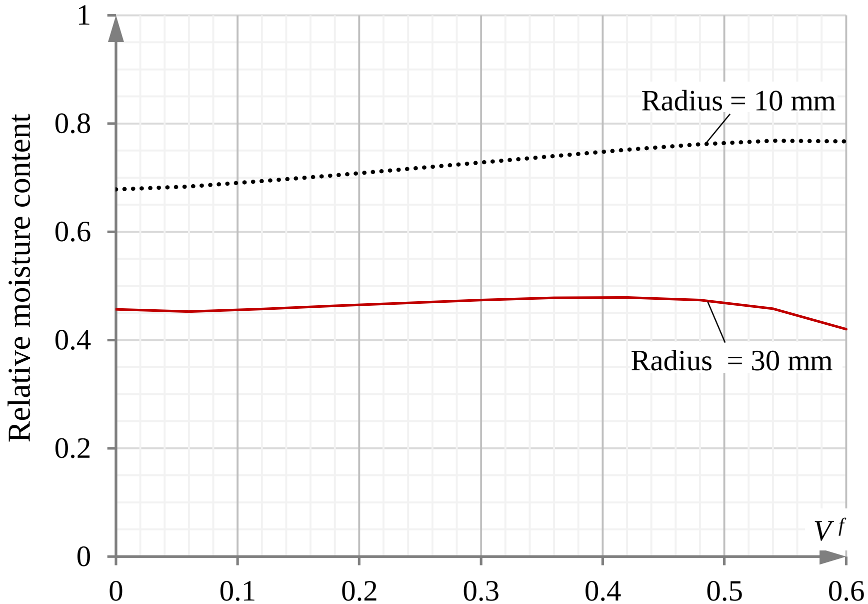


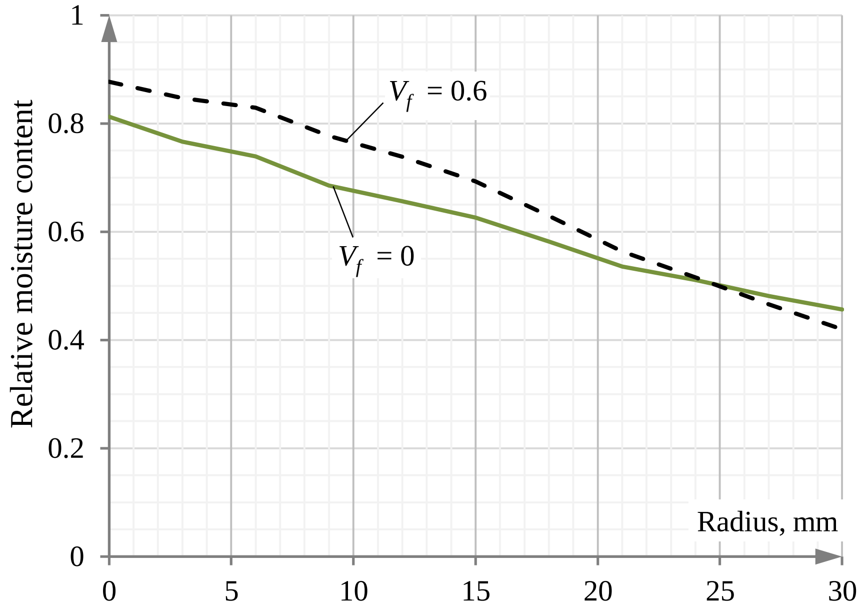
Stiffener core has lower moisture concentration

The effect of fiber fraction V^f and radius of the stiffener on total moisture content

(Port Harcourt, Nigeria)



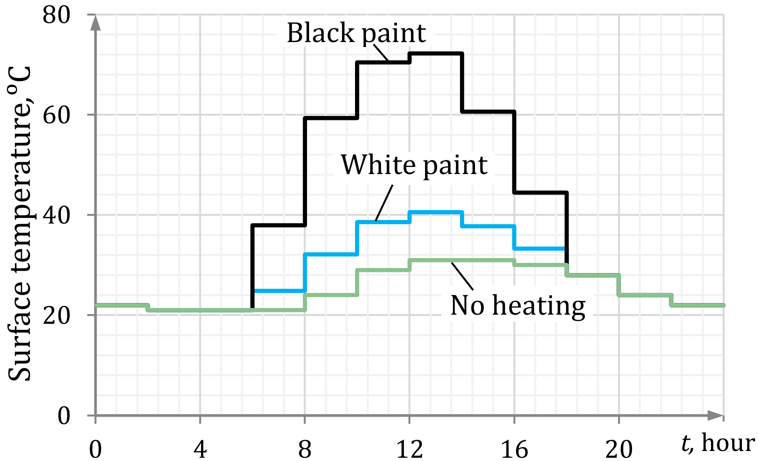




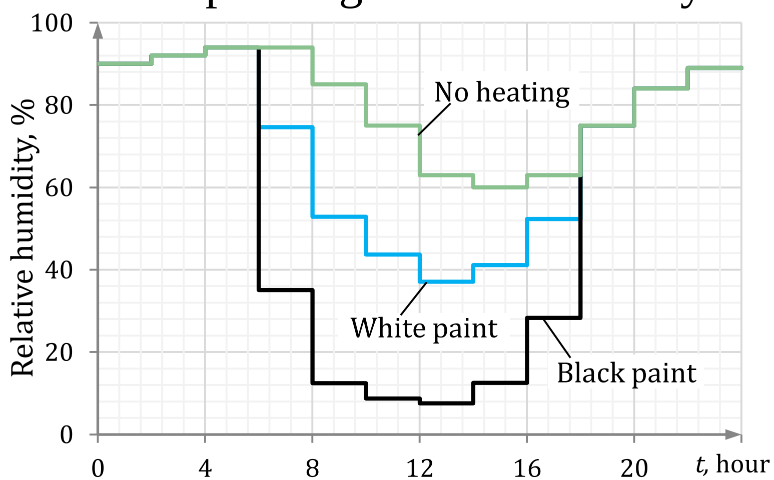
The effect of solar heating on total moisture content

(Port Harcourt, Nigeria)

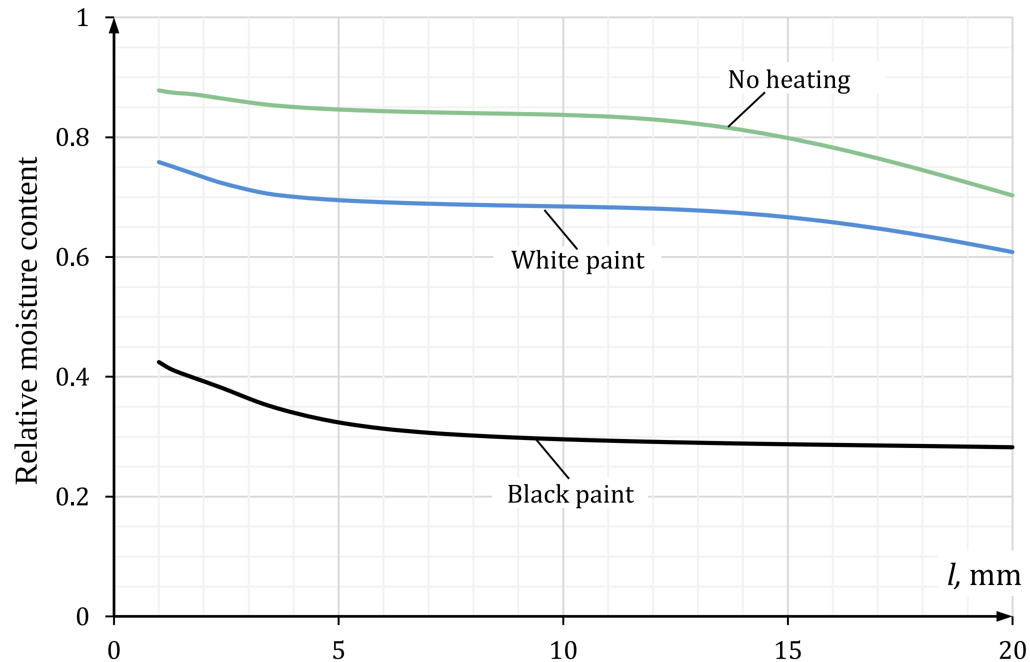
Typical daily surface temperatures



Corresponding relative humidity



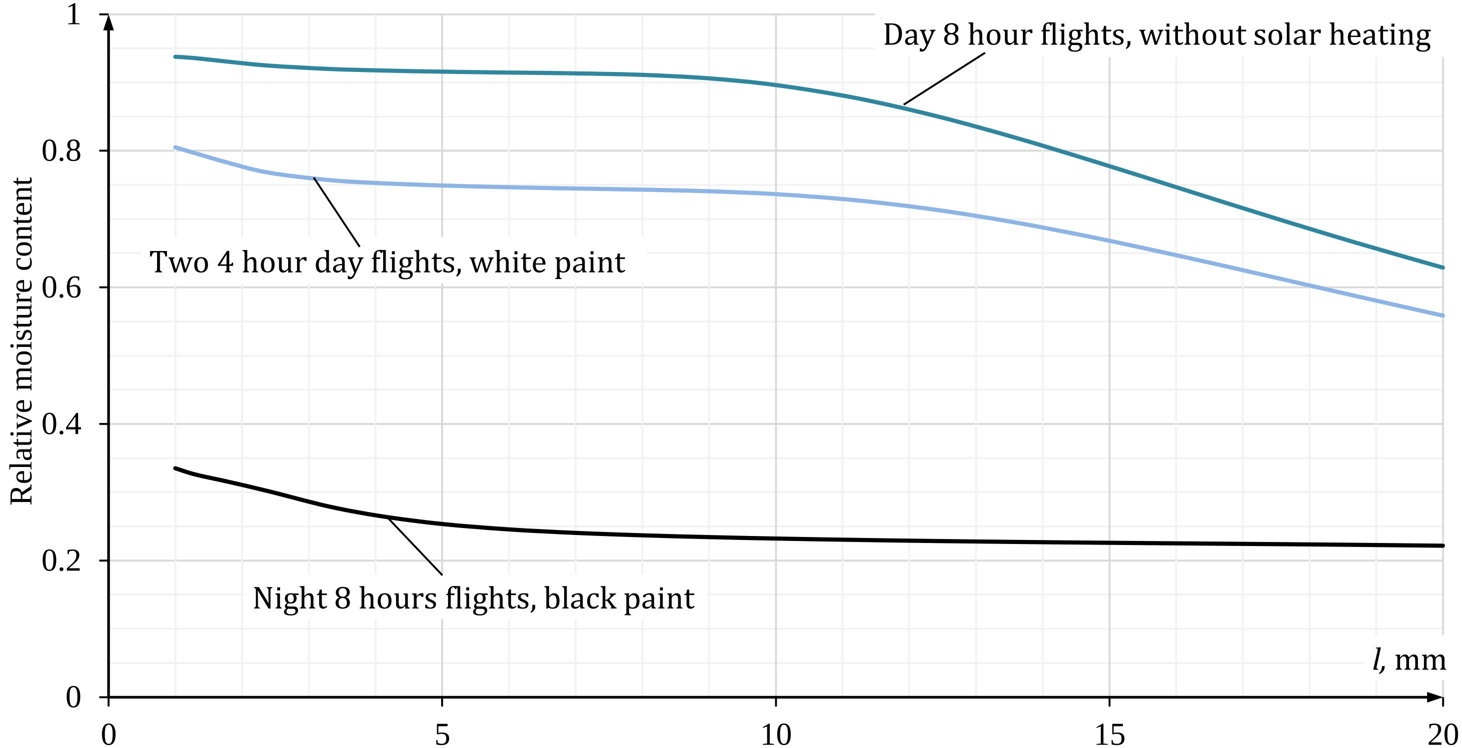
The effect of color on the moisture content of a horizontal panel



Exposure to the sun reduces final moisture content

The effect of operation on total moisture content

(Port Harcourt, Nigeria)



Flight exposure disperses the total moisture content

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Application of operational temperature and moisture content

Numerical method: Laminated theory

Material: CYCOM 977

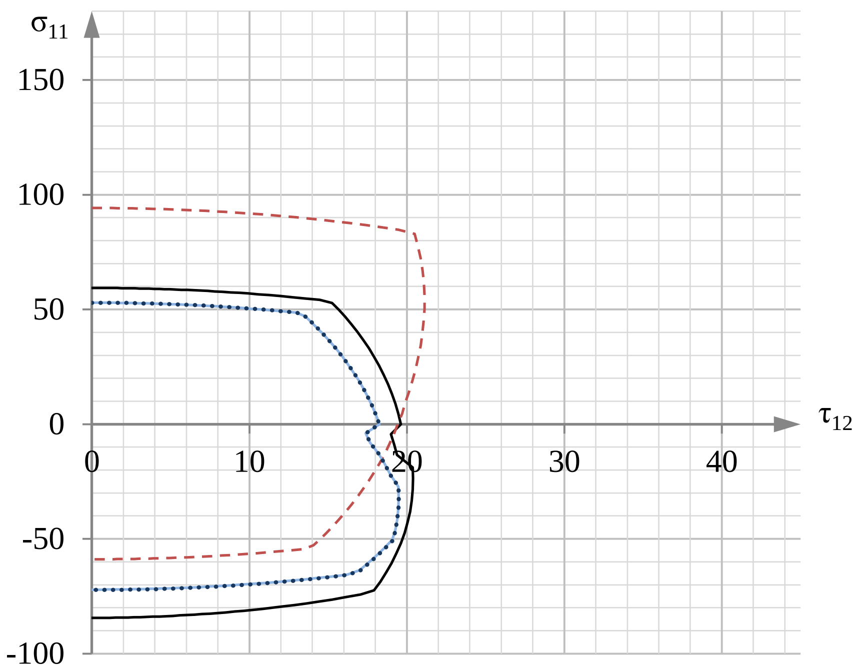
Lay-up configuration: $\{-45/0/45/0/0/90/0/0/45/0/-45\}_n$

Failure criterion: Tsai-Hill

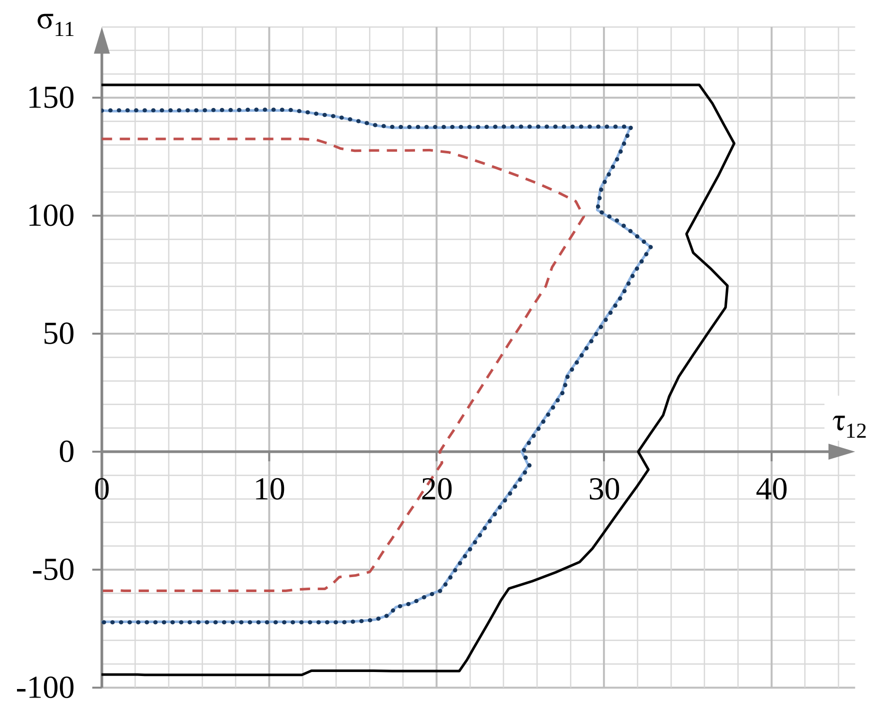
Thickness, mm	Temperature °C	Moisture content
2	54	0.84
8	60	0.83
20	65	0.70

Failure envelopes for 2 mm laminate

Initial failure



Ultimate failure



normal conditions
high temperature and moisture content
realistic temperature and moisture for top surface
realistic temperature and moisture for bottom surface

Application of operational temperature and moisture content

Thickness, mm	Temperature °C	Moisture content	K_{WT}			**Average degradation**
			σ_{11T}	τ_{12}	σ_{11C}	
2	54	0.84	0.93	0.78	0.76	**17%**
8	60	0.83	0.93	0.73	0.72	**21%**
20	65	0.70	0.90	0.69	0.68	**24%**

Standard case	82	0.85	0.85	0.63	0.63	**30%**

Summary

- Takeoff cooling reduces the maximum operating temperature of thin components

- Thick laminates does not reach the equilibrium moisture level over the operational lifetime

- Realistic temperature and moisture content may reduce structural test's overload factors

Thank you for your attention!