CHARACTERIZATION OF RESIDUAL STRESSES IN WOUND COMPOSITE TUBES

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SCOPE OF THE STUDY

1. Origin of residual stresses
2. Principle of residual stresses characterization
3. Results from experiments
4. Predictions from a residual stress model
5. Comparison
6. Conclusion

ORIGIN OF RESIDUAL STRESSES

Manufacturing process

\+

Environmental conditions

↔

Residual curing stress

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Internal (hygrothermoelastic) stress

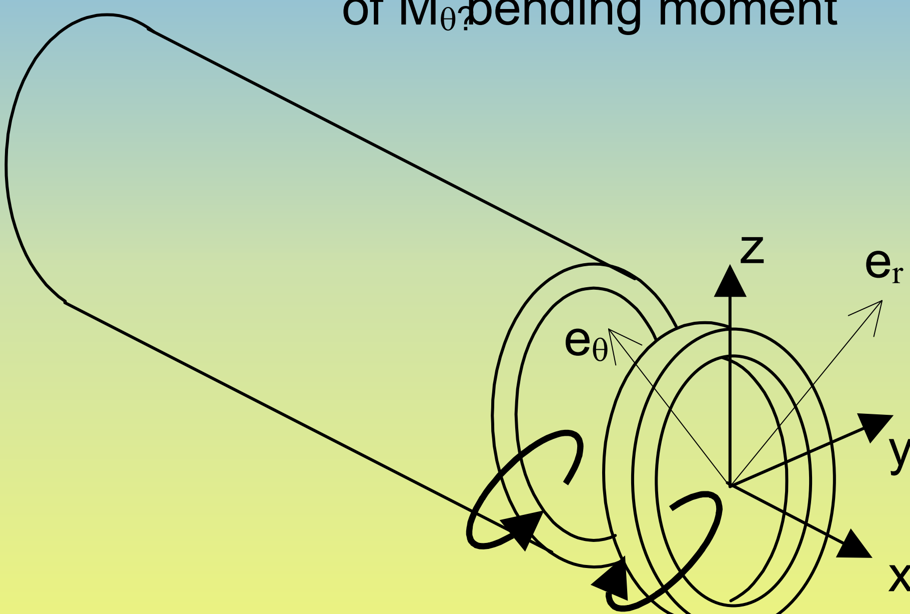
Internal stress state

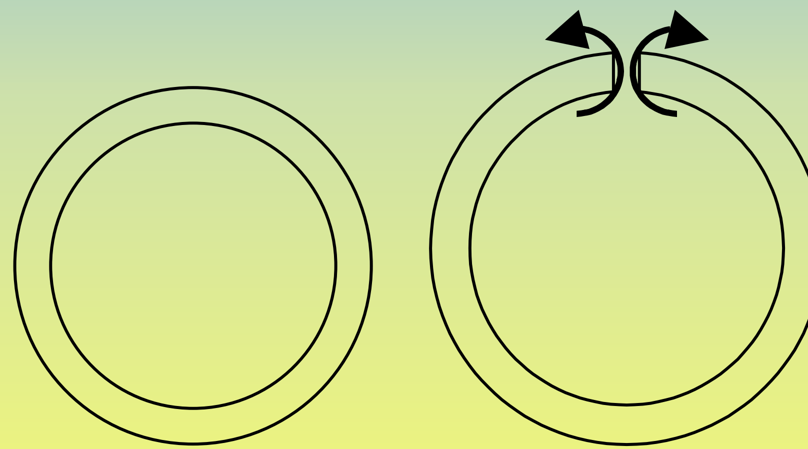
Goal: to measure internal stresses and
to compare them to numerical predictions

PRINCIPLE OF STRESSES REVEALED BY CUTTINGS IN COMPOSITE TUBES

Peripheral cut: release of M_{θ}? bending moment

Axial cut: release of the remaining part of M_{z}? bending moment



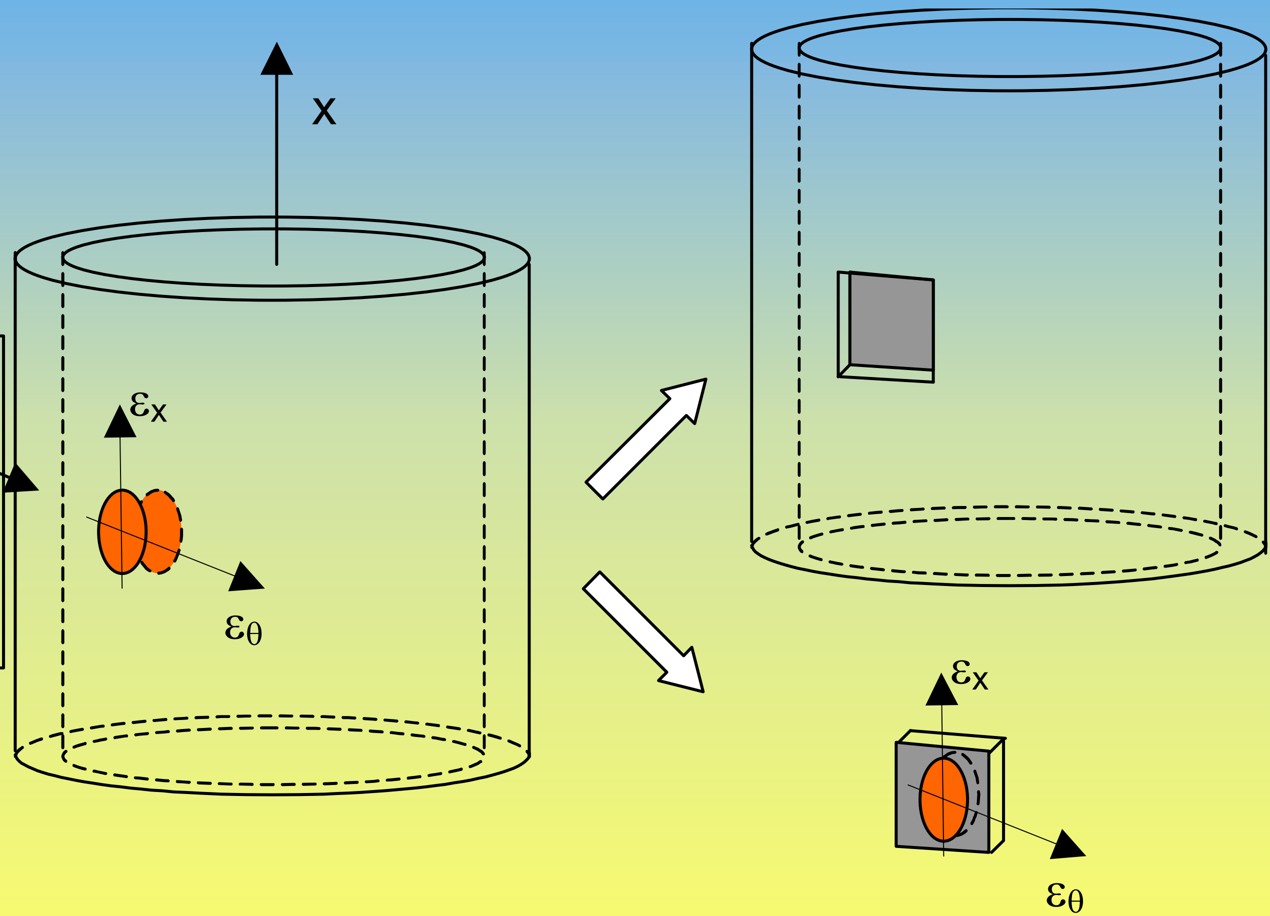


Release of bending moments due to internal stresses

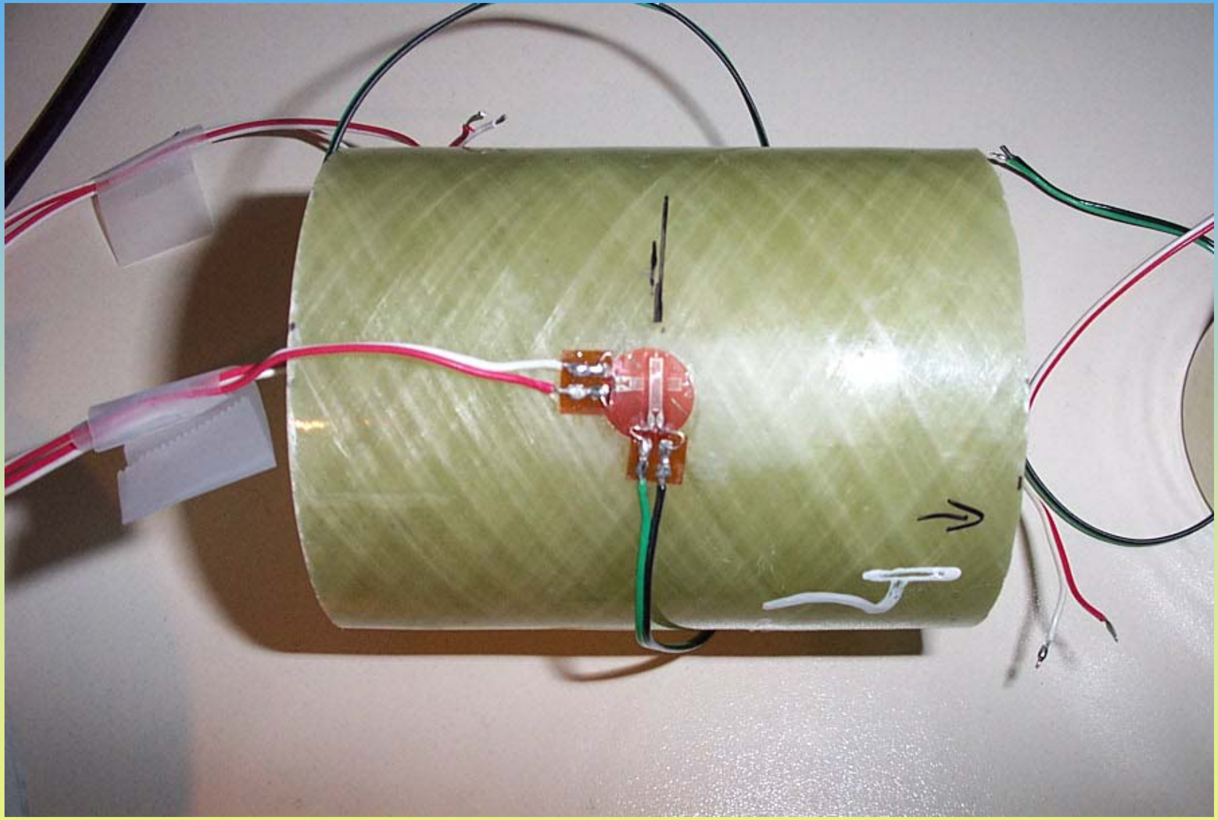
STRAIN-STATE MEASUREMENT

- Sketch of strain measurement on a biaxial gage

Two biaxial strain gages bonded inside and outside the tube at the same location

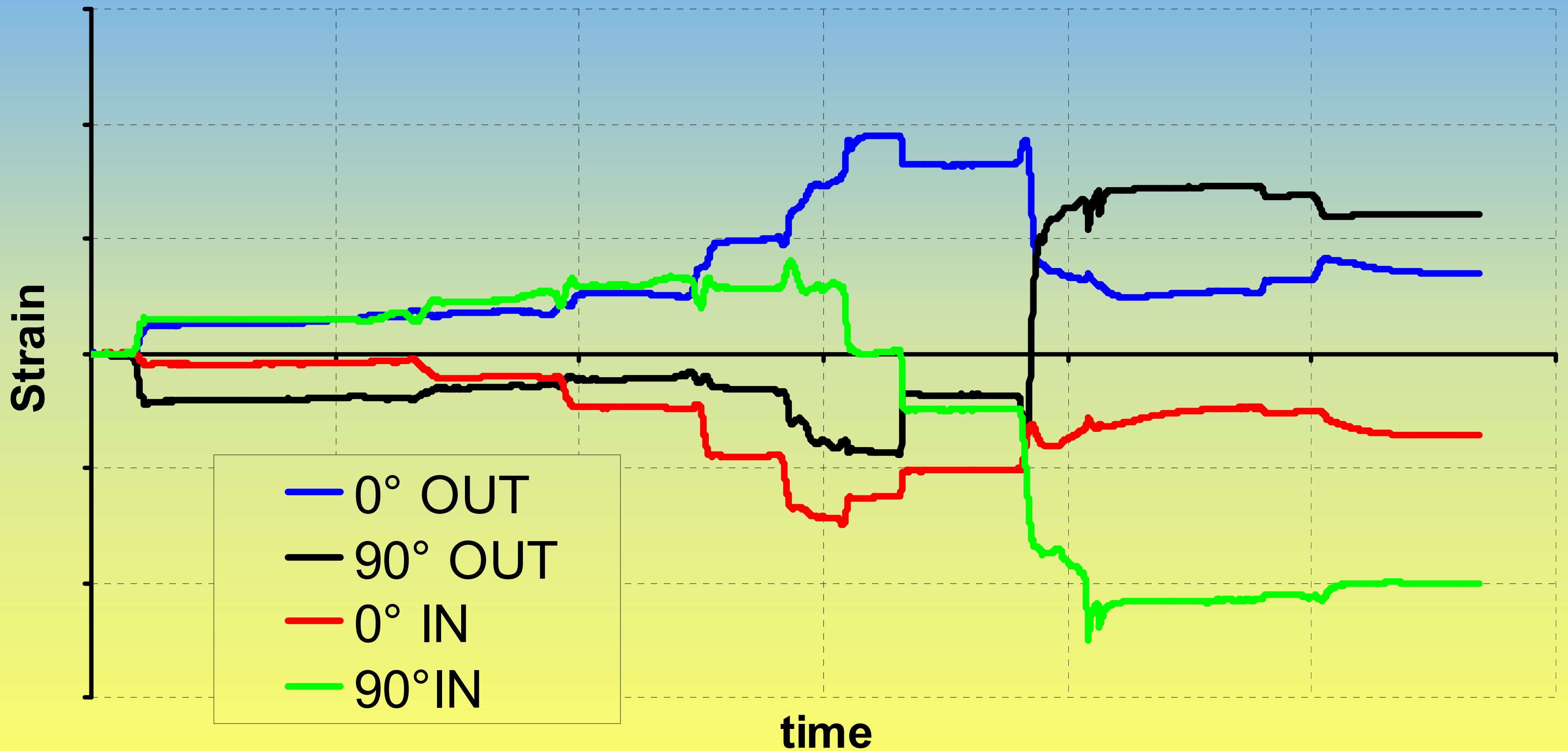


PIECE OF TUBE AND STRAIN GAGES



RINGS ARE REMOVED FROM THE TUBES WITH A CIRCULAR DIAMOND SAW MOUNTED ON A LATHE

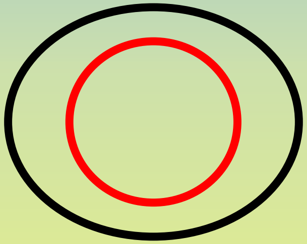
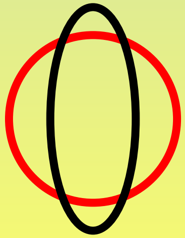
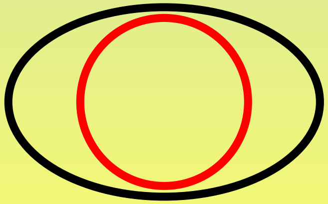
TYPICAL RESPONSE OF A TUBE EQUIPPED WITH STRAIN GAGES DURING CUTTINGS



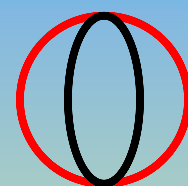
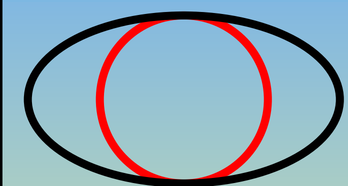
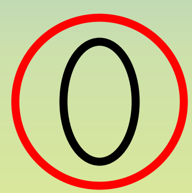
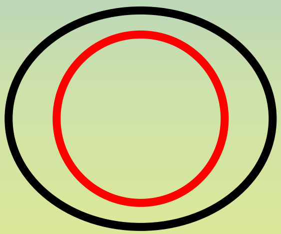
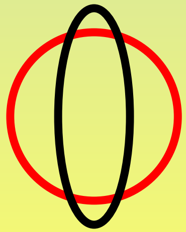
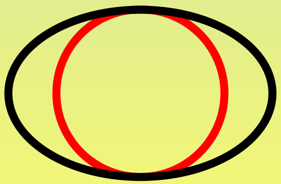
TUBES SELECTION

- Three types of reinforcement
  - E Glass, R Glass, T 700 Carbon
  - Same matrix
- Three winding angles
  - 35°, 55° and 85°
- Manufactured in 1998

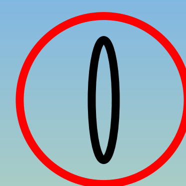
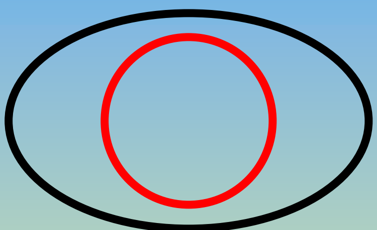
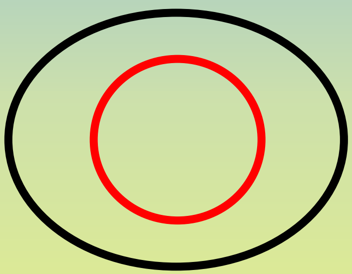
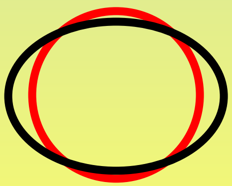
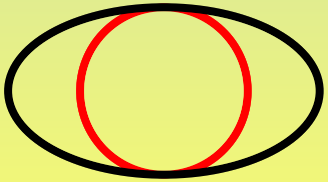
Results - E Glass

Strains x 10^6	Inside		Outside	
$\pm 35°$				
$\pm 55°$	$\varepsilon_x = -79$ $\varepsilon_\theta = -600$		$\varepsilon_x = 60$ $\varepsilon_\theta = 500$	
$\pm 85°$	$\varepsilon_x = 160$ $\varepsilon_\theta = -640$		$\varepsilon_x = 18$ $\varepsilon_\theta = 550$	

Results - R Glass

Strains x 10^6	Inside		Outside	
± 35°	$\varepsilon_x = -72$		$\varepsilon_x = 34$	
	$\varepsilon_\theta = -560$		$\varepsilon_\theta = 550$	
± 55°	$\varepsilon_x = -300$		$\varepsilon_x = 270$	
	$\varepsilon_\theta = -390$		$\varepsilon_\theta = 470$	
± 85°	$\varepsilon_x = 170$		$\varepsilon_x = 6$	
	$\varepsilon_\theta = -590$		$\varepsilon_\theta = 390$	

Results - Carbon T700

Strains x 10^6	Inside		Outside	
± 35°	$\varepsilon_x = -120$		$\varepsilon_x = 170$	
	$\varepsilon_\theta = -930$		$\varepsilon_\theta = 680$	
± 55°	$\varepsilon_x = -160$		$\varepsilon_x = 190$	
	$\varepsilon_\theta = -640$		$\varepsilon_\theta = 510$	
± 85°	$\varepsilon_x = -74$		$\varepsilon_x = 18$	
	$\varepsilon_\theta = 150$		$\varepsilon_\theta = 550$	

PREDICTIONS FROM A RESIDUAL STRESS MODEL

- **Internal stress generated by the ambient conditions**

Hygrothermal ambient conditions ➤ **internal stress**

Calculation within the framework of thermo-hygro-elasticity

$$\sigma = \mathbf{L} : (\varepsilon^{e} - \alpha(T - T_0) - \beta(m - m_0))$$

$$\text{with} \quad m = \frac{c}{\rho}$$

+ Classical equations of solid mechanics

PREDICTIONS FROM A RESIDUAL STRESS MODEL

- Process-induced stresses

At the beginning of the cool-down stress-free state: $\sigma_{ij} = 0$

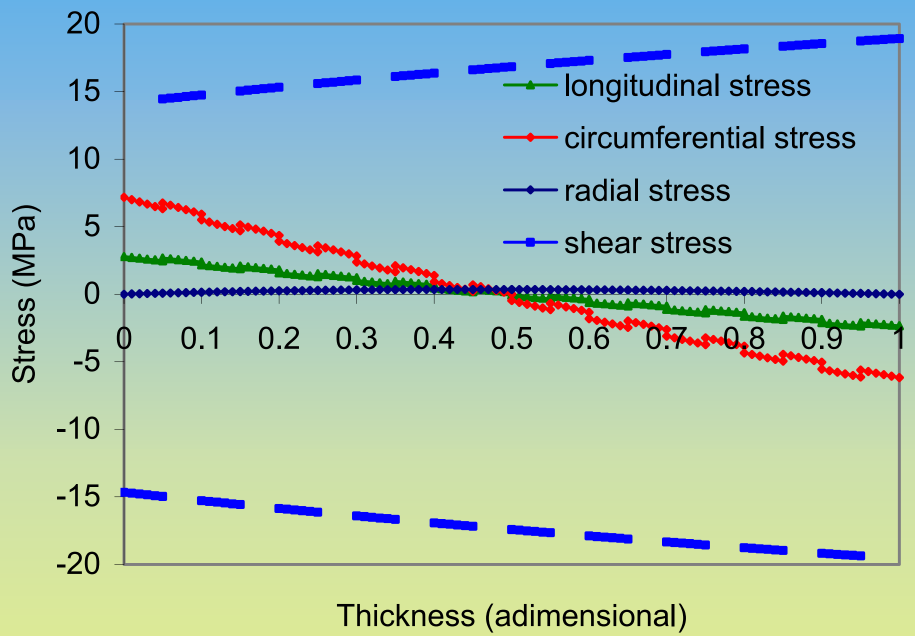
Classical equations of solid mechanics:

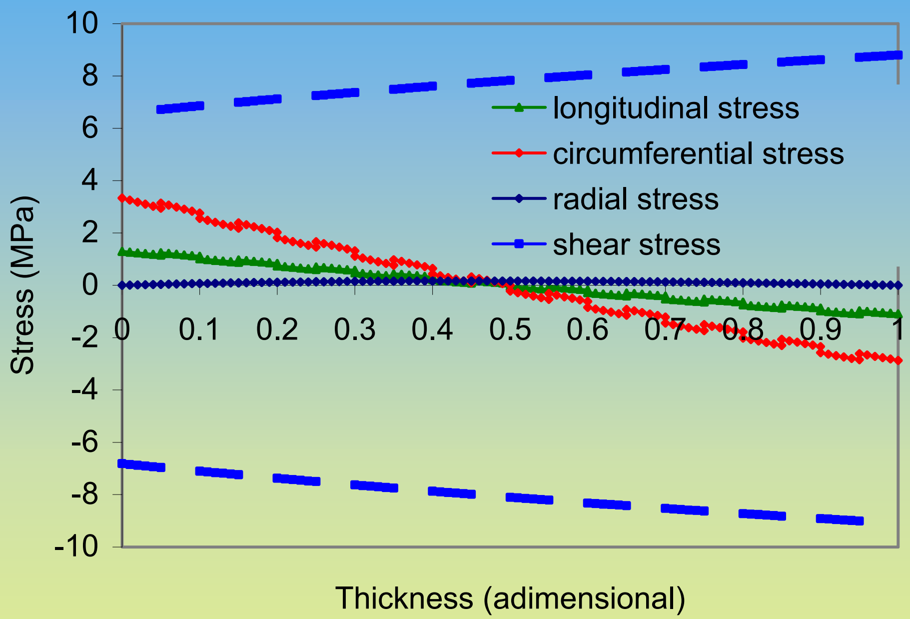
- Constitutive laws of thermoelastic orthotropic materials

$$\sigma = \mathbf{L} : (\varepsilon^e - \alpha(T - T_0))$$

- Strain-displacement relations
- Compatibility and equilibrium equations and boundary conditions

PREDICTIONS FROM A RESIDUAL STRESS MODEL





Stress distribution in a [±55] E glass/epoxy tube due to cooling from 125°C to 20°C

Stress distribution in a [±55] E glass/epoxy tube at saturation.

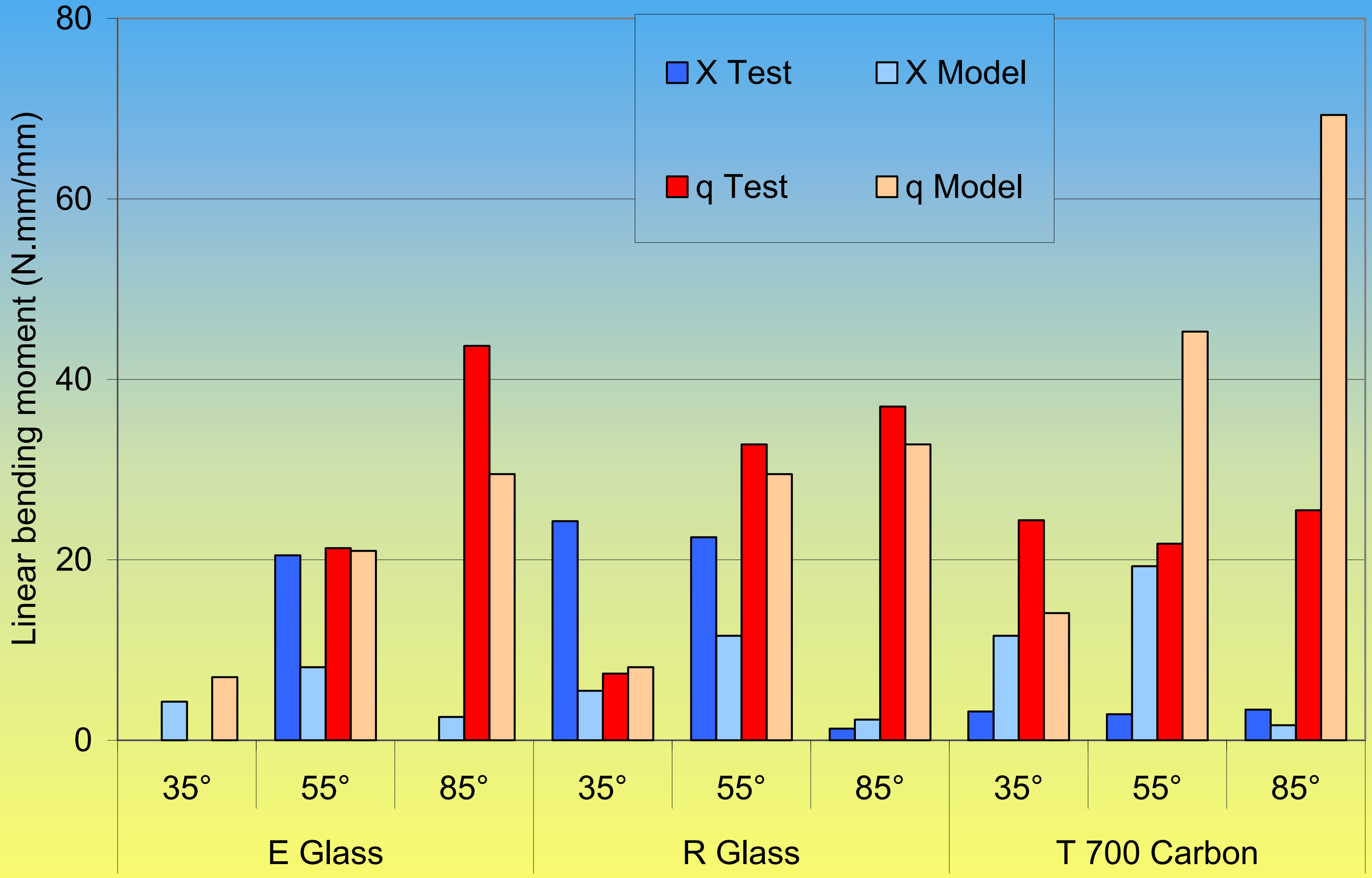
PREDICTIONS FROM A RESIDUAL STRESS MODEL

To make a comparison with the experimental assessment, the corresponding bending moments are calculated by the following relations (since thin tubes are considered) :

$$\left\{ M_x = \int_{-\frac{H}{2}}^{\frac{H}{2}} \sigma_{xx} z dz \quad \text{and} \quad M_\theta = \int_{-\frac{H}{2}}^{\frac{H}{2}} \sigma_{\theta\theta} z dz \right.$$

where H is the thickness of the tube.

COMPARISON BETWEEN TESTS AND CALCULATIONS



CONCLUSIONS

The order of magnitude of moments is significant and needs to be taken into account in design

- Good agreement for Glass reinforcement
- Mismatch for Carbon tubes

Need of characterization of hygrothermal properties of composite laminates