Application of the ***Open Hole Tensile Test*** *to the* ***Identification*** *of the* ***in-plane Characteristics*** *of* ***Orthotropic Plates***

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Presentation summary

- Introduction

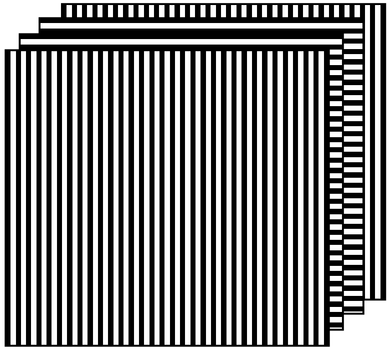
- Identification procedure

- First results

- Interaction between anisotropy and geometrical modelling errors

- Conclusion

Introduction: global overview



Orthotropic laminate

Elastic properties ?

↓

OFFM

↓

Specimen geometry for an evaluation using only one test ?

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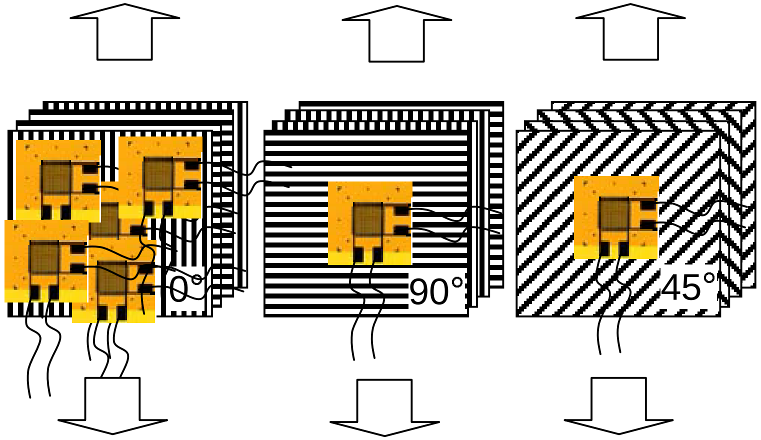
Hole on plate tensile test

Classical approach

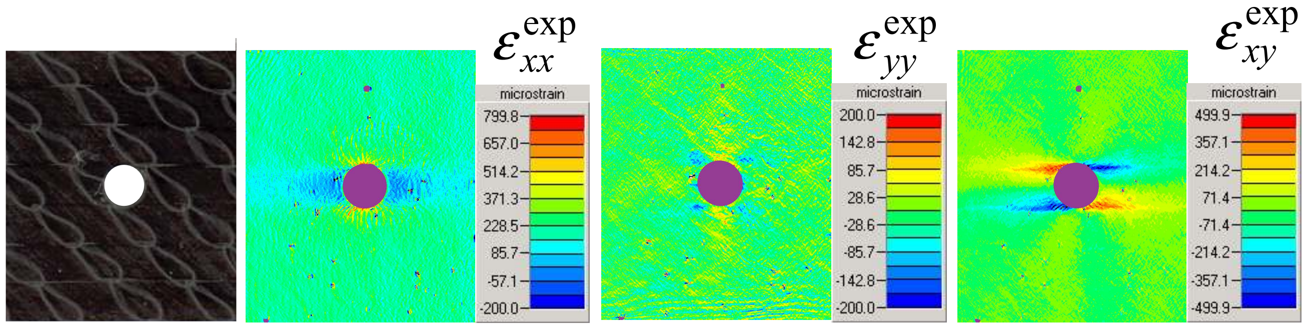
Reference values

$E_{xx}, \nu_{xy}, E_{yy}, G_{xy}$

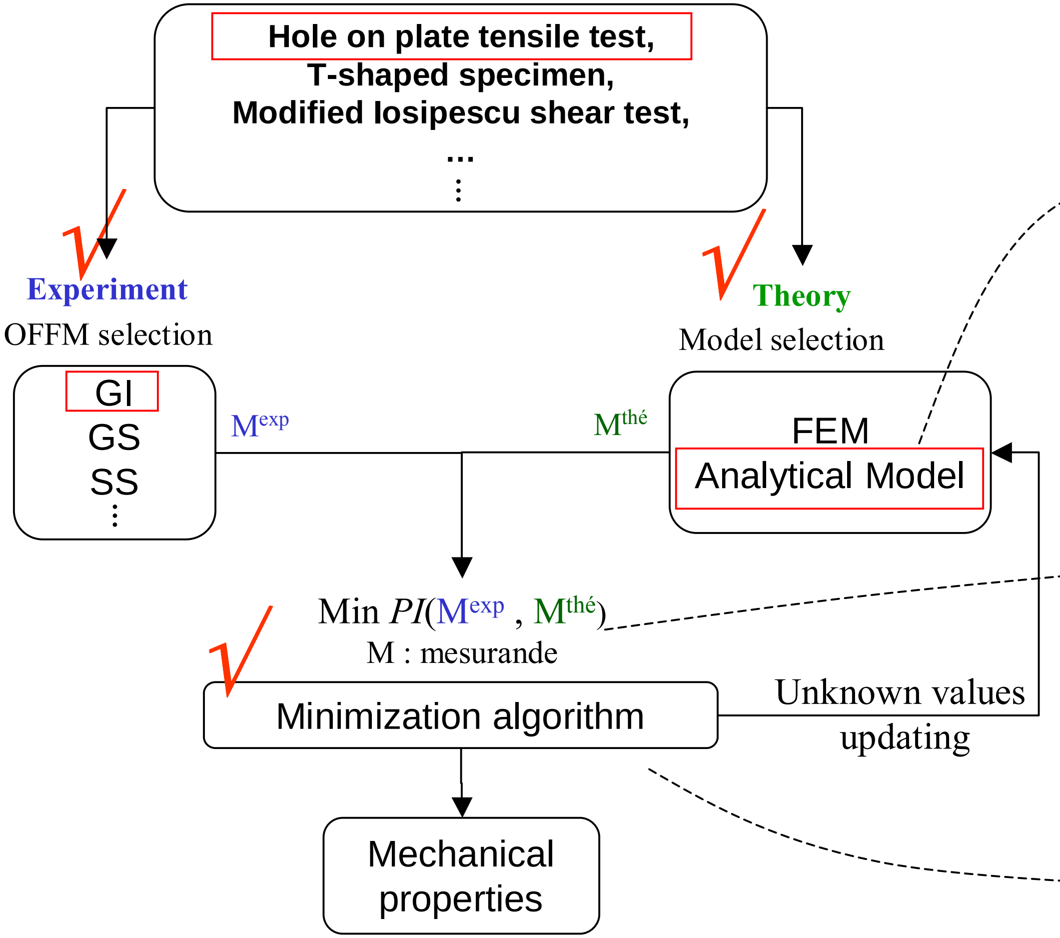
Hypothesis :
Uniform strain field



Strain field strongly localized near the hole boundary:
High spatial resolution and strains known near the hole boundary



Introduction: identification strategy



Lekhnitskii solution for a hole on infinite orthotropic plate (plane stress conditions)

$$PI = \frac{1}{2n_p}\mathbf{R}^T\mathbf{R}$$

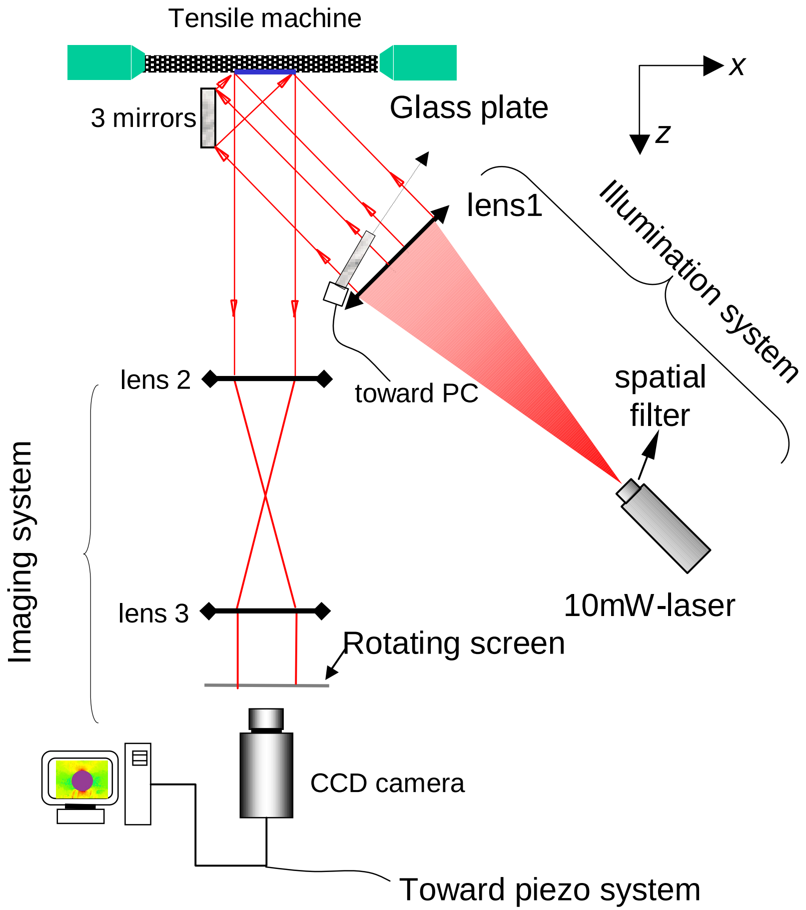
n_p : number of measures
R : residue vector

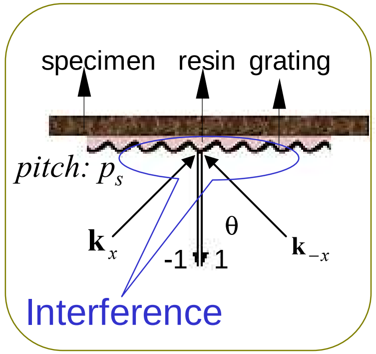
$$R_i = \sqrt{\left(\varepsilon_{xx,i}^{\exp} - \varepsilon_{xx,i}^{ana}\right)^2 + \left(\varepsilon_{yy,i}^{\exp} - \varepsilon_{yy,i}^{ana}\right)^2 + \left(\varepsilon_{xy,i}^{\exp} - \varepsilon_{xy,i}^{ana}\right)^2}$$

$$i = 1, 2, \ldots, n_p$$

Modified Levenverg-Marquardt algorithm

Experimental technique: digital phase-shifting grating interferometry





$$\Delta\phi_h = (\mathbf{k}_x - \mathbf{k}_{-x})\cdot\mathbf{d} = \frac{4\pi}{p_s}u$$

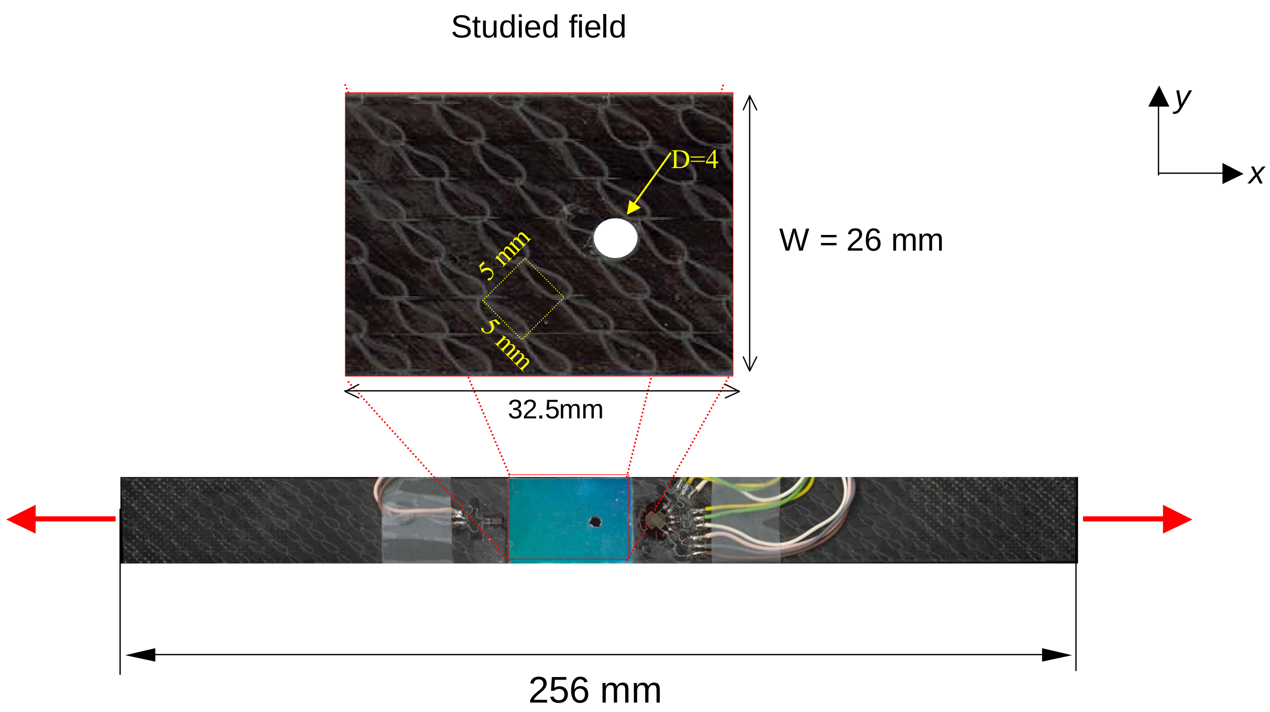
Phase difference
$$\Delta\phi_h = \phi_h^d - \phi_h^r$$

$$\mathbf{g}_h = \mathbf{k}_x - \mathbf{k}_{-x}$$
$$\mathbf{d} = [u\ v\ w]$$

$$\boxed{u = \frac{p_s}{4\pi}\Delta\phi_h}$$

Experimental technique: mechanical set-up and specimen

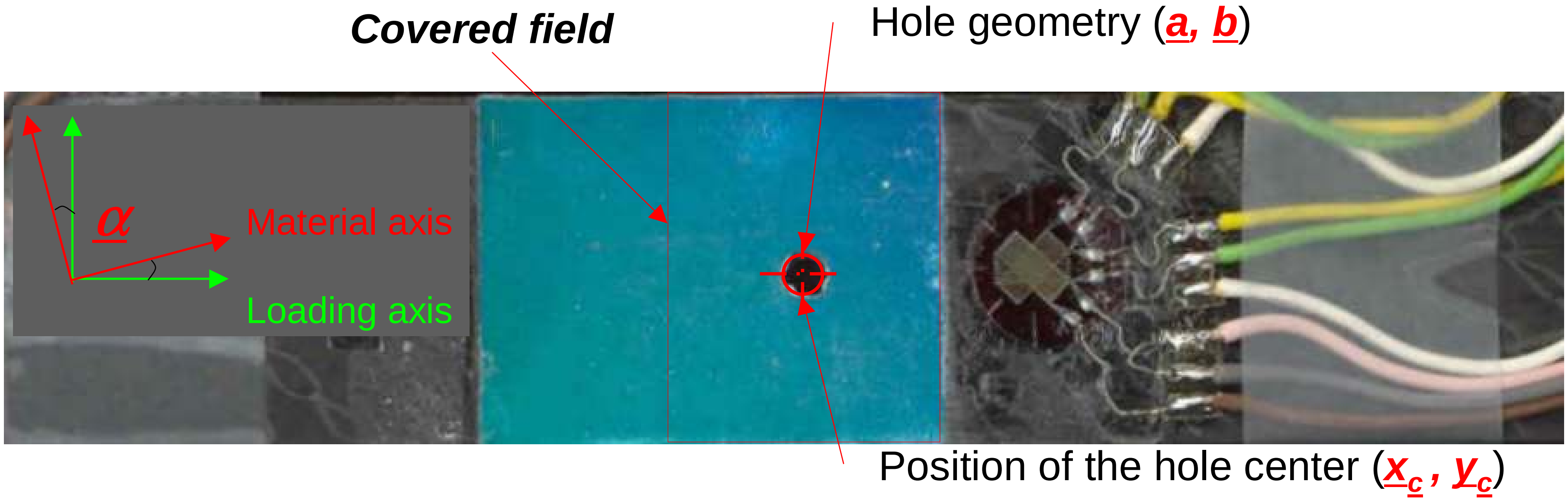
- Specimen: NC2® reinforcement from Hexcel Composite
  + Epoxy resin processed in a RTM mold
  Stacking sequence $[\{0/90\}_3]_s$



- Mechanical set-up: Table-top **tensile** device
  Applied stress 10 MPa

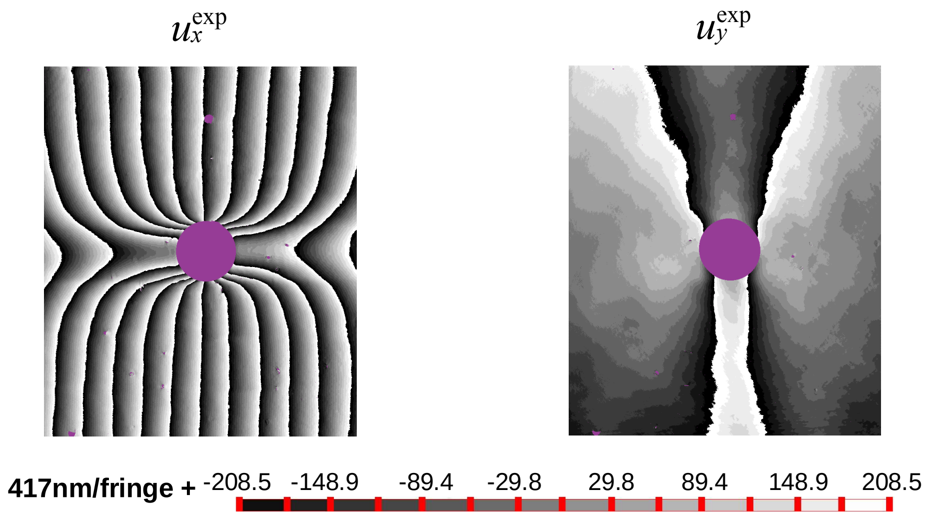
Identification procedure: Unknown parameters

- Geometrical parameters:

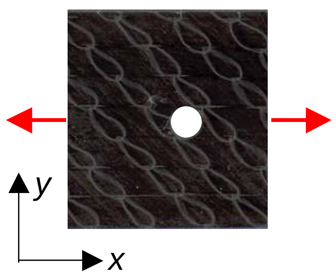


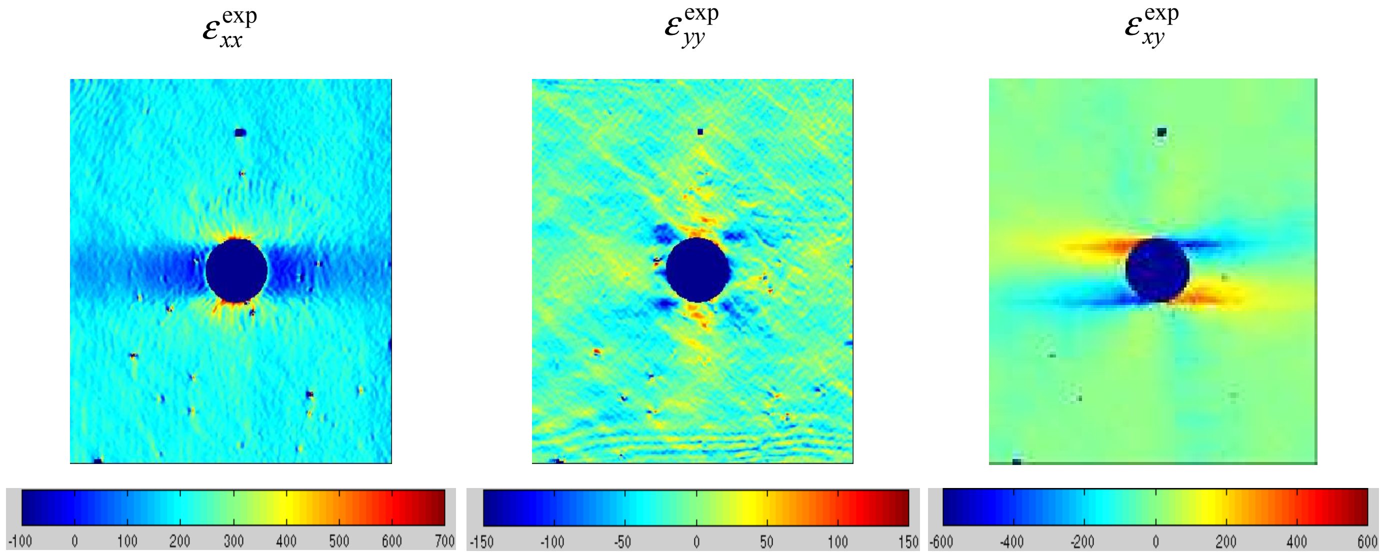
- Material parameters:
  - E_{xx}
  - E_{yy}
  - G_{xy}
  - ν_{xy}

First results: displacements and strains maps



- Metrological aspects:
  - Field: 779 by 917 pixels
  - Spatial resolution: 244 µm
  - Resolution: 6 µstrains
  - Derivation: least square (7 pixels)



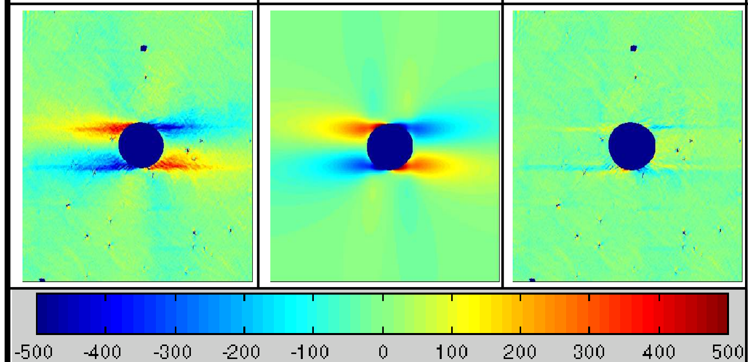


First identification results

Identified values

	E_{xx}	E_{yy}	G_{xy}	ν_{xy}
Reference values	60 GPa	56 GPa	4.3 GPa	0.05
Identified values	57.1 GPa	58.1 GPa	4.48 GPa	0.062
Difference	4.1 %	4.0 %	5.2 %	26.5 %

$\varepsilon_{xy}^{\exp}(i,j)$	$\varepsilon_{xy}^{num}(i.j)$	$\varepsilon_{xy}^{\exp}(i,j)-\varepsilon_{xy}^{num}(i,j)$	statistics

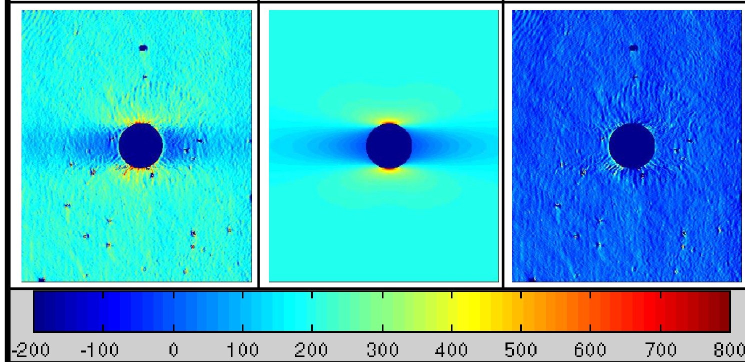


E[$\varepsilon_{xy}^{\exp}-\varepsilon_{xy}^{num}$] = -0.6957 με

s.d. [$\varepsilon_{xy}^{\exp}-\varepsilon_{xy}^{num}$] = 32.1672 με

Differences between experimental and numerical strain maps

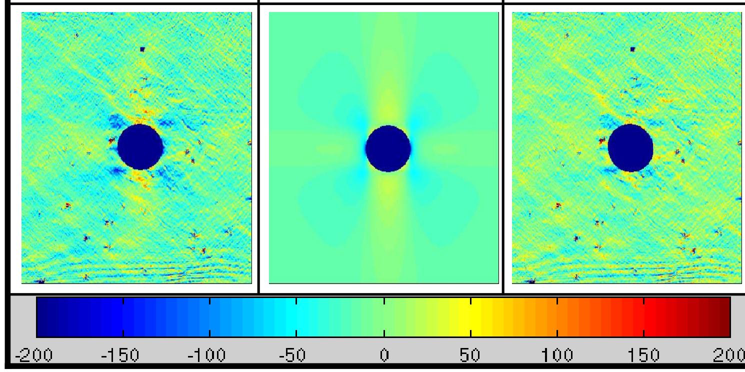
$\varepsilon_{xx}^{\exp}(i,j)$	$\varepsilon_{xx}^{num}(i.j)$	$\varepsilon_{xx}^{\exp}(i,j)-\varepsilon_{xx}^{num}(i,j)$	statistics



E[$\varepsilon_{xx}^{\exp}-\varepsilon_{xx}^{num}$] = 0.7691 με

s.d. [$\varepsilon_{xx}^{\exp}-\varepsilon_{xx}^{num}$] = 58.9253 με

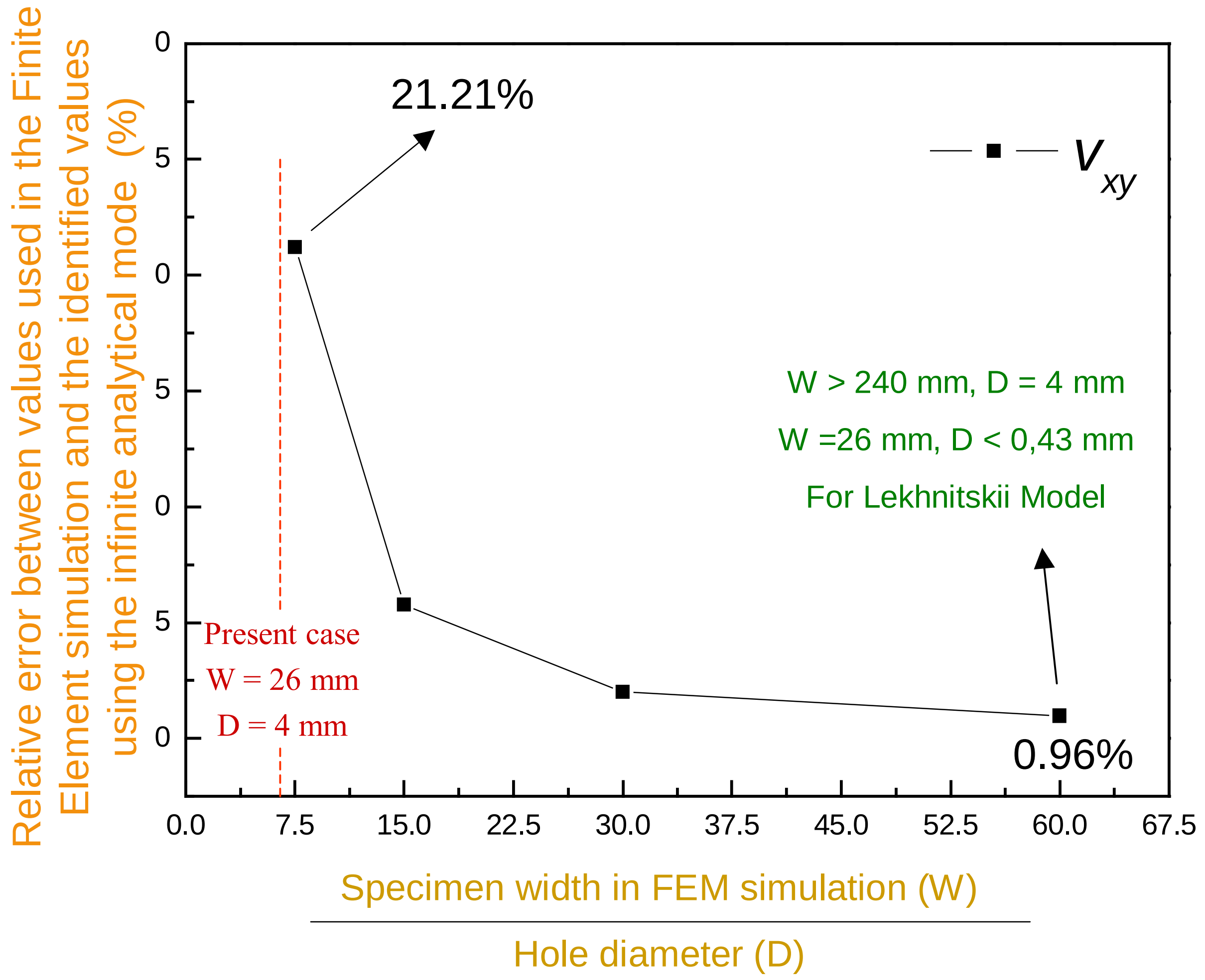
$\varepsilon_{yy}^{\exp}(i,j)$	$\varepsilon_{yy}^{num}(i.j)$	$\varepsilon_{yy}^{\exp}(i,j)-\varepsilon_{yy}^{num}(i,j)$	



E[$\varepsilon_{yy}^{\exp}-\varepsilon_{yy}^{num}$] = 0.4395 με

s.d. [$\varepsilon_{yy}^{\exp}-\varepsilon_{yy}^{num}$] = 32.3187 με

Study of geometrical modelling error



Study of anisotropy vs geometrical modelling errors

1st- Simulation of various material cases using a micro/macro approach

- *glass or carbon fibres*
- *2 epoxy resins*
- *fibre volume fraction from 30 % to 60 %*
- *$[0]_4$, $[90]_4$ or $[0, 90]_S$ stacking sequence*

2nd- Calculation of the 3 required strain fields

- *with the normalized test geometry*
- *using a FEM approach*

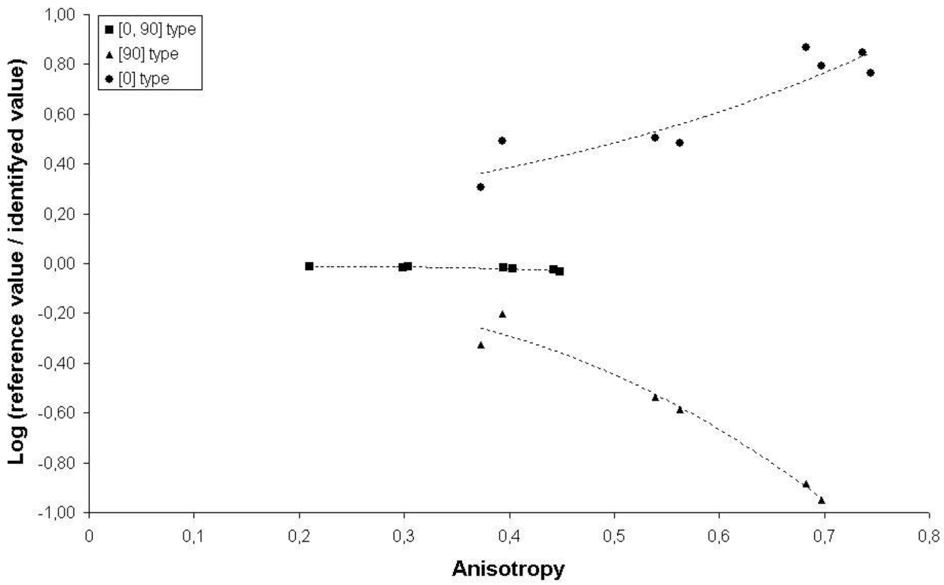
3rd- Identification of the 9 parameters

- *with the Lekhnitskii-based algorithm*

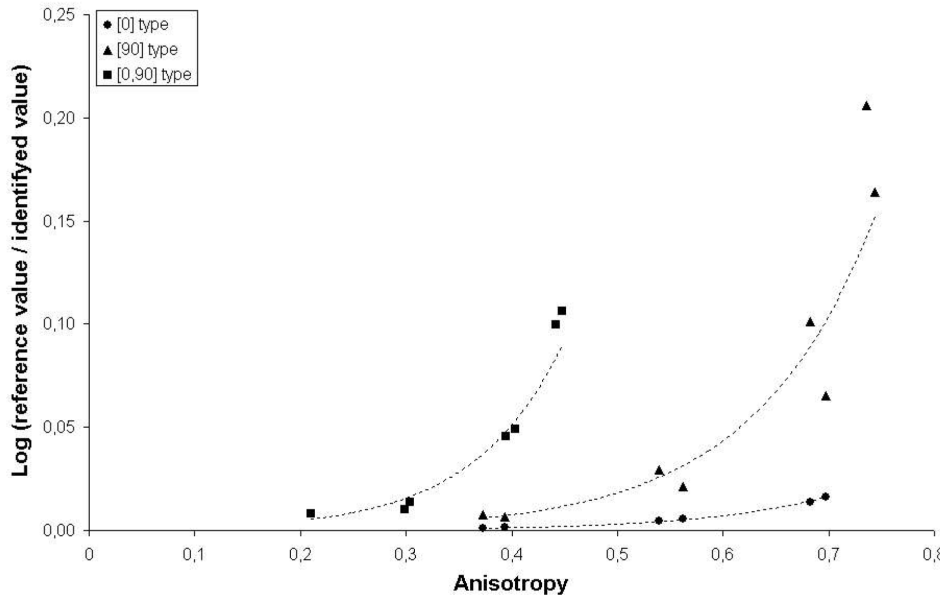
4th- Results expressed as a 'ratio' vs. 'anisotropy'

→ ***24 different cases***
Anisotropy ratio from 0.20 to 0.74

Study of anisotropy vs geometrical modelling errors



Poisson ratio ν_{xy}



Transverse Young modulus E_{yy}

- ***Geometrical modelling errors grow with anisotropy***
- ***Use regression curves to correct identified material parameters***

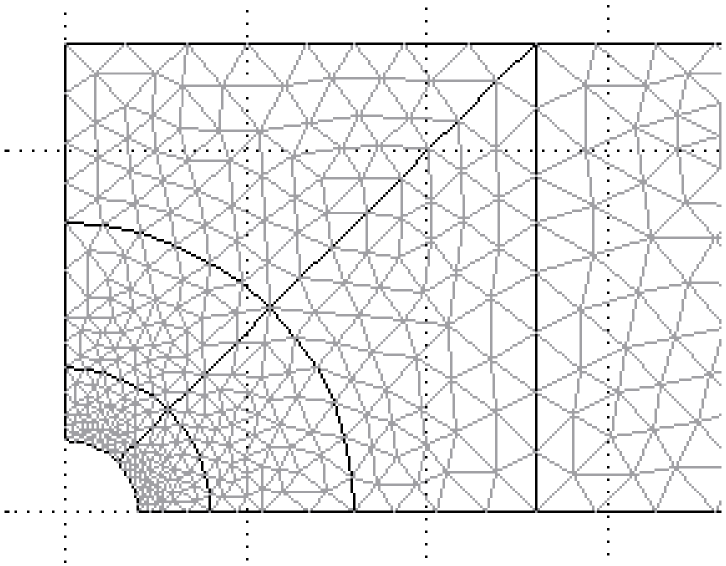
An attempt to correct geometrical modelling errors

	E_{xx}	E_{yy}	G_{xy}	ν_{xy}
Reference values	60 GPa	56 GPa	4.3 GPa	0.05
Identified values	57.9 GPa	63.5 GPa	4.43 GPa	0.059
Mean error for all studied cases	-	7.5 %	-	92.6 %

Correction approach too simple and regression curves unable to follow data scattering induce low confidence in corrected values. In particular, highest errors (up to 98%) for low Poisson's ratio.

It is necessary to include the FEM within the identification procedure

Final results using experimental maps and a FEM



	E_{xx}	E_{yy}	G_{xy}	ν_{xy}
Reference value	59.5 GPa	55.8 GPa	4.26 GPa	0.049
Identified value	57.6 GPa	55.3 GPa	4.48 GPa	0.046
Difference (%)	4.1%	4.0%	5.2%	6.1%

(reference values from 3 classical tensile tests)

Conclusions and Perspectives

Conclusions

Finally, identified mechanical parameters in agreement with classical tests (<6 %)

Necessity of using a FEM within the identification procedure

These identification studies show that extrapolating the normalized open hole tensile test to other geometries is questionable because of the anisotropy / geometry interaction.

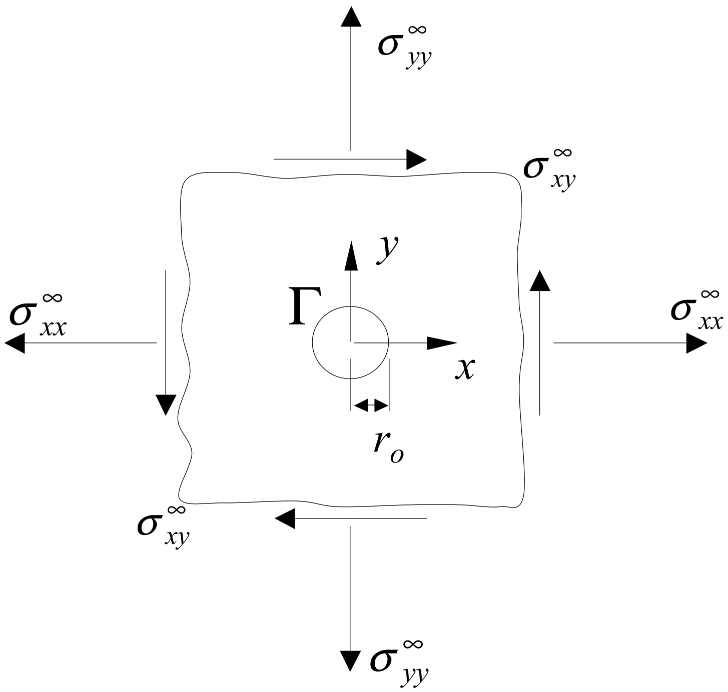
Perspectives

Experimental techniques

Use of a simpler OFFM Technique (Speckle shearography)

Further results with other reference materials

Numerical simulation: Lekhnistskii's analytical approach



A hole subjected to uniform remote load at infinity

Lekhnitskii's solution in the case of the hole on a thin plate of which size are considerably larger than the hole diameter

Solution

$$\mathbf{q} = -r_o \begin{Bmatrix} \sigma_{xy}^{\infty} \\ \sigma_{yy}^{\infty} \end{Bmatrix} + i r_o \begin{Bmatrix} \sigma_{xx}^{\infty} \\ \sigma_{xy}^{\infty} \end{Bmatrix}$$

$$\mathbf{\Phi}_{\Gamma} = 0$$

$$\sigma_{yy}^{\infty} = \sigma_{xy}^{\infty} = 0$$

$$\sigma_{xx}^{\infty} = \sigma_A$$

$$\mathbf{u}^{\infty} = x \begin{Bmatrix} \varepsilon_{xx}^{\infty} \\ 2\varepsilon_{xy}^{\infty} \end{Bmatrix} + y \begin{Bmatrix} 2\varepsilon_{xy}^{\infty} \\ \varepsilon_{yy}^{\infty} \end{Bmatrix}$$

$$\mathbf{\Phi}^{\infty} = x \begin{Bmatrix} \sigma_{xy}^{\infty} \\ \sigma_{yy}^{\infty} \end{Bmatrix} - y \begin{Bmatrix} \sigma_{xx}^{\infty} \\ \sigma_{xy}^{\infty} \end{Bmatrix}$$

Solution for in-plane deformation in the case of plane stress state

traction-free boundary condition along Γ

Under the condition of the uniform stress at infinity

$$\mathbf{u} = \mathrm{Re}\left\lfloor \boxed{\mathbf{A}} \left\langle \varsigma^{-1} \right\rangle \boxed{\mathbf{B}^{-1}} \boxed{\mathbf{q}} \right\rfloor + \boxed{\mathbf{u}^{\infty}}$$

$$\mathbf{\Phi} = \mathrm{Re}\left\lfloor \boxed{\mathbf{B}} \left\langle \varsigma^{-1} \right\rangle \boxed{\mathbf{B}^{-1}} \boxed{\mathbf{q}} \right\rfloor + \boxed{\mathbf{\Phi}^{\infty}}$$