Elastic characterization of a poro-elastic layer in a sandwich structure

Lei LEI

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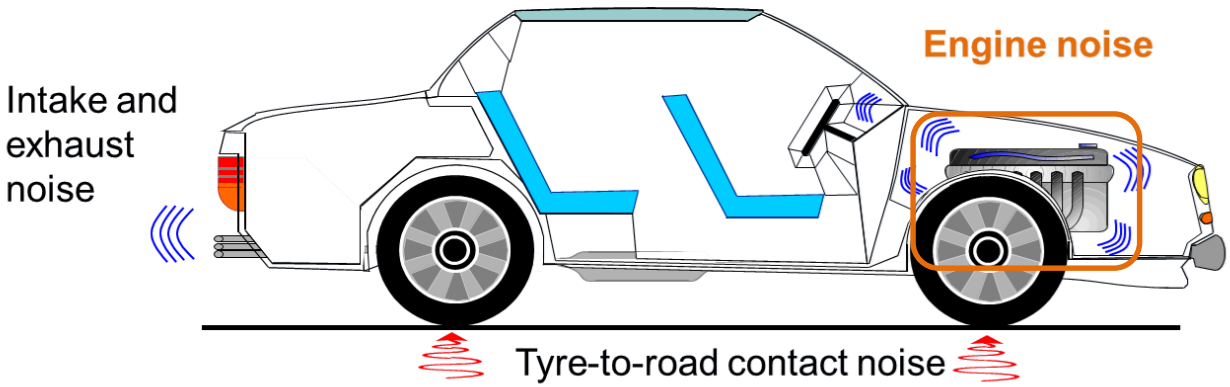
Sapem, 6 - 8 December 2017, Le Mans

Context
Industrial problems

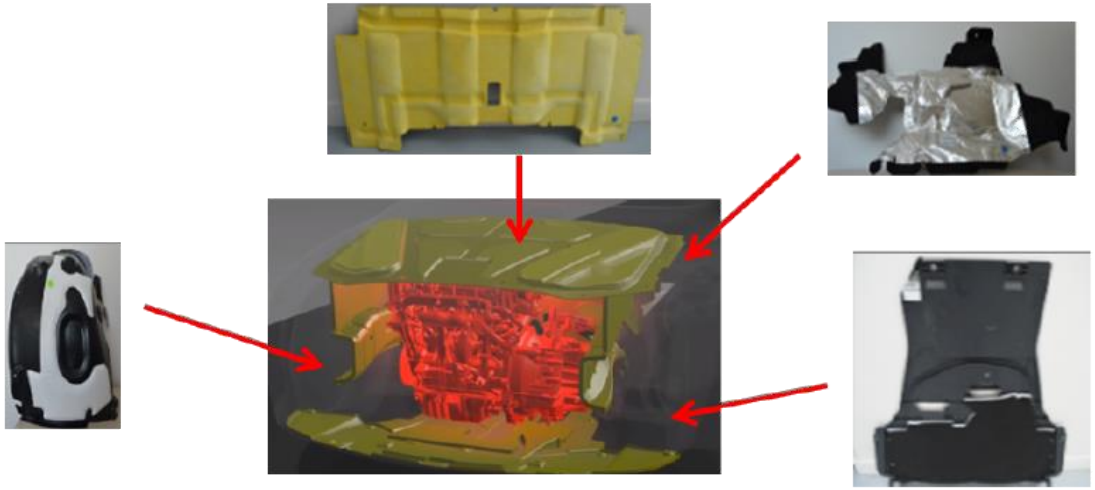
- Industrial problems: **reduction** of vehicle's **pass-by noise** in Europe



-6 dB of engine noise

- Solutions: **Acoustic shield system**

  - Engine hood
  - Heat cover
  - Mud flap shield
  - Underfloor shield

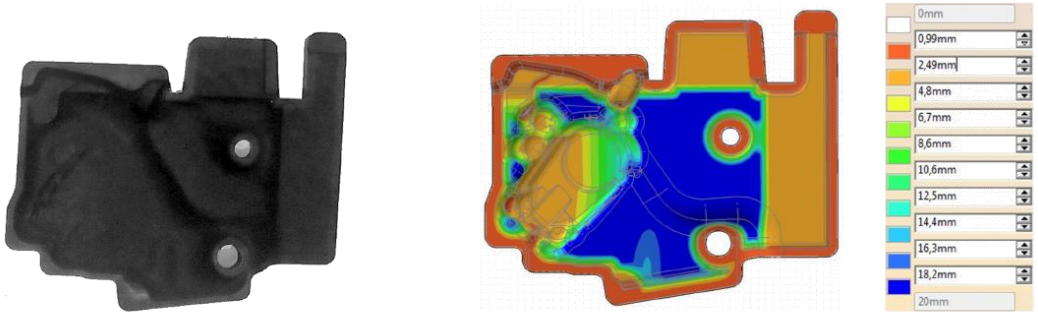


Context
Thermo-compression

- Manufacturing process: **thermo-compression**

uniform layer — compressed at 210°C — molded part

- Automotive Hood liner: **thickness map**



(a) (b)

How to model

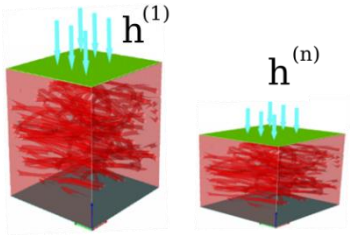
Vibro-acoustic response of a **sandwich structures** with local material's properties?

Predicted material's properties from their non-compressed **original value** and the **compression rate n**

Effect of compression on material's properties
Non-acoustical parameters

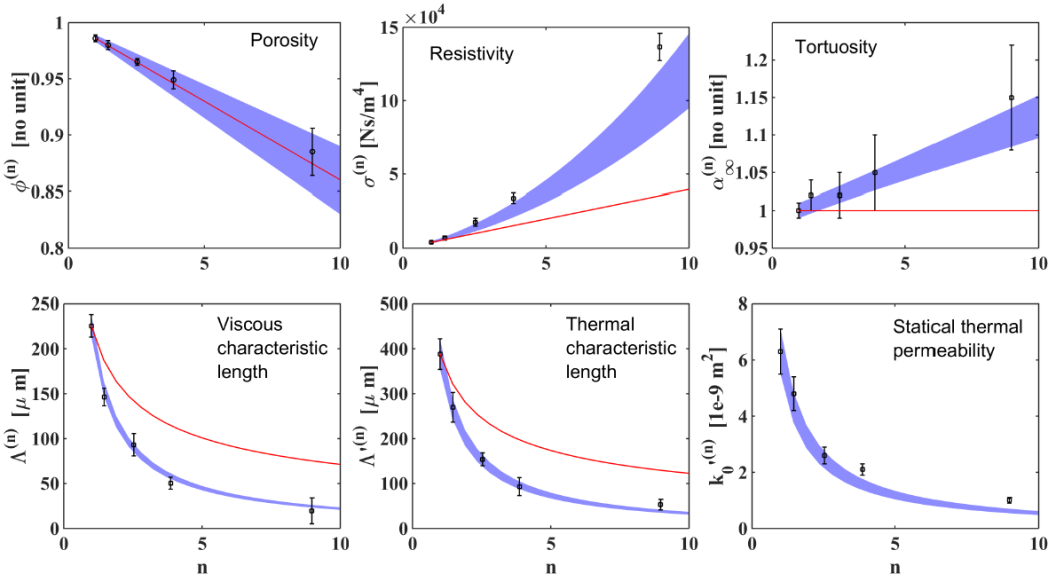
- Definition of **compression rate n**

$$n = \frac{h^{(1)}}{h^{(n)}}$$



- Non-acoustical parameters (JCAL model) vs compression rate *(ref [1,2])*

$$(\phi,\ \sigma,\ \alpha_\infty,\ \Lambda,\ \Lambda',\ k_0')$$



Measured parameters (○), Estimated from new formulas (■), Castagnède estimation (–)

[1] Lei L., Nicolas D., Jean daniel C., Compression of porous materials: physical parameters of the equivalent fluid model revisited Appl. Acoustics(2017

[2] Castagnède B., Aknine A., Brouard B., Tarnow V., Effects of compression on the sound absorption of fibrous materials, Appl. Acoustics (2000)

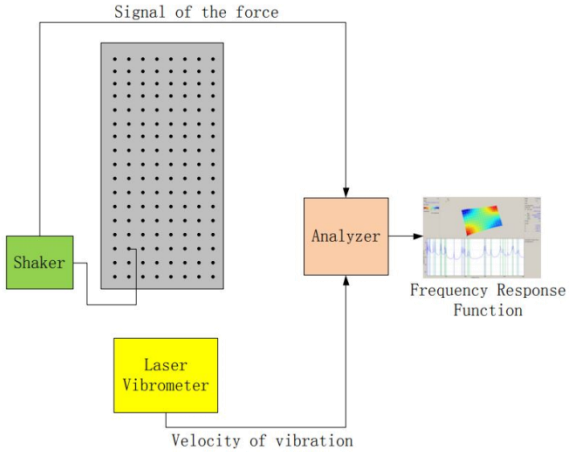
Measurements method for the elastics parameters

- **Classic method:** Quasi-static mechanical characterization of **poro-elastic materials** [1]

Characterized properties**:**

E_L – Longitudinal Young's modulus
v – Poisson's ratio
η – damping loss factor

- **In-situ method:** inverse identification from the **velocity /force FRFs** of **sandwich structure** with a **porous core**



Characterized properties:

G – shear moduli

[1] C. Langlois, R.Panneton, and N. Atalla, Polynomial relations for quasi-static mechanical characterization of isotropic poroelastic materials, J. Acoust. Soc. Am (2001).

Objectives

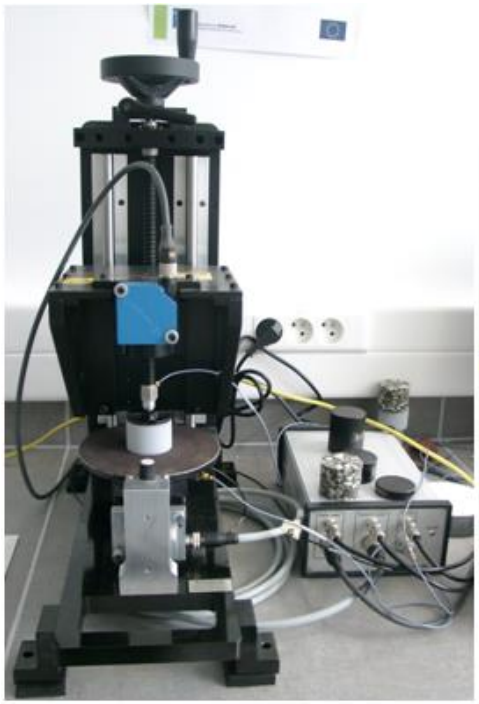
Effect of the compression on elastic properties

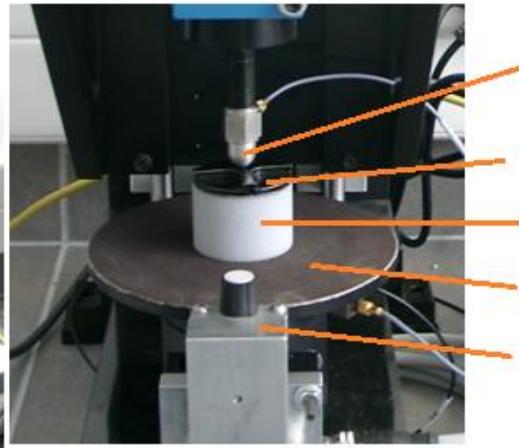
- Longitudinal Young's modulus
- In-plane Shear moduli

Longitudinal Young's modulus

- Young's modulus for an isotropic material is estimated from the dynamic stiffness:

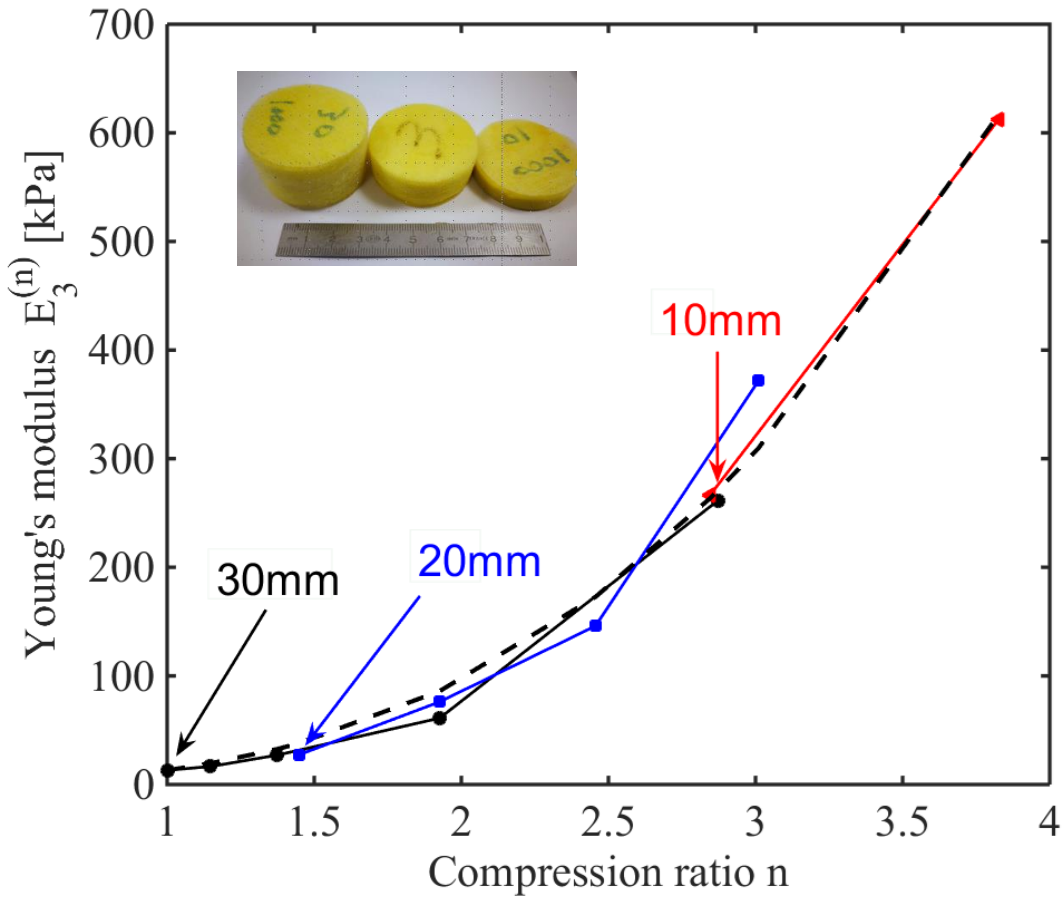
$$E = \frac{k*L}{S} f(\nu),\ \nu = 0, f(\nu) = 1 \text{ for the fibrous material}$$





Preload : m = 42.36 g for fibrous material (<50 Pa for foam)
Excitation amplitude: < 0.1% static deformation

Longitudinal Young's modulus vs compression



$$E_L^{(n)} = E_L^{(1)} \times n^{(2.87)}$$

A power law for Longitudinal Young's modulus

In-plane Shear moduli

- Manufactured sandwich plates (**Aluminum + glass wool + Aluminum**)

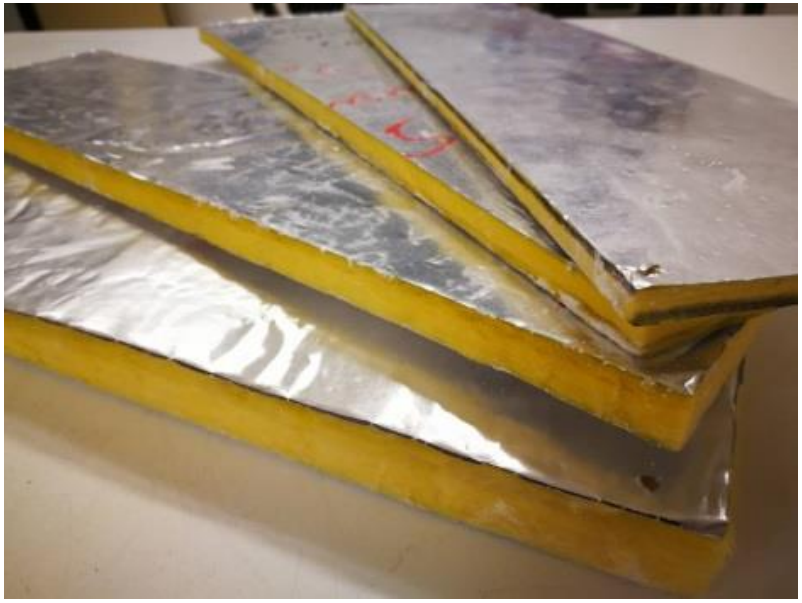


Plate thicknesses: 13 mm, 10 mm, 7 mm
210°C compressed for 5 min

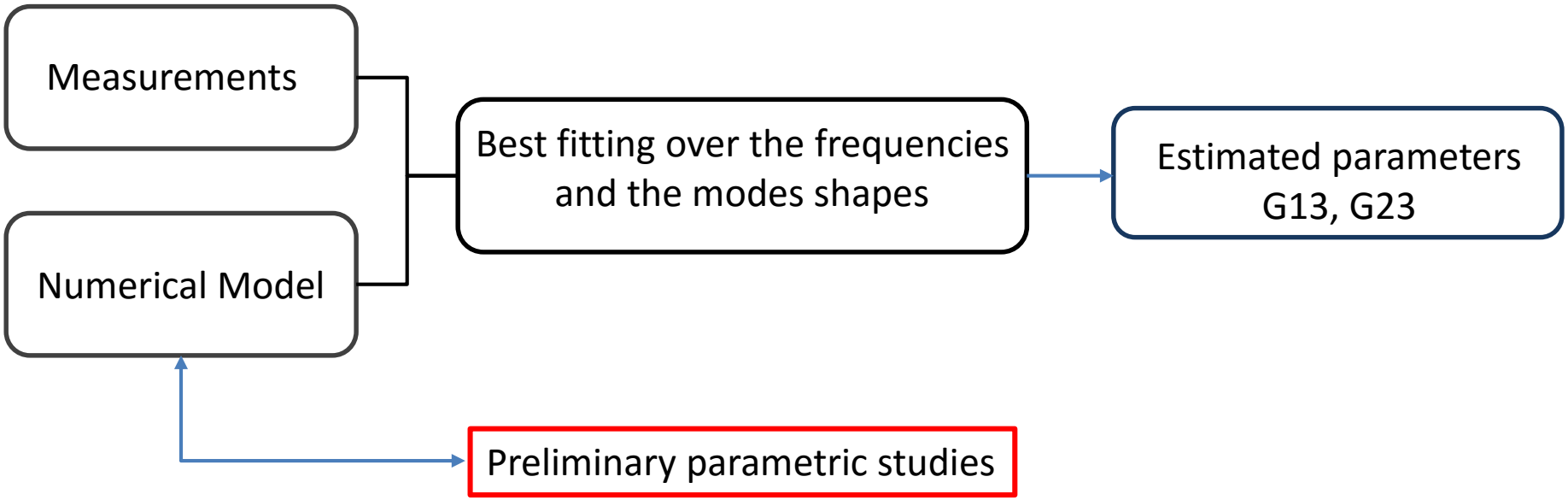
Aluminum thickness: **0.1 mm**

Dimensions
Lx = 42.7 cm, Ly = 12 cm,
Lz = 0.7 cm, 1 cm, 13 cm

Flexural behavior driven by the shear moduli

In-plane Shear moduli

- **Inverse characterization method** :

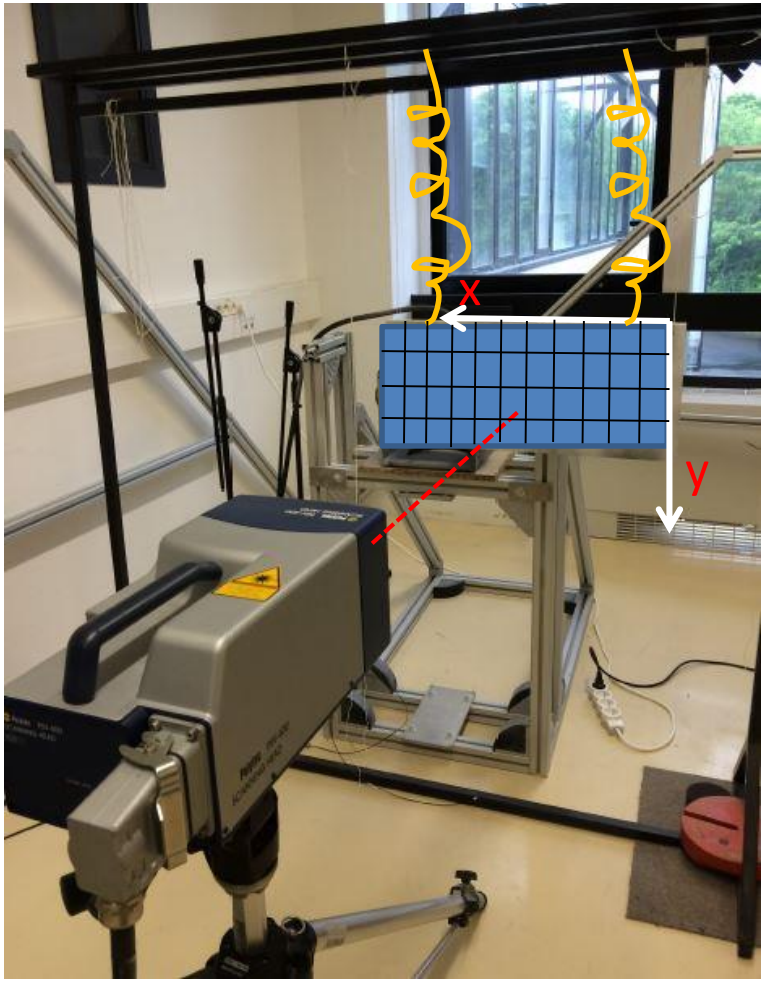


Measurements of the FRFs (Velocity/Force)

The plate is **suspended** with two strings and excited by a shaker

The **quadratic normal velocity** is measured by a scanning laser vibrometer over **190 points**

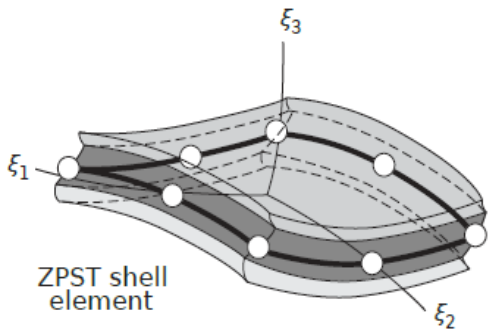
Linear behavior at low excitation

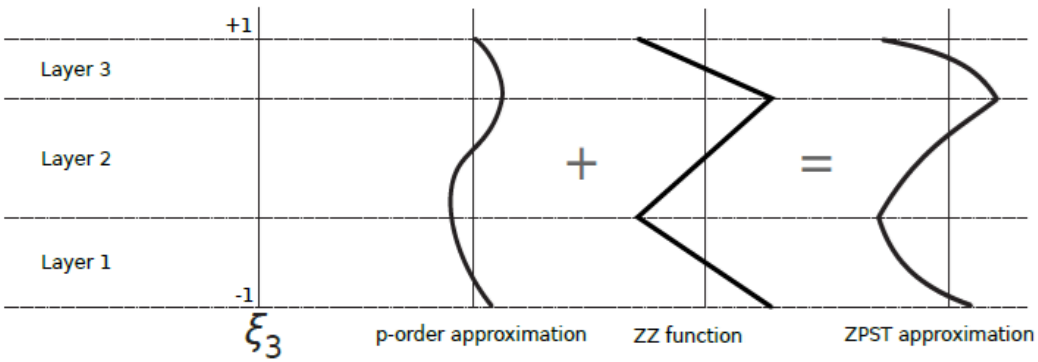


Numerical model - ZPST element

Overview of the ZPST element (ref [3]):

- shell element
- multilayered element (**elastic** and **poro-elastic** layers)
- **polynomial interpolation** and a **zigzag function** in the thickness





[3] J.-D. Chazot, B. Nennig et E. Perrey-Debain. Harmonic response computation of poroelastic multilayered structures using ZPST shell elements. Computers and Structures (2013)

Numerical model - ZPST element

- For **elastic layers**:

$$\int_V \delta\boldsymbol{\varepsilon} : \boldsymbol{\sigma} + \rho\, \delta\mathbf{u} \frac{\partial^2 \mathbf{u}}{\partial t^2}\, \mathrm{d}V - \int_S (\boldsymbol{\sigma}.\mathbf{n})\, \delta\mathbf{u}\, dS = 0$$

- For **poro-elastic layers** $(\mathbf{u}, p_f)$ **:**

$$\begin{aligned} &\boldsymbol{\nabla}\boldsymbol{\sigma}^s + \omega^2 \tilde{\rho}\mathbf{u} = -\tilde{\gamma}\boldsymbol{\nabla} p_f\ , \\ &\Delta p_f + \omega^2 \tfrac{\rho_{22}}{R} p_f = \omega^2 \tilde{\gamma} \tfrac{\rho_{22}}{\phi^2} \boldsymbol{\nabla}\mathbf{u}\ . \end{aligned}$$

with **orthotropic** stress-strain relation:

$\boldsymbol{\sigma}^s_{ij} = C_{ijkl}\boldsymbol{\epsilon}^s_{kl}$ and C_{ijkl} with 9 elastic parameters (E_1, E_2, E_3, ν_{12}, ν_{13}, ν_{23}, G_{12}, G_{13}, G_{23})

- **Coupling conditions** :

$$\begin{aligned} &\boldsymbol{\sigma}^t_1.\mathbf{n} = \boldsymbol{\sigma}^t_2.\mathbf{n}, \\ &\mathbf{u}_1 = \mathbf{u}_2, \\ &\mathbf{U}_2.\mathbf{n} - \mathbf{u}_2.\mathbf{n} = 0. \end{aligned}$$

[4] N. Atalla, M.A. Hamdi, R. Panneton,. Enhanced weak integral formulation for the mixed (u, p) poroelastic equations J Acoust Soc Am (2001)

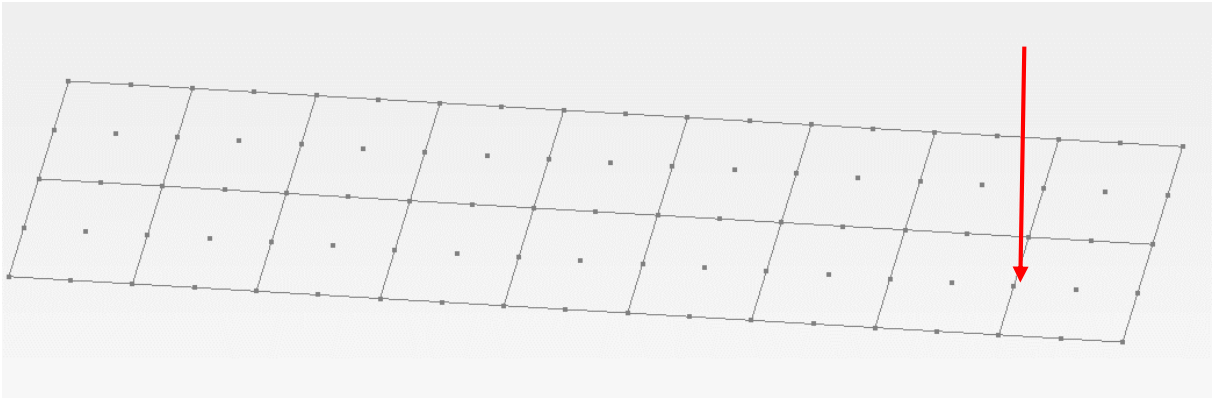
Numerical model - ZPST element

Mesh:

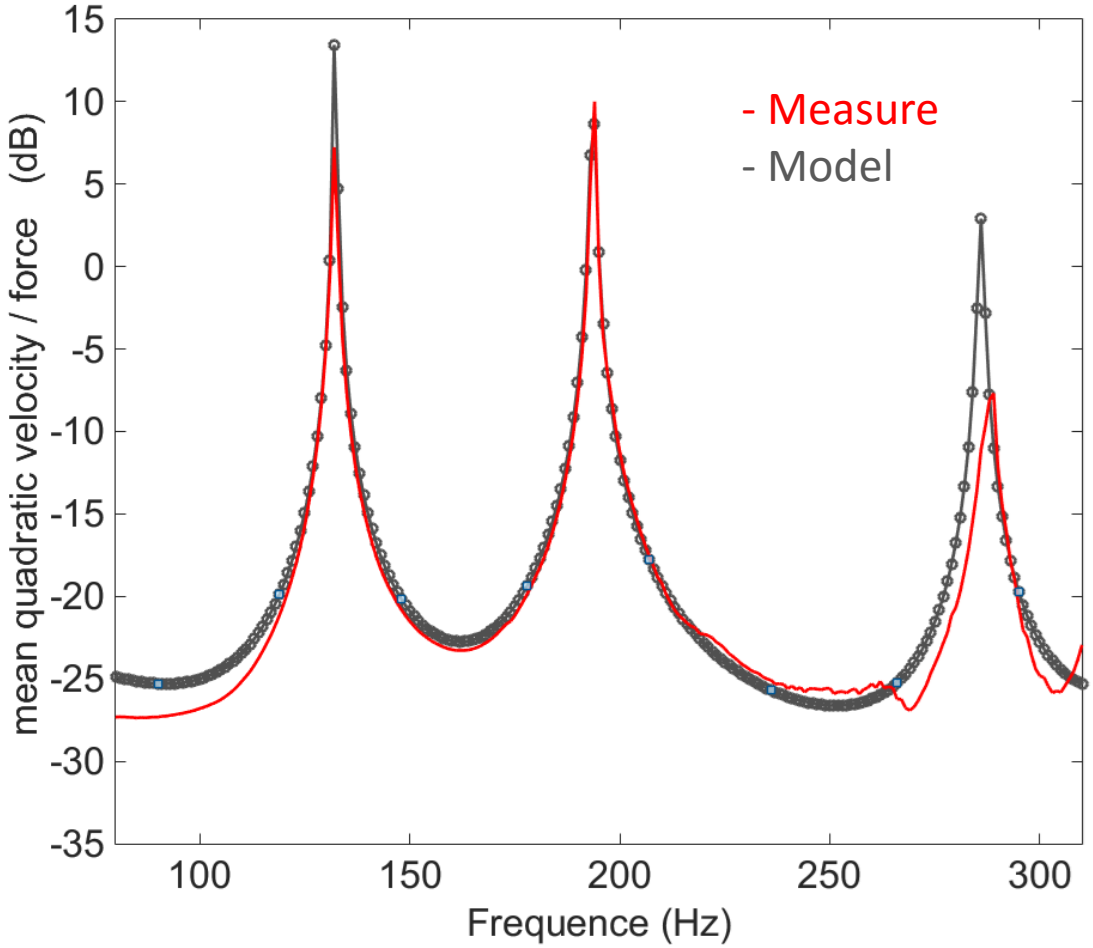
- 40 elements, **1425 DOFS**
- Quadratic quadrangles Q8
- Order of interpolation (p=2) for the displacement and pressure approximations

Calculation times:

- **3.5 second per calculation** 50 – 350Hz



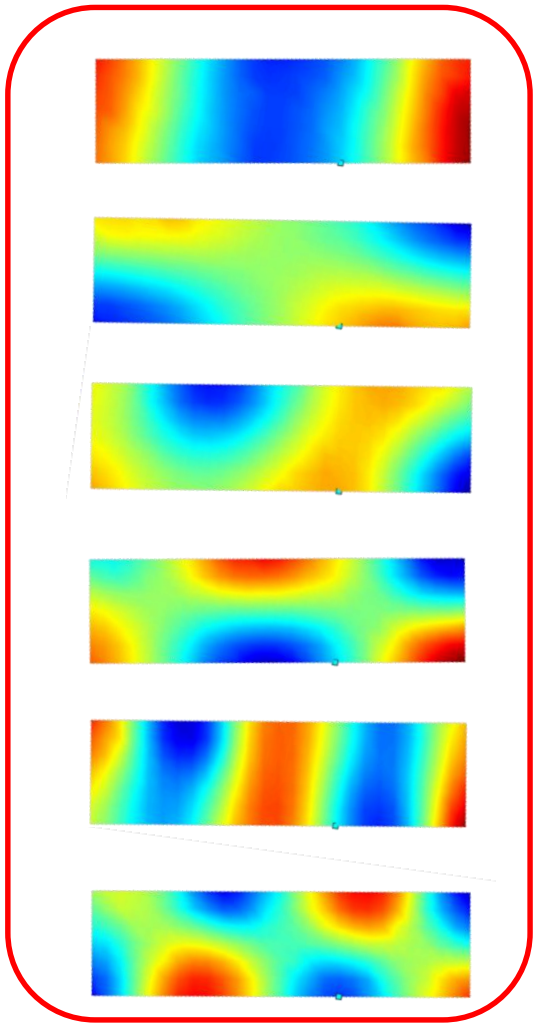
Results
Sandwich plate 7 mm



Estimated Parameters : **G_{13}= 1.55 MPa G_{23} =3.28 MPa**

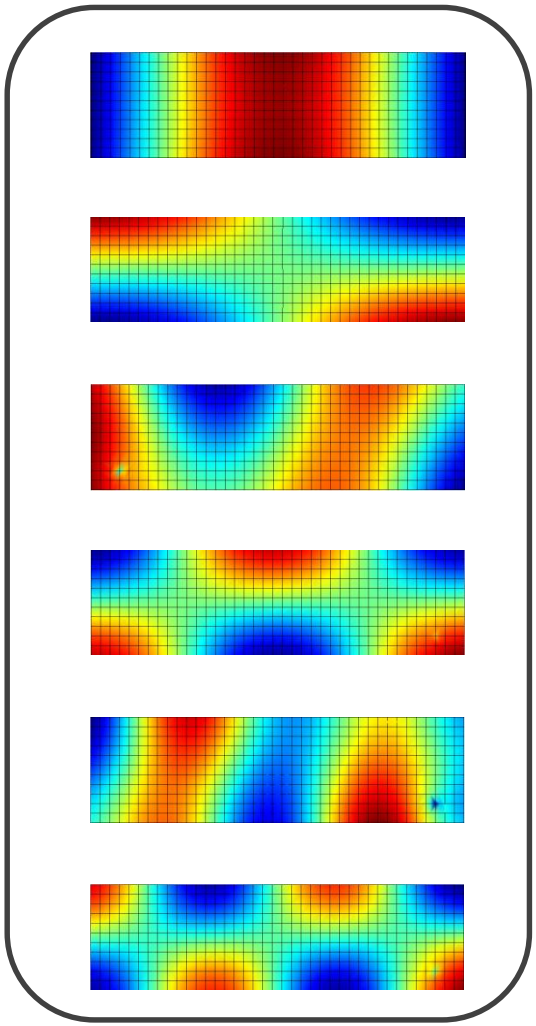
Results
Sandwich plate 7 mm

Measure

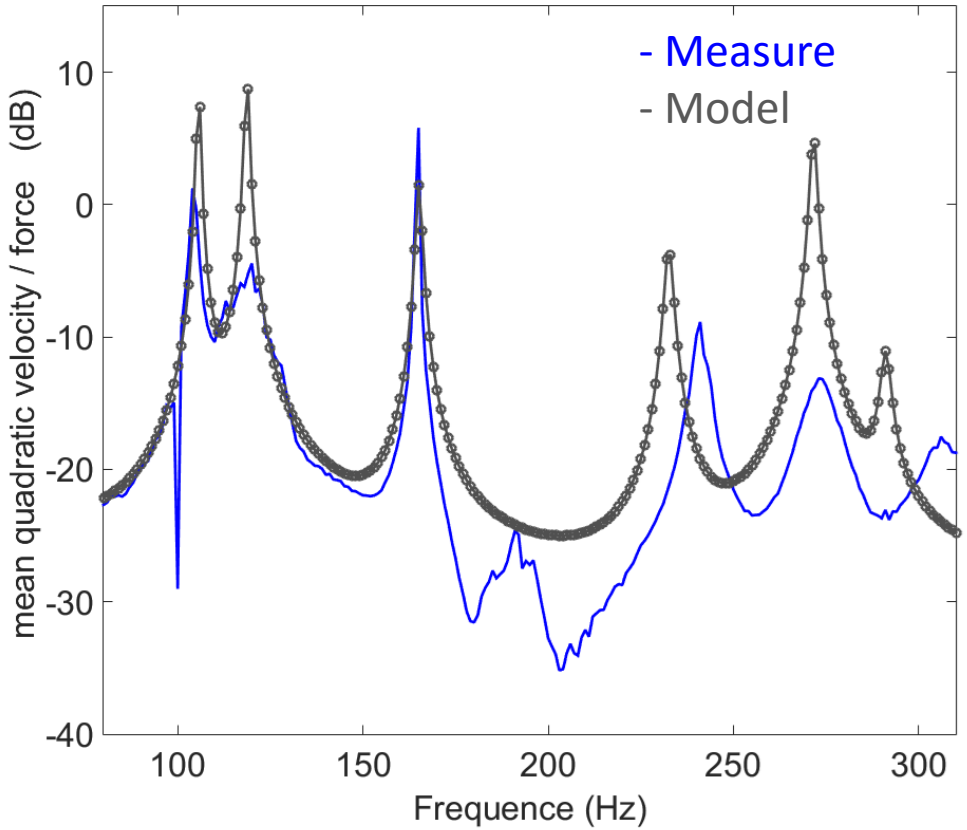


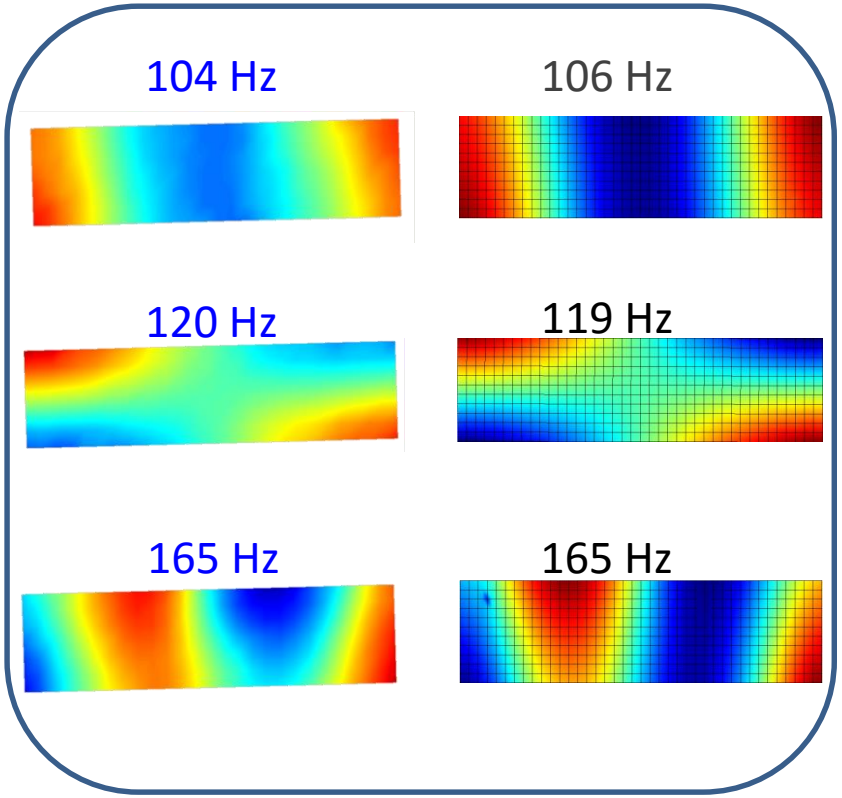
Frequency（Hz）	
132	132
194	194
289	286
317	357
426	445
477	488

Model



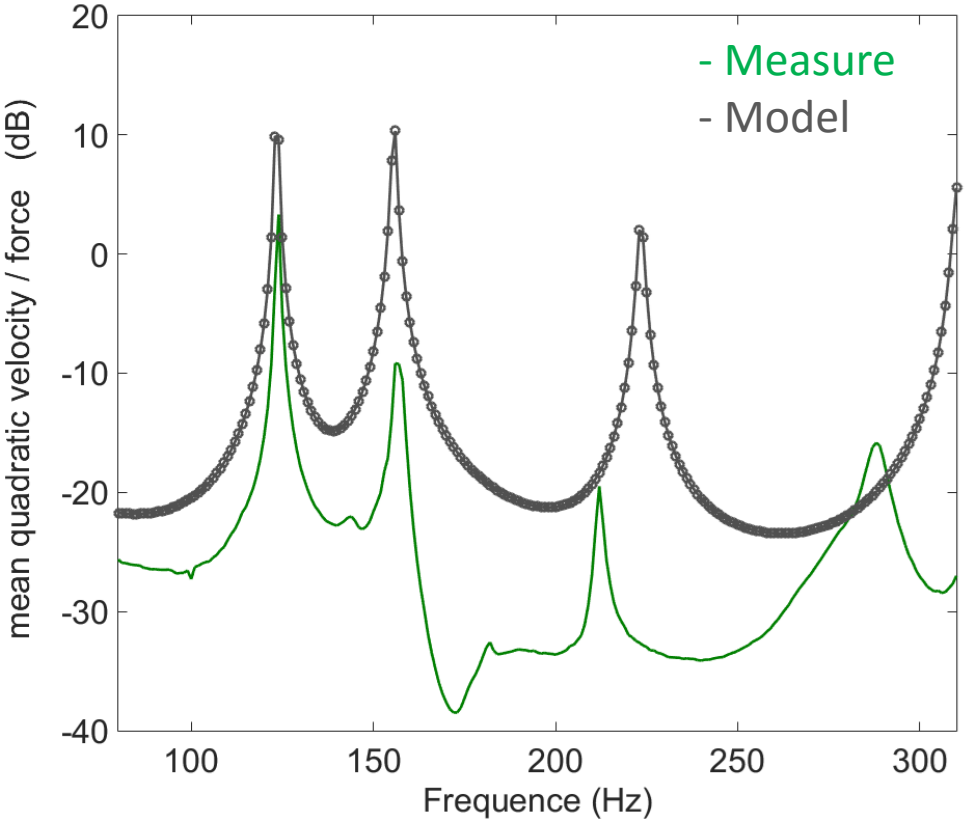
Results
Sandwich plate 10 mm

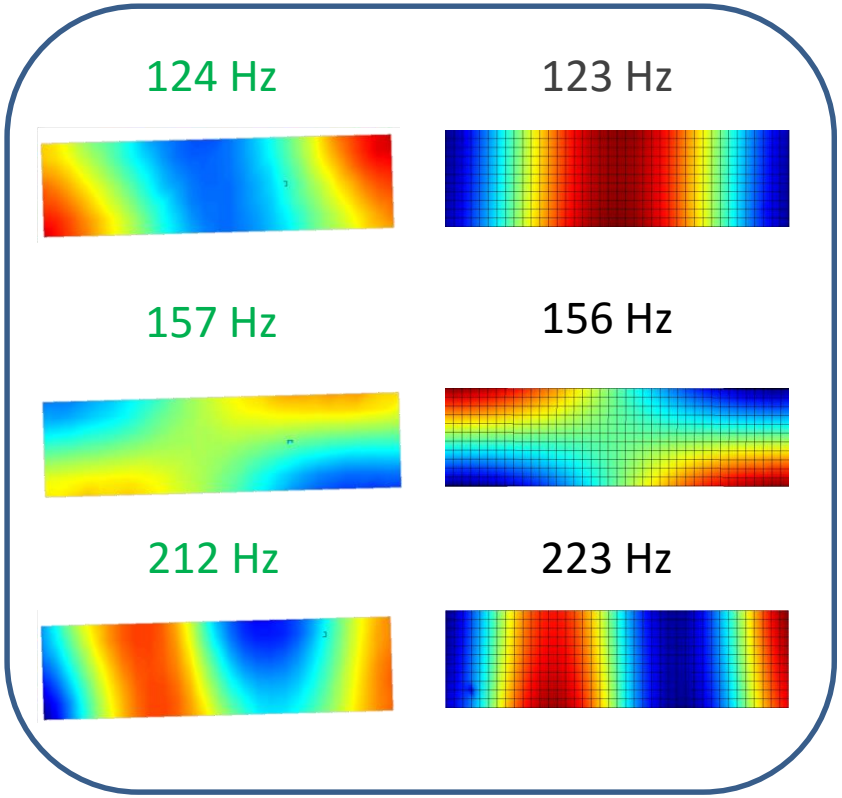




Estimated Parameters : **G_{13} = 0.4 MPa , G_{23} = 2.5 MPa**

Results
Sandwich plate 13 mm





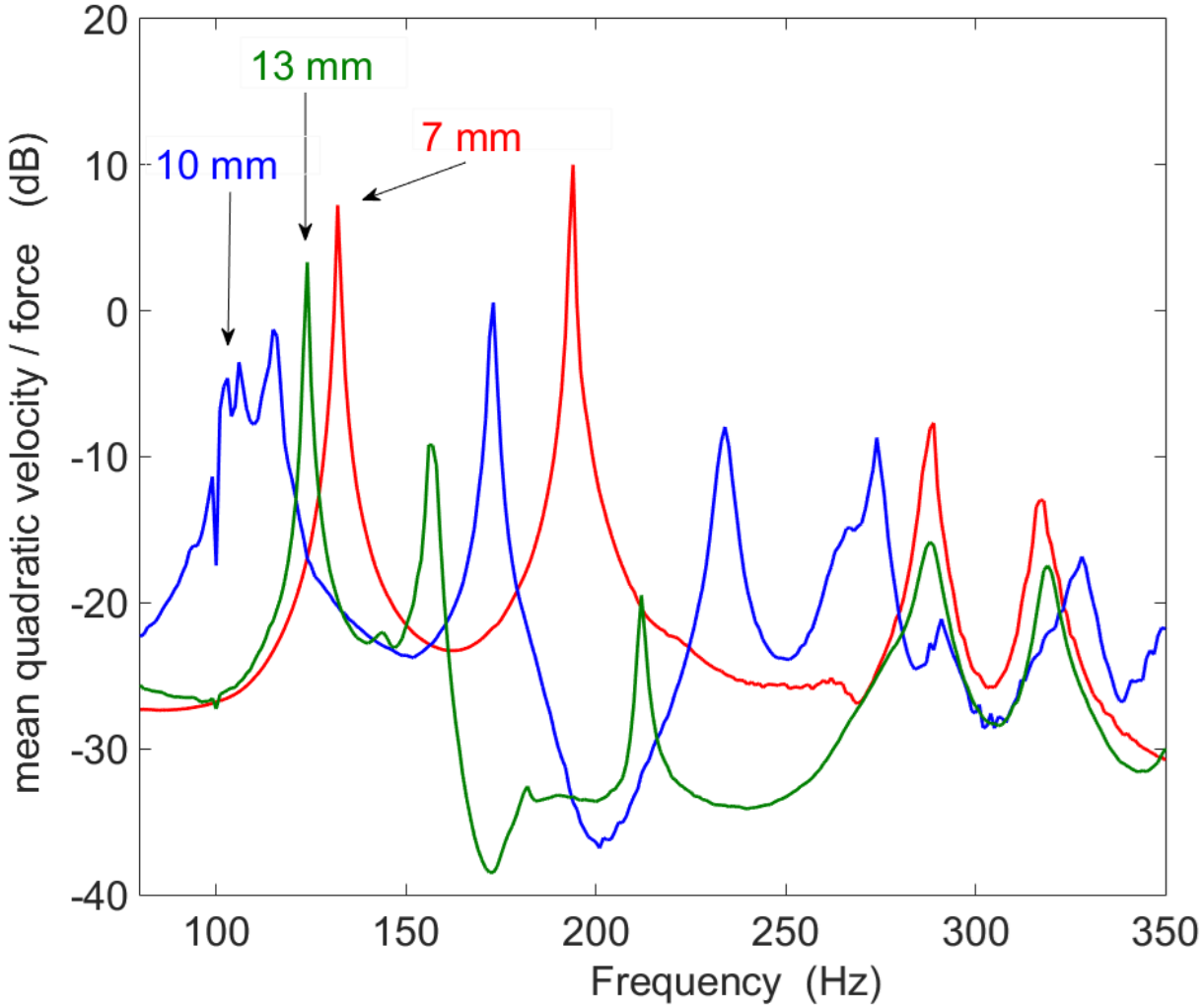
Estimated Parameters : **G_{13} = 0.65 Mpa, G23 = 2.1 MPa**

Polymerization effect

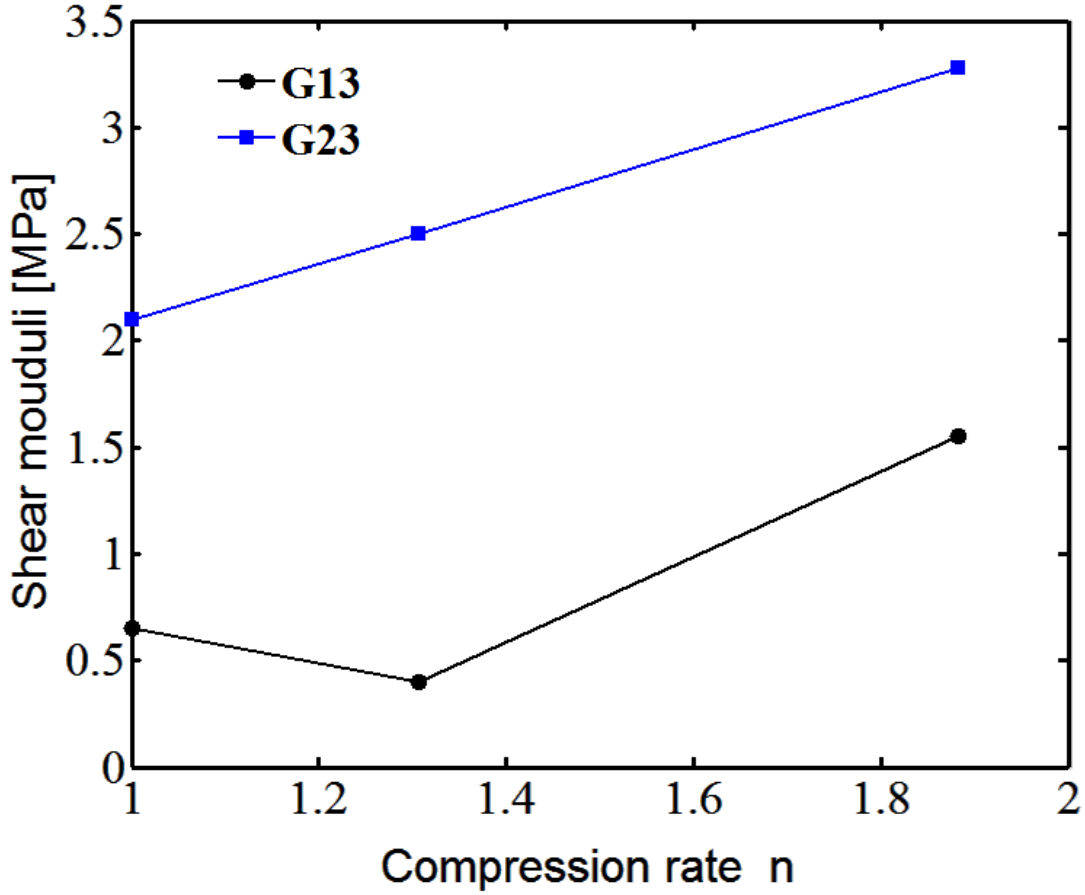
Target thickness :
12 mm, 10 mm, 8 mm

↓

Compressed thickness
13 mm, 7 mm, 10 mm



In-plane shear moduli vs compression



No clear tendency for shear moduli due to polymerization effect

Conclusions and perspectives

Conclusions:

- The longitudinal Young's modulus varies as function of the compression rate **by a power law**
- The proposed inverse characterization gives **a fast and good estimation of the shear moduli**
- Nominal values with uncertainty ranges are necessary to take into account the **variability**
- The **polymerization level of the binder** plays an important role on the mechanical behavior

Perspectives:

- Parametric study of the **polymerization** and the **compression effect** to the mechanical properties of a sandwich plate with a porous core

EcOBEx project group member

Thank you for your attention !

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Variability on 2 samples
13 mm