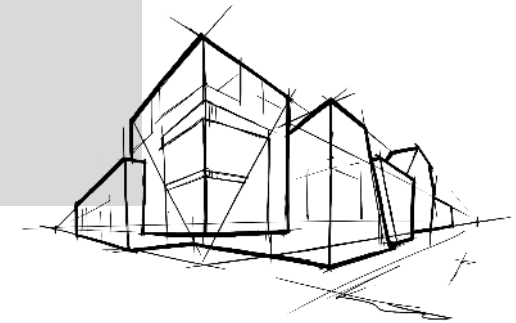


Effects of anisotropic parameters on the acoustical behavior of porous materials with Biot's model through the finite element method

María Mónica Ballesteros Villarreal
Mads Bolberg
Jonas Brunskog

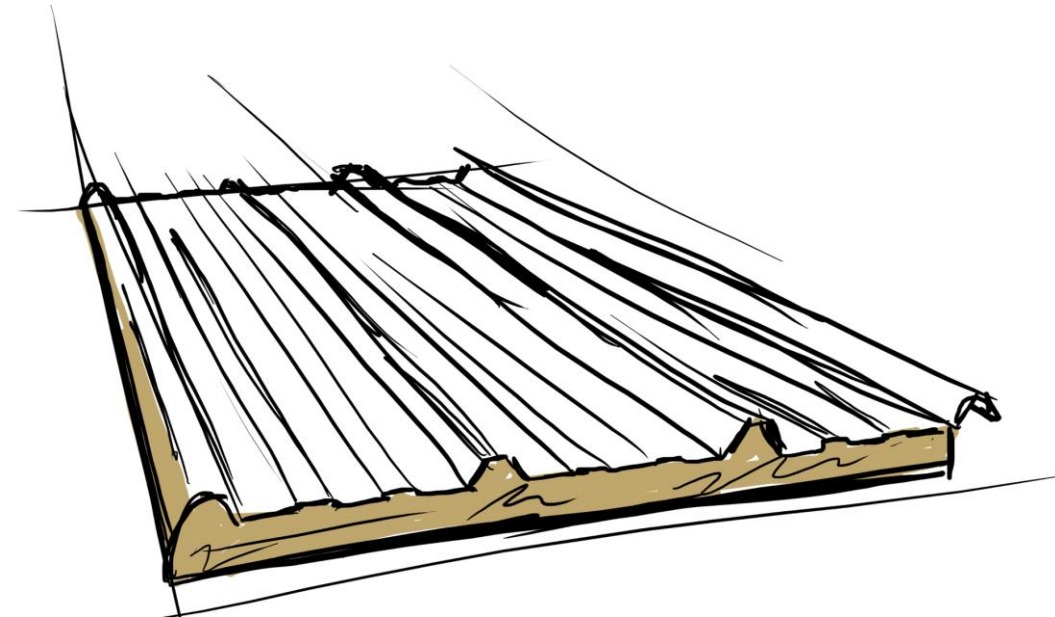
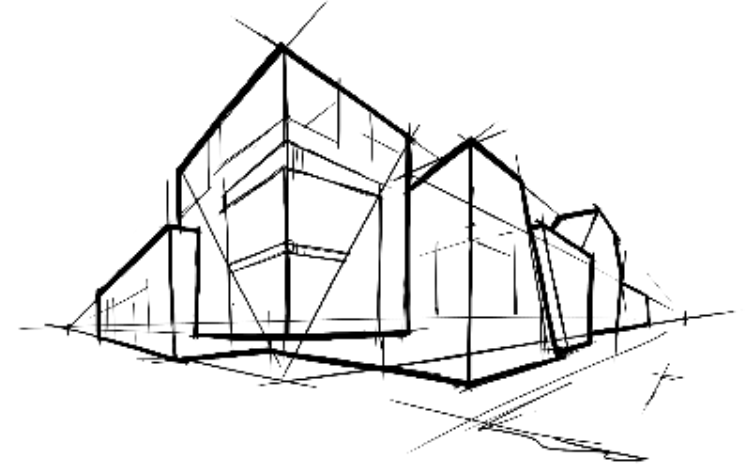
8 November 2023

Symposium on the Acoustics of Poro-Elastic Materials 2023



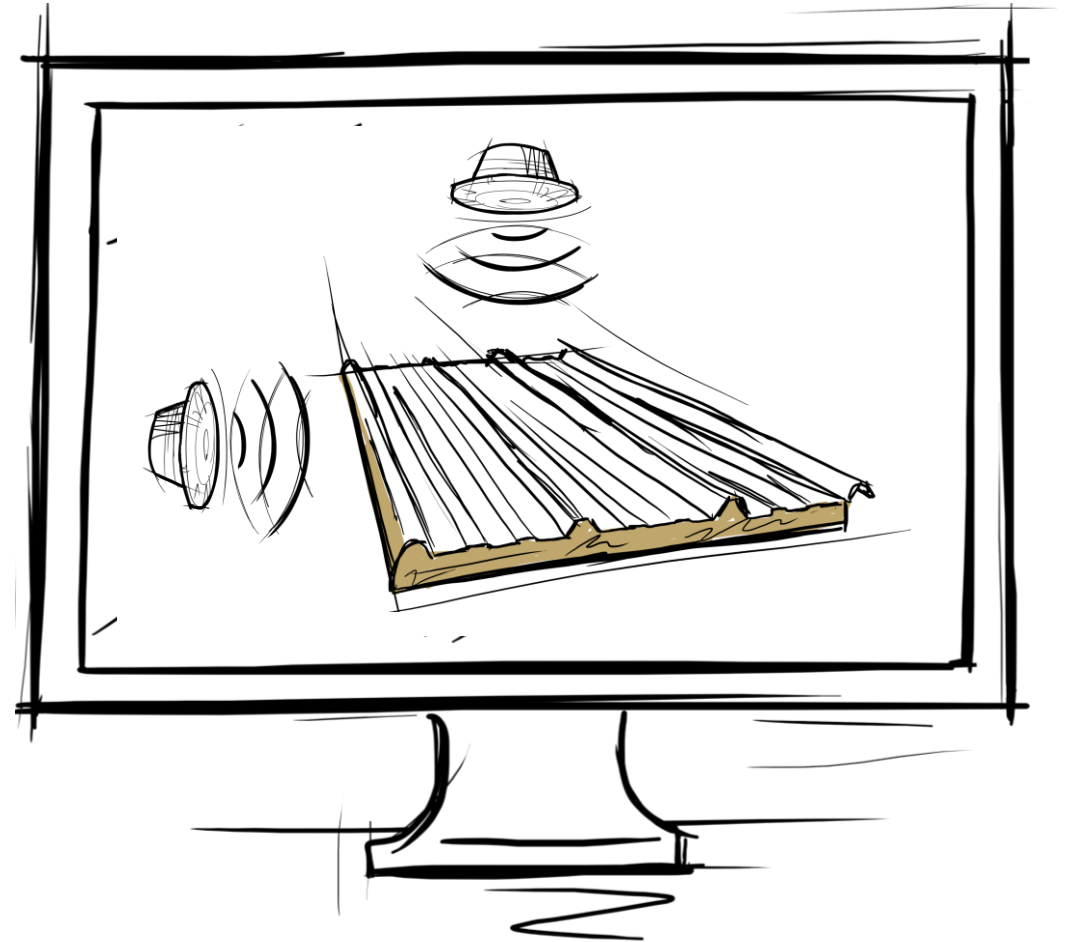
Motivation

- Building acoustics
- **Fibrous materials** → stone wool
- Sound **absorption** and **insulation** properties
- It's **anisotropic parameters** have not been fully researched yet
- **Anisotropy is key**, since it is not a transversely isotropic material
- Overall **knowledge gap** regarding fibrous materials
- In **building elements**, a better understanding of it will be beneficial for **optimization**

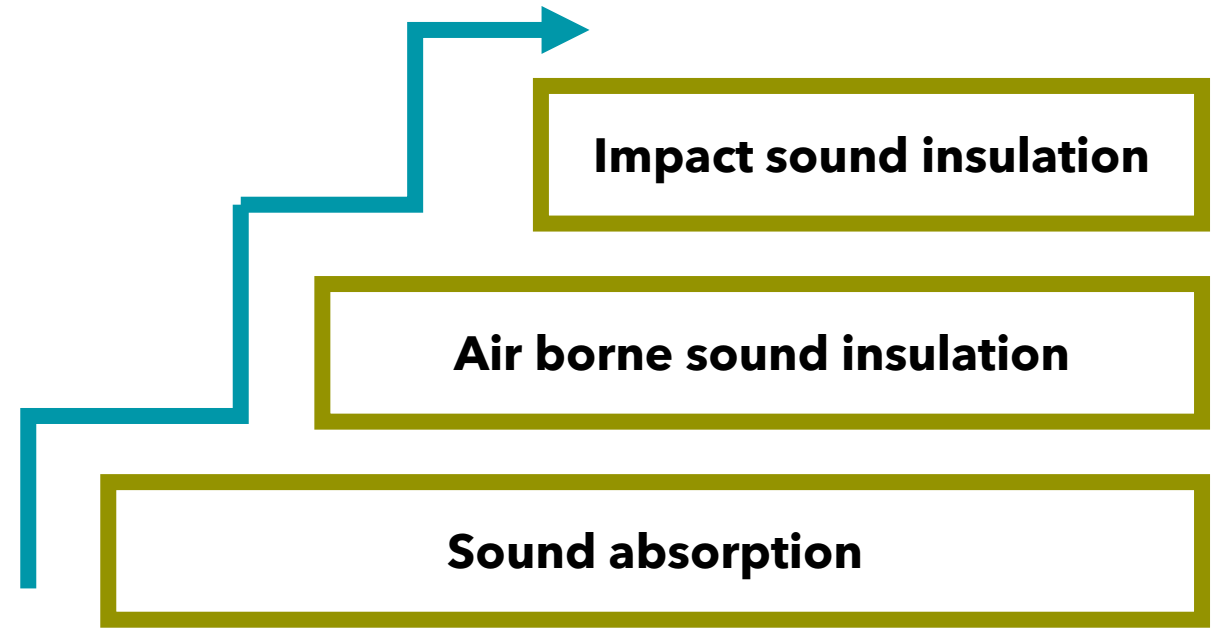
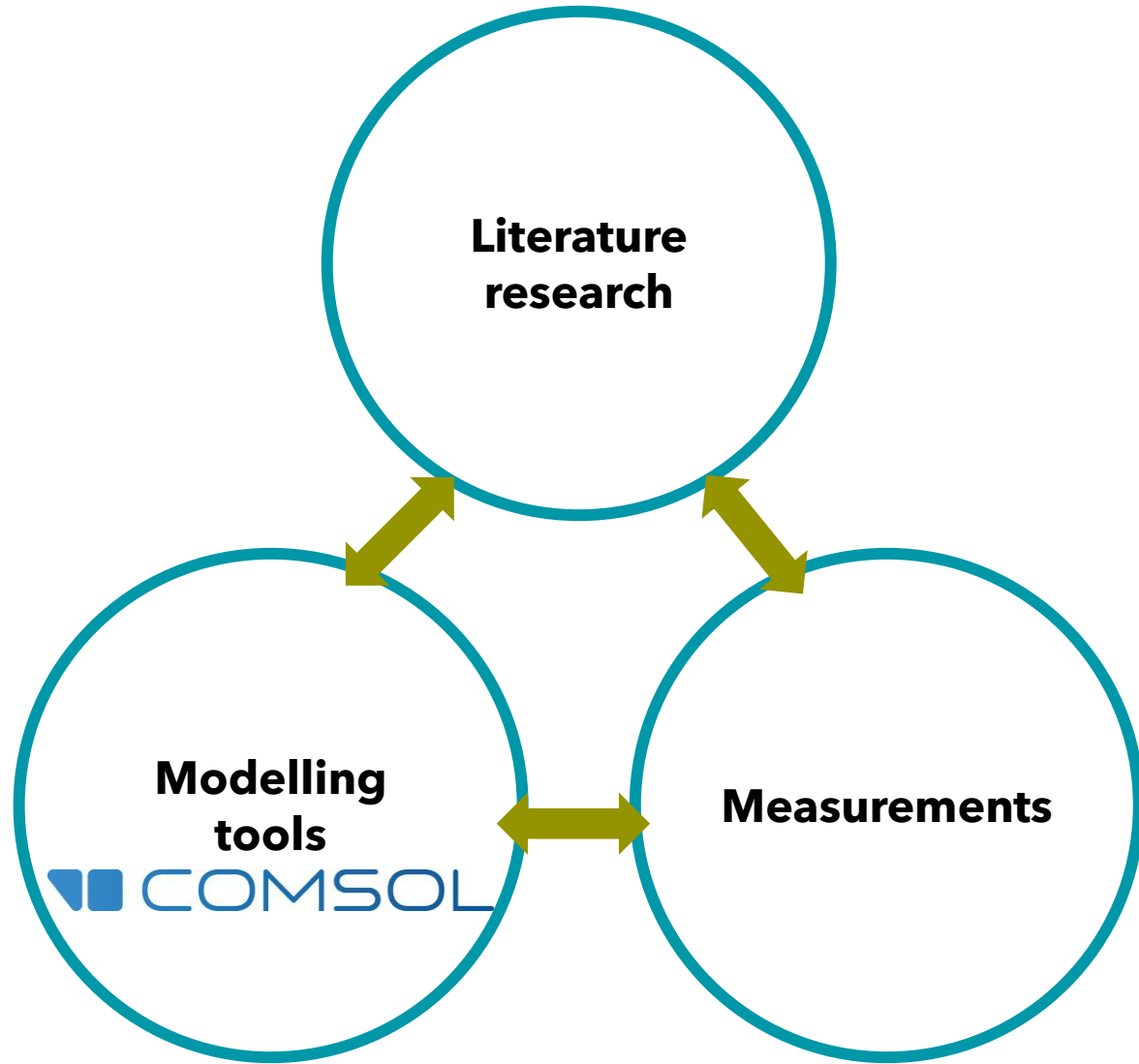




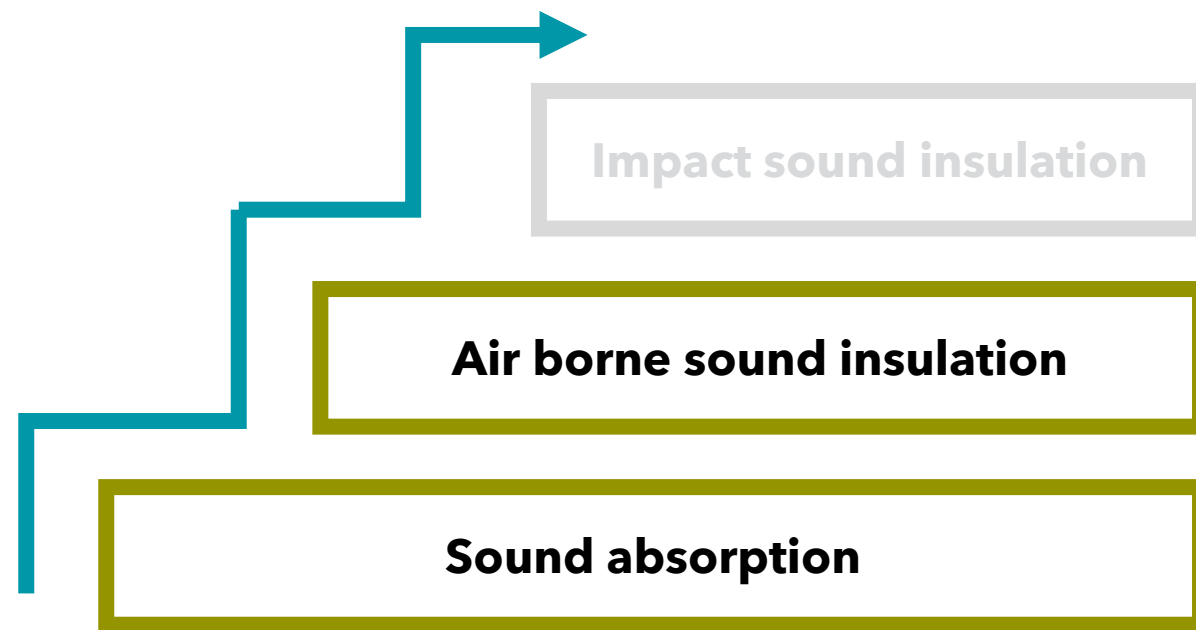
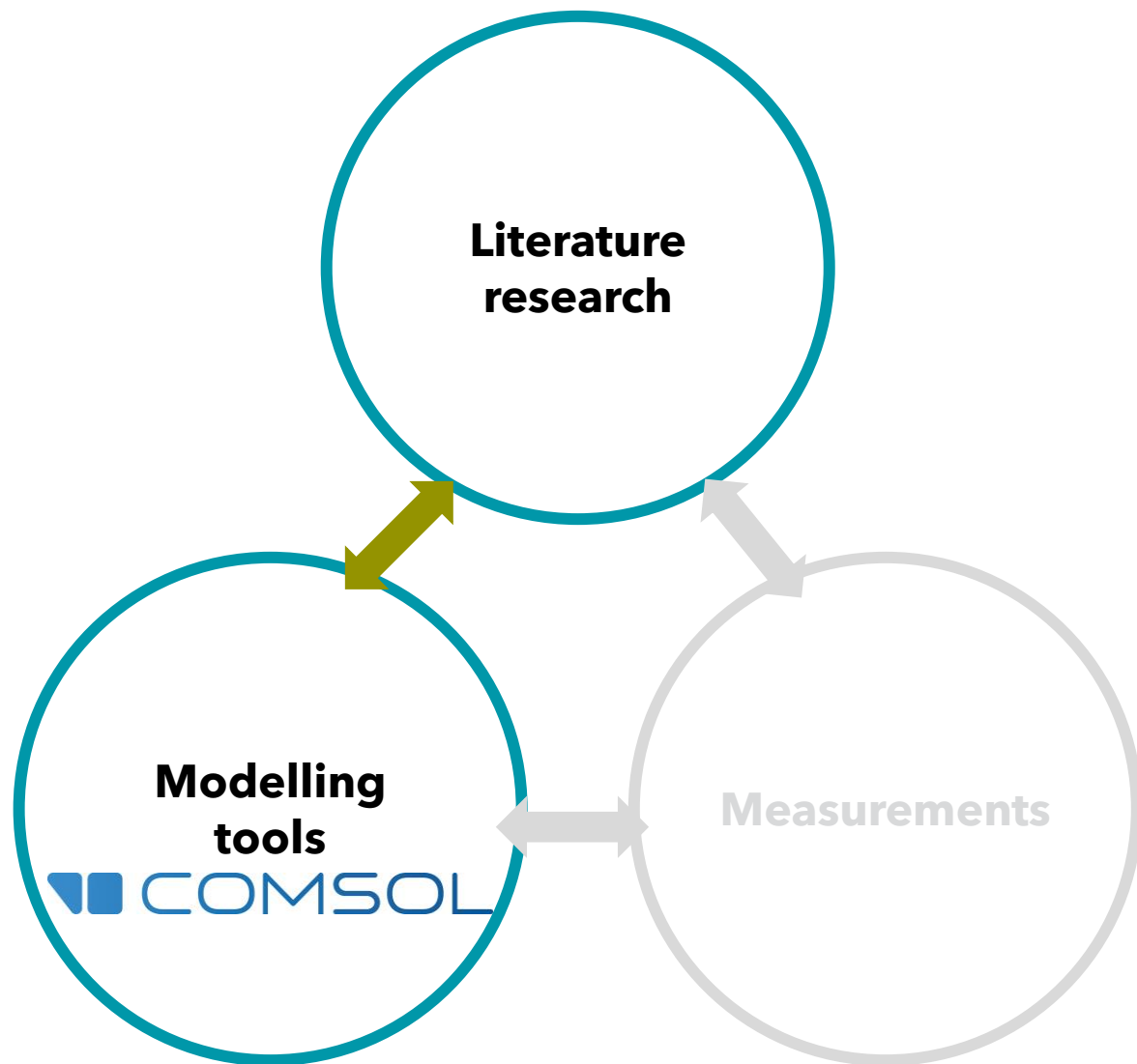
How to accurately **simulate** the **acoustic behavior** of a porous **fibrous material** as part of a building element, and to what extent is its **anisotropy** relevant?



Research project



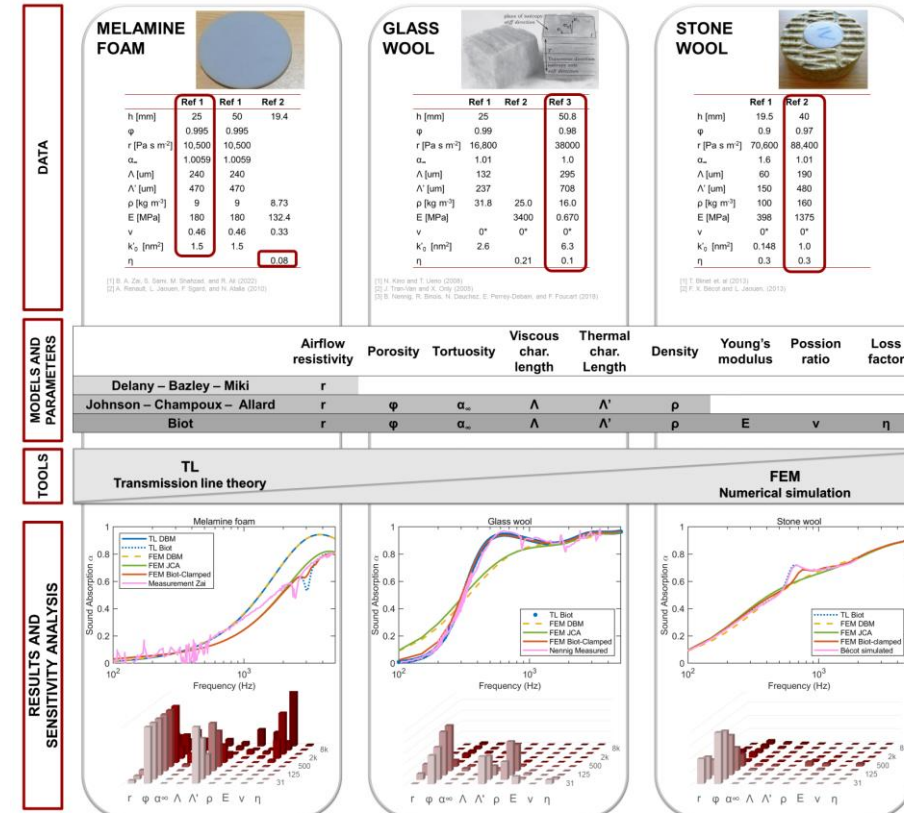
Research project



Previous work

- Data compilation work
 - Data
 - Melamine foam
 - Glass wool
 - Stone wool
- Models
 - DBM
 - JCA
 - Biot
- **Lack of available information** with all the necessary **parameters for the Biot model**

Porous materials currently used in the building industry require to have a high performance in terms of sound insulation and absorption. In reality, each material is characterized differently for each application, focusing on the properties important for each matter. This has led to having a nonuniform collection of data for each material. In this paper the information collected from the available literature has been arranged to suit a finite element model of porous materials, with the purpose of analysing the absorption coefficient and other acoustical behaviours of the materials. By considering the reported properties, plus estimating the missing not-characterized values, the model is completed, and results are compared between porous materials.



- More simulations have to be done with other new sources of information to confirm if the data sources are reliable and if it is possible to mix data from diverse sources and trust the results
- The boundary conditions affect the behavior of the resonance of the structural phase of the material in this samples, so the structural phase does not always have an important effect
- At this stage it is difficult to state what combination of parameters will show an influence on the dip or peak related to the solid phase, access to the information a complete characterizations imposes an important challenge to get proper simulation results and comparing between different materials and samples

How can porous materials be studied?

Delany-Bazley-Miki

**Johnson-
Champoux-Allard
(JCA)**

Biot

r Airflow resistivity

ϕ Porosity

α_{∞} Tortuosity

Λ Viscous char. length

Λ' Thermal char. Length

ρ Density

E Young's modulus

v Poisson ratio

η Loss factor

Johnson-Champoux-Allard model (JCA)

Bulk modulus

$$K_{eq} = \frac{\gamma P_0 / \phi}{\gamma - (\gamma - 1) \left[1 - j \frac{8\kappa}{\Lambda'^2 C_p \rho_0 \omega} \sqrt{1 + j \frac{\Lambda'^2 C_p \rho_0 \omega}{16\kappa}} \right]^{-1}}$$

Equivalent density

$$\rho = \frac{\rho_0 \alpha_\infty}{\phi} \left[1 + \frac{r\phi}{j\omega\rho_0\alpha_\infty} \sqrt{1 + j \frac{4\alpha_\infty^2 \eta_v \rho_0 \omega}{r^2 \Lambda^2 \phi^2}} \right]$$

Anisotropic

$$\rho_{eq} = \begin{pmatrix} \rho_{xx} & \rho_{xy} & \rho_{xz} \\ \rho_{yx} & \rho_{yy} & \rho_{yz} \\ \rho_{zx} & \rho_{zy} & \rho_{zz} \end{pmatrix}$$

Airflow resistivity
can be anisotropic

Biot model

$$\begin{aligned} -\rho_{av}\omega^2 \mathbf{u} + \rho_f \omega^2 \mathbf{w} - \nabla \cdot \boldsymbol{\sigma} &= 0 \\ -\rho_f \omega^2 \mathbf{u} - \omega^2 \rho_c(\omega) \mathbf{w} + \nabla p_f &= 0 \end{aligned}$$

Stress tensor - Hooke's law

$$\begin{aligned} \hat{\sigma}_{xx} &= F e_{zz} + F e_{yy} + C e_{xx} \\ \hat{\sigma}_{yy} &= A e_{zz} + (2G + A) e_{yy} + F e_{xx} \\ \hat{\sigma}_{zz} &= (2G + A) e_{zz} + A e_{yy} + F e_{xx} \\ \hat{\sigma}_{yx} &= 2G' e_{yx} \\ \hat{\sigma}_{xz} &= 2G' e_{xz} \\ \hat{\sigma}_{zy} &= 2G e_{zy}, \end{aligned}$$

$$\rho_c(\omega) = \frac{\alpha_\infty}{\phi} \rho_f + \frac{\mu(\omega)}{i\omega\kappa}$$

$$\mu(\omega) = \mu \sqrt{1 + \frac{4i\omega\alpha_\infty^2 \mu \rho_f}{r^2 \Lambda^2 \phi^2}}$$

Airflow resistivity can be anisotropic

Transversally isotropic Young's modulus

$$\begin{aligned} A &= \frac{E(E'\nu + E\nu'^2)}{(1+\nu)(E' - E'\nu - 2E\nu'^2)} \\ F &= \frac{EE'\nu'}{E' - E'\nu - eE\nu'^2} \\ C &= \frac{E'^2(1-\nu)}{E' - E'\nu - 2E\nu'^2} \\ G &= \frac{E}{2(1+\nu)}. \end{aligned}$$

COMSOL version 6.1

Transversally isotropic glass wool
 Nennig, Binois, Dauchez, et. al. 2018

h [mm]	50.8
ϕ	0.98
rt [Pa s m ⁻²]	38,000
ri [Pa s m ⁻²]	16,720
α _∞	1.0
Λ [um]	295
Λ' [um]	708
ρ [kg m ⁻³]	16.0
E_t [MPa]	0.670
E_i [MPa]	142
ν	0*
k' ₀ [nm ²]	6.3
η	0.1

JCA

**Anisotropic
 airflow resistivity**

**Biot
 (structural)
 Anisotropic
 Young's modulus**

$$\rho = \frac{\rho_0 \alpha_\infty}{\phi} \left[1 + \frac{r\phi}{j\omega\rho_0\alpha_\infty} \sqrt{1 + j \frac{4\alpha_\infty^2 \eta_v \rho_0 \omega}{r^2 \Lambda^2 \phi^2}} \right]$$

$$\begin{aligned} -\rho_{av}\omega^2 \mathbf{u} + \rho_f \omega^2 \mathbf{w} - \nabla \cdot \boldsymbol{\sigma} &= 0 \\ -\rho_f \omega^2 \mathbf{u} - \omega^2 \rho_c(\omega) \mathbf{w} + \nabla p_f &= 0 \end{aligned}$$

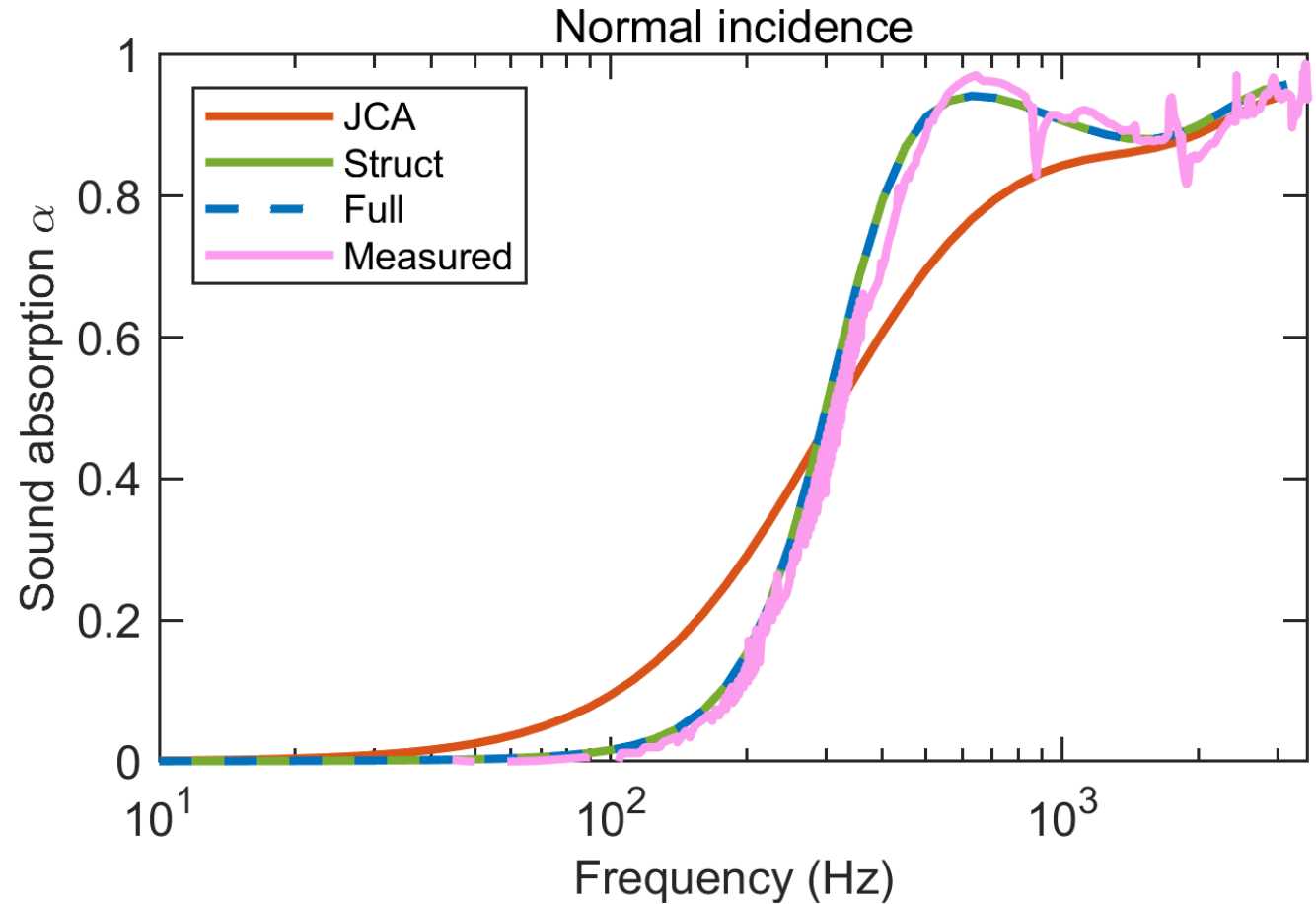
Nennig, Binois, Dauchez, et. al. 2018

- Sound absorption
- Infinite sample
 - For oblique incidence
- Previous work included only JCA and Biot-Structural models vs measured results
- **Current work: Full Biot model, available in COMSOL version 6.2**

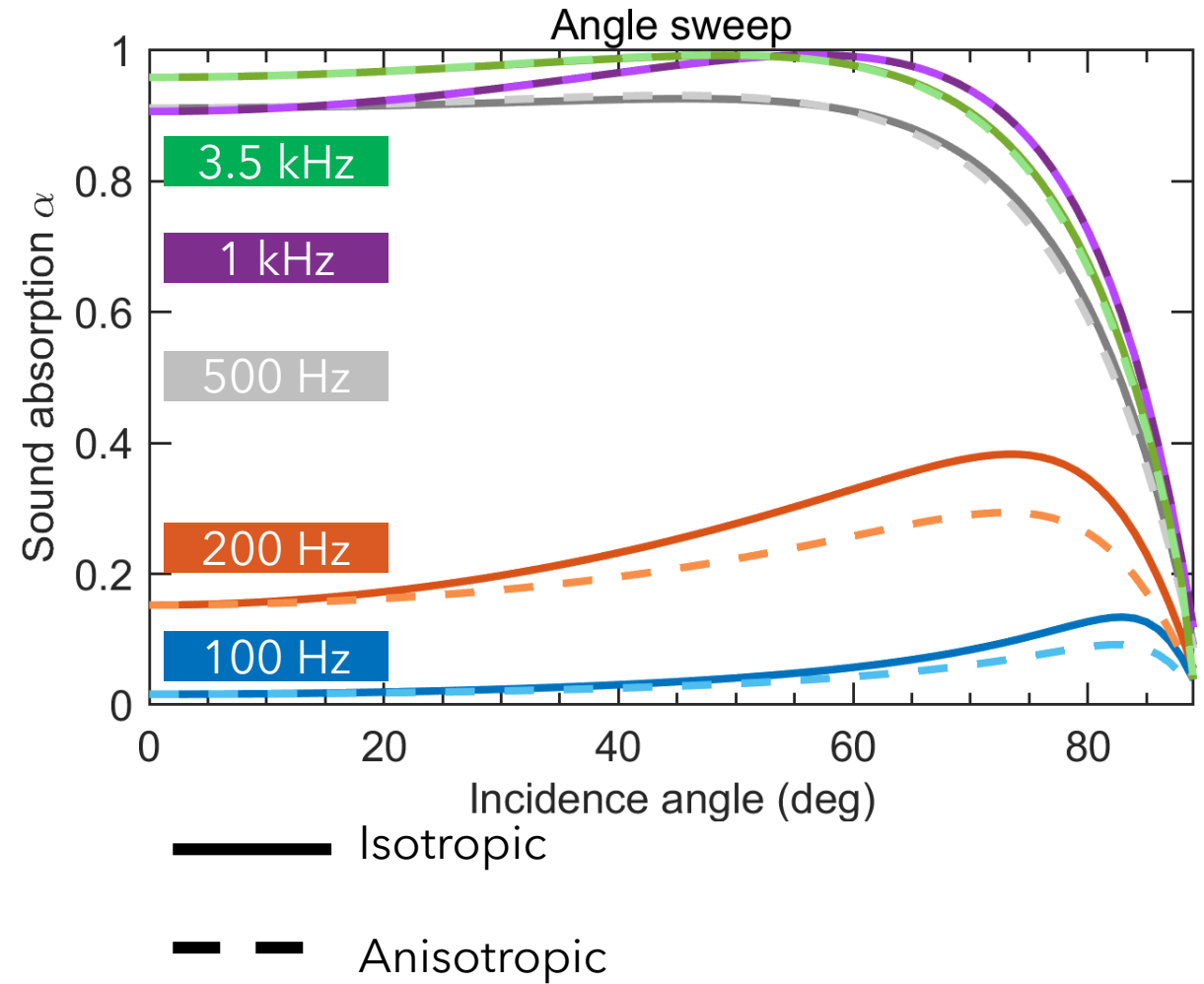
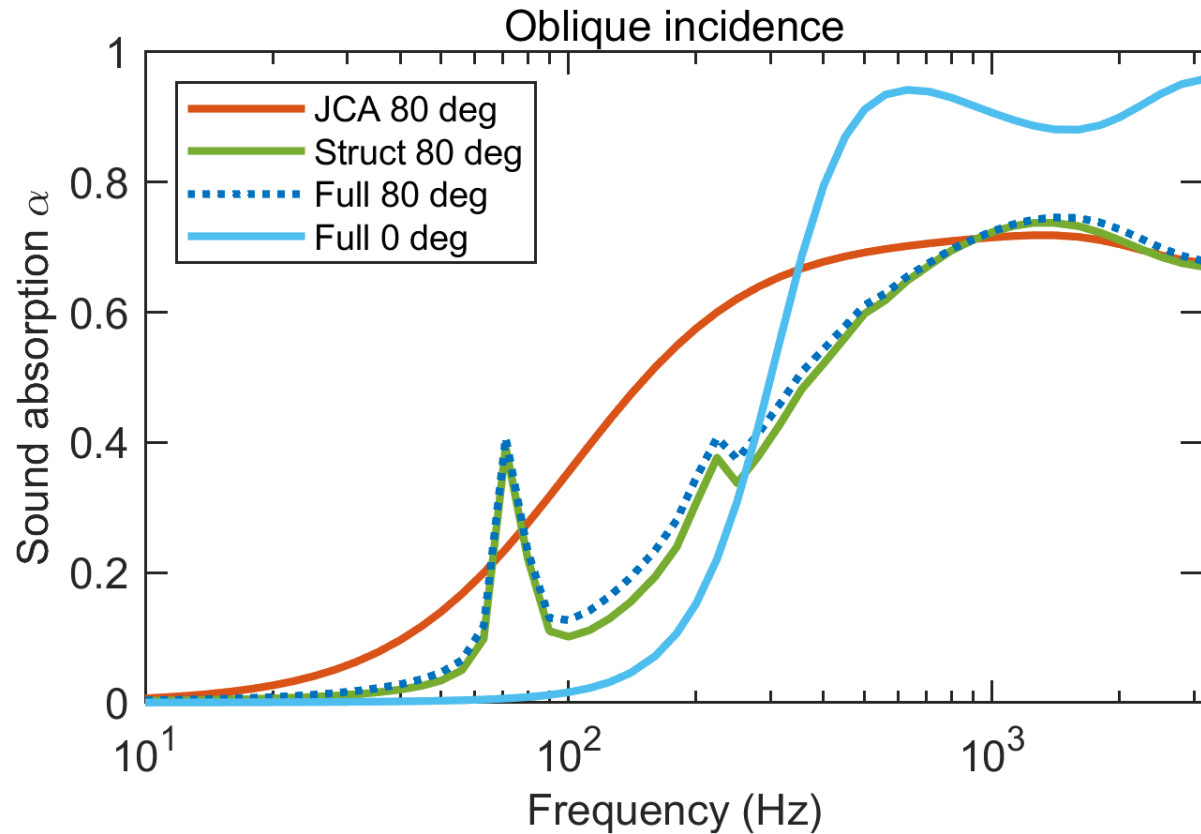
JCA - Only anisotropic airflow resistivity \mathbf{r}

Struct- Biot model with only anisotropic elastic parameters $\mathbf{E}, \mathbf{G}, \mathbf{v}$

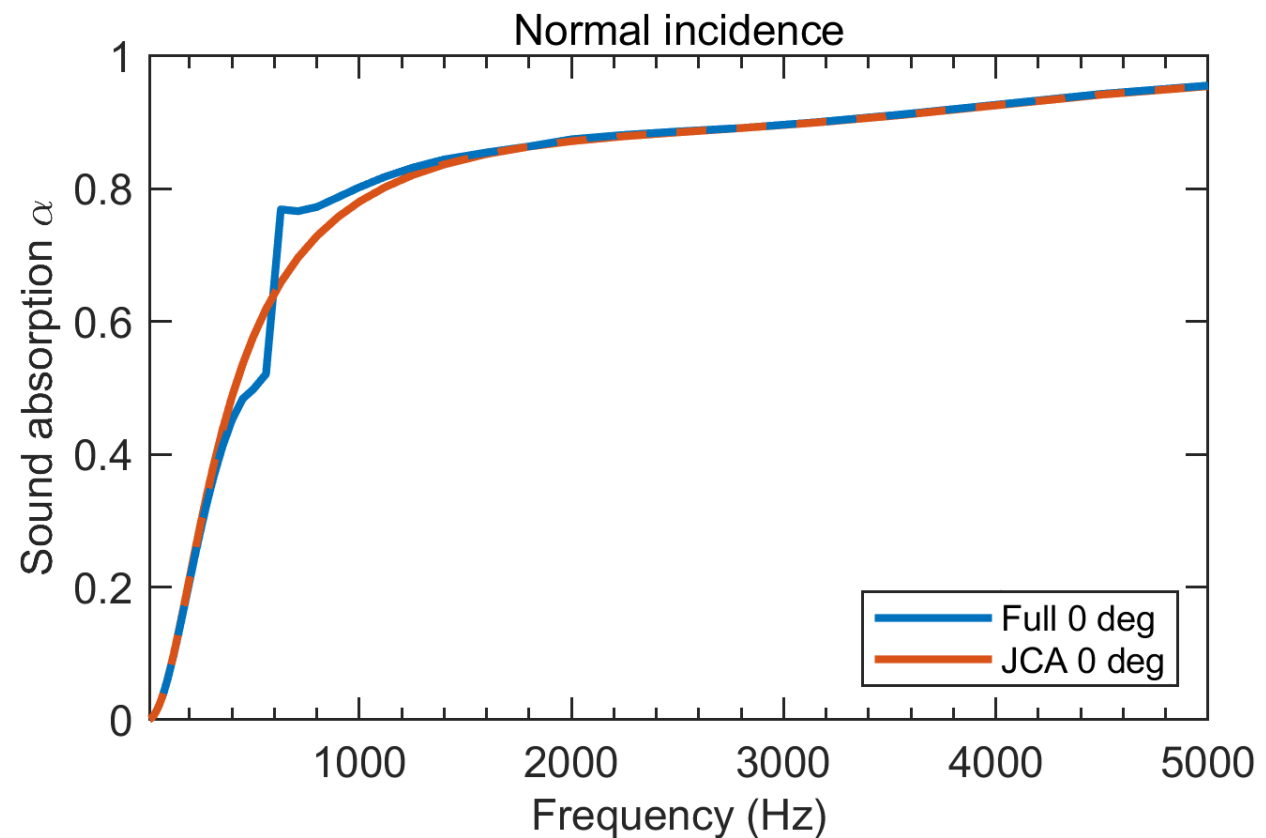
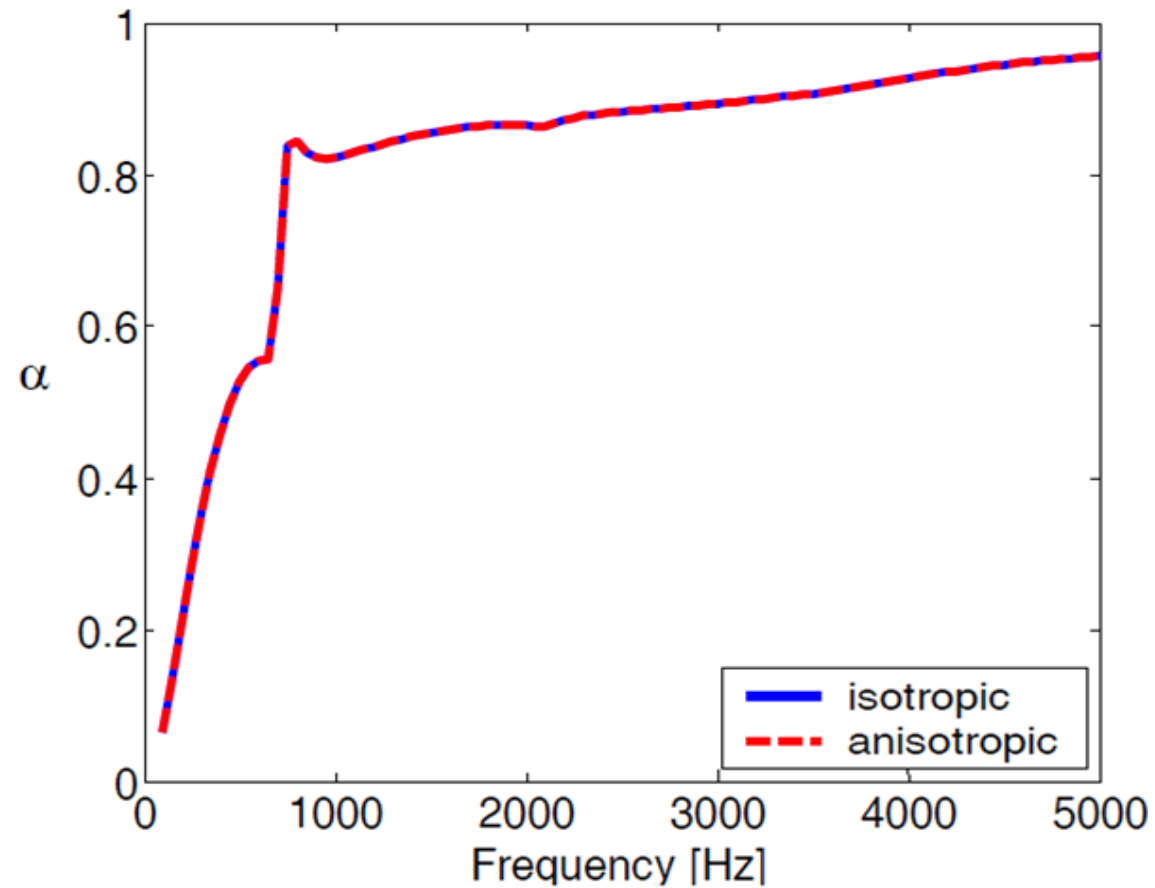
Full- Biot model with anisotropic airflow resistivity \mathbf{r} and elastic parameters $\mathbf{E}, \mathbf{G}, \mathbf{v}$



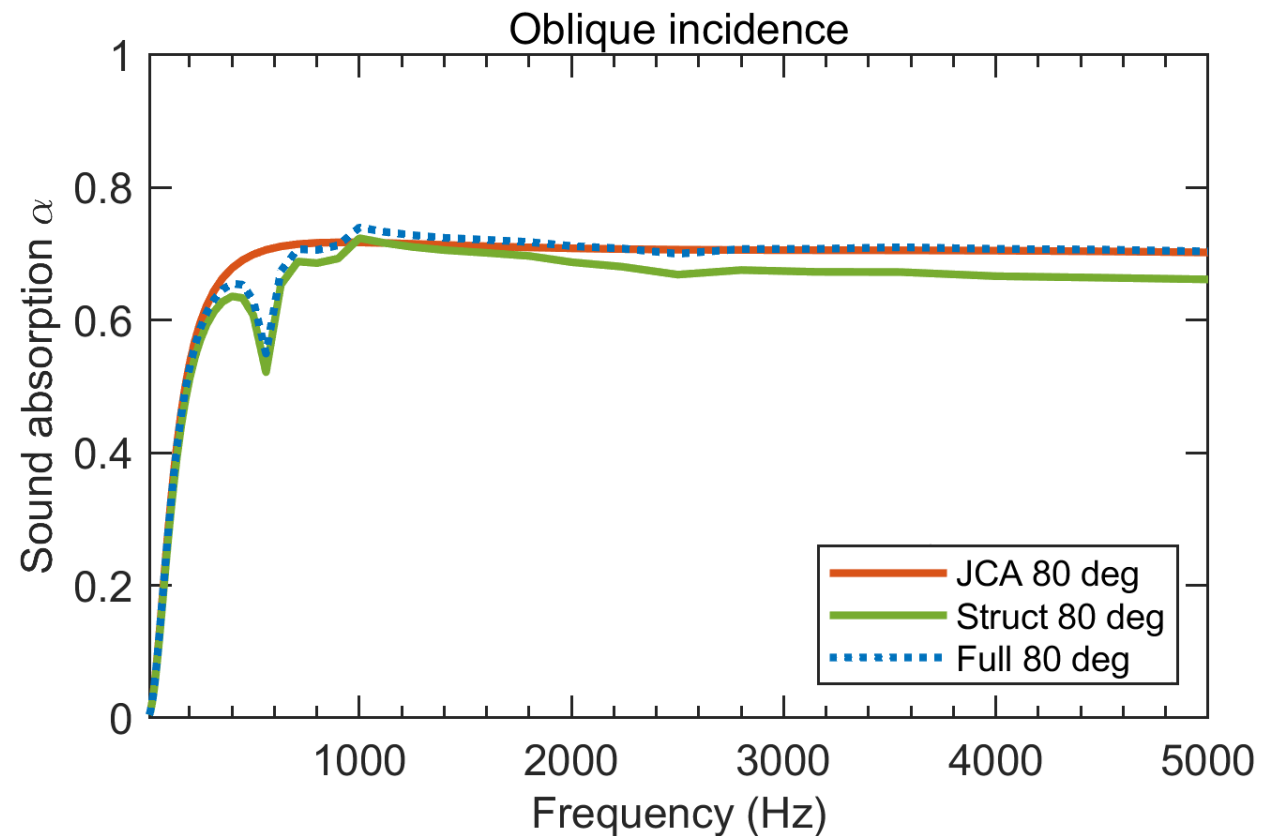
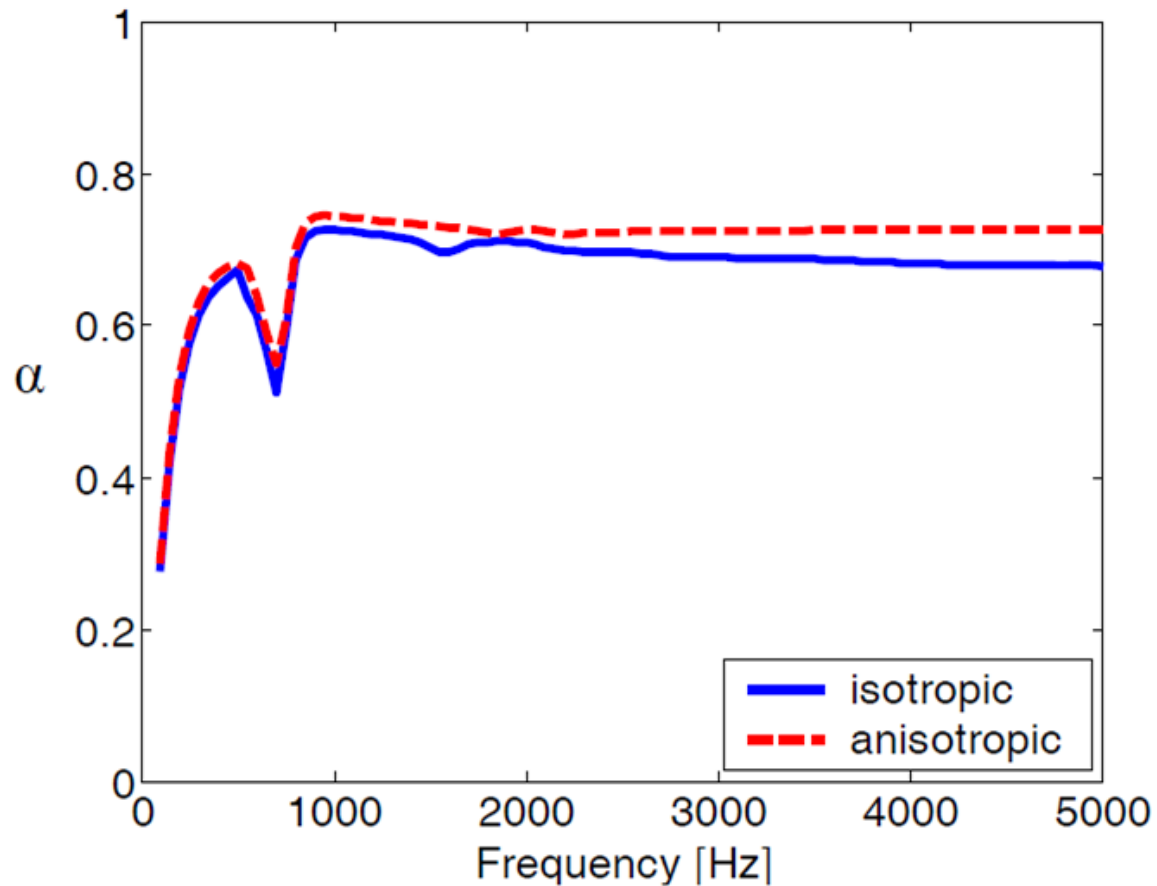
Nennig, Binois, Dauchez, et. al. 2018



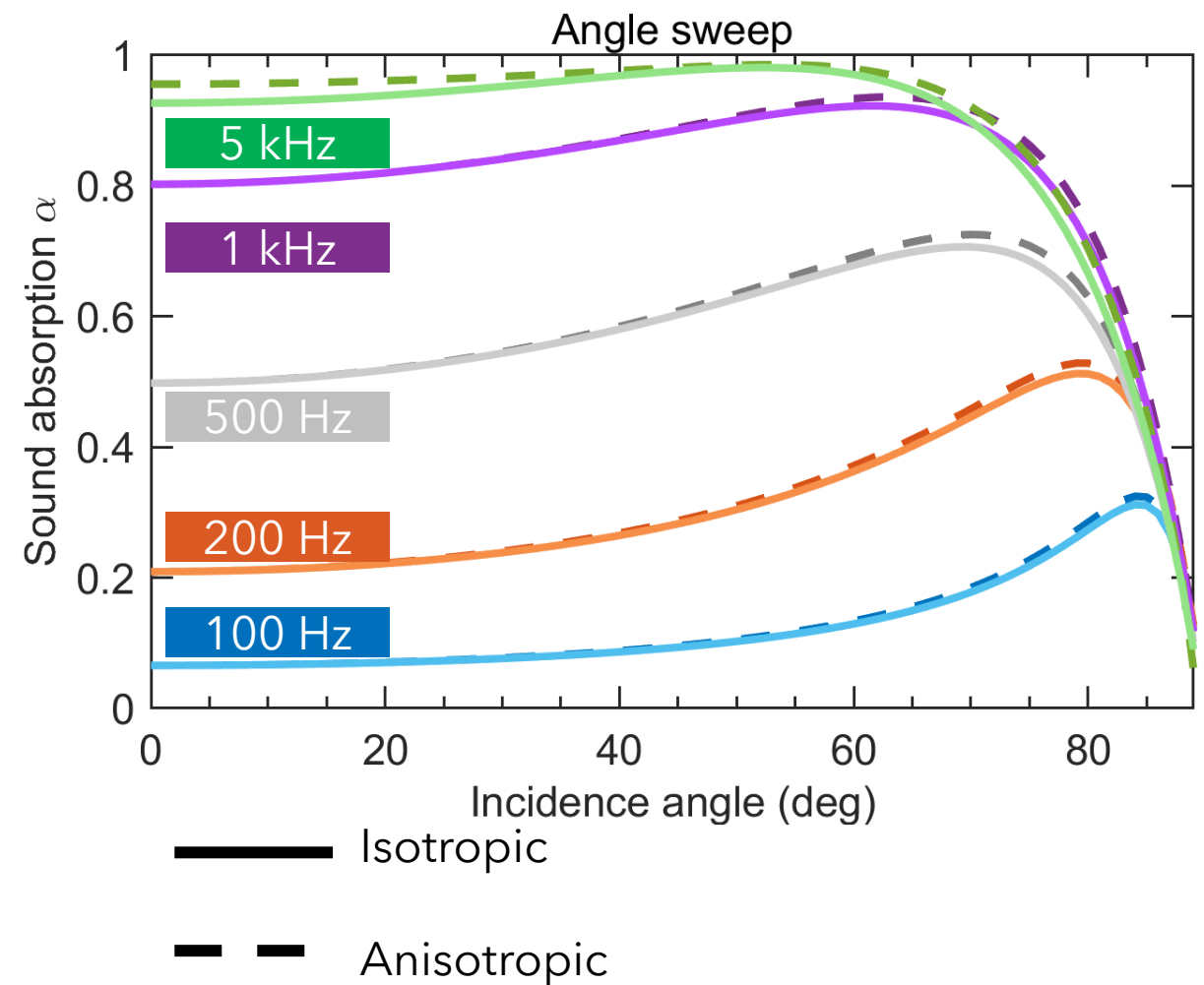
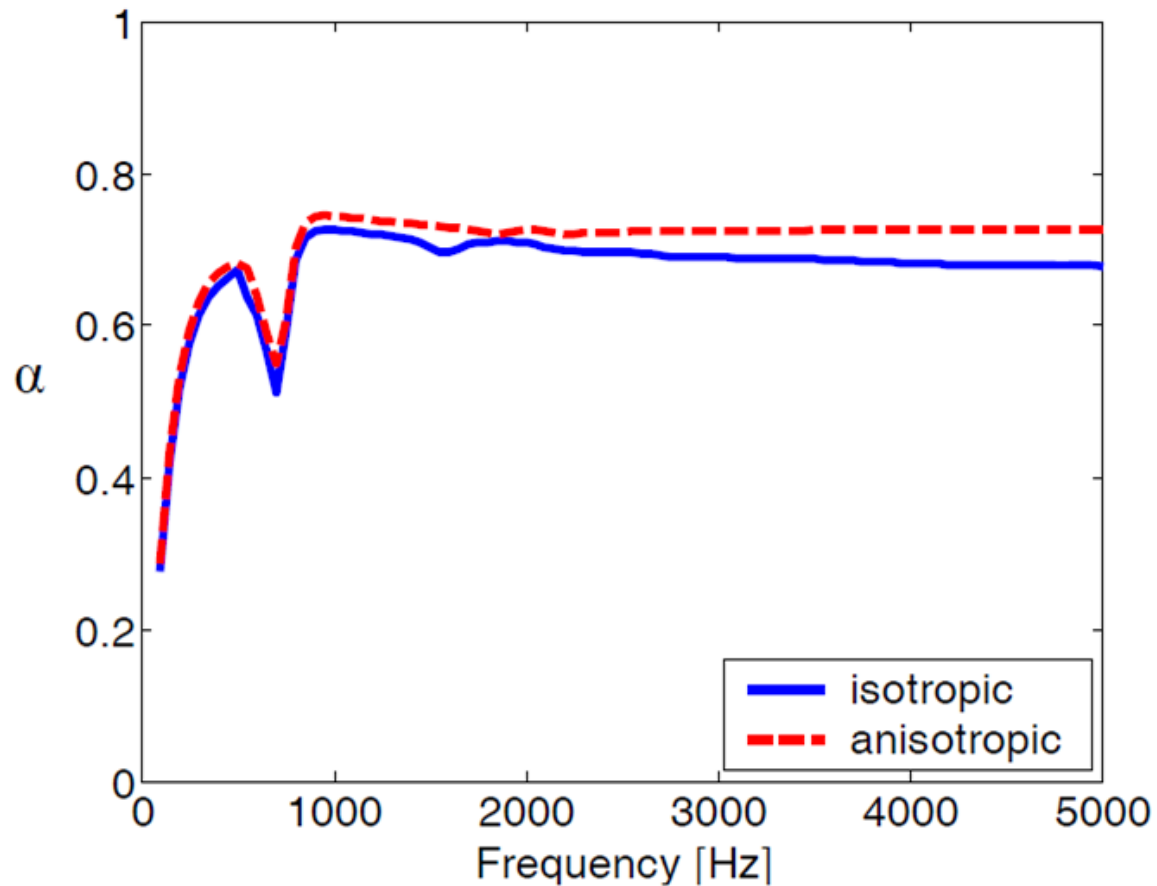
Geebelen, 2008: Stonewool infinite sample Normal incidence



Geebelen, 2008: Stonewool infinite sample Oblique incidence 80°



Geebelen, 2008: Stonewool infinite sample Oblique incidence 80°



Work in progress: Sandwich panels (isotropic), Panneton, 1996

- Sound Transmission Loss
- Finite sample
- Isotropic core
- Biot model
- **Future work: fill with anisotropic core**

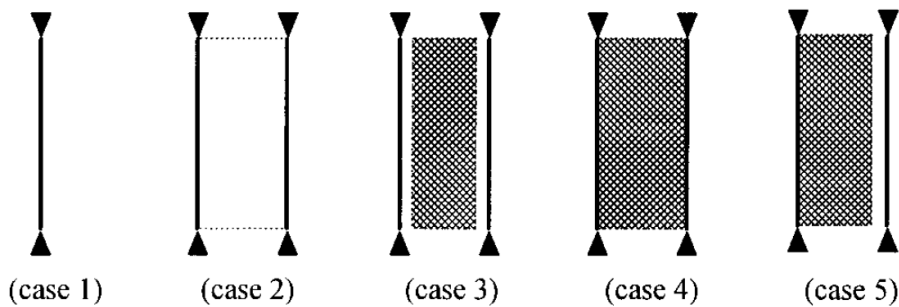
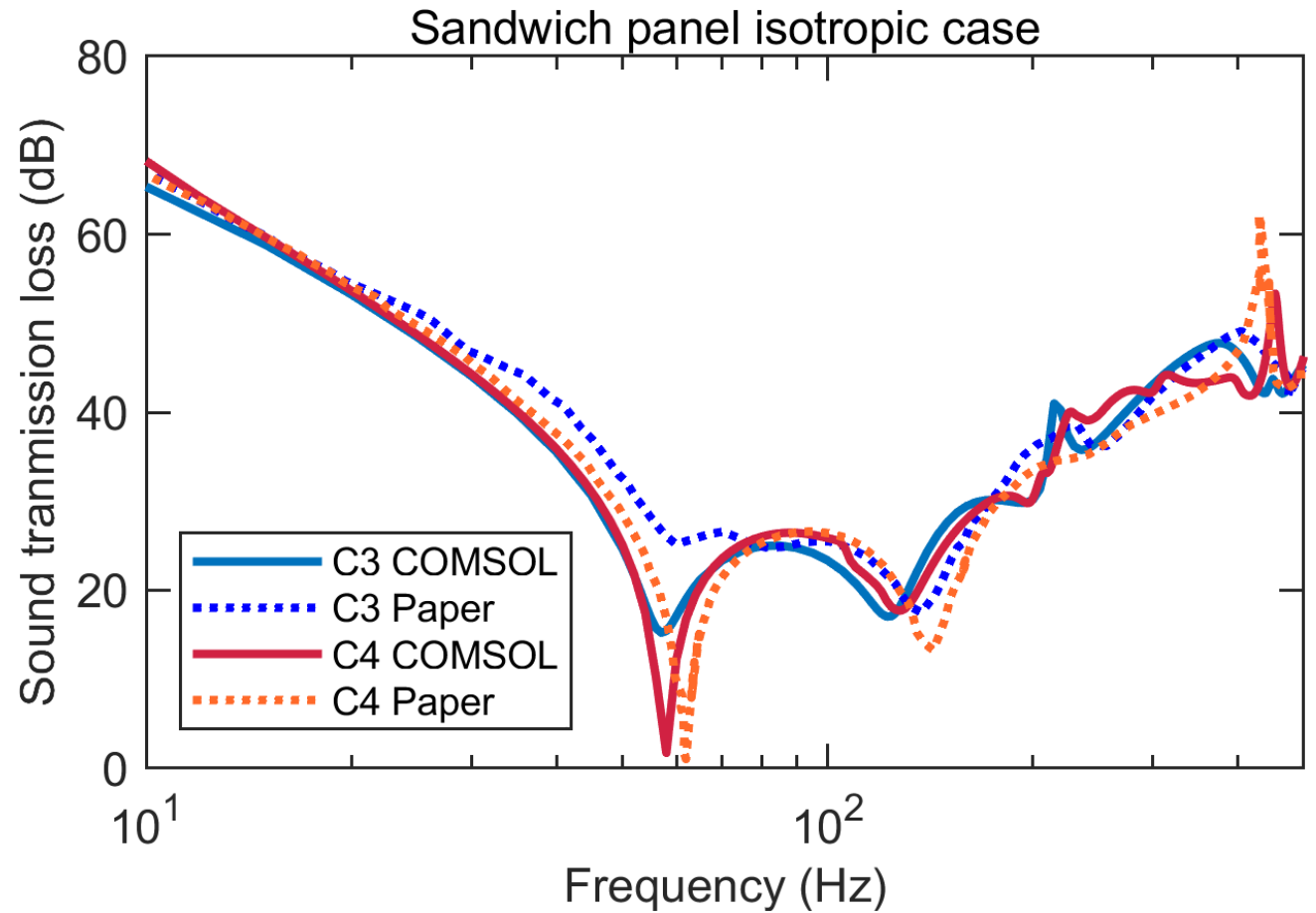


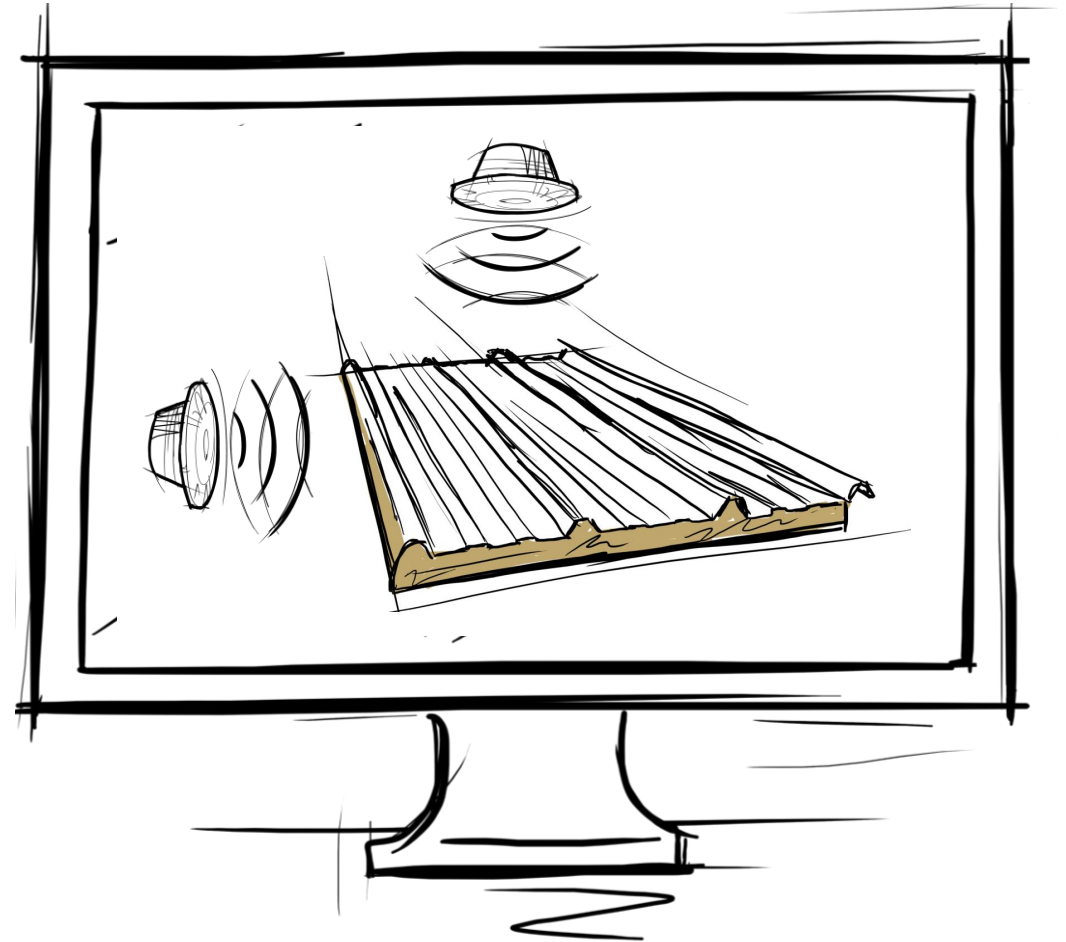
FIG. 2. Studied design configurations: (case 1) single plate; (case 2) un-lined; (case 3) unbonded layer; (case 4) bonded layer; (case 5) bonded-unbonded layer.

Panneton, 1996



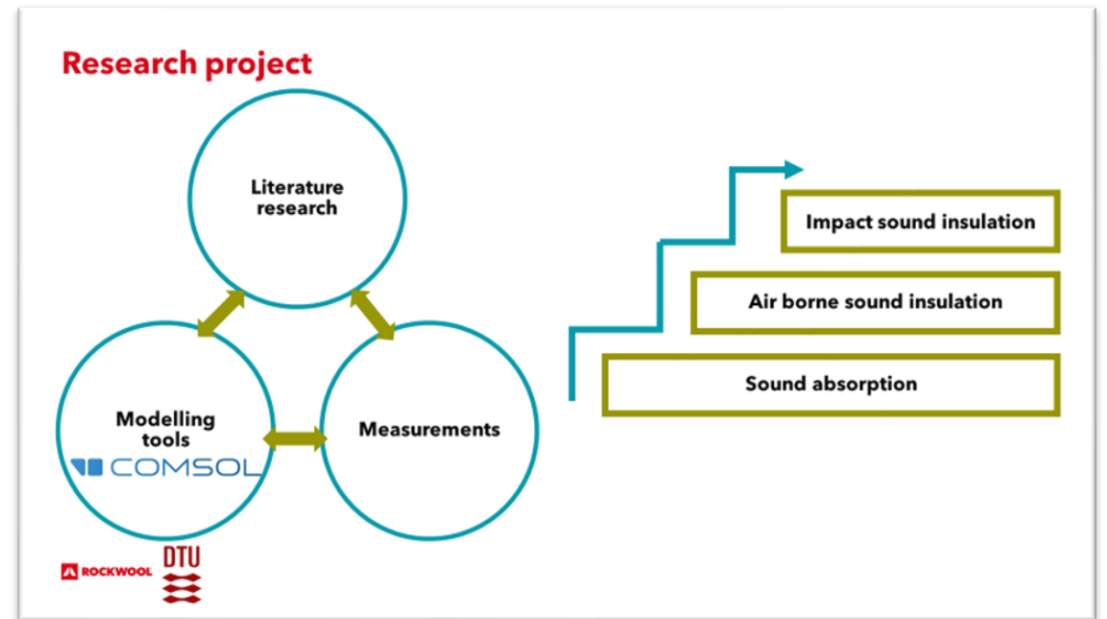


How to accurately **simulate** the **acoustic behavior** of a porous **fibrous material** as part of a building element, and to what extent is its **anisotropy** relevant?



Conclusions & future work

- Anisotropy effects in both models have the same direction and are similar in size. They might add up in a **fully anisotropic model**.
 - Oblique incidence studies offer more information regarding the anisotropy in both the airflow resistivity and elastic parameters
-
- Characterization for anisotropic Biot parameters
 - Gather more information from literature if available
 - Simulation of sandwich panels and sound insulation
 - Simulation of floors and impact sound



Acknowledgements

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