GDR MIC (Composites) - Cours doctoraux: GDR MIC – 13 au 17 novembre 2017

Evaluation non destructive par ultrasons de matériaux composites.

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Définition d'un essai non destructif

Etudier l'état d'un milieu (solide, fluide, poreux, pièces individuelles, structures, assemblages …) sans détérioration ou modification irréversible de celui-ci.
Les essais N.D. permettent de tester et de conserver autant d'échantillons que souhaité, contrairement aux essais destructifs qui consistent à tester, avec modification irréversible, N échantillons d'une famille et à établir une loi probabiliste sur l'état des pièces restantes (coûteux, risqué).

Deux familles d'essais non destructifs

- Contrôle Non Destructif

  Détecter, positionner, identifier, dimensionner des défauts dans le milieu.

- Evaluation Non Destructive

  Mesurer de façon indirecte des caractéristiques du milieu.

Quand utiliser les essais non destructifs ?

- En fabrication

  Contrôle intégrité matière
  Suivi de Process (chaîne de production)
  Certification des produits par rapport normes

- En utilisation

  Suivi de santé (health monitoring), vieillissement, durabilité,…
  Expertise
  Maintenance

Secteurs d'applications des essais non destructifs

- Industries de production

  Métaux, polymères, céramiques, verres, **composites** à matrices organiques, métalliques ou céramiques, structures complexes, pièces de fonderie, etc…

- Industries du transport

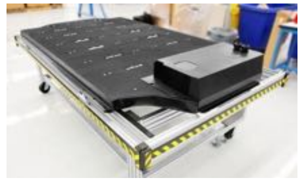
  Ferroviaire, Automobile, Naval, Aéronautique, Aérospatial

- Génie Civil - Ponts & Chaussées

  Béton, béton armé, bâtiments divers, …
  Etat des routes, des ponts, des pistes d'atterrissage, …

- Industries énergétiques

  Stockage et transport de l'eau, du gaz, du pétrole, centrales nucléaires, etc …

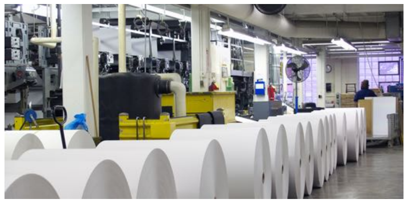


- Industries Agroalimentaires

  Fruits, légumes, confiserie, …

- Industries du bois et du papier

  Planches, meubles, constructions en bois, cartons, feuilles, …



- Médical

  Contrôle de tout le corps humain (os, poumons, dents, …) par échographie, radiographie, …

- etc …

Types de défauts selon l'environnement

- Matériaux solides

  Porosités, criques, micro-fissures, fissures, corrosion, taux de fibre/matrice non conforme, décohésions fibre-matrice, délaminages inter-plis, présence de nœuds, problèmes de cotation, de forme, … chute des propriétés mécaniques…

- Assemblages

  Problèmes liés aux rivets, soudures, serrages de boulon, collages (adhésion, cohésion), revêtements (peintures, dépôts chimiques…), ajustements, jeux,…

- Structures et constructions

  Corrosion sur les rails de chemins de fer, dans les armatures de bétons armés, dans les canalisations de transports de fluides,… Fissuration des ponts, des bâtiments, des routes…

- Nourriture

  Immaturité, pourriture, géométrie non conforme, présence de pépins, … pour les fruits ou légumes
  Trous, géométrie non conforme pour les confiseries (bonbons, sucettes, …)

- Corps humain

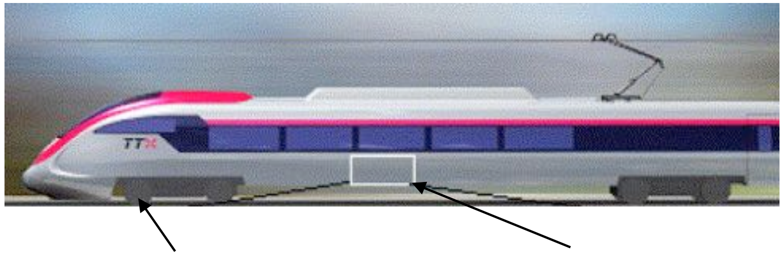
  Fêlure, fissures ou rupture d'un os – Ostéoporose – Eau dans les poumons – Malformation…

- Sol terrestre

  Cavités cachées, nappes d'eau, composition des couches terrestres, fissures …

- etc …

De nombreux secteurs industriels utilisent les matériaux composites



Brake lining *made with metallic and/or ceramic -based composites to* ***reduce heating*** *but brake disks are metallic*

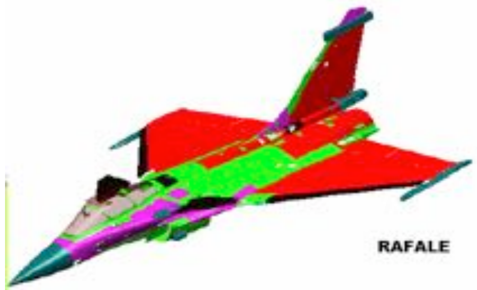
Car-body structure *with aluminium honeycomb core and woven fabric carbon/epoxy face*

Carbon body structure
… light, crash-test

Graphite, Kevlar, Carbon, Epoxy, PEEK
Maximal strength + minimal weight

Carbon or ceramic -based composites
… light and fire-resistant

Glass, Carbon, Polyester, Epoxy
Light structures … No corrosion



- Carbon / Epoxy
- Thermoplastic and others
- Aluminium alloys
- Titanium alloys

High performances + low weight

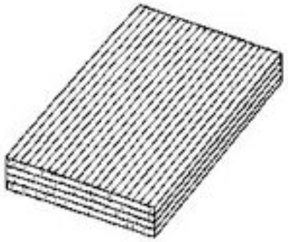
Typical composites used in many industries

Fibre reinforced composites:

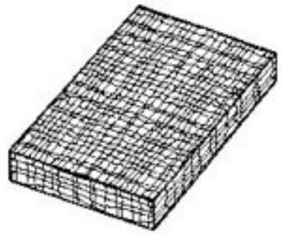
- **Fibres:** Glass, Carbon, Kevlar, Aramid, Boron, …
- **Matrix:** Epoxy, Thermoplastic or thermosetting plastic, Ceramic, Metal, …

Moulding methods:

- Autoclave
- Resin Transfer moulding
- Vacuum or pressure bag moulding
- Filament winding
- etc…

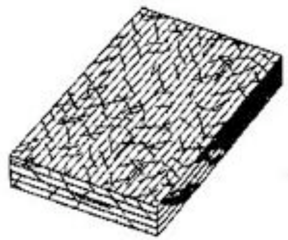


Continuous fibres



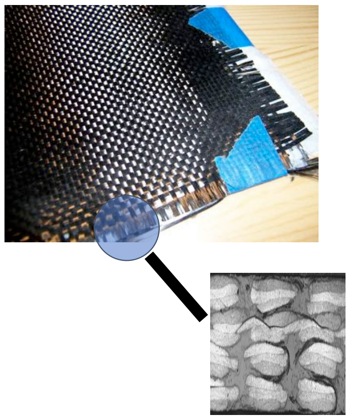
Woven fibres

Chopped fibres

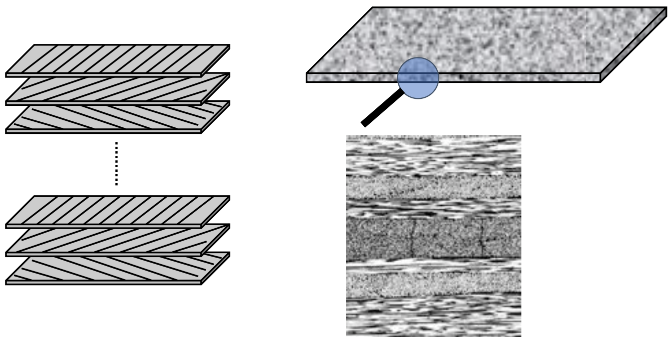


Hybrid composites

Elementary ply



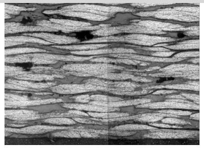
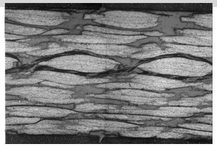
Laminate = stacking of plies with various orientations



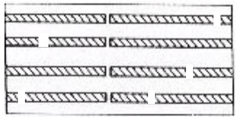
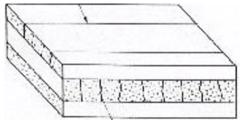
Sandwich structure

Possible defects in composites

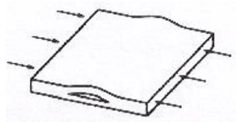
→ Moulding processes of composite materials may introduce **defects**: **porosity**, **fibre misalignment**, **disbonds** …

→ Composite materials are likely to have **properties changing with time = material ageing** due to humid environments, mechanical loading and thermal changes that may cause quite **uniform damaging** like moisture content, matrix micro-cracking, fibre failure and/or fibre-matrix disbonding, for example.

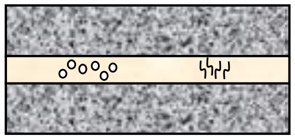
 

→ Corrosion disappears but **impacts** (lost bird, falling tool, …) often cause **local defects** like cracking thru thickness and/or delaminations that may enlarge with time when structure is loaded.

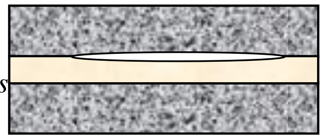
  

→ Composites are more and more **assembled** using **adhesive bonds** that may fail (cohesion or adhesion) at any time during in-service use, when structure is loaded.

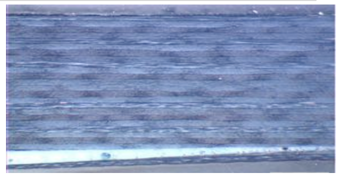
Cohesive defects



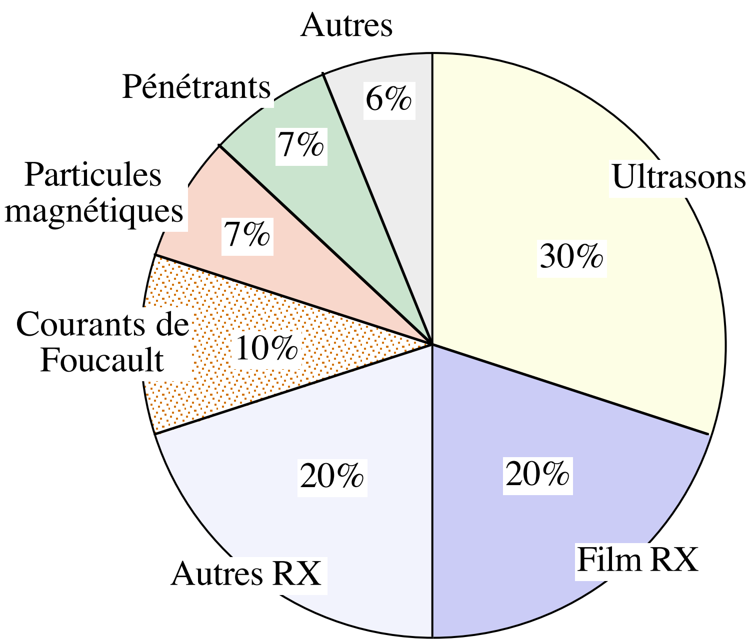
Adhesive defects

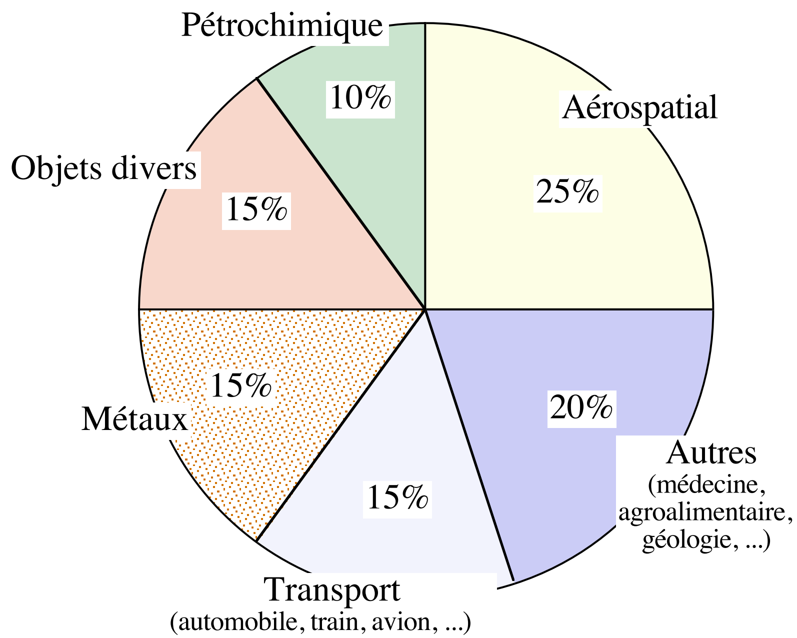


Adhesive concentration

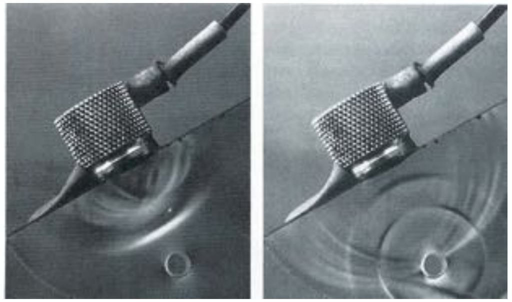


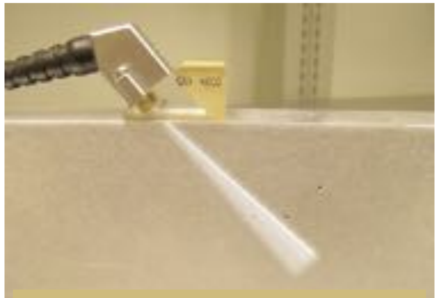
Principales techniques de CND-END



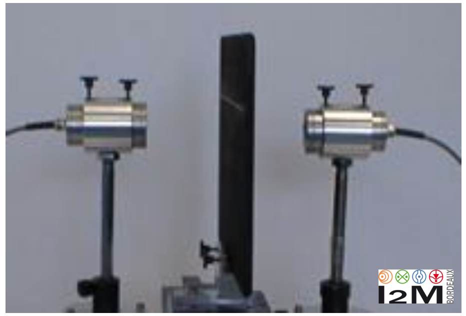


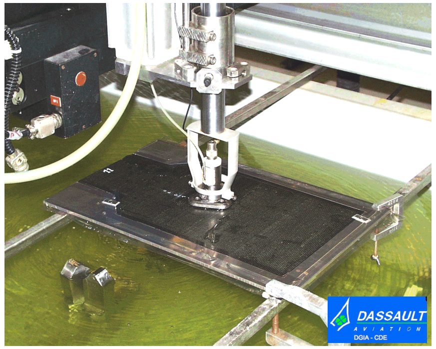
Couplage fluide souvent utilisé pour générer & détecter des ondes ultrasonores dans les solides à inspecter



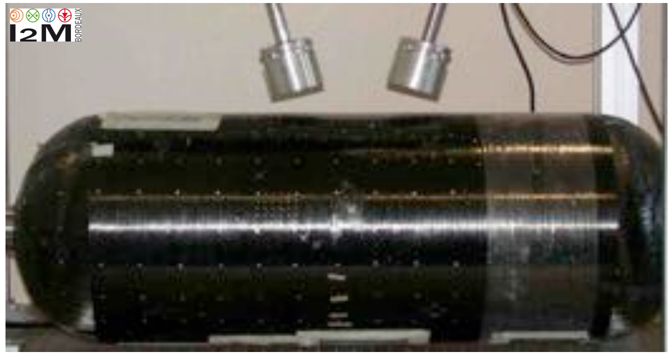


http://www.olympus-ims.com/fr/ultrasonics/intro-to-pa/





Conseil National Recherche Canada
http://iar-ira.nrc-cnrc.gc.ca/smpl_5a_f.html

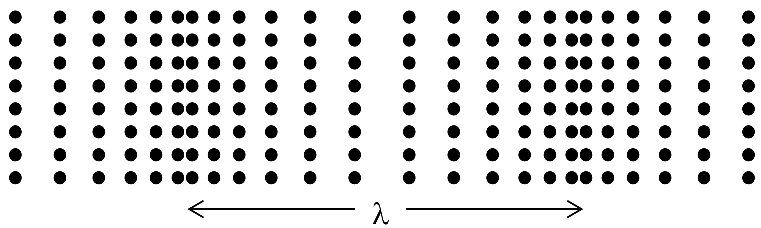


http://metalscan.fr/bassin-16-m-cnd-us-immersion-aeronautique/_dsc4652-web

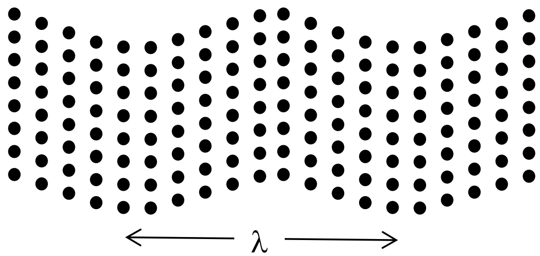
http://onestopndt.com/exhibit/businesses/sonotec/

Ondes ultrasonores : deux modes fondamentaux de propagation dans les solides

Onde de compression (longitudinale ou P)



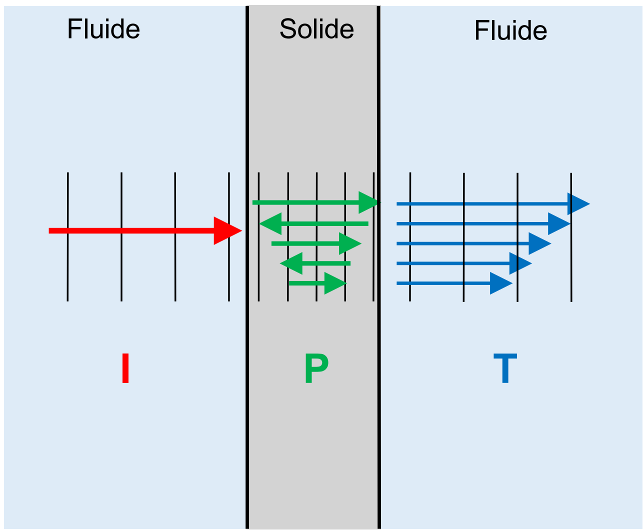
Onde de cisaillement (transversale ou S)

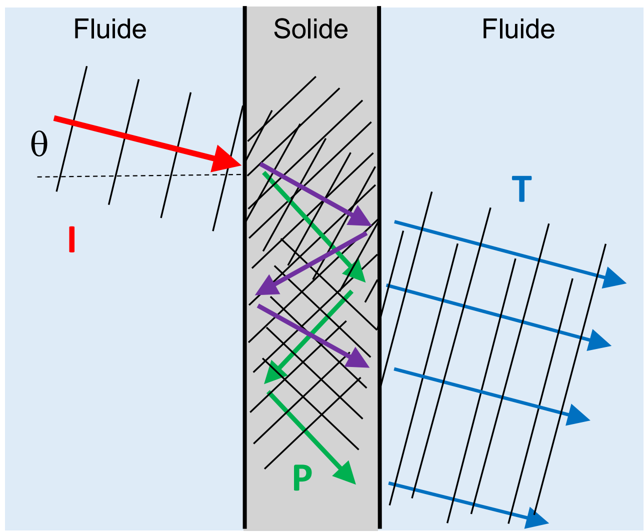


Remarque

Que des ondes de compression dans les fluides non visqueux (pas de cisaillement)

Configuration classique pour générer des ondes dans les solides





Evaluation Non Destructive

E.N.D.

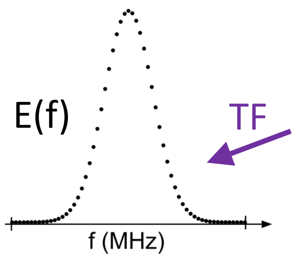
- *Données d'entrées pour les simulations numériques :*

  - Calculs de structures (bureaux d'études) ;

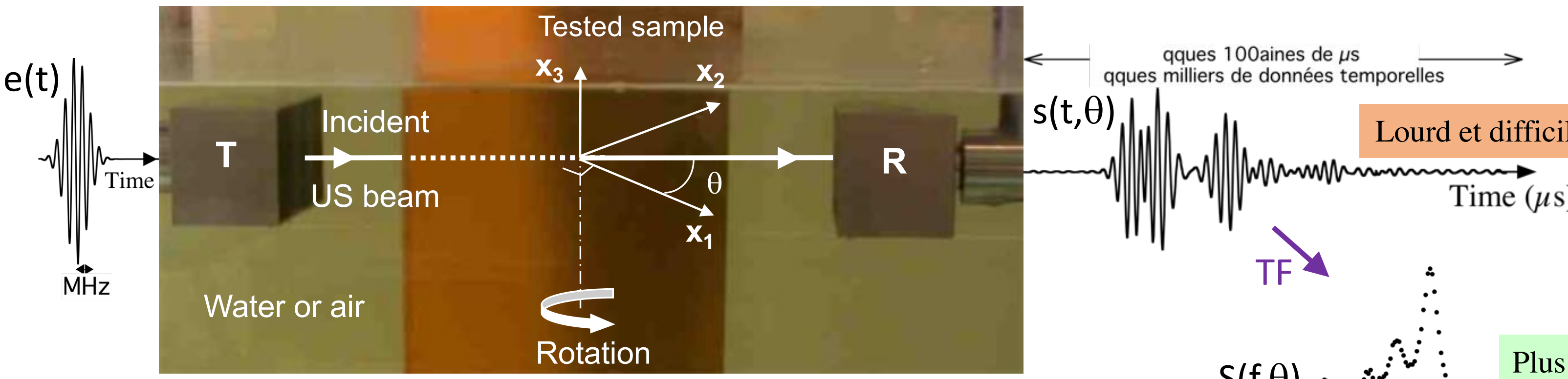
  - Développement ou optimisation de techniques avancées de CND-END ;

- *Contrôle sur chaines de production (conformité des matériaux, cahiers des charges,…) ;*
- *Suivi de santé des matériaux et structures (endommagement, vieillissement, durabilité,…).*

Procédé expérimental pour caractériser les propriétés mécaniques d'un matériau, par ultrasons

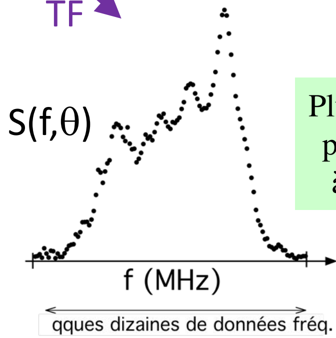


TF

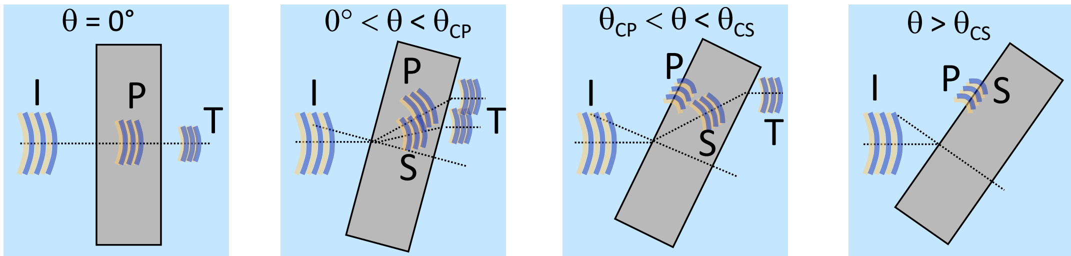


Lourd et difficile à exploiter

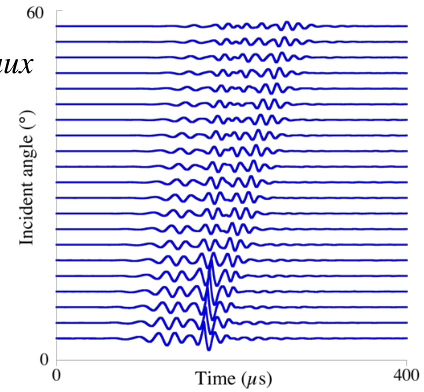
TF



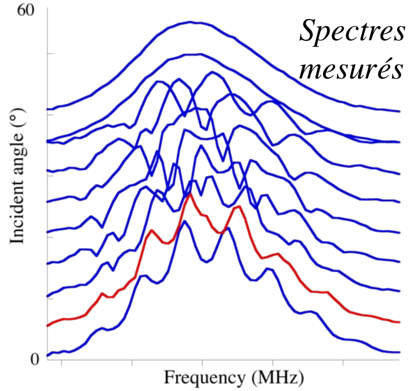
Plus rapide et plus simple à exploiter



Ensemble de signaux mesurés $s(t,\theta)$



TF



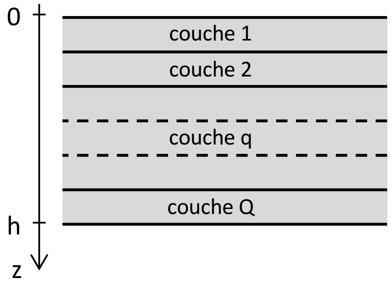
Spectres des signaux mesurés $S(f,\theta)$

Coefficients de transmission expérimentaux

$$T^{exp}(f,\theta) = \frac{S(f,\theta)}{E(f)} = F(f, \theta, h^{1..Q}, \rho^{1..Q}, C_{ij}^{1..Q})$$

Modèle matriciel pour simuler numériquement la propagation des ultrasons dans un matériau stratifié, anisotrope et viscoélastique

Hypothèse : onde plane
Restriction : géométrie plane



Contraintes aux interfaces q-1 et q (surfaces de la couche q) →

$$\begin{bmatrix} \mathbf{T}^{\xi_{q-1}} \\ \mathbf{T}^{\xi_q} \end{bmatrix} = \mathbf{Z}^q \begin{bmatrix} \mathbf{V}^{\xi_{q-1}} \\ \mathbf{V}^{\xi_q} \end{bmatrix} = \begin{bmatrix} \mathbf{Z}^q_{11} & \mathbf{Z}^q_{12} \\ \mathbf{Z}^q_{21} & \mathbf{Z}^q_{22} \end{bmatrix} \begin{bmatrix} \mathbf{V}^{\xi_{q-1}} \\ \mathbf{V}^{\xi_q} \end{bmatrix}$$

← Vitesses particulaires aux interfaces q-1 et q (surfaces de la couche q)

Matrice d'impédance de la couche q (expressions analytiques des ondes P et S) : $\mathcal{F}(h^q, \rho^q, C_{ij}^q, f, \theta)$

Matrice d'impédance pour les q+1 premières couches (démarche récursive) →

$$\mathbf{Z}^{1..q+1} = \begin{bmatrix} \mathbf{Z}^{1..q}_{11} + \mathbf{Z}^{1..q}_{12}\, \mathbf{z}\, \mathbf{Z}^{1..q}_{21} & -\mathbf{Z}^{1..q}_{12}\, \mathbf{z}\, \mathbf{Z}^{q+1}_{12} \\ \mathbf{Z}^{q+1}_{21}\, \mathbf{z}\, \mathbf{Z}^{1..q}_{21} & \mathbf{Z}^{q+1}_{22} - \mathbf{Z}^{q+1}_{21}\, \mathbf{z}\, \mathbf{Z}^{q+1}_{12} \end{bmatrix}$$

où $\mathbf{z} = \left(\mathbf{Z}^{q+1}_{11} - \mathbf{Z}^{1..q}_{22}\right)^{-1}$ et $\mathbf{Z}^{1..q}_{ij}$ (i, j = 1,2) sont les sous matrices d'impédance des q premières couches.

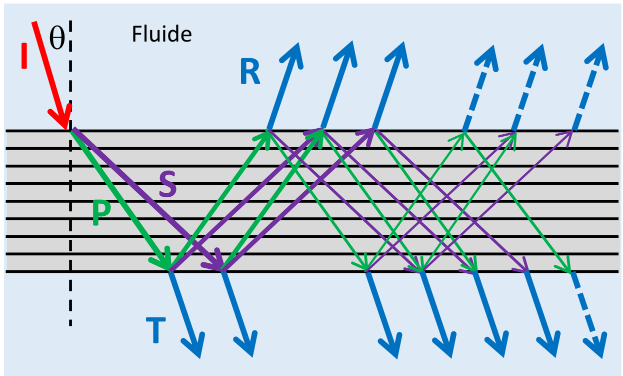
La matrice d'impédance $Z^{1..Q}$ d'un multicouche constitué de Q couches permet de relier les contraintes appliquées aux surfaces externes (z=0 et z=h) avec les vitesses particulaires en ces mêmes surfaces :

$$\begin{bmatrix} \mathbf{T}^{\xi_0} \\ \mathbf{T}^{\xi_Q} \end{bmatrix} = \mathbf{Z}^{1..Q} \begin{bmatrix} \mathbf{V}^{\xi_0} \\ \mathbf{V}^{\xi_Q} \end{bmatrix} = \begin{bmatrix} \mathbf{Z}^{1..Q}_{11} & \mathbf{Z}^{1..Q}_{12} \\ \mathbf{Z}^{1..Q}_{21} & \mathbf{Z}^{1..Q}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{V}^{\xi_0} \\ \mathbf{V}^{\xi_Q} \end{bmatrix}$$

Si le multicouche est immergé dans un fluide, l'écriture des conditions aux limites aux interfaces fluide / solide (en z=0 et z=h) permet d'exprimer le coefficient de transmission (T) pour une onde plane monochromatique sous une incidence θ :

$$T = \frac{2\,\Lambda\, S^{33}_{21}}{(S^{33}_{11} + \Lambda)(S^{33}_{22} - \Lambda) - S^{33}_{21} S^{33}_{12}} = F(f, \theta, h^{1..Q}, \rho^{1..Q}, C_{ij}^{1..Q})$$

avec $\Lambda = \dfrac{\cos\theta}{i\omega\rho_f V_f}$, où ρ_f est la densité du fluide, V_f la célérité dans le fluide, θ l'angle d'incidence et ω la pulsation.



Castaings M., Matrices de raideur de couches – Matrices d'impédance de surface in Matériaux et Acoustique (Tome 1). Ed. Traité MIM, Hermès Lavoisier, pp. 89-96, sous la dir. M. Bruneau & C. Potel, 2006.

Optimisation des modules de rigidité

Minimisation de la fonctionnelle : $\delta = \sum_{\theta_{min}^{Exp}}^{\theta_{max}^{Exp}} \sum_{f_{min}^{Exp}}^{f_{max}^{Exp}} \left[\left| T^{Th}(f,\theta,h,\rho,C_{ij}) \right| - \left| T^{Exp}(f,\theta) \right| \right]^2$

Deux cas de figures

Plaque faite d'un seul matériau homogène à l'échelle des fréquences de travail

↓

Optimisation des C_{ij} du matériau

Plaque vue comme un empilement de plusieurs matériaux chacun étant homogène à l'échelle des fréquences de travail, mais plaque hétérogène

↓

Optimisation des C_{ij} d'une couche (pli, colle,…), les caractéristiques des autres couches étant connues

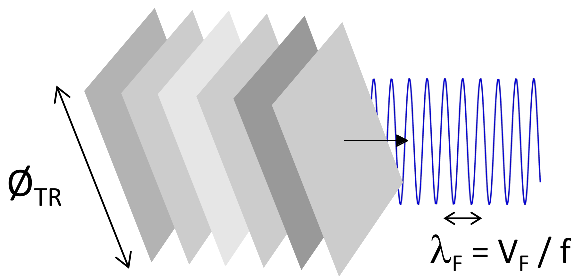
Fréquence

f_{min} — $\frac{V_{mini}}{6\,h_{couche}}$ — f_{max}

← Perte en sensibilité si f.H < 1

Couches (plis) → hétérogènes et modèle non adapté

\+ Dimensions traducteurs / condition « *ondes planes* » satisfaite lors des expériences : $\varnothing_{TR} >> \lambda_F$

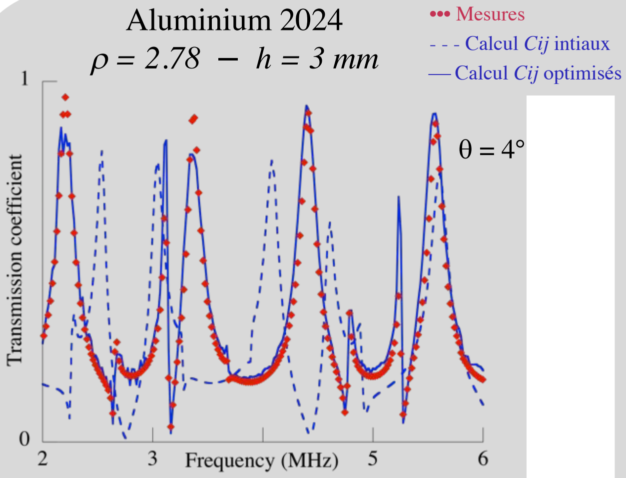


M. Castaings, Materials and Acoustics Handbook, vol. 3, Ed. ISTE-WILEY, London, ISBN 9781848210745, Under supervision of M. Bruneau, C. Potel, 2009

Exemples de caractérisation des propriétés mécaniques de matériaux isotropes

Aluminium 2024

$\rho = 2.78 \;-\; h = 3\ mm$



112	57.1	57.3	0	0	0
	110	–	0	0	0
		109	0	0	0
			–	0	0
	sym			27.2	0
					27.3

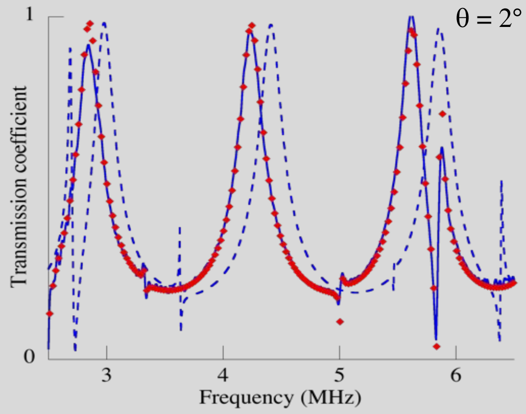
GPa

Erreur ≤ ±5%

	Mes	Th	
E	73.4	73	GPa
ν	0.33	0.33	
G	27.3	28	GPa

Verre

$\rho = 2.51 \;-\; h = 2\ mm$



83.5	25.3	25.4	0	0	0
	84.7	–	0	0	0
		84.2	0	0	0
			–	0	0
	sym			29	0
					29

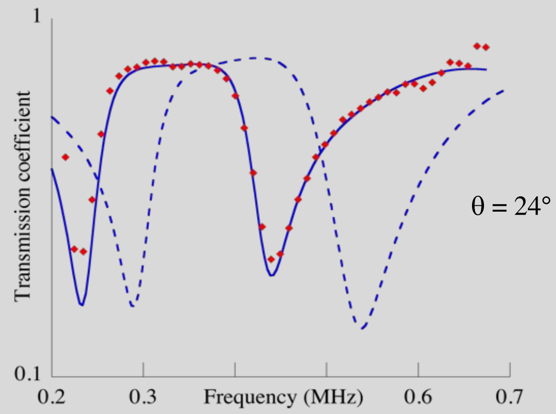
GPa

Erreur < ±5%

	Mes	Th	
E	72	71	GPa
ν	0.21	0.21	
G	29	26.6	GPa

Adhésif epoxy AF 3109

$\rho = 1.18 \;-\; h = 2.46\ mm$



6.7	4.3	4.3	0	0	0
	7.2	–	0	0	0
		7.1	0	0	0
			–	0	0
	sym			1.3	0
					1.3

$+\,i$

0.2	0.05	0.04	0	0	0
	0.15	–	0	0	0
		0.2	0	0	0
			–	0	0
	sym			0.08	0
					0.07

GPa

Erreur < ±5% (partie réelle) — Erreur < ±40% (partie imaginaire)

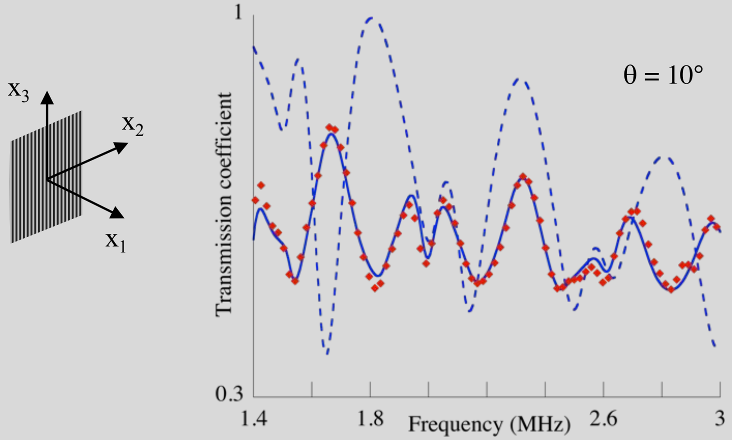
	Mes	Th	
E	3.6	3.4	GPa
ν	0.41	0.4	
G	1.3	1.2	GPa

Exemples de caractérisation des propriétés mécaniques de matériaux composites

Carbone Epoxy UD composite

$\rho = 1.58$ - $h = 4.82$ mm

••• Mesures
- - - Calcul *Cij* intiaux
— Calcul *Cij* optimisés



$$\begin{bmatrix} 14.3 & 7.4 & 8.2 & 0 & 0 & 0 \\ & 13.7 & 7.5 & 0 & 0 & 0 \\ & & 156 & 0 & 0 & 0 \\ & & & 5.8 & 0 & 0 \\ & sym & & & 5.2 & 0 \\ & & & & & 3.4 \end{bmatrix} + i \begin{bmatrix} 0.4 & 0.1 & 0.2 & 0 & 0 & 0 \\ & 0.4 & 0.1 & 0 & 0 & 0 \\ & & 5 & 0 & 0 & 0 \\ & & & 0.08 & 0 & 0 \\ & sym & & & 0.6 & 0 \\ & & & & & 0.12 \end{bmatrix} \text{GPa}$$

Erreur < ±10%   Erreur < ±50%

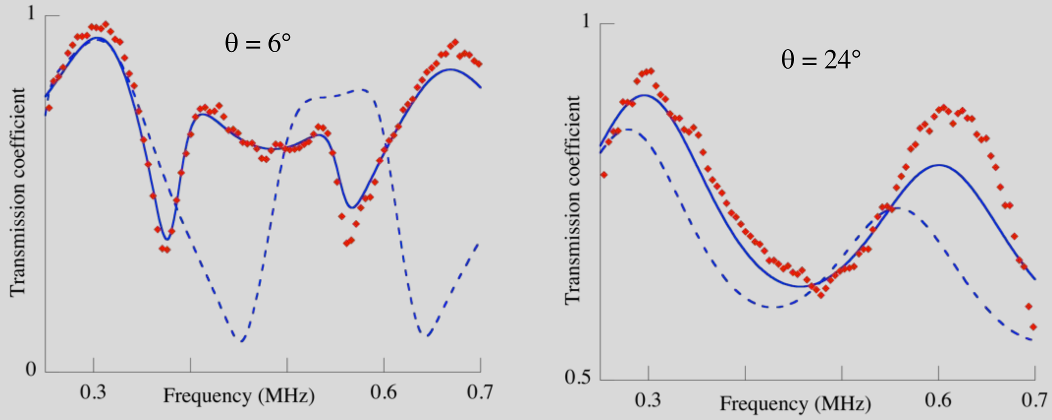
GPa	Mes	Th
E_1	10.2	-
E_2	9.8	-
E_3	150	146

	Mes	Th
ν_{12}	0.5	-
ν_{13}	0.4	-
ν_{23}	0.33	-

GPa	Mes	Th
G_{12}	3.4	-
G_{13}	5.3	-
G_{23}	5.8	5.2

Carbone Epoxy $[0/45/90/-45]_{3s}$ composite

$\rho = 1.58$ - $h = 4.54$ mm



$$\begin{bmatrix} 13.0 & 8.7 & 7.8 & 0 & 0 & 0 \\ & 69 & – & 0 & 0 & 0 \\ & & 74 & 0 & 0 & 0 \\ & & & – & 0 & 0 \\ & sym & & & 3.8 & 0 \\ & & & & & 3.9 \end{bmatrix} + i \begin{bmatrix} 0.2 & 0.02 & 0.03 & 0 & 0 & 0 \\ & 6 & – & 0 & 0 & 0 \\ & & 6 & 0 & 0 & 0 \\ & & & – & 0 & 0 \\ & sym & & & 0.2 & 0 \\ & & & & & 0.16 \end{bmatrix} \text{GPa}$$

Erreur ≤ ±25%   Erreur ↑

Milieu hétérogène car fréquence trop élevée

Si fréquence abaissée, TC pas suffisamment sensible aux Cij car plaque mince ➜ **Limites de la méthode**

Prédiction des propriétés mécaniques de matériaux composites stratifiés

Simulation numérique de l'expérimentation avec des conditions idéales BF (milieu homogène) et un stratifié très épais (grand nombre de super-couches Ex.: $[0/45/90/-45]_{20s}$)

C_{ij} mesurés pour plaque UD assimilés aux C_{ij} de chaque pli

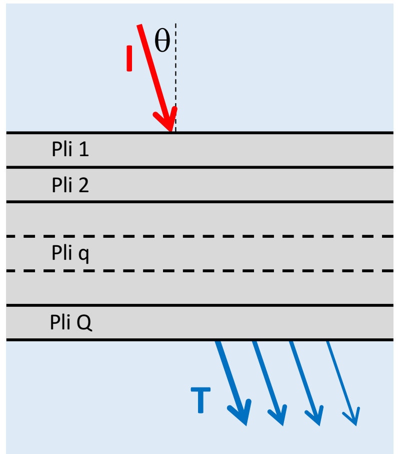
$$\begin{bmatrix} 14.3 & 7.4 & 8.2 & 0 & 0 & 0 \\ & 13.7 & 7.5 & 0 & 0 & 0 \\ & & 156 & 0 & 0 & 0 \\ & & & 5.8 & 0 & 0 \\ & sym & & & 5.2 & 0 \\ & & & & & 3.4 \end{bmatrix} + i \begin{bmatrix} 0.4 & 0.1 & 0.2 & 0 & 0 & 0 \\ & 0.4 & 0.1 & 0 & 0 & 0 \\ & & 5 & 0 & 0 & 0 \\ & & & 0.08 & 0 & 0 \\ & sym & & & 0.6 & 0 \\ & & & & & 0.12 \end{bmatrix}$$

Matrice d'impédance $Z^{1..Q}$ du multicouche constitué de Q couches

$$\begin{bmatrix} \mathbf{T}^{\xi_0} \\ \mathbf{T}^{\xi_Q} \end{bmatrix} = \mathbf{Z}^{1..Q} \begin{bmatrix} \mathbf{V}^{\xi_0} \\ \mathbf{V}^{\xi_Q} \end{bmatrix} = \begin{bmatrix} \mathbf{Z}_{11}^{1..Q} & \mathbf{Z}_{12}^{1..Q} \\ \mathbf{Z}_{21}^{1..Q} & \mathbf{Z}_{22}^{1..Q} \end{bmatrix} \begin{bmatrix} \mathbf{V}^{\xi_0} \\ \mathbf{V}^{\xi_Q} \end{bmatrix}$$

Coefficient de transmission en ondes planes

$$T^{ExpSimul}(f, \theta, \varphi^{1..Q}, h^{1..Q}, \rho^{1..Q}, C_{ij}^{1..Q})$$



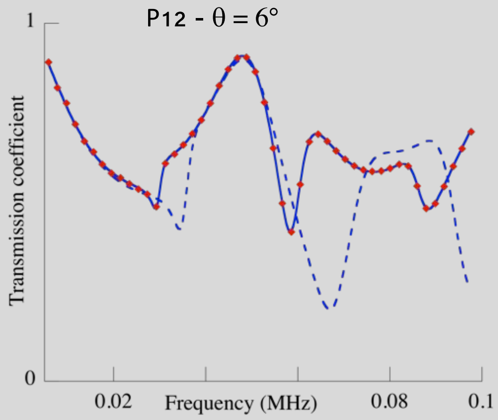
Optimisation des C_{ij} équivalents : $\sum \sum \left[\left| T^{ExpSimul}(f,\theta,\varphi^{1..Q},h^{1..Q},\rho^{1..Q},C_{ij}^{1..Q}) \right| - \left| T^{th}(f,\theta,\varphi,H,\rho,C_{ij}^{EQUIV}) \right| \right]^2$

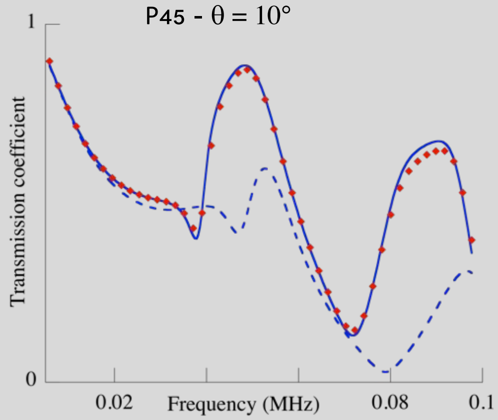
Exemples de simulation ondes dans empilements stratifiés + caractérisation des propriétés mécaniques équivalentes

Carbone Epoxy [0/45/90/-45]$_{20s}$

$\rho = 1.58$ - $h = 30.24$ *mm*

••• Mesures simulées
- - - Calcul *Cij* équivalents intiaux
— Calcul *Cij* équivalents optimisés





$$\begin{bmatrix} 14.3 & 7.8 & 7.8 & 0 & 0 & 0 \\ & 67.9 & 24.5 & 0 & 0 & 0 \\ & & 69.1 & 0 & 0 & 0 \\ & & & 21.6 & 0 & 0 \\ & sym & & & 4.1 & 0 \\ & & & & & 4.1 \end{bmatrix} + i \begin{bmatrix} 0.4 & 0.13 & 0.1 & 0 & 0 & 0 \\ & 2 & 0.18 & 0 & 0 & 0 \\ & & 2 & 0 & 0 & 0 \\ & & & 0.14 & 0 & 0 \\ & sym & & & 0.28 & 0 \\ & & & & & 0.28 \end{bmatrix} \text{GPa}$$

Erreur < ±1% — **Erreur < ±20%**

Modules de l'ingénieur déduits des C_{ij} optimisés :

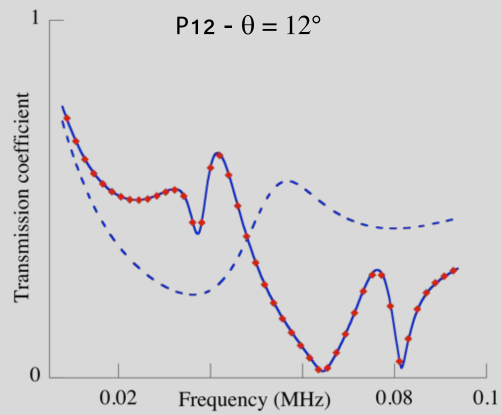
$E_1 = 13$ – $E_2 = 57.3$ – $E_3 = 58.3$ GPa

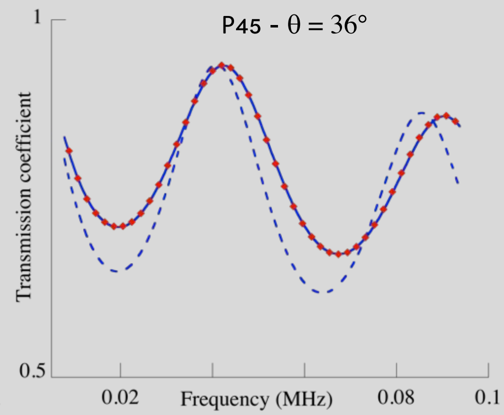
$\nu_{12} = 0.37$ – $\nu_{13} = 0.38$ – $\nu_{23} = 0.32$

$G_{12} = 4.1$ – $G_{13} = 4.1$ – $G_{23} = 21.6$ GPa

Carbone Epoxy [45/-45/90/0/45/…/0/90/-45/45]$_{6s}$ (24 plis)

$\rho = 1.57$ - $h = 38.1$ *mm*





$$\begin{bmatrix} 14.3 & 6.8 & 6.8 & 0 & 0 & 0 \\ & 57.2 & 19.7 & 0 & 0 & 0 \\ & & 57.2 & 0 & 0 & 0 \\ & & & 18.8 & 0 & 0 \\ & sym & & & 4.4 & 0 \\ & & & & & 4.4 \end{bmatrix} + i \begin{bmatrix} 0.25 & 0.2 & 0.2 & 0 & 0 & 0 \\ & 2.1 & 1.6 & 0 & 0 & 0 \\ & & 2.2 & 0 & 0 & 0 \\ & & & 0.3 & 0 & 0 \\ & sym & & & 0.07 & 0 \\ & & & & & 0.07 \end{bmatrix} \text{GPa}$$

Erreur < ±1% — **Erreur < ±20%**

Modules de l'ingénieur déduits des C_{ij} optimisés :

$E_1 = 13.1$ – $E_2 = 49$ – $E_3 = 49$ GPa

$\nu_{12} = 0.33$ – $\nu_{13} = 0.33$ – $\nu_{23} = 0.30$

$G_{12} = 4.4$ – $G_{13} = 4.4$ – $G_{23} = 18.8$ GPa

Characterization of Cohesive and Adhesive Properties of Adhesive Bonds Using Transmitted Ultrasonic Waves

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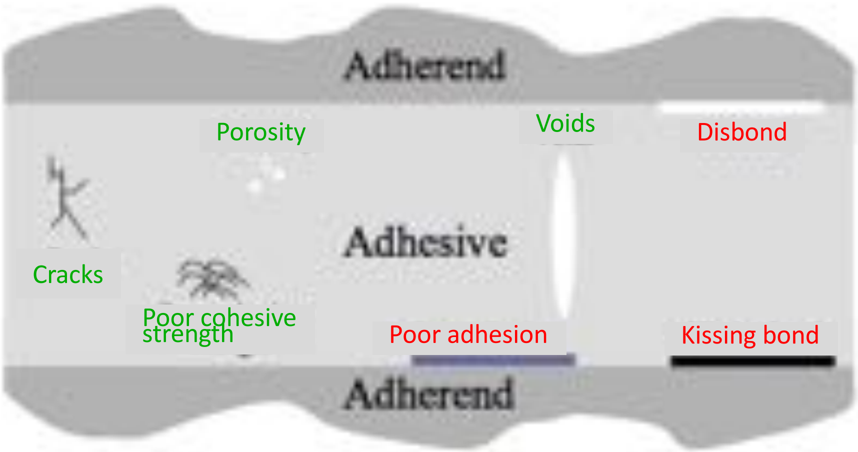
Project ISABEAU (Innovating for Structural Adhesive Bonding Evaluation and Analysis with Ultrasounds) supported by French ANR, AIRBUS-DS and SAFRAN

Context & needs

Context: Replacement of screwing or welding assemblies by adhesive assemblies

➔ *Light weight, uniform stress distribution along the bonded zones*

2 classes of defects:
- Cohesive defects
- Interface defects



NDE methods are required to distinguish between those two classes of defects and to evaluate mechanical weaknesses of the adhesive layer and/or of the interfaces.

Objectives & strategy

➢ Objectives:

1) To infer mechanical properties of the adhesive layer between 2 substrates : cohesive properties;

2) To study the influence of surface treatment and incomplete cross-linking on that estimation of mechanical properties of the adhesive layer;

3) To infer mechanical properties of interphases connecting substrates to adhesive: adhesion properties

Zone of 1 or few μm thick

➢ Approach:

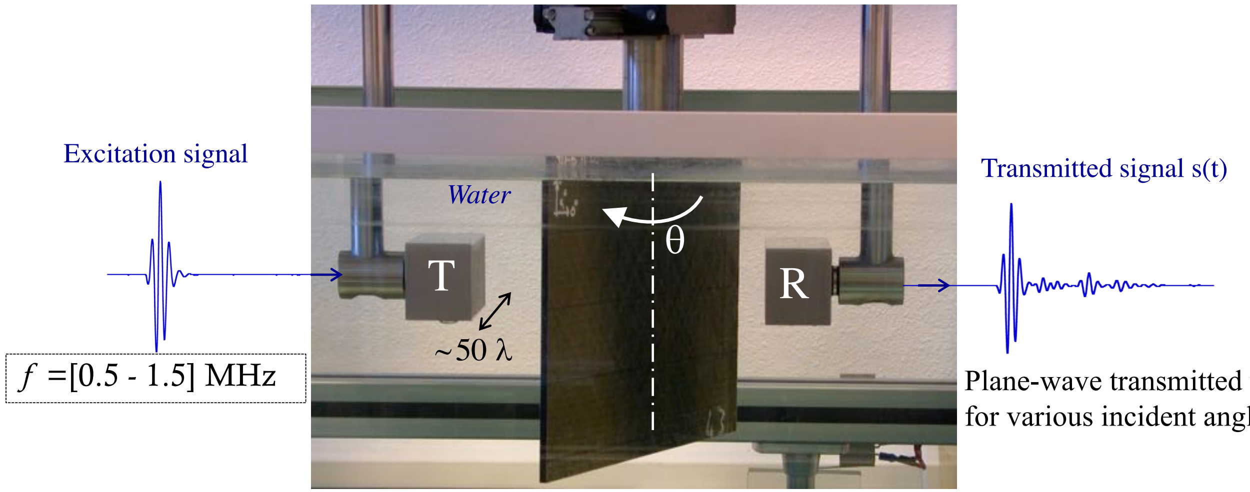
- Assemblies made of Aluminium substrates and Epoxy adhesive (isotropic & homogeneous materials);

- Immersion measurements of plane-wave transmitted ultrasonic field (PWTUF) for:

a) Optimization of C_{ij} of adhesive layer without the assumption of isotropic medium
+ investigation of the influence of the preparation of substrates' surfaces on these *Cij* ;

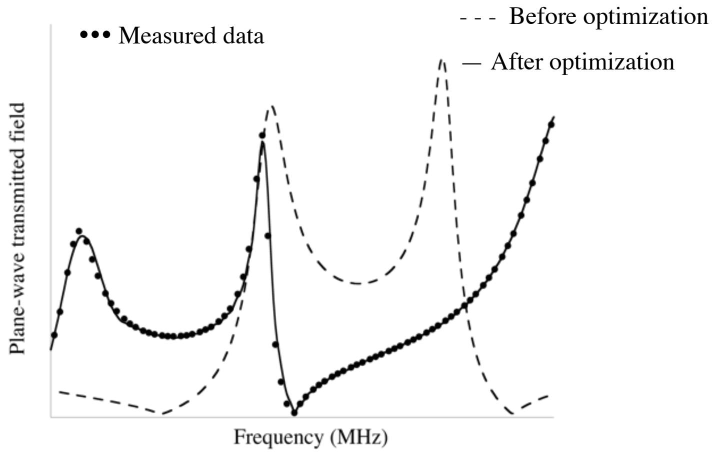
b) Optimization of two stiffness's k_L and k_T for mechanical properties of interphases.

Measurements of (visco)elastic *moduli* using the plane-wave transmitted ultrasonic field (PWTUF) method



Plane-wave transmitted ultrasonic field is measured for various incident angles (0° ≤ θ ≤ 50°)

Example of PWTUF for one given incident angle



Transmitted acoustic fields are computed;

Assumptions: incident plane wave, homogeneous, anisotropic, visco-elastic material, perfect fluid.

$$\left|A_T^{Th}(f,\theta,C_{ij})\right| = \left|T^{Th}(f,\theta,C_{ij}).A_I^{Exp}(f)\right|$$

Optimization routine (Simplex method) is used to infer complex $C_{11}, C_{22}, C_{12}, C_{66}$ (in P_{12} plane) of material to be characterized.

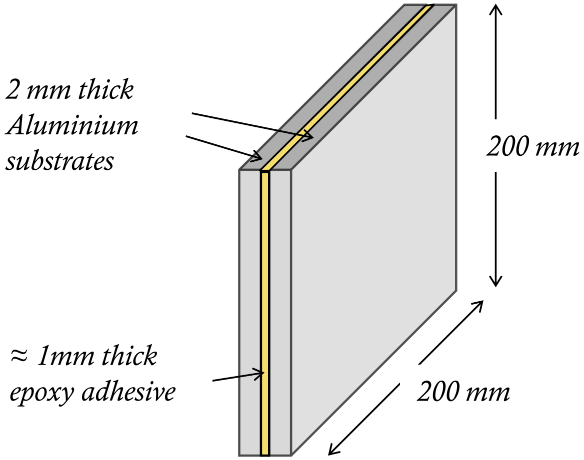
M. Castaings et al., NDT&E Int. 33, 2000

Characterization of components of the assembly from individual plate-like samples

Aluminium	Epoxy (fully cured)	Epoxy (80% cured)
h_{alu}=2 mm ± 3%	$h_{adhesive}$=2.92 mm ± 3%	$h_{adhesive}$=2.96 mm ± 3%
C_{11}= 106 GPa	C_{11}= 7.77 + i 0.23 GPa	C_{11}= 7.56 + i 0.16 GPa
C_{22}= 109 GPa	C_{22}= 7.75 + i 0.30 GPa	C_{22}= 7.52 + i 0.25 GPa
C_{66}= 26 GPa	C_{66}= 1.71 + i 0.10 GPa	C_{66}= 1.53 + i 0.06 GPa
C_{12}= 55 GPa	C_{12}= 4.35 + i 0.07 GPa	C_{12}= 4.25 + i 0.05 GPa
$\Delta C'_{ij} \approx \pm 2\%$	$\Delta C'_{ij} \approx \pm 2\%$ $\pm 3\% \leq \Delta C''_{ij} \leq \pm 10\%$	$C'_{ij} \approx \pm 2\%$ $\pm 5\% \leq \Delta C''_{ij} \leq \pm 16\%$

- Isotropy found for all materials;
- C_{ij} of 80% cured Epoxy are slighty $<$ C_{ij} of fully cured Epoxy.

Manufacturing of adhesively-bonded tri-layer assemblies & characterization process of cohesive properties of adhesive layer



Plane-wave transmitted ultrasonic field is measured

for various incident angles (0° ≤ θ ≤ 35°)

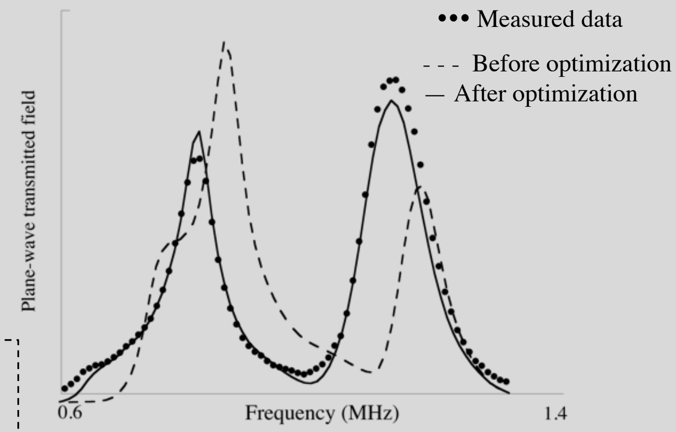
Optimization routine is used to infer C_{ij} of adhesive layer

Aluminium properties are known

h & ρ for adhesive are known

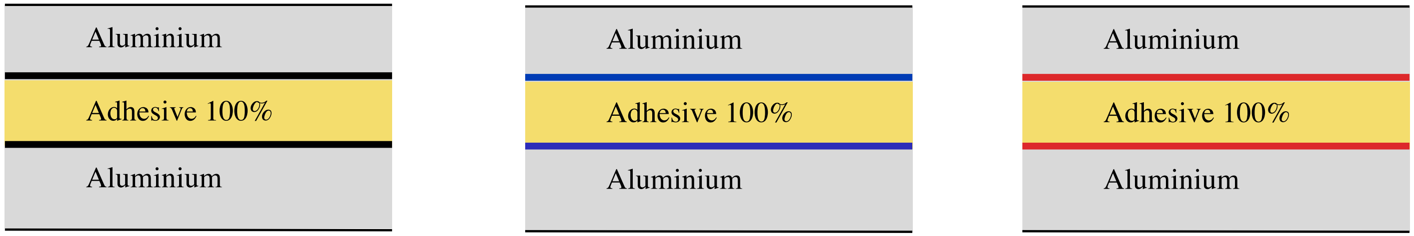
Interphases are supposed to be nominal

Inverse problem
(Simplex method)



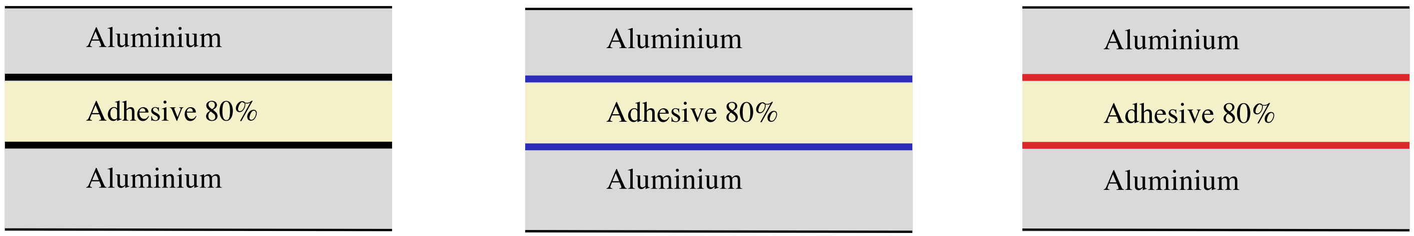
Manufacturing of adhesively-bonded tri-layer assemblies & characterization process of cohesive properties of adhesive layer

1st set of assemblies with totally cured epoxy (100%)



DSSi100 *DS100* *D100*

2nd set of assemblies with partially cured epoxy (80%)



DSSi80 *DS80* *D80*

DSBSi = Degreasing + Sand-blasting + Silane

a priori nominal adhesion

DSB = Degreasing + Sand-blasting

a priori intermediate adhesion

D = Degreasing

a priori (very) weak adhesion

Evaluation of mechanical *moduli* of the adhesive layer and investigation of the influence of the preparation of substrates' surfaces on this evaluation

$$\beta_1 = \frac{C_{22}^{app} - C_{11}^{app}}{C_{22}^{app}}$$

$$\beta_2 = \frac{C_{12}^{app} - (C_{11}^{app} - 2C_{66}^{app})}{C_{12}^{app}}$$

	100% cured Epoxy			80% cured Epoxy		
Assembly	***DSSi100*** Nominal	***DS100*** Intermediate	***D100*** Weak	***DSSi80*** Nominal	***DS80*** Intermediate	***D80*** Weak
Thickness (mm)	*0.98*	*0.87*	*0.96*	*1.09*	*0.78*	*0.75*
C_{11} *(GPa)*	*7.9*	*6.6*	*5.7*	*7.4*	*6.2*	*5.5*
C_{22} *(GPa)*	*7.1*	*6.8*	*6.9*	*7.0*	*6.8*	*6.8*
C_{66} *(GPa)*	*1.8*	*1.6*	*1.4*	*1.7*	*1.4*	*1.3*
C_{12} *(GPa)*	*4.6*	*4.3*	*4.1*	*4.4*	*4.1*	*3.9*
$\beta = \beta_1 + \beta_2$	**0**	**0.23**	**0.45**	**0**	**0.26**	**0.45**

- ✓ Changes in apparent C_{ij} of adhesive layers of various samples $>$ measurements errors $\Delta C_{ij} \approx 3\%$;
- ✓ Measured C_{ij} of adhesive layers in DSSi samples are close to those obtained for individual epoxy plates;
- ✓ Measured C_{ij} of adhesive layers show apparent anisotropy (β), which increases as Aluminium surfaces are not well prepared (weak interphases), for both series of samples (100% & 80% cure adhesive). This was confirmed by numerical simulations of experiments & optimization process from simulated signals;
- ✓ Cohesive defect (incomplete curing DSSi80) leads to uniform change in all elastic *moduli* and respect of isotropy if interphases are nominal => Cohesive defect has a different signature than adhesion defect !!

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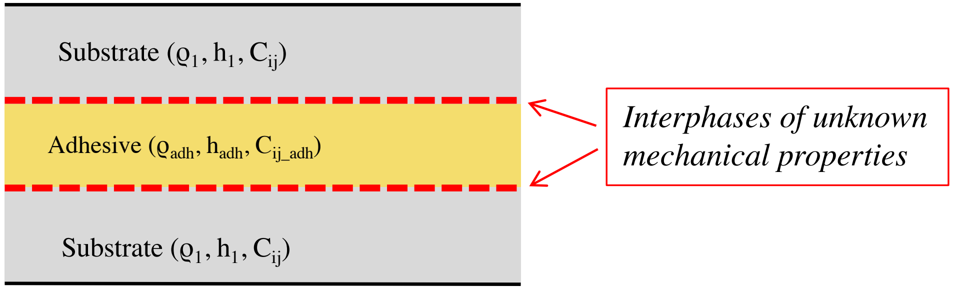
Estimation of mechanical stiffnesses k_L and k_T of interphases

ρ and C_{ij} of substrates and adhesive are known, and given values previously measured on individual plate samples – Thicknesses are also known (or measured separately)

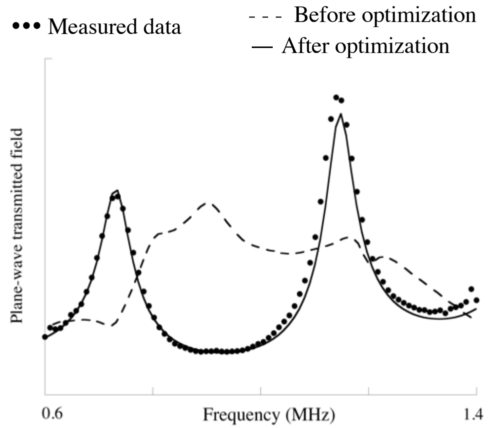


✓ Numerical sensitivity study of ultrasonic PWTUF to k_L and k_T changes

=> optimal incident angles: $\boldsymbol{\theta_{inc} = 0°}$ **to optimize** $\boldsymbol{k_L}$ and $\boldsymbol{\theta_{inc} = 21°}$ **to optimize** $\boldsymbol{k_T}$ *(for this structure)*

✓ Use of previously measured PWTUF ($\theta_{inc} = 0°$ and $\theta_{inc} = 21°$ only) + optimization routine => numerical values of k_L and k_T of interphases to be characterized

Inverse problem (Least square method)



Numerical estimation of interfacial stiffnesses

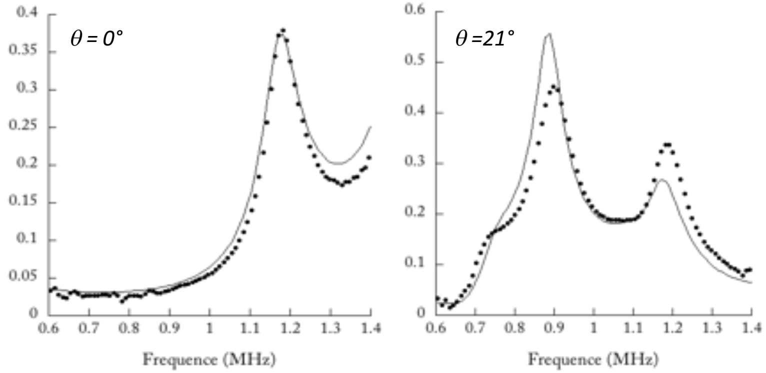
1st set of assemblies with totally cured epoxy (100%)

	DSSi100	***DS100***	***D100***
$k_L(PPa/m)$	2.08	0.25	0.10
$k_T(PPa/m)$	1.00	0.10	0.02

$k_{L\_D100} \approx k_{L\_DSSi100}/21$ & $k_{T\_D100} \approx k_{T\_DSSi100}/50$

1 PPa/m = 10^{15} Pa/m

Measured (•) and simulated with optimized stiffness's (—) PWTUF for assembly DSSi100

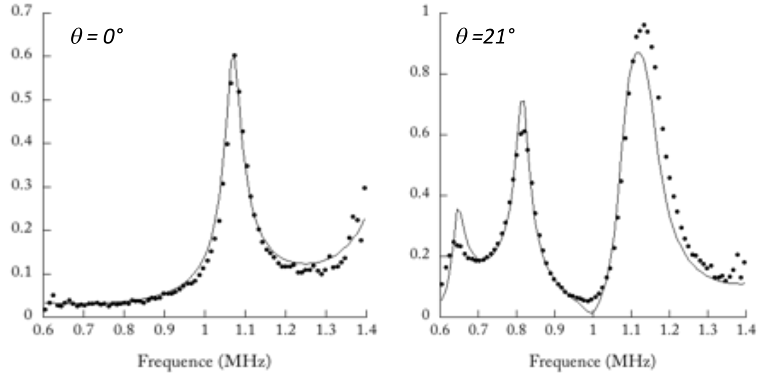


2nd set of assemblies with partially cured epoxy (80%)

	DSSi80	***DS80***	***D80***
$k_L(PPa/m)$	2.09	0.23	0.13
$k_T(PPa/m)$	1.00	0.10	0.02

$k_{L\_D80} \approx k_{L\_DSSi80}/15$ & $k_{T\_D80} \approx k_{T\_DSSi80}/50$

Measured (•) and simulated with optimized stiffness's (—) PWTUF for assembly DSSi80

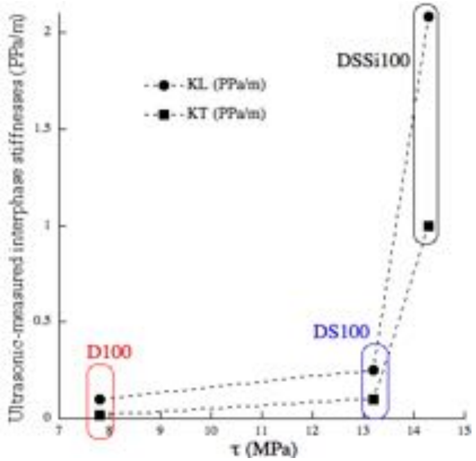


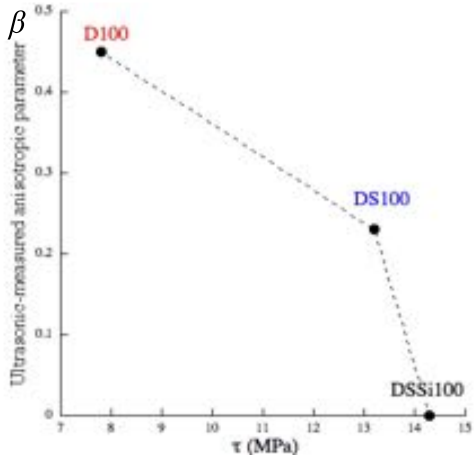
k_T decreases more significantly than k_L as interphases get degraded, independently of adhesive curing state !

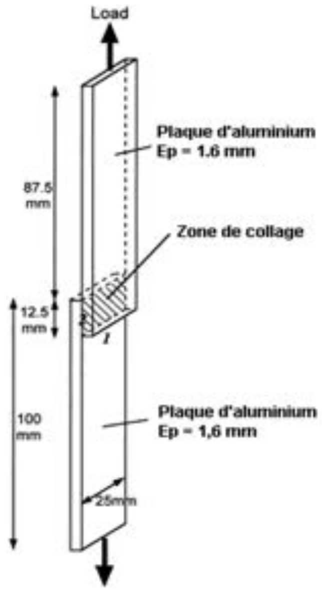
Comparison with destructive mechanical tests

- Standard shear lap-joint tests:
- NF-EN 2243-1
- Adhesive thickness ~ 300 μm

	DSSi100	***DS100***	***D100***
$\tau\,(MPa)$	14.3 ± 1.1	13.2 ± 1.3	7.8 ± 0.7
$k_L\,(PPa/m)$	2.08	0.25	0.10
$k_T\,(PPa/m)$	1.00	0.10	0.02
β	0	0.23	0.45







J. Galy, N. Ylla, J. Moysan and A. El Mahi, Conference paper, Thermosets, (2015).

⇒ Mechanical strength (τ) decreases as interphases get degraded. Not in the same proportion than the ultrasonically-measured k_L , k_T or β

⇒ However, as τ versus k_L, k_T or β are monotonic plots, then the ultrasonically-measured quantities could be good indicators of level of adhesion at interphases.

Conclusions and Outlooks

Conclusions

- PWTUF measurements + optimization process allow elastic *moduli* of adhesive layer or stiffness coefficients of interphases between adhesive and adherents to be inferred;
- An **uncured state of the adhesive** layer is revealed by **low values of the estimated elastic *moduli***, but that adhesive layer is still viewed as an **isotropic medium** (if interphases are of good quality);
- A **weak adhesion** is revealed by low values of the elastic *moduli* and an **apparent anisotropy** of the adhesive layer;
- If adherents' and adhesive properties are known, then **stiffness coefficients of interphases**, k_L & k_T, can be assessed. Their values are sensitive (but not in the same proportion) to the surface treatment of the substrates and therefore good indicators of the quality of bonded surfaces;
- Ultrasonically-measured data have been successfully compared with mechanical destructive tests and monotonic plots link both types of quantities, confirming that **apparent anisotropy** and **stiffness coefficients** are **good indicators of the adhesion level**.

Outlooks

- To investigate the effect of **one imperfect surface** only on PWTUF measurements and on associated evaluation process of **cohesive and adhesion properties**;
- To use ultrasonic **beams** of small sizes (collimated or focused beams) in order to **locally characterize adhesive bonds**;
- To extend this study to adhesively-bonded **composite** panels.

Contrôle Non Destructif

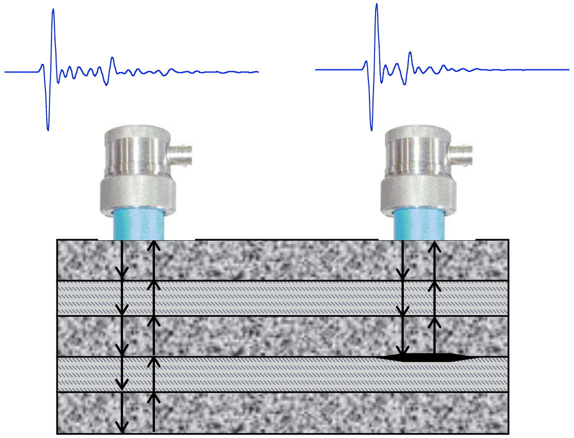
C.N.D.

- *Détection, localisation, quantification, imagerie de discontinuités ;*
- *Contrôle en sortie de chaines de production (conformité des matériaux, cahiers des charges,…) ;*
- *Suivi de santé des matériaux et structures (endommagement, durabilité,…).*

Ultrasonic NDT of composite structures

Not so easy to control as metals because:

- Ply orientation causes **anisotropy** which makes waves **speed** to depend on **direction of propagation**
- Matrix is often **viscoelastic** and causes **absorption** of ultrasounds
- Medium is heteregeneous and **multi-reflections** at interfaces cause ultrasound **attenuation** or make **signals complex**



Pulse-Echo contact Technique / Manual ultrasonic testing

- Easy to use +
- Slow point-by-point technique
- Coupling-dependent
- Remove and clean-up gel after testing

} -

Laser Ultrasonics

- **Non-contact technique** based on conversion of electromagnetic energy into elastic energy and *vice-versa* +
- Slower and more **expensive** than conventional systems on flat components -
- **Less sensitive to probe alignment than conventional US techniques → significant advantage for curved components** +
- Low signal levels ⇒ **retro-reflective coating** sometimes **used** to cover the structure … not convenient for large areas -
- **Need to scan tested structures** (≈10m^2/h with 12.5×12.5mm pixel size, using **rotating mirrors** to deflect laser beams) -
- Used by US aerospace manufacturers for **inspection of complex composite components used in modern aircrafts**

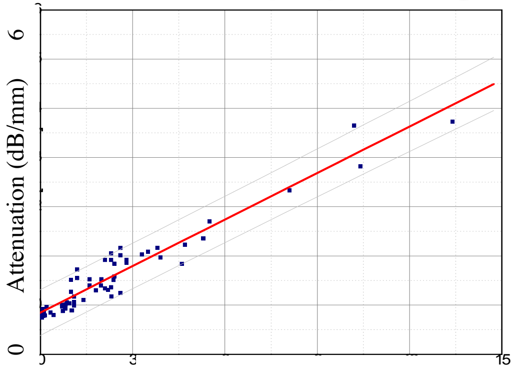
UltraOptec (*Canada*)
Laser Ultrasonic Inspection System (LUIS)

DASSAULT AVIATION DGIA - CDE EADS

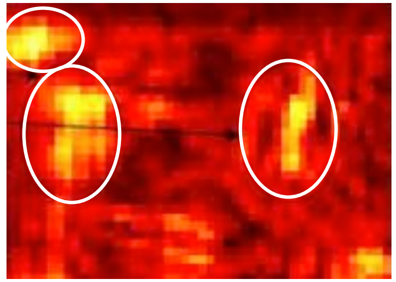
Many research centres developing Laser -based ultrasounds:
- Bremen Institute of Applied Beam Technology (Germany)
- Industrial Materials Institute (Canada)
- Università Politecnica delle Marche (Italia)
- Institute of Acoustics of Tongji Univ., (Shangai, China)
- I_2M University Bordeaux (France)
- etc…

Through-transmission ultrasonic technique
Water jet

Ultrasonic Attenuation coefficient
Sensor 1MHz, 4mm jet of water, squirted

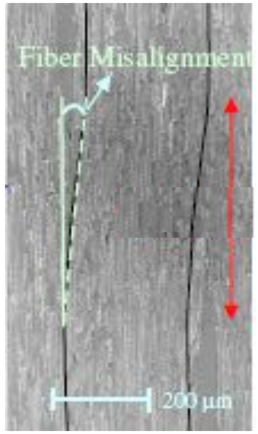


Detection of delaminations



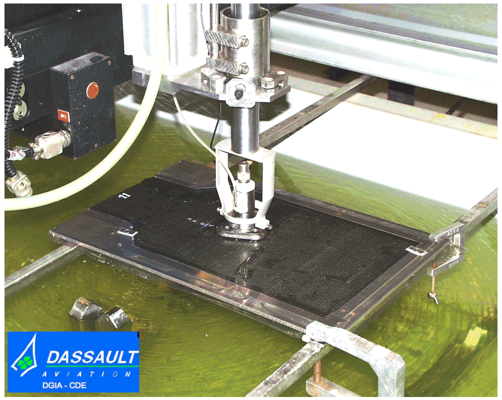
http://www.wavelength-ndt.com/composites.htm

Detection of fibres misalignment

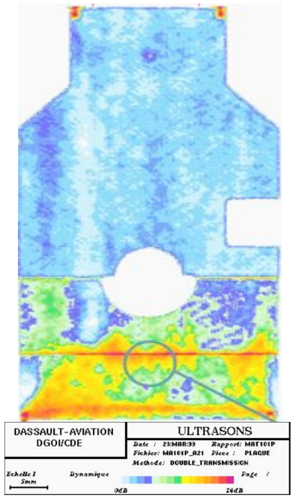


J. Cho, Scripta Materialia 56, 2006

Pulse-echo ultrasonic technique / Immersion tank



US cartography of porous zone of RTM



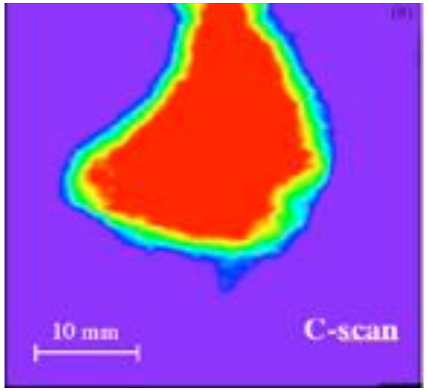
- Large choice of frequencies depending on size of searched defect (+)
- Point-by-point scanning techniques (-)
- Need to dismantle tested pieces (-)

Imaging impact damages for composite materials

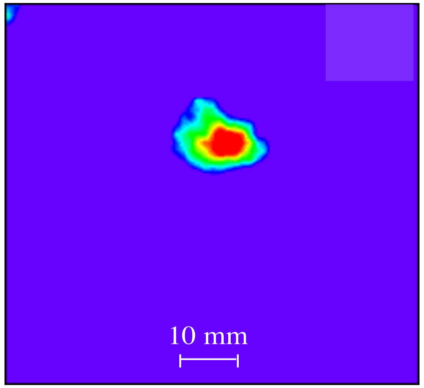
Ex.: Carbon Kevlar composite plates - 3 mm

Photography | *Ultrasound scan - 250 kHz*

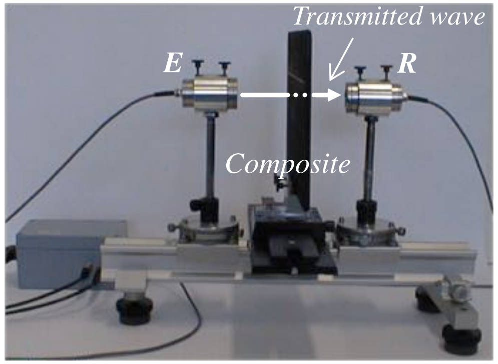
High impact



Low impact

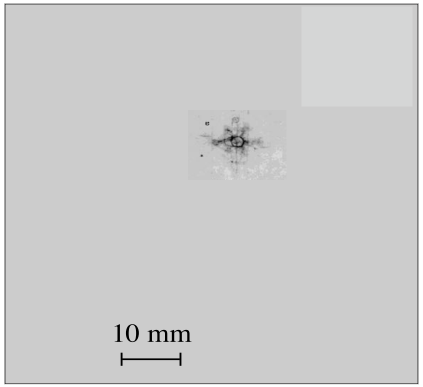


Air-coupled transducers



GDAŃSK UNIVERSITY OF TECHNOLOGY

RX measurements



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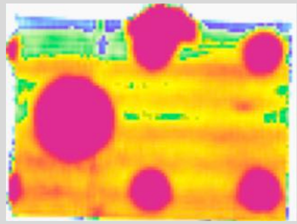
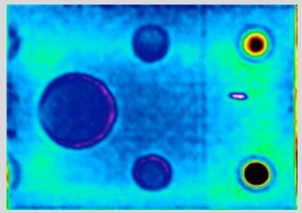
Contact-less ultrasonic scan of sandwich composite component

US C-scan

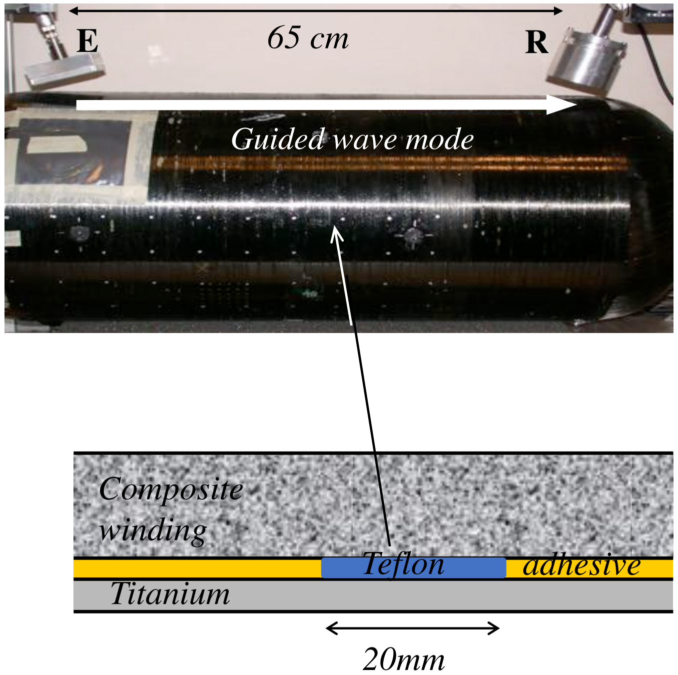


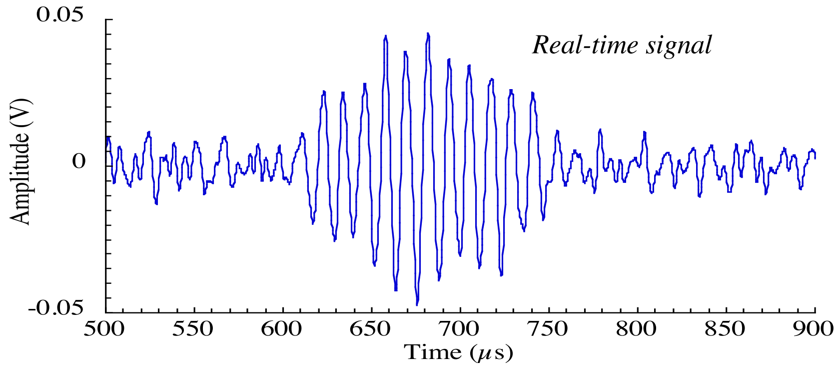
Thermography

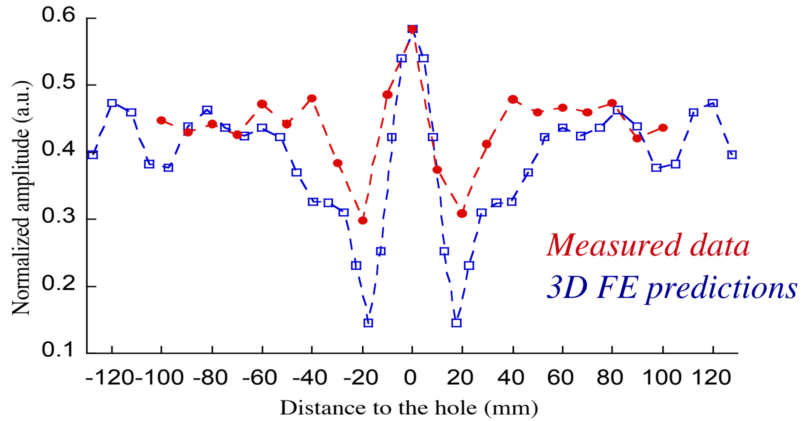


Air-coupled ultrasonic transducers for contact-less and single-sided detection and localisation of defects in complex composite structures

e.g. High pressure composite tank (ARIANE) = Titanium liner + adhesive layer + Carbon Epoxy winding



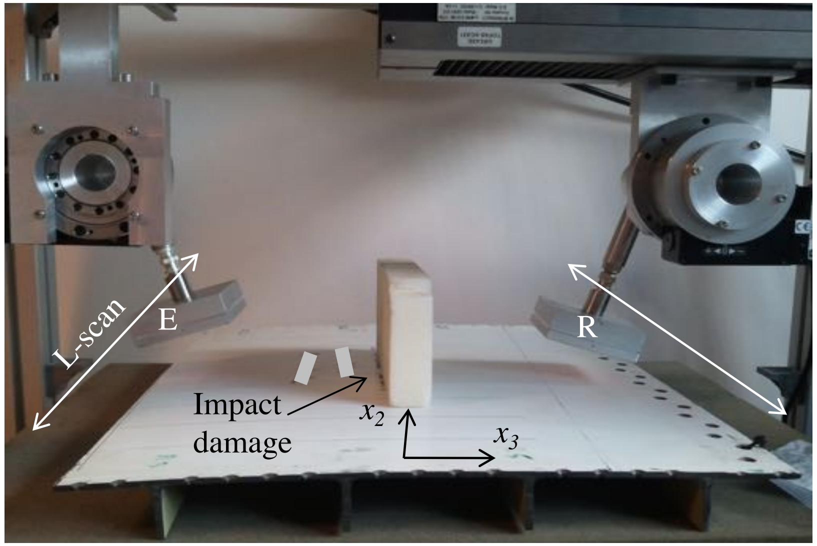




ARA = AQUITAINE + BORDEAUX 1 + EADS astrium

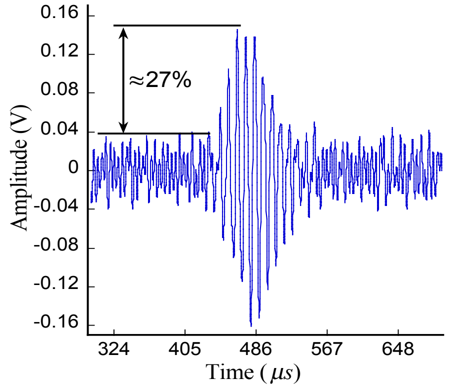
W. Ke, M. Castaings NDT&E Intern., vol. 42, p. 524-533, 2009

Inspection of aeronautic composite structures using guided waves generated and detected by single-sided access, ultrasonic, air-coupled transducers

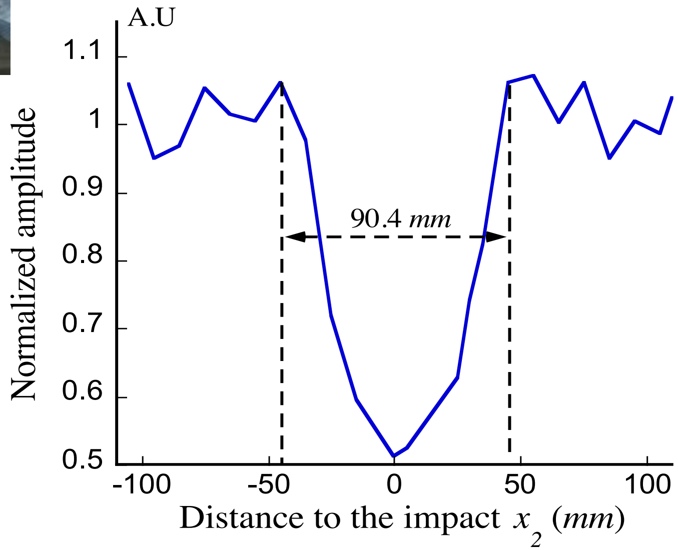


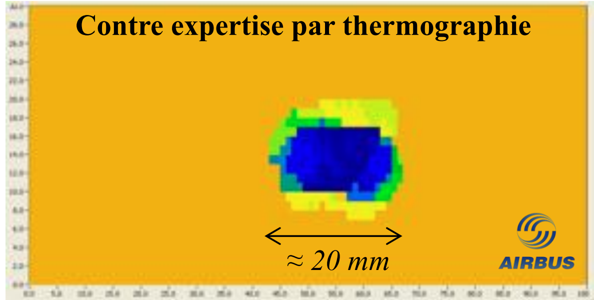
Air-coupled ultrasonic transducers
Frequency = 100 *kHz*
Angles = ± 15°
Guided mode = A_0 along x_3
Path of propagation =300 *mm* overs 3 stiffeners
Scanning along x_2

Real-time A_0 waveform generated and detected by air-coupled transducers



U-shaped measured distribution of A_0 amplitude reveals presence of impact damage.





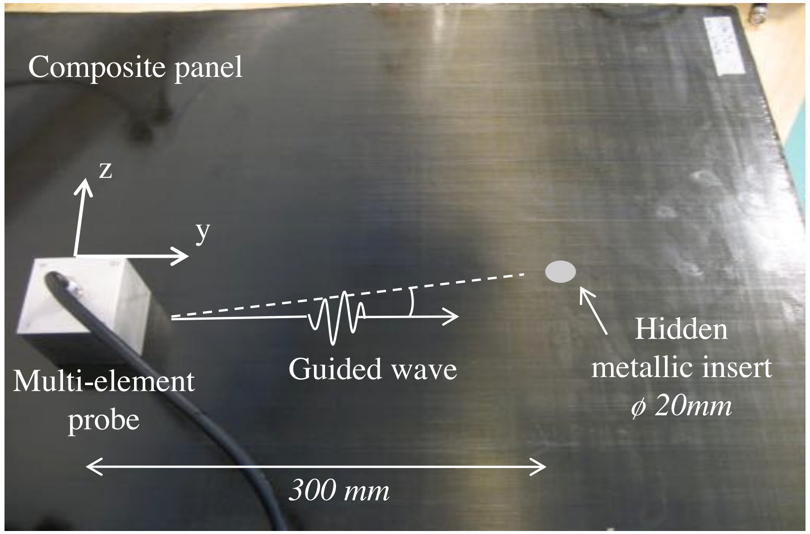
$W_{signal\_drop} \approx 90\ mm$
$W_{transducers} = 70\ mm$

$\Rightarrow\ W_{damage} = W_{signal\_drop} - W_{transducers} \approx 20\ mm$

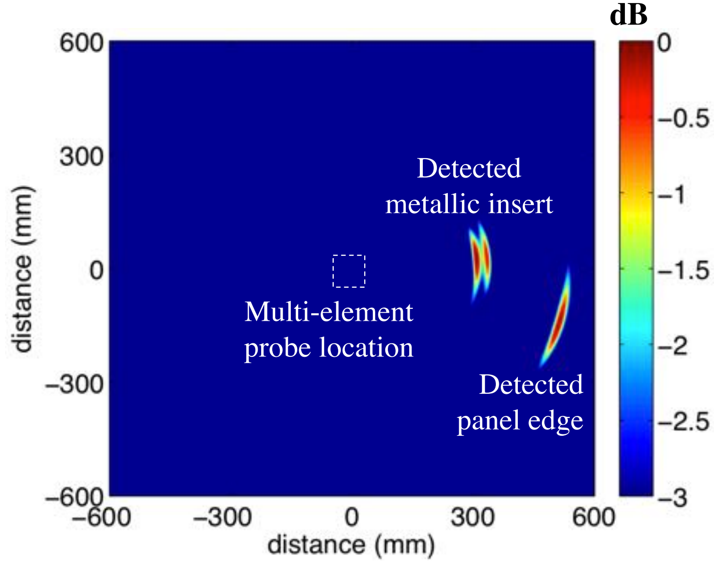
M. Masmoudi, Thèse Univ. Bx 1, Fév. 2012

Inspection of large composite structures using guided waves generated and detected by remote ultrasonic multi-element probe

Ultrasonic multi-element probe is gel-coupled at a fixed position, and electronically driven by multi-channel device to inspect remote (eventually non accessible) zones of large composite panel.



Photography of experimental set-up



Ultrasonic image of panel.

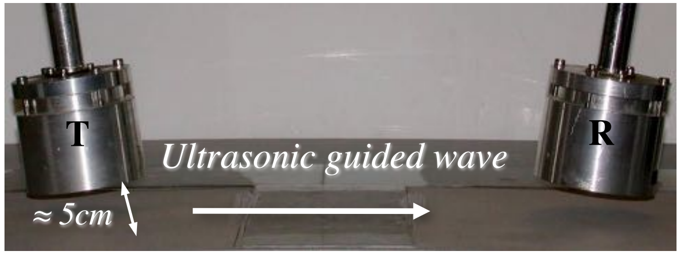
A. Leleux, Thèse Univ. Bx 1, Nov. 2012

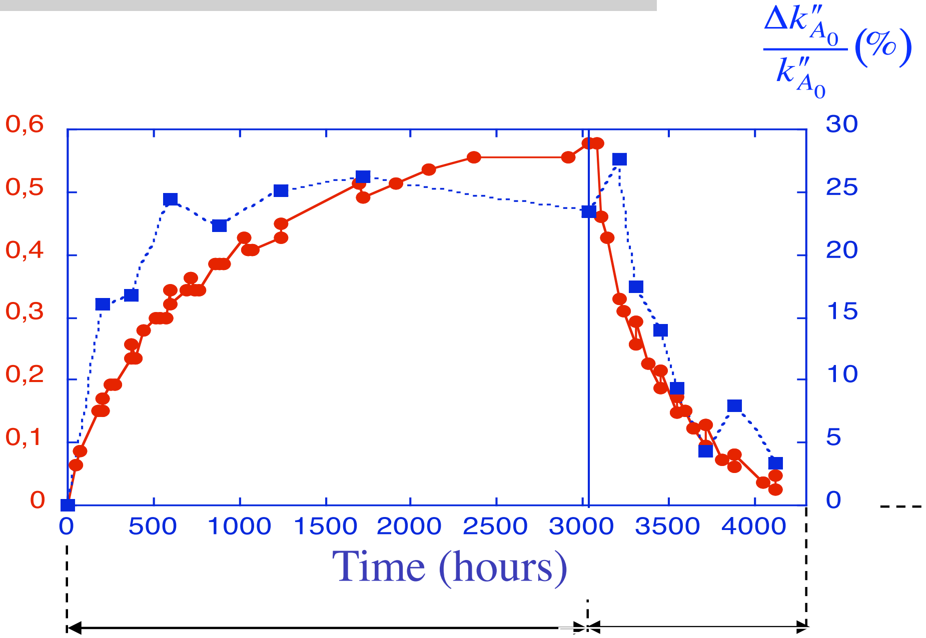
Merci pour votre attention.

Autres techniques US d’E.N.D.

Air-coupled guided waves - Composite materials ageing

Ex.: Health monitoring of moisture content in 5 mm Carbone Epoxy $[0/90]_{6s}$ plates





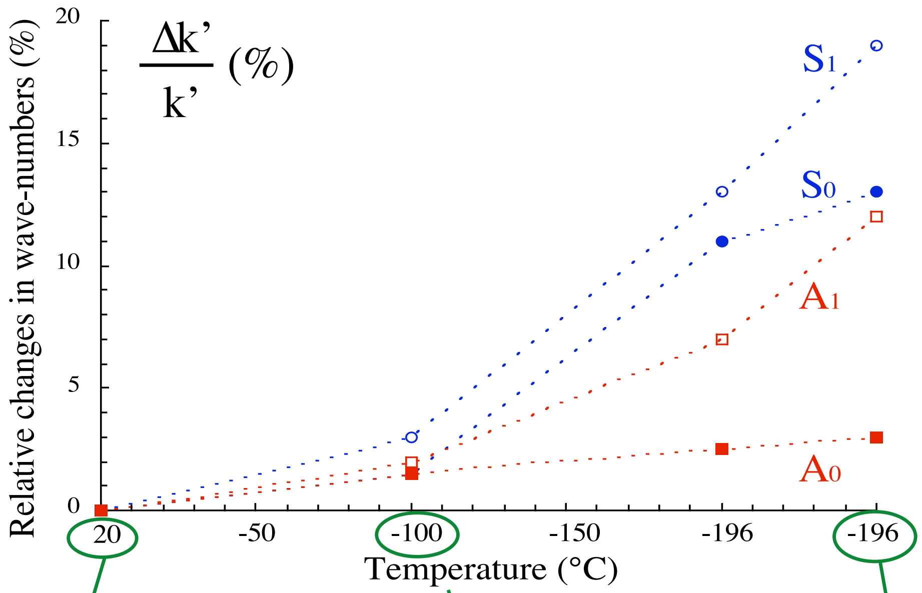
(65°C - 70%H_2O - 4 months) (65°C - 2 months)

Inverse problem

≈ 30% change in imaginary part of Coulomb modulus

ARA = REGION AQUITAINE + UNIVERSITÉ BORDEAUX 1 Sciences Technologies + EADS astrium

Health monitoring of micro-cracking in 16.5 mm thick $[0/+60/-60]_{11s}$ Carbone Epoxy laminate

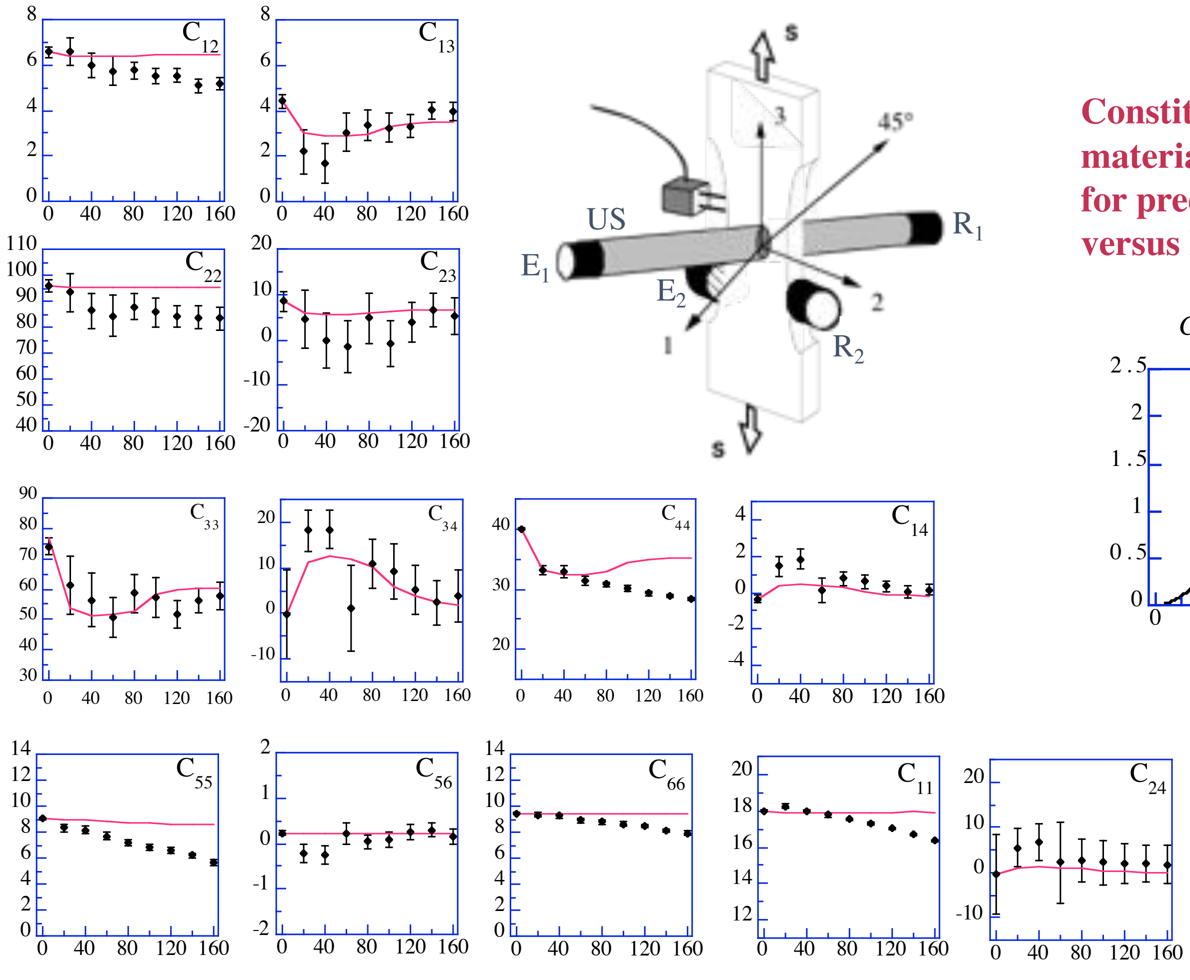


Micrographies

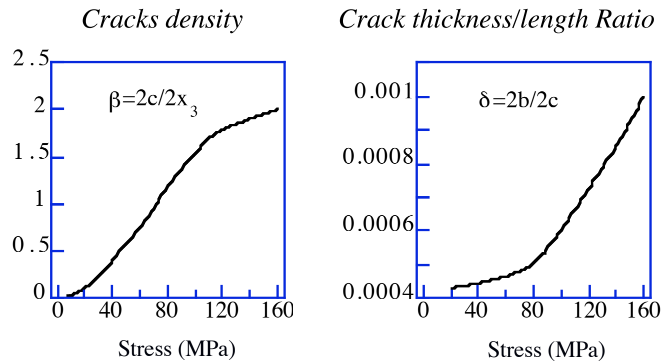
Inverse problem ≈ 10 to 20% decrease of C'_{ij}

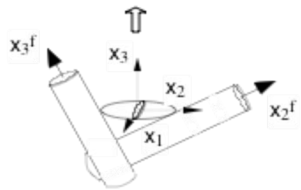
Time of flight immersion technique
Characterization of material anisotropy induced by cracks in composites under load

••• : Experimental evaluation of complete material stiffness (GPa) versus loading (Mpa)

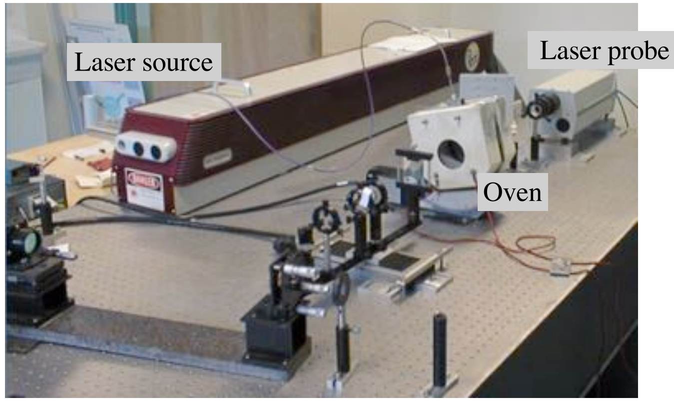


Constitutive law built-in for anisotropic materials with tilted cracks and used for predicting changes in material stiffness versus loading: —

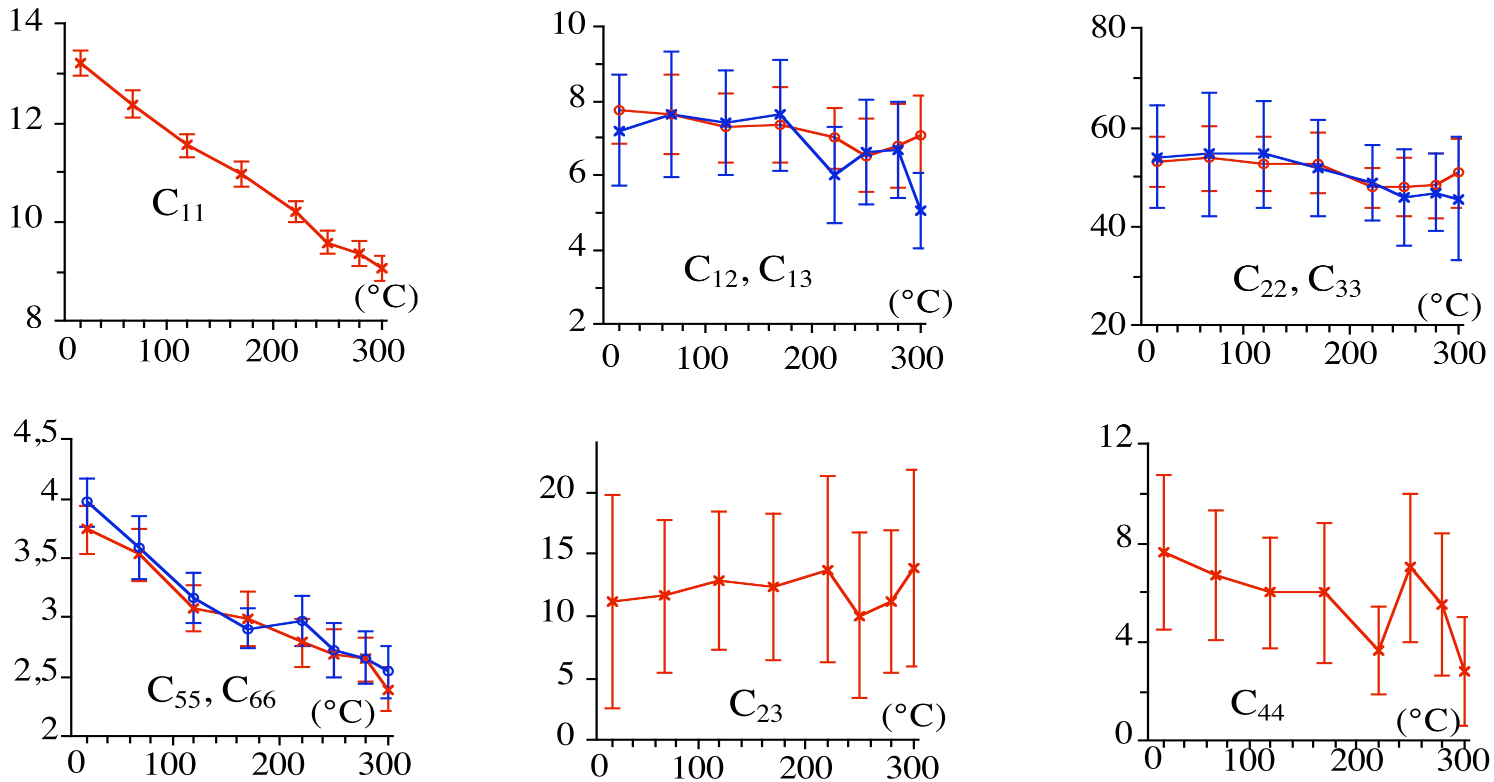




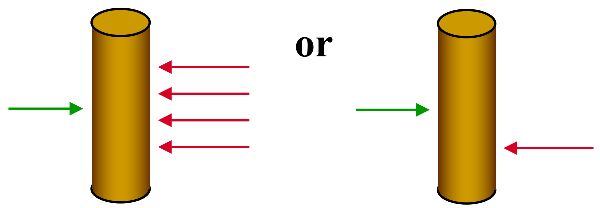
Laser-US for characterization of the anisotropic degradation produced by temperature

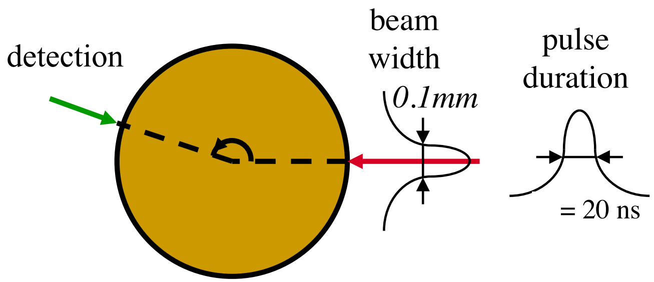


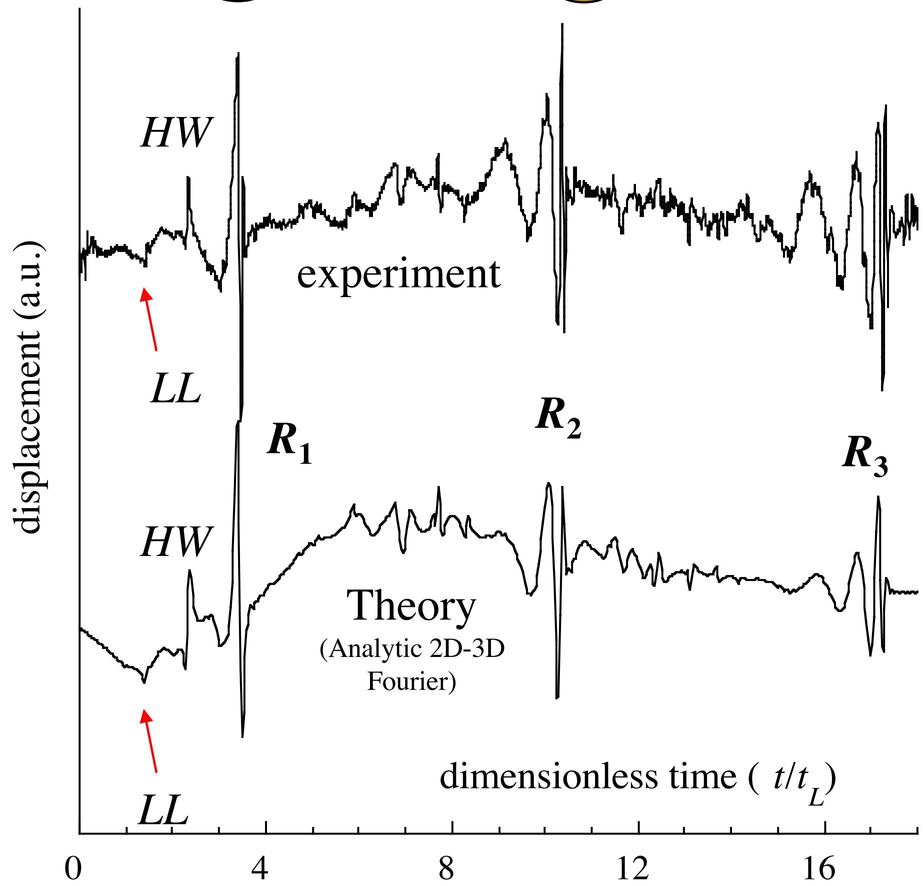
Ex. : Measured elastic moduli (GPa) of 2D woven composite during temperature increase / DGA-SNECMA 1998

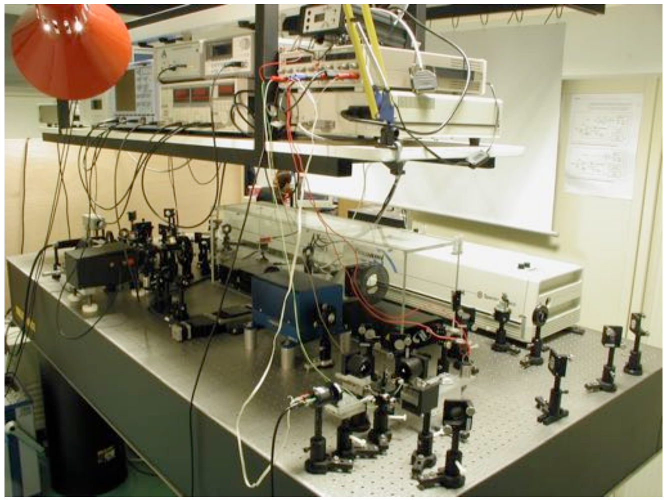


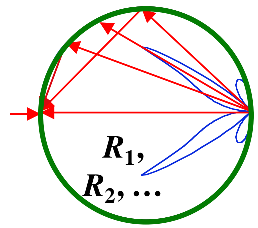
Laser-US for wave propagation in small isotropic or anisotropic cylinders

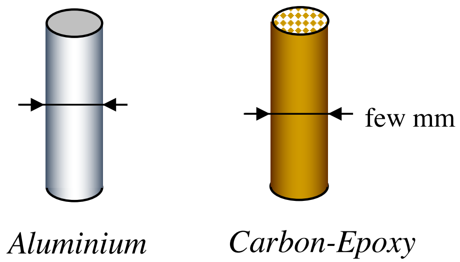








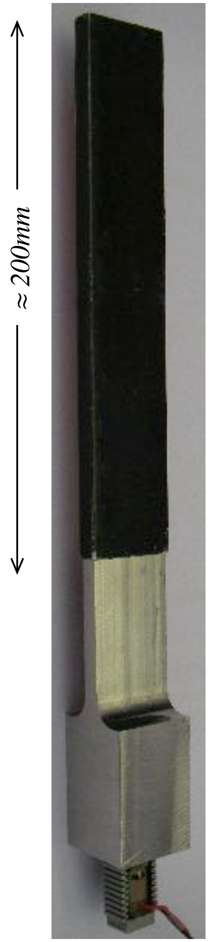


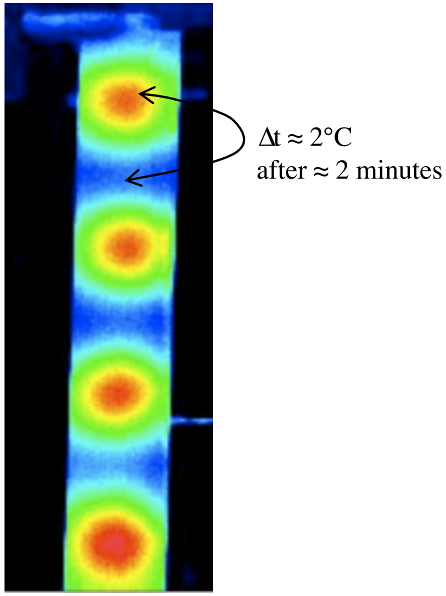


Thermosonics … Viscoelastic propagation of standing waves with energy dissipation causing heating

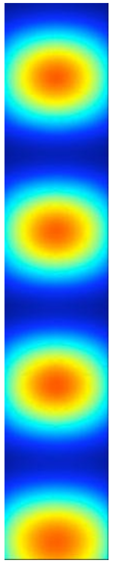
… Measurements + **Linear FE-based model**

Ex.: Preliminary results on 5mm Perspex plate

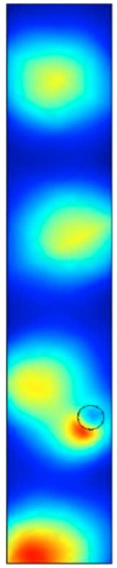




Measurements



FE modelling
No defect

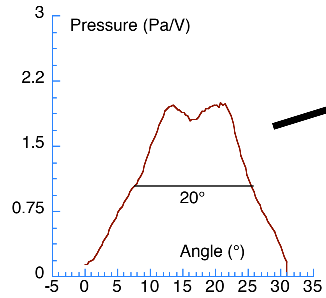


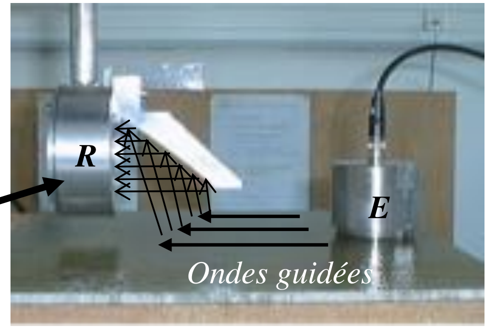
FE modelling
Defect - Linear effects

PROJECT:

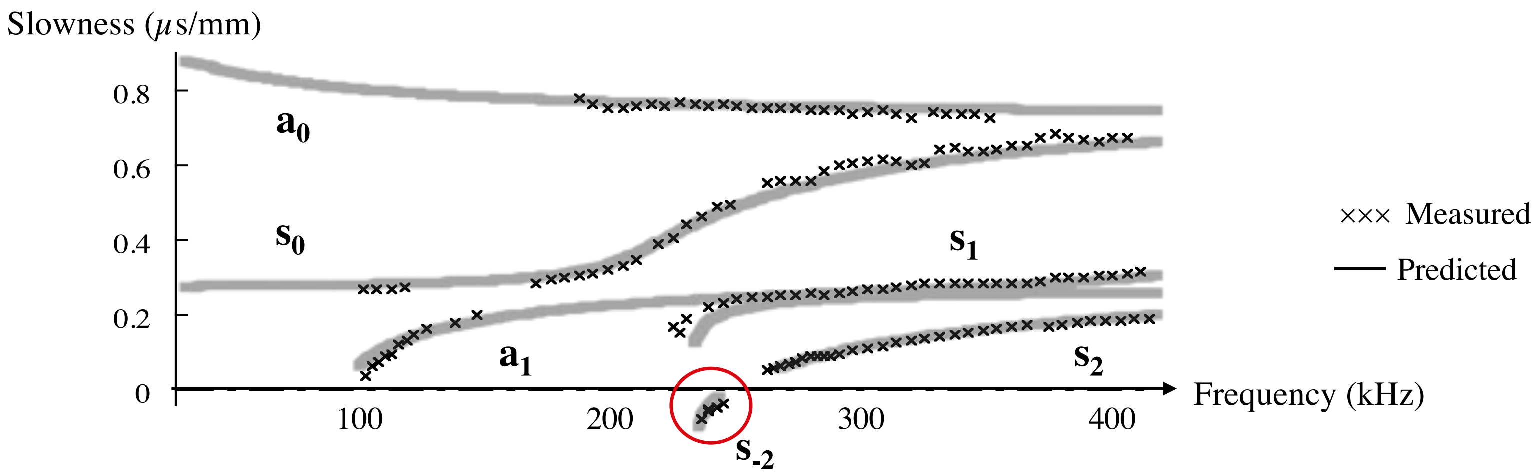
- To perform measurements on composite materials
- To **characterize thermal properties**, **viscoelasticity** and/or **defects** using FE linear model
- To develop non-linear model in order to further **characterize defects** producing non-linear phenomena

Air-coupled guided waves - Material characterization



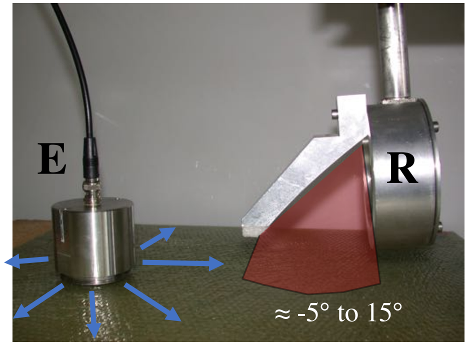


Ex. : Crossed-ply Carbone Epoxy - 5 mm

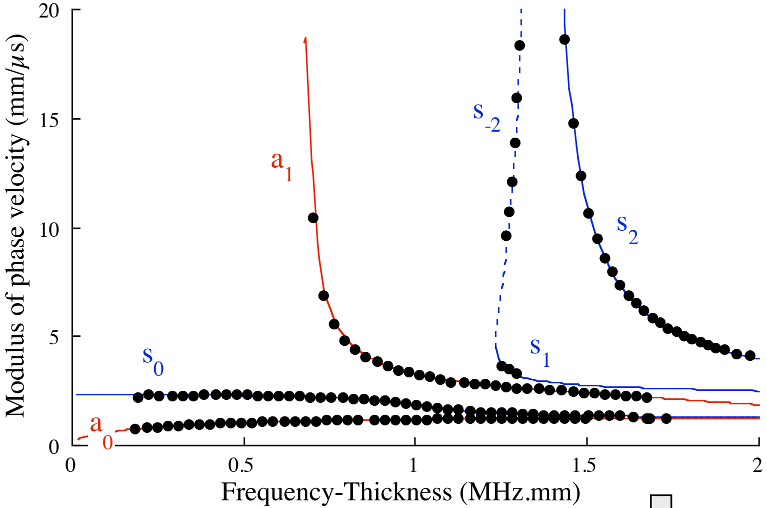


C_{11}	C_{12}	C_{22}	C_{66}	C_{13}	C_{33}	C_{55}	
14 ± 0.3	8.2 ± 0.2	32 ± 3	3.5 ± 0.1	8.1 ± 0.2	30 ± 3	3.4 ± 0.1	GPa

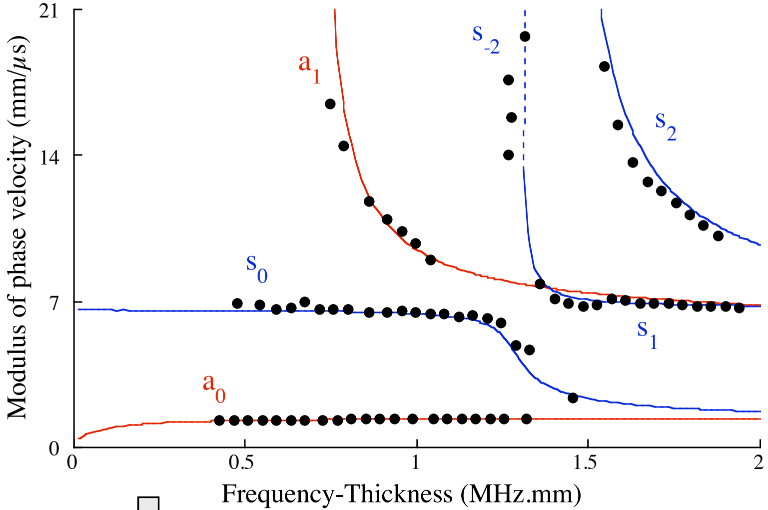
Examples of measured negative phase velocities



Ex. : *3.9 mm Plexiglas plate*



Ex. : *4.2 mm [0°/45°/90°/-45°]$_{6s}$ Carbon-Epoxy plate*



→ *Optimised C_{ij} in plane of propagation (in GPa)*

C_{11} = 8.6 ±0.3	C_{11} = 11.8 ±0.7
C_{22} = 8.7 ±0.3	C_{22} = 75 ± 4
C_{12} = 4.2 ±0.2	C_{12} = 7.3 ±0.4
C_{66} = 2.2 ±0.1	C_{66} = 3.1 ±0.2