Table of content:

Testing Methods

Book ‘Composites for Construction’, L. Bank, Chapter 3.3

Content

- **Introduction**
- **Codes: different tests on different levels**
  - **Fibre and Resin**
  - **Lamina and Laminate**
  - **Full-sections**
- **(Advanced) laboratory testing methods**
  - **Static**
  - **Dynamics**

Introduction

- Experimental determination of properties
  - Mechanical properties:
    - Strength
    - Stiffness
    - Density
    - Fiber Volume Fraction
  - Electrical properties:
    - Electrical Resistivity [Ohm · Meter]
  - Thermal properties:
    - Thermal Expansion Coefficient
    - Thermal Conductivity
  - Chemical resistance …

Introduction

Knowledge of properties is necessary to:

- Design structural elements
  - Ultimate Load (strength)
  - Serviceability (stiffness, strength … fatigue)

- Material selection:
  - Thermal- and electrical insulation
  - Chemical resistance

Introduction

- Tests can be performed on different levels:
  - Fibre / Resin
  - Lamina / Laminate
  - Full-section

- For structural engineering application most testing is performed on lamina/laminate and on full-section level.

- ASTM (American Society for Testing and Materials) and ISO (International Organization for Standards) offer **standardized test methods** for testing fibres, resins, laminas and laminates

Introduction

- Testing procedures have been developed which are directly related to the use of FRP composites in structural engineering.

  ACI … American Concrete Institute

  CEN … European Committee for Standardization

  JSCE … Japan Society for Civil Engineering

  CSA … Canadian Standards Association

- Most testing and specification of FRP profiles concentrate on specifying properties after their manufacturing.

  → Manufacturers provide most of the properties of lamina/laminate and full-section profiles in their product sheets. Be careful: data has to be interpreted!

Testing on Fibre Level

- **ASTM C 1557**
  “Standard Test Methods for Tensile Strength and Young’s Modulus of Fibres”
- Fibre tests are very difficult to perform (handling of single fibres) → it is more practical to determine properties of the structural elements.

Properties Carbon Fiber

Property		Value								
Material		XAS,HTA,T300	34-700, T650/35	UMS2526	HM	HS40	P25	P100	F180	F500
Coefficient of thermal expansion - Longitudinal	$x10^{-6}$ K^{-1}	-0.1to-0.5	-0.6	-0.7	-1.3	-0.5	-	-1.5		
Coefficient of thermal expansion - Transverse	$x10^{-6}$ K^{-1}	+26	-	+37	+25					
Density	g cm^{-3}	1.76-1.8	1.77-1.8	1.78	1.86	1.85	1.87	2.15	-	2.1
Extension to break	%	1.5-1.7	1.7-1.9	1.2	0.8	0.9	1.0	0.3	-	2.1
Filament diameter	µm	7	7	4.8	8	5	11	10	-	9
Precursor		PAN	PAN	PAN	PAN	PAN	Pitch	Pitch	Pitch	Pitch
Tensile modulus	GPa	230-40	230-40	380	350-70	450	140-60	720	180	500
Tensile strength	GPa	3.6-4	4.5	4.9	2.5-2.7	4.4	1.4	2.2	2.0	3.0
Thermal Conductivity	W m^{-1} K^{-1}	17-24	14	46	105	52	22	520		
Volume Resistivity	µOhmcm	1400-1600	1500	1000	900	1000	1300	250	1100	400

Carbon fibre properties, provided by the manufacturer: www.goodfellow.com

Testing on Lamina/Laminate-Level

- Most tests are performed on coupons cut from as-fabricated FRP composite-parts.
- The same tests are performed for lamina and for laminate.
- The material is assumed to be **anisotropic** and **homogenous**
- Additionally, system performance has to be investigated:
  - pull-out test of FRP-reinforcing bars in concrete
  - pull-off (lap-shear) test of CFRP-sheet externally bonded on concrete
  - …

Testing on Lamina/Laminate-Level

TABLE 3.1 Recommended Test Methods for FRP Composites at the Lamina and Laminate Levels

Ply or Laminate Property	ASTM Test Method(s)	Test Required
Mechanical properties		
Strength properties		
Longitutinal tensile strength	D 3039, D 5083, D 638, D 3916	Unidirectional ply and multidirectional laminate
Longitudinal compressive strength	D 3410, D 695	
Longitudinal bearing strength	D 953, D 5961	
Longitudinal short beam shear strength	D 2344, D 4475	
In-plane shear strength	D 5379, D3846	
Impact resistance	D 256	
Transverse tensile strength	D 3039, D 5083, D 638	Multidirectional laminate only
Transverse compressive strength	D 3410, D 695	
Transverse short beam shear strength	D 2344	
Transverse bearing strength	D 953, D 5961	
Stiffness properties		
Longitudinal tensile modulus	D 3039, D 5083, D 638, D 3916	Unidirectional ply and multidirectional laminate
Longitudinal compressive modulus	D 3410, D 695	
Major (longitudinal) Poisson ratio	D 3039, D 5083, D 638	
In-plane shear modulus	D 5379	Multidirectional laminate only
Transverse tensile modulus	D 3039, D 5083, D 638	
Transverse compressive modulus	D 3410, D 695	
Physical properties		
Fiber volume fraction	D 3171, D 2584	Unidirectional ply and multidirectional laminate
Density	D 792	
Barcol hardness	D 2583	
Glass transition temperature	E 1356, E 1640, D 648, E 2092	
Water absorbed when substantially saturated	D 570	
Longitudinal coefficient of thermal expansion	E 831, D 696	
Transverse coefficient of thermal expansion	E 831, D 696	
Dielectric strength	D 149	
Flash ignition temperature	D 1929	
Flammability and smoke generation	E 84, D 635, E 662	

Source: Adapted from Bank et al. (2003).

Testing on Lamina/Laminate-Level

- **Example:** Specification of pultruded profiles **EN 13706**

Tabelle 1 — Übersicht von festzulegenden Eigenschaften und zugehörige Prüfverfahren

	Eigenschaft	Einheit	Prüfverfahren
1.1	Prüfung in Originalgröße	GPa	Anhang D, EN 13706-2
1.2	Axialer Zugmodul	GPa	EN ISO 527-4
1.3	Transversaler Zugmodul	GPa	
1.4	Axiale Zugfestigkeit	MPa	
1.5	Transversale Zugfestigkeit	MPa	
1.6	Axiale Bolzentragfähigkeit	MPa	Anhang E, Teil 2
1.7	Transversale Bolzentragfähigkeit	MPa	
1.8	Axiale Biegefestigkeit	MPa	EN ISO 14125
1.9	Transversale Biegefestigkeit	MPa	
1.10	Axiale, interlaminare Scherfestigkeit	MPa	EN ISO 14130

Testing on Lamina/Laminate-Level

- Determination of tensile properties: (ISO 527-4)
  Test conditions for isotropic and orthotropic fibre-reinforced polymer composites.

- Every detail is defined in the code:
  - Definition of technical terms
  - Technical details of the test unit
  - Test specimen: how to produce, geometry →
  - Applying the Force: Material and form of clamps
  - Measurement: locations, application of gages, velocity [Newton/Minutes] …
  - Data analysis: determination of strain, stress, modules …
  - Structure and content of the test report

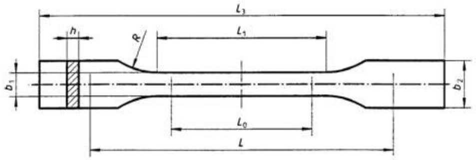


Bild 3: Probekörper des Typs 1B

Tabelle 1: Abmessungen des Probekörpers des Typs 1B

Abmessungen des Probekörpers		Typ 1B (mm)
Gesamtlänge[1])	L_3	≥ 150
Länge des schmalen parallel-seitigen Teils	L_1	60 ± 0,5
Radius	R	≥ 60
Dicke[2])	h	2 bis 10
Breite des schmalen Teils	b_1	10 ± 0,2
Breite an den Enden	b_2	20 ± 0,2
Anfangsabstand zwischen den Klemmen	L	115 ± 1
Meßlänge (für Längenmeßeinrichtungen empfohlen)	L_0	50 ± 0,5

[1]) Für einige Materialien kann es erforderlich sein, daß die Länge der Krafteinleitungselemente erweitert wird (z. B. L_3 = 200 mm), um Bruch oder Gleiten in den Prüfklemmen zu verhindern.
[2]) Es sollte beachtet werden, daß ein Probekörper mit einer Dicke von 4 mm identisch ist mit dem Probekörper des Typs 1B in ISO 527-2 und ISO 3167 : 1993, Plastics — Multipurpose test specimen.
ANMERKUNG: Die Anforderungen an Qualität und Parallelität des Probekörpers sind in Abschnitt 6 angegeben.

Video clip: Mixing of resin

Video clip: Impregnation of composite

Video clip: Cutting of composite tensile test samples

Video clip: Tensile test, resin samples

Video clip: Tensile test, composite samples

Full-section tests

- Due to inhomogeneities and anisotropy in FRP members, the stiffness and strength properties are dependent on the location within the cross-section.

  → for designing purposes this is too complicated!

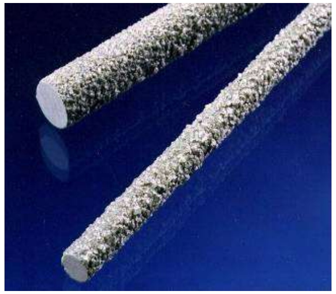
- FRP members are considered to be **homogeneous** on a **full-section level**. (for investigation of local effects, inhomogeneities have to be considered!)

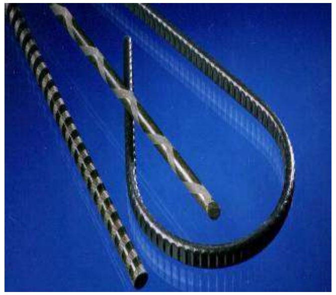
- Full-section test are performed to determine **effective** properties.

- Since the members are quite large, they need special supports and fixation.

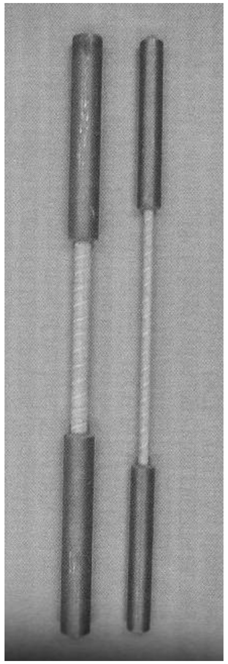
- Three types are distinguished:
  - FRP reinforcing bars
  - Pre-cured strips and sheets
  - FRP profiles

Full-section tests: FRP reinforcing bars





- **ACI 440.3R-04:** Guide Test Methods for FRP for Reinforcing or Strengthening Concrete Structures
- **Part 1:** Definitions etc.
- **Part 2:** Test Methods for FRP Bars for Concrete Structures.
  - **B1:** FRP bars have different cross-sections and surface irregularities, that are required to enhance bond properties → a standardized method has been developed to determine the **nominal cross-section area and diameter.**
  - **B2:** Specification of the test requirements for determination of **tensile strength**, **modulus of elasticity** and **ultimate elongation**.
    (special attention to the clamping is necessary: since the tensile strength is much higher than the transversal, they tend to crush in the grips → it is recommended to embed the bar ends into steel sleeves.



Full-section tests: FRP reinforcing bars

- **B3: Bond strength** of FRP bars by pullout testing.
  The average bond shear stresses are determined and the slip at each load level is calculated.
- **B4: Transverse shear strength** of FRP bars.
  (only used for research and development purposes).
- **B5: Strength of FRP bent bars** and stirrups at bend locations.
- **B6:** Accelerated test method for **alkali resistance of FRP** bars.
- **B7: Tensile fatigue test** for FRP bars
- **B8: Creep rupture of FRP bars**
- …

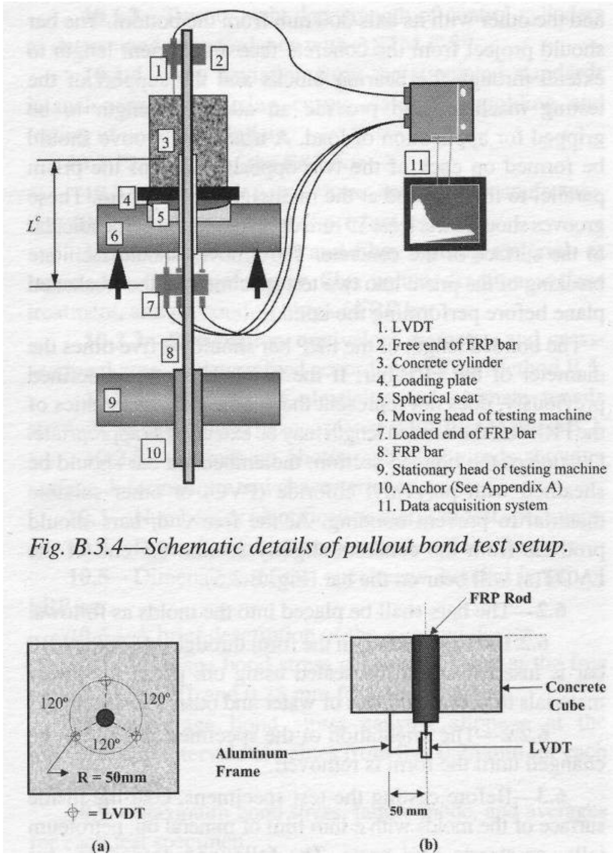


Fig. B.3.4—Schematic details of pullout bond test setup.

Pullout test setup.

Full-section tests: Pre-cured strips and sheets

- Full-section tests are determined in **ACI 440.3R-04 Part 3:** Test methods for FRP laminates for concrete and masonry.
  - **L1:** Direct tension pull-off test. Core drill of square cut through the laminate. The pull-off bond stress is calculated by the measured pull-off force divided by the area.
  - **L2:** Tension test of flat specimen.
  - **L3:** Overlap splice tension test .
- **Important:** all tests have to be performed with panels with the full thickness:

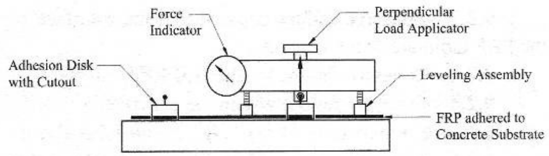


Fig. L.1.1—Direct tension pulloff test setup.

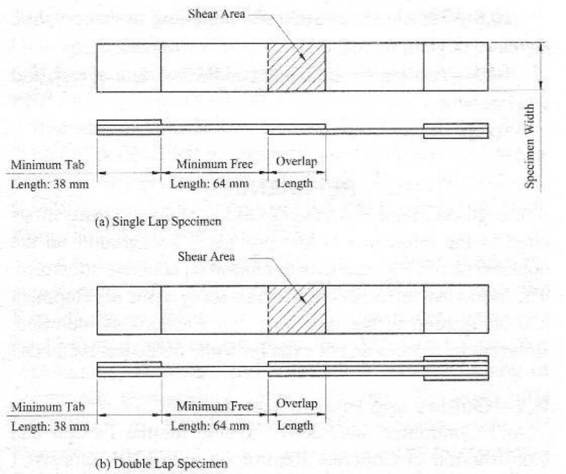


Fig. L.3.1—Overlap tension specimen.

Full-section tests: FRP-profiles

- Since designs of pultruded profiles are often controlled by serviceability and buckling criteria, the stiffness values are needed.
- Since the shear modulus is an order of magnitude smaller then the Young's modulus, shear deformation have to be taken into account.
- Stiffness values are determined by the manufacturer, there exist no standardized approach till now.

Typical stiffness figures and transverse contraction (dry condition)			
		[MPa]	[--]
Modulus of elasticity	$E_{0°}$	23 000 / 28 000	
Modulus of elasticity	$E_{90°}$	8 500	
Modulus in shear	G	3 000	
Poisson's ratio	$\nu_{0°,90°}$		0.23
Poisson's ratio	$\nu_{90°,0°}$		0.09

Material parameters given by www.Fiberline.com

Strength values for use in calculations			
		Short-term value [MPa]	Long-term value [MPa]
Flexural strength, 0°	$f_{b, 0°,d}$	185	75
Flexural strength, 90°	$f_{b, 90°,d}$	75	30
Tensile strength, 0°	$f_{t, 0°,d}$	185	75
Tensile strength, 90°	$f_{t, 90°,d}$	40	30
Compressive strength, 0°	$f_{c, 0°,d}$	185	75
Compressive strength, 90°	$f_{c, 90°,d}$	75	30
Shear strength	$f_{\tau,d}$	20	8

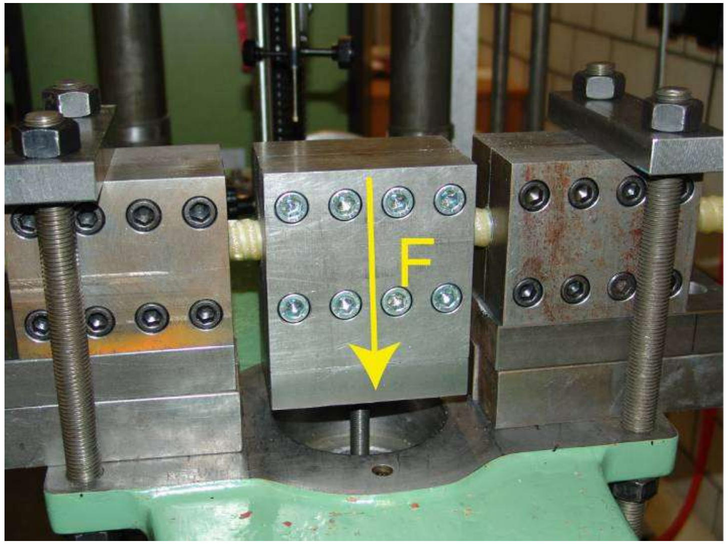
Laboratory testing methods: Statics

- Determine the Young's modulus and tensile strength by tensile testing

Tensile test on a FRP-rebar @ Empa

Tensile force, elongation and longitudinal strains are recorded during measurement.

- Determine the shear modulus by a shear experiment

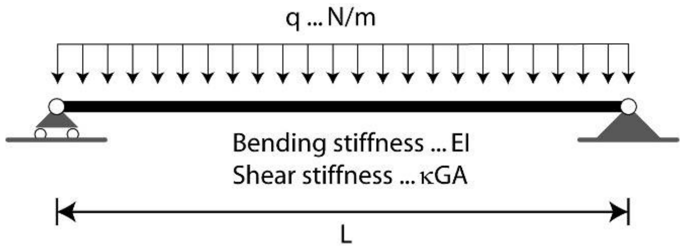


Shear experiment @ Empa

Force and displacement are recorded. Shear modulus and strength can be calculated.

Advanced laboratory testing methods: Static

- Determine Young's and shear modulus by bending tests!



- Deflection at mid-span (Timoshenko Beam Theory)

$$w(L/2) = \frac{5 \cdot qL^4}{384 \cdot EI} + \frac{qL^2}{8 \cdot \kappa GA}$$

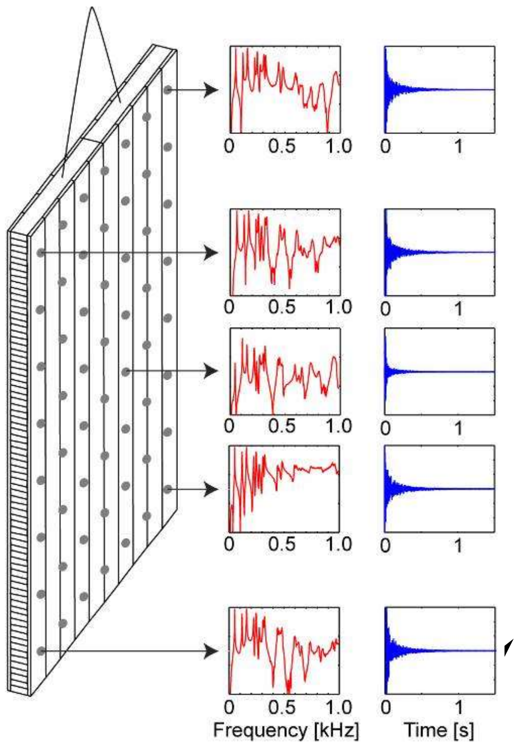
- Since the influence of the shear deformation is differently dependent on the span length L, measuring the mid-span deflection for 2 or more different span lengths, allows determination of κ**GA** and **EI**.

- In practice, experiments are done using point forces (easier to apply)

Advanced laboratory testing methods: Dynamics

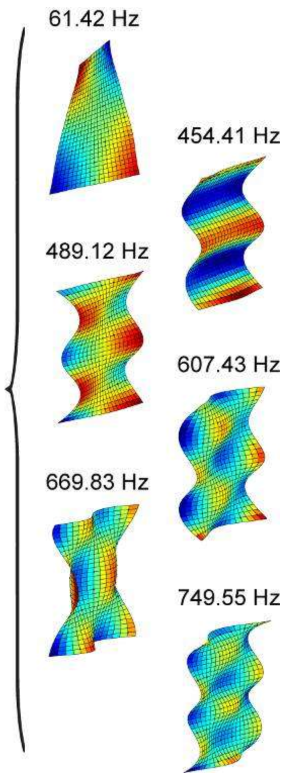
- Determine the stiffness elements based on experimental and theoretical modal analysis.

- **Perform experimental modal analysis with the test specimen**



- Excite the specimen with an impact hammer at different locations.
- Record the answer using accelerometers.
- Calculate the impulse-response functions.
- Analyze the impulse response functions and determine resonance frequencies, associated damping values and amplitudes.
(→ frequencies and mode shapes on the right)

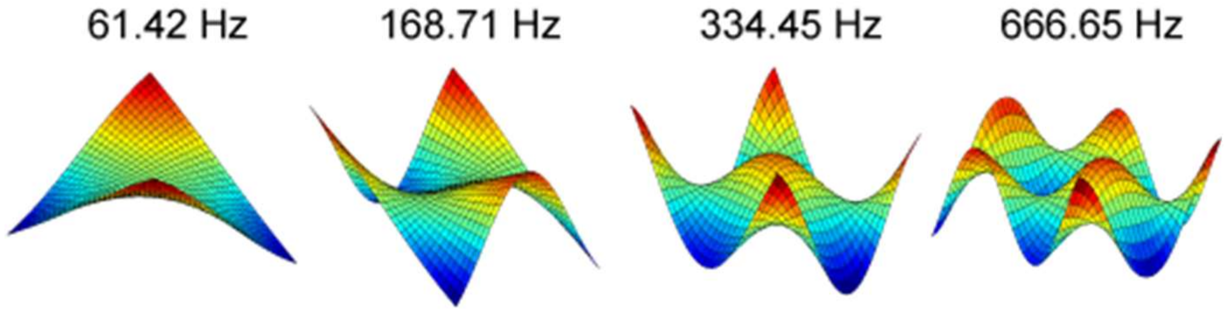
$$u(t) = \sum_{m=1}^{M} a_m \cdot e^{i\cdot(\omega_m + i\cdot\delta_m)\cdot t} + w(t)$$



Advanced laboratory testing methods: Dynamics

- **Use an analytical (or numerical) model of the specimen to calculate frequencies and mode shapes**

$$\int \delta \boldsymbol{\varepsilon}^T \cdot \mathbf{C} \cdot \boldsymbol{\varepsilon} \cdot dV + \int \delta \mathbf{u}^T \cdot \rho \cdot \ddot{\mathbf{u}} \cdot dV = 0$$



- The resonance frequencies and mode shapes are dependent on the stiffness values as well as geometry and density of the specimen !

Advanced laboratory testing methods: Dynamics

- **Use a nonlinear optimization algorithm** (e.g. total least squares) **to match measured and calculated resonance frequencies, by adjusting the "unknown stiffness values"**

$$\min\left(\sum(\mathbf{freq}_{\mathbf{meas}} - \mathbf{freq}(\mathbf{C}_{\mathbf{ij}})_{\mathbf{theo}})^2\right) \rightarrow \mathbf{C}_{\mathbf{ij}}$$

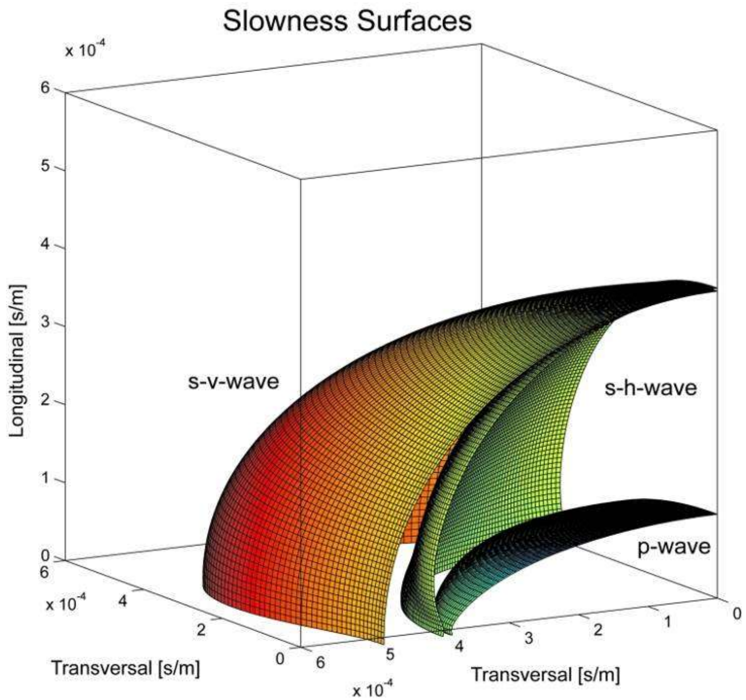
C_{ij} … stiffness values

- Ideally, all relevant stiffness values of a structure can be determined by one single experiment!
- Samples of different geometries can be investigated: *beams, plates, cubes …*
- Compare to the static tests, where large forces have to be applied and the supports have to be designed very carefully, the dynamic test is quite easy, inexpensive and nevertheless very accurate results are obtained!

Advanced laboratory testing methods: Dynamics

- Determine all stiffness parameters using ultrasonic wave propagation.

- In anisotropic materials the velocities of elastic waves are dependent on :
  - the mechanical properties (stiffness and density)
  - the wave type (p- or s-waves)
  - the directions they travel



Picture: Calculated slowness surface (slowness = 1/phase velocity) of an unidirectionally carbon fibre reinforced test specimen. The three surfaces correspond to the three different types of existing waves in the medium.

Advanced laboratory testing methods: Dynamics

- Measuring the velocities of the different wave types travelling in different material directions allows a highly accurate determination of the anisotropic elastic properties.

  See for example: *Joseph L. Rose, Ultrasonic Waves in Solid Media, Cambridge University Press 1999*

- Standard ultrasonic transducers can be used. Depending on the material and geometry frequencies between 50 kHz and 5 MHz are commonly used.

- Time-of-flights are measured.